ULTIMATE
WATER SMART INDUSTRIAL SYMBIOSIS

Deliverable D1.4

New approaches and best practices for closing the energy cycle within symbioses clusters

Disclaimer: This deliverable has not yet been approved by the European Commission and should be seen as draft!

Authors: Kleyböcker, A., Bloemendal, M., Beernink, S., van den Broeke, J., Gimenez Lorang, A., Monsalva, V., Baransi Karkaby, K., Massalha, N., Hassanin, M., Sabbah, I., Pidou, M., Gritti, C., Reguer, A., Deveughele, S., Schütz, J., Bendix Larsen, S., Kristensen, M.

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General

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Author(s)	A. Kleyböcker, M. Bloemendal, S. Beernink, J. van den Broeke, A. Gimenez Lorang, V. Monsalvo, K. Baransi Karkaby, N. Massalha, M. Hassanin, I. Sabbah, M. Pidou, C. Gritti, A. Reguer, S. Deveughele, J. Schütz, S. Bendix Larsen, M. Kristensen
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[1] PU = Public
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Executive Summary

Summary of Deliverable

The European Horizon 2020 ULTIMATE promoted circular economy concepts within the framework of water smart industrial symbioses. It focused on industrial wastewater streams as resource for water, energy and material recovery. ULTIMATE, in nine case studies, developed and demonstrated 24 circular economy related technologies. In six out of the nine case studies, a total of ten energy-related technologies were investigated. These concerned heat recovery, storage and reuse, biogas production and valorisation, as well as a joint control system to increase the energy efficiency of two connected wastewater treatment plants (WWTPs).

Heat recovery, storage and reuse

Solutions for heat recovery, storage and reuse were developed and demonstrated in the ULTIMATE case studies in the Netherlands (Nieuw Prinsenland), United Kingdom of Great Britain and Northern Ireland (Tain) and France (Chemical Platform Roussillon).

The Dutch case study analysed the feasibility of a high temperature – aquifer thermal energy storage (HT-ATES). Excess heat from a geothermal doublet was to be stored in the HT-ATES in summer for its reuse in winter to heat greenhouses. The feasibility study showed that the concept is economically and technically feasible. For a very large greenhouse area, such as the one studied for the Dutch case study, in combination with a geothermal powerplant under construction, a 5-6% reduction in fossil fuel expenditure for the annual heat supply could be achieved. This reduction is very site specific, and in this instance was limited by the very high continuous demand for heat from the plant, which meant only a small excess capacity to supply heat to the HT-ATES was available. In case a heat source with a larger excess capacity is available, for an average sized greenhouse area, a reduction in fossil fuel demand of up to 20-30% of fossil fuel substitution could be expected.

The feasibility study showed that the identification of potential external customers for the energy produced by the recovery and storage systems is very important. Furthermore, the heat source must match (part of) the demand and provide the right conditions for storage or recovery for reuse. Additionally, the quantities of heat supplied must be large enough to make storage and recovery cost effective. In order to ensure economic operation, it is essential to have suitable hydrogeological conditions for thermal energy storage with a sufficiently high recovery factor. In practice, it usually takes several years to obtain permits for drilling and construction of a HT-ATES, which is seen as a barrier to rapid replication of this technology. Therefore, the development and implementation of a regulatory framework for the licensing of a HT-ATES is required to enable the competent authorities to consider HT-ATES licence applications in a consistent manner. Accelerating the permitting process for an HT-ATES (<1a) and promoting the demonstration of full-scale pilot plants will contribute significantly to its

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replication. It is therefore necessary to develop appropriate policies and to demonstrate in practice that HT-ATES is a renewable, clean and safe technology.

The Scottish case study investigated the reuse of heat from the effluent of an anaerobic membrane bioreactor (AnMBR) to reduce operating costs by reducing the energy or chemical consumption of two processes: RO filtration and ammonia stripping. Increasing the process temperature of the ammonia stripping process allows the pH to be reduced and NaOH to be saved. Increasing the temperature of the RO filtration reduces the viscosity of the water to allow a lower transmembrane pressure and therefore saves energy. For the filtration process, the available heat was sufficient to increase the flux by 11% and to save energy. However, for the ammonia stripping, the available heat alone was insufficient. An additional heat source was required to achieve the desired pH reduction and to decrease the demand for chemicals.

The French case study investigated the reuse of heat from an incineration process at a hazardous waste incinerator to produce electricity using the Organic Rankine Cycle (ORC) or to produce steam using a heat pump. Neither option proved to be technically or economically feasible. Either the residual heat recovery rates were below the target of 25% or the steam production would have to be on such a large scale that the capacity of the existing technical system would be too small. In parallel with the feasibility studies, an application for data monitoring and analysis was developed and successfully tested. This application was designed to be easily adaptable to other heat recovery concepts and to serve as a basis for future concepts.
The French feasibility study showed that minimising the distances between the systems to avoid heat losses and maximise the benefits of increased temperature in each system had a very large impact on the feasibility of the concepts. In addition, pipe and system insulation was critical to avoid losses even in colder climates and a carbon impact assessment was necessary to assess its overall carbon footprint.

Biogas production and utilisation

Solutions for the production and use of biogas were developed and demonstrated in Spain (Lleida) and in Israel (Karmiel and Shafdan).

In the Spanish case study, a new high-rate anaerobic reactor, called electrostimulated anaerobic reactor (ELSAR), was implemented as a full-scale pre-treatment of brewery wastewater. This was the first application of ELSAR on this scale in the world. In addition to the conventional anaerobic treatment processes, an integrated bioelectrochemical system enables electroactive microorganisms to oxidise organic matter and release electrons to the anode, hydrogen ions and CO_2. The different biochemical pathways allow for high flexibility and a stable biogas production process. During commissioning, the ELSAR was successfully operated at an organic loading rate (OLR) of 12.5 kg COD/(m^3*d) and has the potential to treat 25 kg COD/(m^3*d). The COD removal rate was between 90 and 96% and the average methane yield was 0.34 m^3 CH_4/(kg COD). The ELSAR is able to treat fluctuating OLRs, allows for short

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stabilisation times after shock loads and has a higher calorific value of the biogas due to a higher H_2 content. At the case study level, the ELSAR successfully reduced the energy demand of the industrial wastewater treatment plant by 10%. This was achieved by treating only 33% of the brewery's wastewater, which is equivalent to 500 m^3/d.

The ELSAR system was combined with an anaerobic membrane bioreactor (AnMBR) to improve effluent quality. However, the improved effluent quality did not seem to compensate for the increase in operating costs (gas for sparging, chemicals for cleaning the membranes, etc.) and capital costs for membranes, tank for membranes and pipelines including recirculation, etc., despite lower effluent taxes.
The investigations showed that for an optimal performance of the ELSAR and an AnMBR, equalised, between pH 6 and 8, warm, sulphate-light and biodegradable wastewaters such as brewery wastewater were essential. The higher the content of biodegradable COD in the substrate was, the greater the benefits over traditional aerated alternatives were in terms of operational expenditures and biogas profits. Furthermore, the higher the price of electricity, gas (or heat) or sludge treatment, the more attractive the anaerobic processes became.

In addition, a solid oxide fuel cell (SOFC) was successfully tested in Lleida at pilot scale using biogas to produce electricity and heat as by-product. Compared to a combined heat and power system, which is the state of the art for producing electricity and heat from biogas, the SOFC had a higher electrical efficiency of 50%. As the Spanish case study had a higher demand for electricity than for heat, the higher electrical efficiency was a big advantage in this case. As a result, 30% more energy could be recovered and reused to replace fossil fuels in Lleida.
The draft of the new Urban Wastewater Directive foresees the energy self-sufficiency of WWTPs to which the SOFC technology could make a significant contribution, if biogas is produced on site. However, public support for the grid injection of biogas in the form of biomethane could negatively influence the market uptake of SOFCs. Hence, as a next step to full implementation, a techno-economic market study for a 60-250 kW SOFC is planned by the Spanish partners to better understand the potential of the SOFC solution.

In the Israeli case study, another innovative anaerobic reactor was successfully tested for olive mill, winery, slaughterhouse and dairy effluents. In particular olive mill wastewater (OMW) contains a high fraction of polyphenols, which can lead to a microbial inhibition at certain concentrations. Removal of these inhibiting substances will greatly improve the treatability of the wastewater. In this case study, an innovative anaerobic immobilised high-rate reactor (AAT) was used as stand-alone treatment and in a combination with activated carbon and an anaerobic membrane bioreactor. In Karmiel, a pilot AAT treated a mixture of municipal and OMW at an OLR of maximum 11 kg COD/(m^3*d) with an OMW fraction of 2-3 kg COD/(m^3*d) and a total flow rate of 100 m^3/d. The COD removal rate and methane yield were between 40-55% and 0.04-

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0.06 m^3 CH_4/(kg COD), respectively. An innovative combination of the AAT with an activated carbon treatment and an AnMBR was piloted at Shafdan. However, due to the war in Gaza and Israel, the pilot could not be operated until the end of the project. Therefore, laboratory experiments were conducted that showed the successful treatment of agro-industrial wastewater with municipal wastewater (mWW) with the AAT concept. At a maximum OLR of 11 kg COD/(m^3*d), 83-86% COD removal and a methane yield of 0.29 m^3 CH_4/(kg COD) were achieved. Both systems successfully removed between 18-52% of the polyphenols. At the case study level, the anaerobic treatment systems have the potential to reduce the energy demand of the WWTPs between 20 and 50%.

The Israeli case studies showed that low temperatures (< 18 °C) over a long period, such as in winter, had a negative effect on the biogas production performance. In addition, OMW contained inhibiting compounds such as polyphenols. Their accumulation inhibited anaerobic microbial activity and a higher OLR of OMW than 3-4 kg COD/(m^3*d) in addition to mWW was found to be the limiting factor for the biogas production performance. Results on successfully recovering polyphenols from OMW to avoid microbial inhibition are presented in deliverable D1.5. The combination of the AAT with an AnMBR showed that their separation was essential to ensure adequate performance and protection of the membrane unit from the anaerobic biomass and solids, as high TSS loads significantly damaged the membranes. Despite the technical findings, acceptance of the technology by the stakeholders (e.g. Ministry of Environmental Protection and the Water Authority) was identified as the most important and critical factor prior to full implementation.

Increase in energy efficiency through a joint control system for two connected WWTPs

In the Danish case study, a joint control system was implemented at two interconnected WWTPs. There, an industrial WWTP (iWWTP) pre-treats wastewater from the biotech sector, before it enters a municipal WWTP (mWWTP), where the industrial wastewater is mixed with municipal wastewater for further treatment. The joint control system was designed to provide early warnings of nitrogen shock loads from the iWWTP. This allowed the aeration system at the mWWTP to be operated based on the actual aeration demand and prevented over-aeration. In three months of operation, the demand driven aeration increased the energy efficiency of the entire plant, resulting in a 15% reduction in its energy consumption. This increase in energy efficiency still needs to be validated over a longer period of operation and also with actual nitrogen shock loads from the iWWTP.

A trusting relationship and very good communication between the two plant operators were a prerequisite for the practical implementation of the joint control system. The modelling of the mWWTP helped to identify the potential for optimisation of the aeration system and data quality was of significant importance. The joint control system was designed to use real-time data from different sensors at different locations in the iWWTP. In this way, gradual alerts were generated 37 h, 70 min and 0 min before the

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industrial wastewater entered the mWWTP, allowing the operator to confirm the early alerts and to control data quality.

EU-added value of the deliverable

Energy-related technologies were developed and demonstrated in five different European countries and Israel, where the WSIS proved to be a very suitable framework for the implementation of the technologies in the real word and their successful operation. Table 1 provides on overview about the summarised results.

The comparison of innovative anaerobic technologies, such as the ELSAR and the AAT and AAT/AC/AnMBR, showed a high potential of all technologies for the treatment of wastewater from the agro-food and beverage industry with high organic loadings, as all systems were quite resistant to process disturbances and were able to stabilise the biogas production process in short periods of time, even if the OLR and/or process temperature were fluctuating.

The HT-ATES was shown to be a technically and economically feasible concept having the potential to substitute between 5 and 30% of fossil energy for heating, depending on the size of the system. The HT-ATES has a high replication potential for industries/suppliers having a high seasonal demand for heat such as greenhouses, district heat suppliers, process industries needing low grade heat. Target sectors to form a WSIS are geothermal plants, waste incineration plants, refineries and steel and concrete producing industries, which are spatially close to a potential end-user.
Reuse of heat from industrial effluents to increase the flux in a subsequent filtration process was also shown to be successful and is suitable for all effluents with temperatures of 35 °C and above. It has a high replication potential for distillery effluent.

Both the joint control system and the SOFC reduced the energy demand of the associated WWTP by 15 and 50%, respectively. The joint control system has a high replication potential for all types of WWTPs that are interconnected. However, a minimum of 4 sensors is needed for its implementation and the modelling of the system is recommended in order to determine the new aeration strategy. The SOFC has a high replication potential for WWTPs with an integrated anaerobic treatment. However, a techno-economic market study is recommended first.

The energy recovery concepts and results were discussed in workshops (D1.10) and allowed the project partners, together with the partners from their sister projects (B-WaterSmart, REwaise, WiderUptake and WaterMining), to learn from each other and to identify the need for common policy recommendations. These were the need for stable prices for upgraded biogas and electricity, the need for a Europe-wide minimum quota of biomethane in the gas grid, as is already the case in Denmark, the need for simplification of administrative formalities and financial support related to the gas grid connection, the need for a legal framework for the approval process of a HT-ATES and

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its acceleration and the need for further demonstration and research projects especially for HT-ATES and SOFC systems.

The energy recovery technologies can make a significant contribution to achieving the objectives of the European Green Deal. For further promotion and replication of the technologies in Europe and worldwide, the technologies are presented in the Technology Evidence Base (D1.7) of the Water Europe Marketplace. The Water Europe Marketplace enables the matching of problem owners and solution providers. Through the scientific assessment of the technologies, as presented in this deliverable and also in the environmental, cost and risk assessments (D2.2), problem owners can have access to an honest and neutral assessment of the technology performance, which increases their confidence in the technologies and hence, their willingness to invest in them.

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Table 1 Summary of ULTIMATE energy recovery technologies showing their capacities, KPIs and feasibility

CS	Technology	TRL	Energy type produced or saved	Inflow flowrate/ capacity	Energy recovery rates (KPIs)	Feasibility and/or successful operation
2	HT-ATES	5→7	Heat for greenhouses	244-410 m³/h 15-25 MW	65-80% thermal energy recovery of HT-ATES	Technically and financially feasible
5	ELSAR	5→7	Biogas	500 m³/d 25 kg COD/m³/d	0.34 m³ CH_4/(kg COD) 90-96% COD removal	Successful full-scale operation
5	SOFC	7→9	Electricity	10 m³ biogas/d	1.3 kW electricity with electrical efficiency of 55%	Successful pilot operation
6	AAT	5→8	Biogas	100 m³/d 9-11 kg COD/m³/d 99.5 vol.-% mWW 0.5 vol.-% OMW	0.04-0.06 m³ CH_4/(kg COD) 40%-55% COD removal 18-47% polyphenol removal	Successful pilot operation
6	AAT+ AC/AnMBR	5→6	Biogas	2.4-18 L/d 1.5-11 kg COD/m³/d 99 vol.-% mWW 1 vol.-% OMW	0.29 m³ CH_4/(kg COD) 83-86% COD removal 52% polyphenol removal	Successful lab-scale test (pilot plant in Shafdan successfully construc-ted, but no operation possible due to war)
7	RO filtration	5→6	Heat reuse for RO filtration	0.1L/s inflow to RO	T increase: 20 °C → 30-40 °C flux increase by 11%	Successful lab-scale operation
7	Ammonia stripping	5→7	Heat reuse for ammonia stripping	0.5 m³ WW/h inflow to stripping unit	T increase: 20 °C → 60 °C enables lower pH conditions (11 → 9) in stripping process	Successful lab-scale operation, but additional energy required
8	ORC	2→4	Heat reuse for electricity production	Cooling water: 190-230 m³/h Flue gas: 60 000 Nm³/h	Energy recovery yields: Cooling water:5% Flue gas: 0.6%	Economically not feasible
8	Heat pump	2→4	Heat reuse for steam production	Cooling water: 190-230 m³/h	Energy recovery yields: 16, 32 and 49%	16%, 32%: neither economically 48%: nor technically feasible
9	Joint control system	5→8	Energy for aeration saved	Appr. 20.000 m³ WW treated in mWWTP	Increase in energy efficiency by 18%	3 months of operation → results need to be confirmed with a longer time in operation

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Abbreviations

AAT	Advanced anaerobic treatment: high-rate immobilised anaerobic reactor
AC	Activated carbon
AD	Anaerobic digestion
AnMBR	Anaerobic membrane bioreactor
ASM	Activated sludge model
ATEX	Atmospheres explosibles (explosive atmosphere)
CAS	Conventional activated sludge
CAPEX	Capital expenditures
CC	Carbon cloth
CE	Circular economy
CHP	Combined heat and power plant
COD	Chemical oxygen demand
COD/E	COD removed/(energy consumption of the whole plant)
CS	Case study
CSO	Combined sewer overflow
DAF	Dissolved air flotation
DM	Dry matter
DO	Dissolved oxygen
Ei	Overall model efficiency
ELSAR	Electrostimulated anaerobic reactor
EQN	Effluent quality index (nitrogen)
fA	XI/(particulate COD)
fB	ISS/TSS
fS	SI/(total COD)
fCOD	Fraction of SS from bio-degradable COD
FC	Fuel cell
GAC	Granular activated carbon
GMP	Good modelling practice
HRT	Hydraulic retention time
HT-ATES	High-temperature aquifer thermal energy storage
IQN	Influent quality index (nitrogen)
ISS	Non-volatile (inert) suspended solids
iWW	Industrial wastewater
iWWTP	Industrial wastewater treatment plant
JCS	Joint control system
KPI	Key performance indicator
ME	Mixing energy
MLSS	Mixed liquor suspended solids
MWCO	Molecular weight cut off
mWW	Municipal wastewater
mWWTP	Municipal wastewater treatment plant

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N/E	Nitrogen removed/(energy consumption of the whole plant)
NSE	Nash-Sutcliffe efficiency
oDM	Organic dry matter
OLR	Organic loading rate
OMW	Olive mill wastewater
OPEX	Operational expenditures
ORC	Organic Rankine cycle
PE	Pumping energy
PES	Polyether sulphone
PLC	Programmable logic controller
pWW	Power plant wastewater
RAS	Return activated sludge
R&D	Research and development
RMSE	Root mean square error
RO	Reverse osmosis
RTU	Remote terminal unit
SAE	Standard aeration efficiency
SC	Secondary clarifier
SCADA	Supervisory control and data acquisition unit
SOFC	Solid oxide fuel cell
SOTR	Standard oxygen transfer rate
SRT	Sludge retention time
SVI	Sludge volume index
TMP	Transmembrane pressure
TN	Total nitrogen
TOC	Total organic carbon
TP	Total phosphorus
TRL	Technology readiness level
TSS	Total suspended solids
VFA	Volatile fatty acid
VOC	Volatile organic compounds
VSS	Volatile suspended solids
WAS	Waste activated sludge
WSIS	Water smart industrial symbioses
WW	Wastewater
WWTP	Wastewater treatment plant

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1. Introduction

The Green Deal aims to make Europe climate neutral by 2050. Circular economy is an important step towards this goal. In this frame ULTIMATE aims to promote, establish and extend water smart industrial symbioses (WSIS) between the industrial sector and service providers of the water sector. Industrial symbiosis is the association between industrial facilities or companies in which the waste or by-products of one become raw materials for another - a win-win situation for both partners. In WSIS water/wastewater plays a key role both as a reusable resource per se but also as a vector for energy and materials to be extracted, treated, stored and reused. For example, wastewater can be used as a valuable resource for water reclamation. In wastewater treatment, synergies often allow energy to be recovered at the same time (Figure 1). Wastewater contains energy in the form of biomass and heat. Its recovery and reuse can contribute significantly to reducing the global warming potential of a water reclamation treatment system.

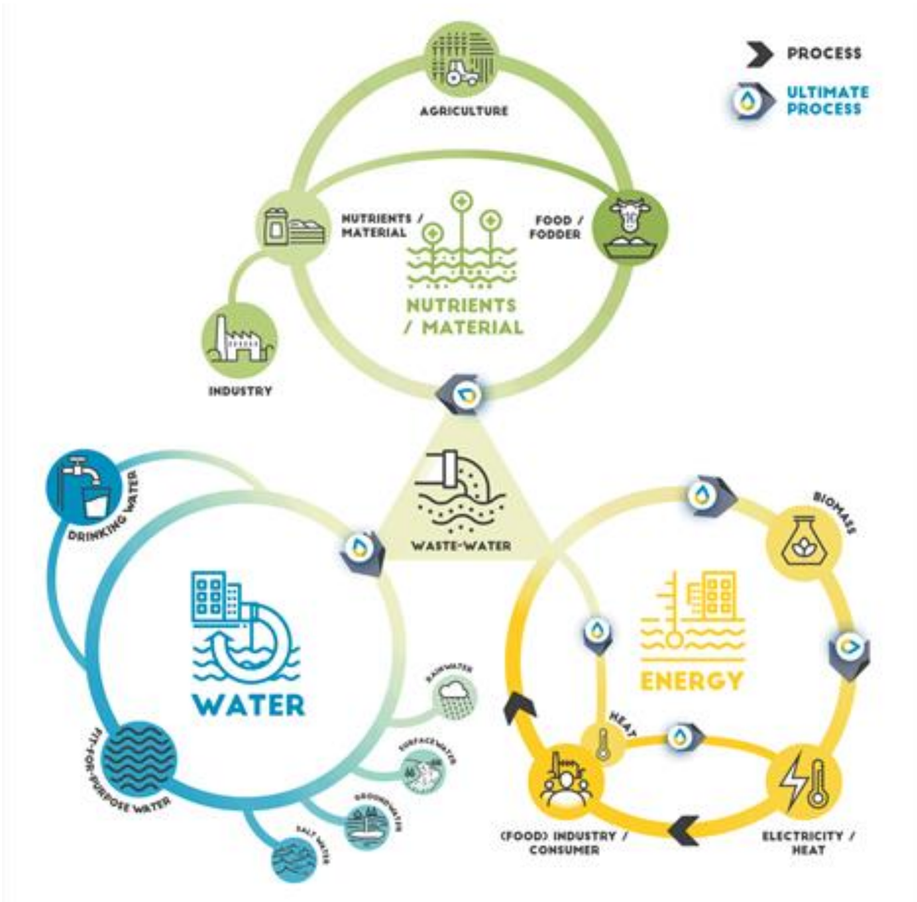

Figure 1 Wastewater is a valuable resource for water, material and energy recovery: ULTIMATE icon indicates, where the ULTIMATE technologies contribute to recover the corresponding products.

ULTIMATE developed, investigated, optimised and demonstrated 24 CE technologies in and for the water sector. The CE technologies related to water recovery and reuse, material and energy recovery and were operated within water smart industrial symbioses (WSIS) clusters. WSIS are a form of partnership between the industry, such

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as the (petro-)chemicial, beverage, agro-food and biotech industries, and the water sector represented by e.g. utilities or service providers (Figure 2).

Figure 2 *Water Smart Industrial Symbioses (WSIS) between the industrial and water sectors represented by different service providers*

The WSIS were showcased at nine case studies distributed across Europe and Israel (Figure 3).

Figure 3 *Location of ULTIMATE case studies*

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This deliverable is one of three deliverables that present the results of the ULTIMATE technologies and focuses on energy recovery. D1.3 (Naves Arnaldos et al. 2024) and D1.5 (Gonzalez Camejo et al. 2024) deal with water recovery and reuse and material recovery, respectively. Table 2 provides an overview of the case studies and energy recovery technologies conceptualised, developed, optimised and demonstrated in ULTIMATE.

Table 2 Overview about the energy recovery related case studies in ULTIMATE showing the resource for energy recovery, the used technology and the end product; feasibility studies are indicated in grey

Case study	Resource	Technology	Energy Product
CS2 Nieuw Prinsenland	Geothermal heat	High temperature – aquifer thermal energy storage (HT-ATES)	Heat
CS5 Lleida	Brewery wastewater	Electrostimulated anaerobic reactor (ELSAR)	Biogas
CS5 Lleida	Brewery wastewater	Anaerobic membrane bioreactor (AnMBR)	Biogas
CS5 Lleida	Biogas	Solid oxide fuel cell (SOFC)	Electricity and heat
CS6 Karmiel	Municipal wastewater + olive mill wastewater	Advanced anaerobic treatment (AAT): high-rate immobilised anaerobic reactor	Biogas
CS6 Shafdan	Municipal wastewater + olive mill wastewater	AAT with anaerobic membrane bioreactor (AAT/AnMBR)	Biogas
CS7 Tain	Distillery wastewater	Low-grade heat recovery for heat reuse in ammonia stripping and for reverse osmosis filtration	Heat
CS8 Chemical platform of Roussillon	Washing water from hazardous waste incineration	Heat recovery	Heat
CS9 Kalundborg	Industrial + municipal wastewater	Joint control system to increase energy efficiency of two WWTPs	Increased energy efficiency

The objective of this deliverable is to explain the innovative ULTIMATE energy recovery solutions, to present their performance, to demonstrate their technical feasibility and to provide recommendations for best practice implementation and application of the technologies under different process conditions.

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2. ULTIMATE technologies and new approaches for energy recovery

The sections in this chapter present the concepts and outcomes of the case studies related to energy recovery.

2.1. Aquifer thermal energy storage and recovery for Nieuw Prinsenland (NL)

Martin Bloemendal (KWR), Stijn Beernink (KWR), Joep van den Broeke (KWR)

2.1.1. Case study and ULTIMATE concept

Case study description

This case study investigated the possibilities of industrial symbiosis in the greenhouse horticulture in the Netherlands. In the Netherlands, well over 9000 ha. of greenhouses is used for the production of fruits, vegetables and ornamental crops. The sector is economically important, contributing approximately 1% to the Dutch GDP. The majority of greenhouses in the Netherlands is artificially heated; under the Dutch climatologic conditions the growing of Mediterranean and/or (sub)tropical crops (such as tomato, cucumber, aubergine) requires additional heating during the winter half-year. Greenhouses are traditionally heated using natural gas fired boilers. To improve the sustainability of the sector, the heating demand should be reduced or alternative heat sources for heating should be implemented. Fossil free heating of greenhouses is pioneered in the Netherlands.

Figure 4 Greenhouse Horticulture in the Netherlands

Geothermal energy can be used as an alternative source of heat for greenhouses. However, geothermal systems typically produce excess heat in summer, while capacity in winter is not enough to meet peak demand. By storing the produced heat in summer and delivering this in winter during peak demand increases utilisation of available geothermal heat and reduces emissions. Hence, the combination of a geothermal system and HT-ATES allows for optimal utilisation of the available heat as well as cost effective and carbon free supply of peak demand,

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Figure 5.

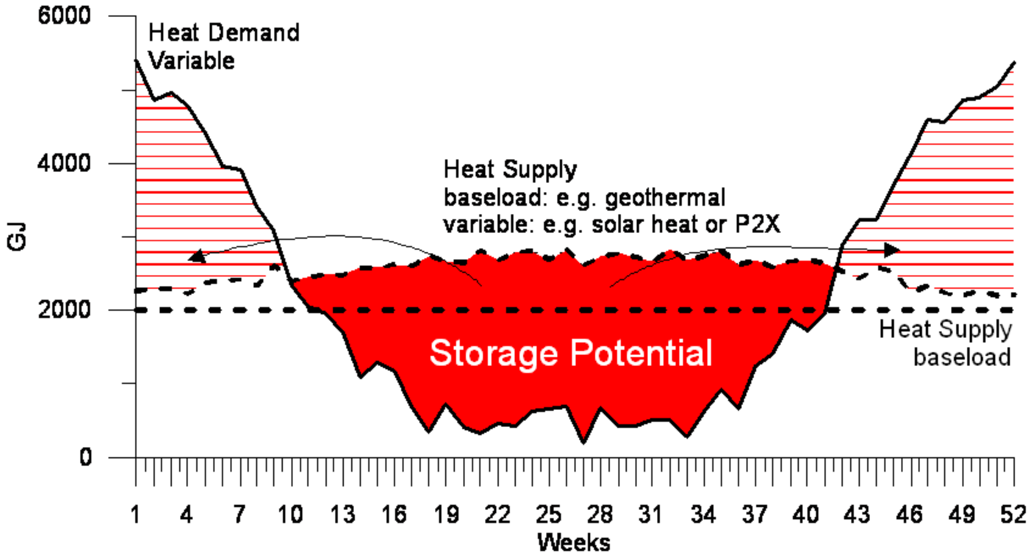

Figure 5 Benefit of HT-ATES heat storage (Hartog et al., 2017)

The objective of the energy-related component of CS2 is to study the feasibility of using HT-ATES as a cost-effective measure to reduce the demand for fossil fuels for heating greenhouses by temporarily storing excess heat from a renewable heat source (geothermal well). In the Westland greenhouse-area in the Netherlands, the geothermal well of TRIAS Westland has been developed. The TRIAS Westland project consists of 2 geothermal doublets, which have been commissioned in 2019 and 2021. The doublets have a combined maximum capacity of about 45 MW. A district heating network is used to distribute the heat from the wells to users: mainly greenhouses and several urban areas, Figure 6.

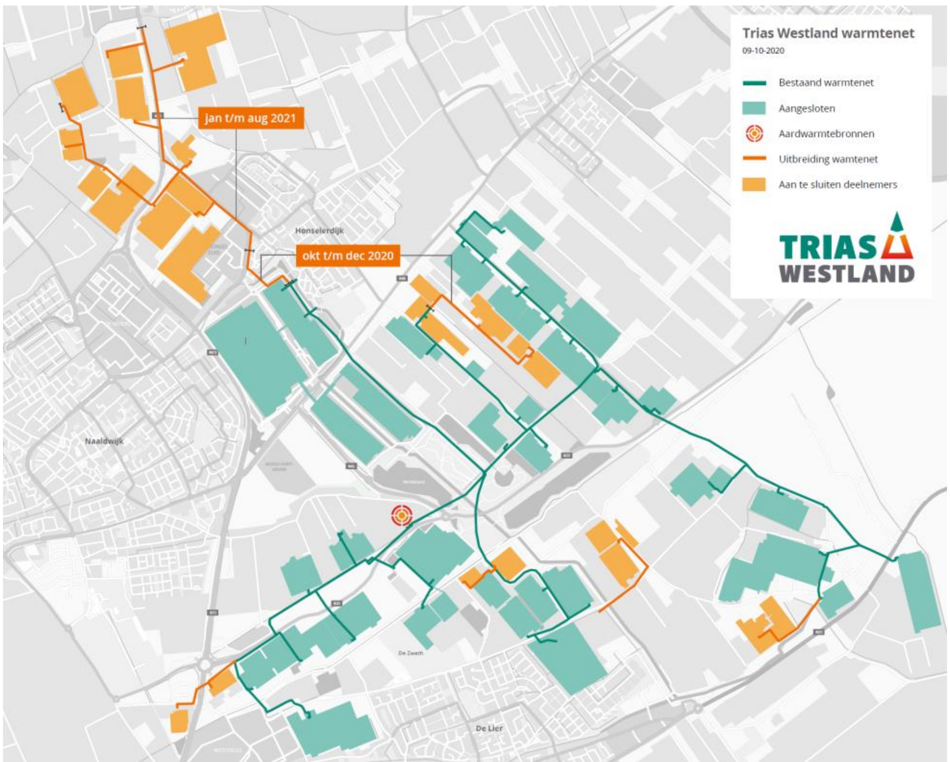

Figure 6 TRIAS Westland district heating network (www.triaswestland.nl).

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Technology description

In moderate climates, during winter months there is a large heat demand, while in the summer months there is a net heat surplus, e.g. from wind, solar, geothermal energy or residual heat from industries. To prevent wasting the excess heat, temporary storage and recovery of heat during periods in which there is a demand for this heat, is a solution to deal with changes in supply and demand over the year. Aquifers (water-bearing underground layers) provide space to store large amounts of heat in systems, so called aquifer thermal energy storage (ATES) systems.

The general principle of ATES systems is that excess energy is stored as thermal energy in the groundwater, i.e. by increasing (heat) or decreasing (cold) the temperature of the groundwater (Figure 7). The excess energy is mostly available in summer months when heat demand is low. When the heat demand is high, mostly in the winter months, the heat is extracted and used. Storage temperatures vary depending on project-specific heat supply and demand, but for commonly applied ATES systems temperatures are limited by regulations to a maximum of 25 °C. Low temperature ATES systems use a heat pump and are commonly applied in the Netherlands, with over 3 000 systems installed, and are typically installed in buildings with a cooling demand in the summer and a heating demand in the winter.

For geothermal systems (and other sources of high temperature excess heat) a higher storage temperature is required; these systems are known as high-temperature (HT)-ATES systems (Drijver et al. 2019; Kallesøe and Vangkilde-Pedersen 2019). Temperatures vary by project, but are limited by the temperature at which the water at a certain depth and pressure remains liquid.

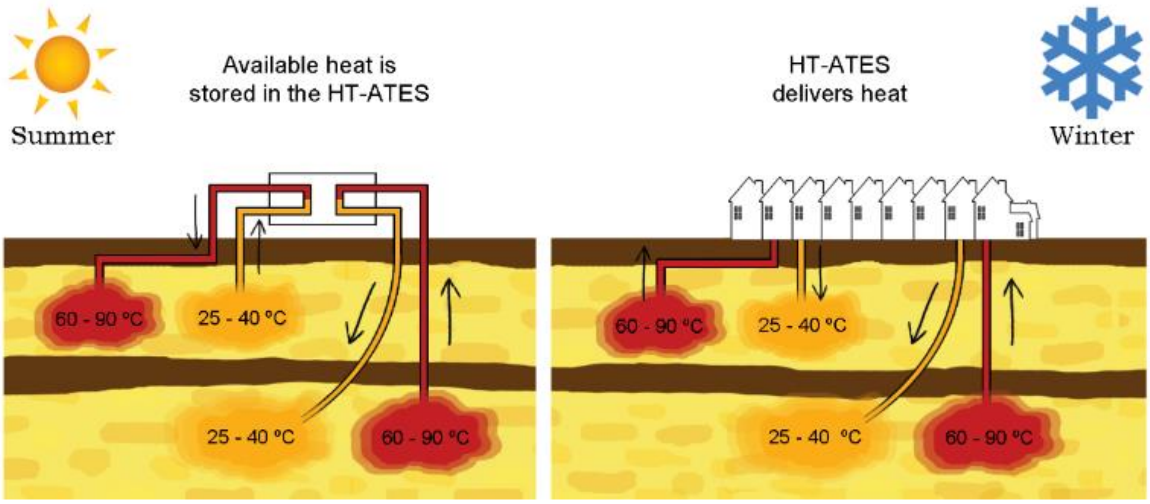

Figure 7 HT-ATES in combination with geothermal well working principle

There are several advantages of HT-ATES systems but also potential disadvantages. Table 3 provides an overview of these pro and cons.

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Table 3 Overview of advantages and disadvantages of HT-ATES systems

Advantages	Disadvantages
• Reduction of energy cost	• Possible impact on groundwater quality
• Positive climate effect (less emissions)	• Feasible only for large (>200,000 m^3) capacity storage
• Little space needed at the surface	• Specific subsurface conditions required
• Efficient use of heat sources • Excess heat can be stored over a long time period e.g. a season or even longer • High storage capacity • Heating and cooling dependent on the season	

HT-ATES is not a proven technique yet. Although it has been demonstrated on small scale at a technology readiness level (TRL) of 5, uncertainties remain. To reduce uncertainties in technical, financial and regulatory fields and to gain trust with developers to apply the technology, it is important to demonstrate the applicability of HT-ATES in full scale applications.

Requirements for its implementation and operating conditions

The geohydrological conditions play an important role in the performance of HT-ATES systems. The thermal recovery efficiency and extraction temperature are the main indicators of the performance of HT-ATES systems. The thermal recovery efficiency is defined by the total extracted energy over the total injected energy during one recovery cycle. The amount of energy that can be extracted after storage is influenced by the losses that occur during storage.

The main geohydrological properties and operational conditions that affect heat loss in HT-ATES systems are among others (Beernink et al. 2024):

- the vertical/horizontal hydraulic conductivity [m/d]
- thickness of the aquifer [m]
- the presence and thickness of confining layers [m]
- the total yearly storage volume [m^3]
- the temperature (difference) and cut-off temperature [K, °C]

These properties all affect the losses due to conduction and buoyancy flow, triggered by the large differences in temperature, as schematically shown in Figure 8. The thickness of the aquifer affects the geometric shape of the heat bubble, and with that

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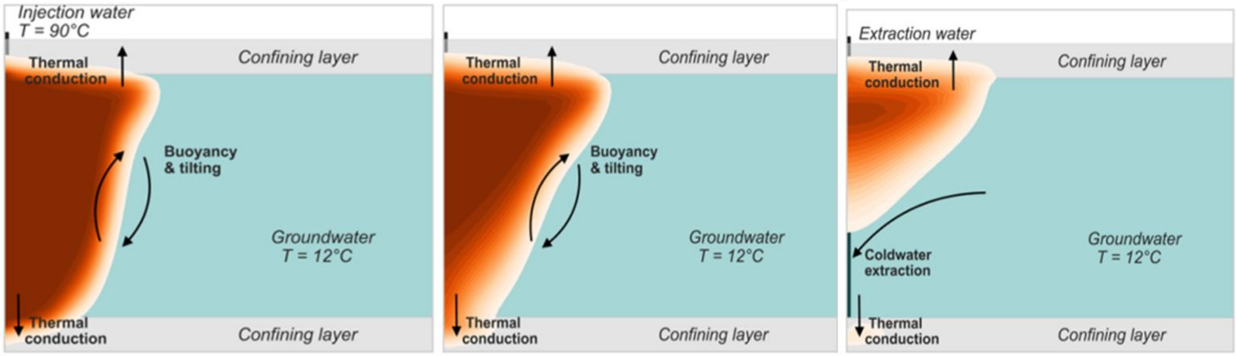
the losses by conduction and dispersion. In addition to heat losses, legal and financial considerations affect the suitability of a layer.



a) After injection b) After storage c) After extraction

Figure 8 Buoyancy flow affecting extraction temperature of an HT-ATES system (Lopik et al., 2016)

Restrictions include potential interference with other subsurface users; it is important to have an overview of the location and depth of other ATES systems and geothermal wells, Aquifer Storage and Recovery (ASR) systems and to assess if there is potential to impact aquifers used for drinking water production.

2.1.2. Results of feasibility study

Analysis of heat demand and supply

Supply data of both the existing geothermal doublet at TRIAS Westland and the heat delivered to existing users were used to identify the HT-ATES storage volumes required for the optimisation of heat utilisation from the geothermal doublet. Data from 2022 shows that demand from existing users does not undercut 20 MW, even on the hottest days in summer. The data from the summer periods were used to assess how much heat can be stored in the HT-ATES. A bandwidth of the amount of heat that can be stored in the summer period was subsequently identified. The maximum capacity of the geothermal wells is 45 MW, including the valorisation of additional heat from the natural gas by capture from the geothermal well (GT). In addition to this maximum scenario, a scenario is also explored in which the geothermal well reduces in capacity to 35 MW (including gas) during summer months (July and August). To create a worst-case scenario for the amount of heat available to charge the HT ATES in one of the cases this minimum is set to 30 MW. Results are presented Table 4. Adding an HT-ATES to the TRIAS Westland district heating system offers the opportunity to additionally deliver about 75-40 TJ heat, depending on the demand conditions in summer (Table 4). This results in an increase of 6%-points of the utilisation of the heat available from the geothermal wells, from 92% yield in the situation without HT-ATES to 96-98%.

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Table 4 Required HT-ATES capacity and size

Scenario	*GT* [MW]	*Total heat utilised** [TJ] *[%]****	*Utilised from HT-ATES*** [TJ]	*HT-ATES Volume* [Mm³]	*HT-ATES capacity* [MW – m³/hr]
0.No HT-ATES	45	1 315 *92%*	-	-	-
1.HT-ATES	45	1 390 *98%*	75	0.52	25 - 410
2.HT-ATES with min 30 MW delivery	45	1 375 96%	60	0.43	15 - 244
3. HT-ATES with GT 35 MW in summer	45-35	1 355 *98%*	40	0.31	25 - 410

* Please note that at 45MW 24/7 the total yield from the geothermal wells is 1420 TJ/year. When GT production is reduced to 35MW in July and August, total yield is 1370 TJ/year.
** Considering an initial estimation of the losses in HT-ATES: 30% for case 1 and 35% for case 2, and 40% for case 3.
*** Total percentage of heat coming from GT utilised

Suitability of subsurface for HT-ATES at TRIAS Westland

In the Westland area, down to 500m depth, different formations are present that have potential as a storage aquifer for HT-ATES. Based on the regional REGIS II model, aquifers are present in the Peize/Waalre formation, the Maassluis formation, the Oosterhout formation (Figure 9). The Brussels formation, which starts at 370m depth according to REGIS II, also has a sand member which has been identified as a potential aquifer for shallow geothermal storage.

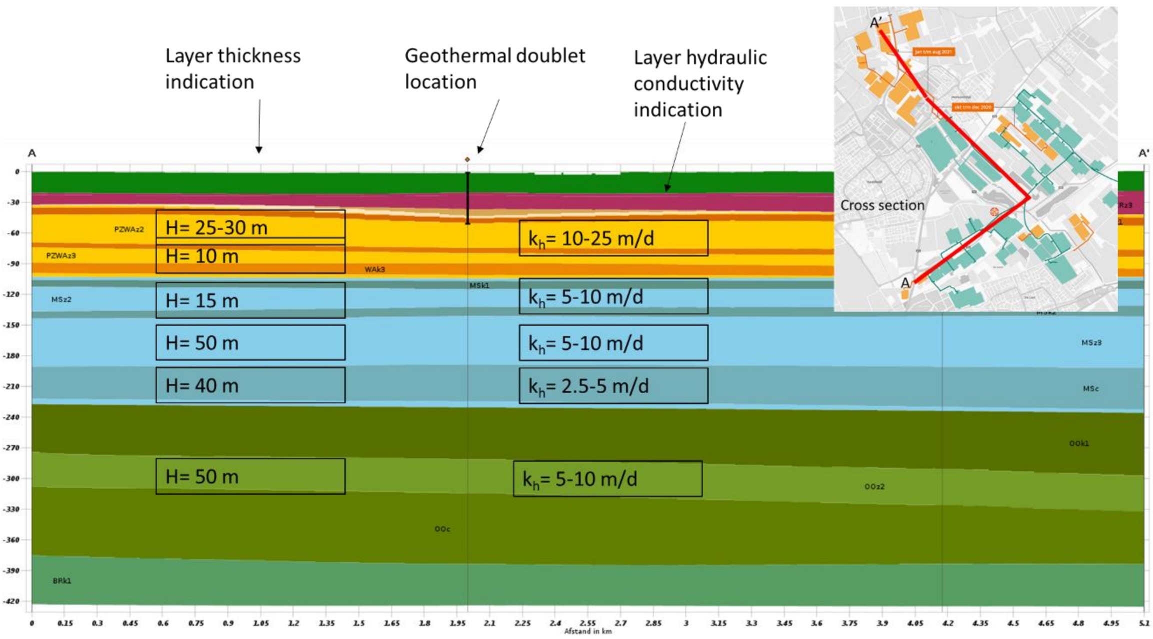

Figure 9 Geohydrological layering up to 400m depth according to the regional REGIS II model; layers: formation Peize/Waalre (PZWA), formation Maassluis (MS) and the formation Oosterhout (OO); figure and information is obtained from REGIS II (TNO, 2017).

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Because the Province of Zuid-Holland reserved the Peize/Waalre formation solely for freshwater storage and recovery (ASR), this aquifer is not available for HT-ATES use. Hence, three potential formations are identified that have potential for HT-ATES in the TRIAS Westland area.

The local properties of the Maassluis formation were investigated with a deepening drilling in Maasdijk, which was combined with geothermal drilling work. In the Maassluis formation, two suitable aquifers are present. This was verified by drillings (so called deepening drillings performed in combination with geothermal drilling work). One point of attention for the Maassluis aquifers is their relative shallow depth, application of HT-ATES in shallow layers have a larger risk of affecting other groundwater users/functions which are more often present in shallow confining layers, compared to deep ones. The presence and suitability of aquifers in the Oosterhout and Brussels formation (<500m depth) is highly uncertain and was not verified by drilling due to their depth. Moreover, drilling and installation costs are expected to be high in these formations.

Simulation of HT-ATES performance

A sensitivity analysis of HT-ATES performance for variation in both the system design (storage volume) and the subsurface conditions was performed using thermos-hydraulic simulator SEAWAT. The SEAWATv4 model, which combines the MODFLOW and MT3DMS models, is used to simulate density and viscosity dependent flow of heat and groundwater. These simulations are of exploratory nature hence the following straightforward model set-up is applied:

- Both the hot and warm well are simulated separately using an axisymmetric grid, interaction between the wells or ambient groundwater flow are not considered.
- Fully penetrating wells are implemented.
- Hydraulic conductivity is anisotropic and varied according to the scenarios in the following section.
- The aquifers and aquitards are modelled as homogeneous layers with isotropic thermal properties. Hence, well in- and out-flow are distributed evenly along the aquifer thickness.
- The injection and extraction volumes are distributed over the year by a sine function.
- The model input and output are controlled, recorded and processed on a daily timestep.

Scenarios

In all scenarios the storage temperature of the hot well is 85 °C, the warm wells storage temperature is 35 °C. For worst-case efficiency calculation, a cut-off temperature of 45 °C is assumed for all scenarios. For the system design of HT-ATES combined with min 30 MW delivery of the geothermal well, the calculated storage volume is 430,000 m^3/year. This is the storage volume used for most simulations in this part (Table 5, scenario 2). To evaluate the effect of different storage volumes, the estimated

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maximum (scenario 3) and minimum (scenario 1) size of the HT-ATES are also simulated, following the scenarios identified in Table 5.

Table 5 HT-ATES system design scenarios evaluated

	Storage temperature hot [°C]	Storage temperature warm [°C]	Cut off temperature [°C]	Storage volume [m^3]
Scenario 1	85	35	45	525,000
Scenario 2	85	35	45	435,000
Scenario 3	85	35	45	310,000

Results

During storage, heat is conducted into the aquitards above and below the aquifer and into the aquifer surroundings (Figure 10). After 10 years, the 50 °C contour travelled almost 10 meters in the aquitard at the top. Also, the thermal front tilts due to the density difference between the stored hot (light) and ambient cold (dense) groundwater. This results in the extraction of relatively cold groundwater from the bottom of the well screen (at ~-45m depth in the model) at the end of the unloading cycle (right, Figure 10).

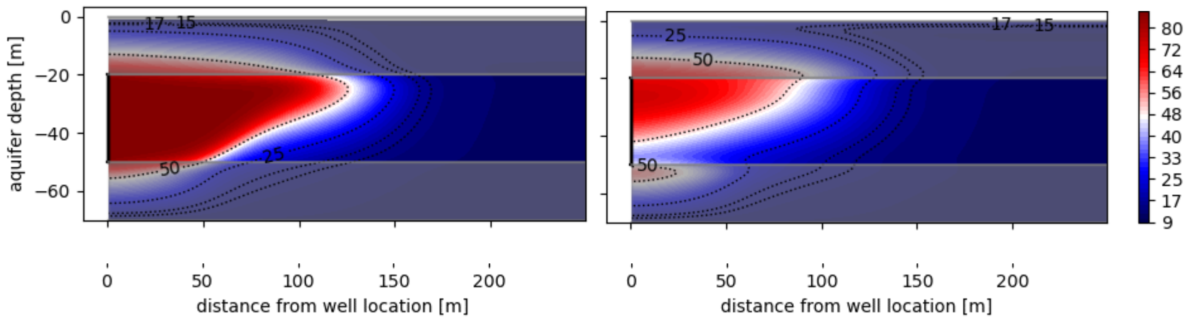

Figure 10 Cross-section of the simulated temperature in the hot well after 10 years of operation; left: when the well is fully loaded (end of summer) and right: at end of unloading cycle (end of winter)

The temperature in the well is given in Figure 11. During injection, the temperature in the well is the injection temperature. During extraction, the temperature decreases because increasingly more cold groundwater is extracted because of the processes that distribute the stored heat during storage (mainly conduction and buoyancy-driven flow). During heat delivery, water is extracted from the hot well until the cut-off temperature is reached (45 °C). As the heat that is not recovered warms up the subsurface surrounding the well screen, the performance of the well increases each year and becomes relatively constant after ~7 years. This is the case for both the hot and the warm well.

The yearly recovered energy is calculated for the individual wells and the system. For the warm well, the recovery efficiency is not calculated for the first year because no

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heat that was previously stored was recovered (starts with extraction of ambient groundwater). The warm well has a higher recovery efficiency compared to the hot well, this occurs because the energy losses due to buoyancy flow are stronger for the hot well. After 3 years of operation, both wells have already a recovery efficiency >80%, and for the warm well, this increases to 90% after 10 years of operation. For the hot well, the recovery efficiency increases only very modestly after the first 3 years of operation, resulting in 85% recovery efficiency in year 10 of operation.

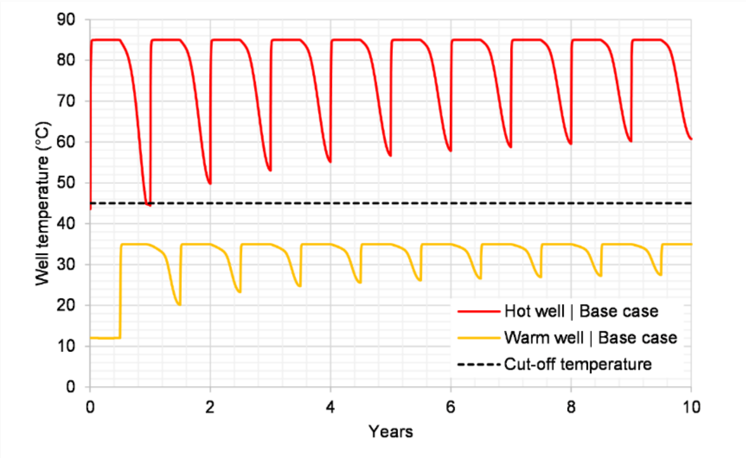

Figure 11 Well temperatures of the Base case (scenario 2). The Cut-off is reached once, at the end of unloading season in year 1.

Because the system operates at a ΔT of 50 K between the hot and warm well, the resulting system performance is high, with 70% after 4 years and already 78% after 10 years. An increase of 90,000 m^3/year in storage volume (scenario 1) results in a slightly better performance of 1%, while a smaller storage volume (decrease of 125,000 m^3/year) results in a decrease of the system recovery efficiency of 3%.

Concluding, in the subsurface of the Westland multiple aquifers with potential for HT-ATES are present. The two aquifers in the Maassluis formation are most suitable. A sensitivity analysis of HT-ATES performance for variation in both the system design (storage volume) and the subsurface conditions show that the deepest aquifer in the Maassluis formation between 210 and 240 m depth has the highest potential for seasonal heat storage with system recovery efficiencies higher than 65% and 75% after 3 and10 years respectively.

Financial feasibility

The specific costs of the HT-ATES system are divided in two categories, CAPEX (capital expenditures) occurring during system build/installation phase and OPEX (operational expenditures) recurring throughout the operation timeline of the installation. A quick scan study was performed, with the costs and savings interpolated from a recent cost estimate carried out for a nearby HT-ATES in Delft of similar size and in the same target aquifer (Bloemendal et al. 2020). From this it was established that the yearly costs (including depreciation) for the HT-ATES to deliver the 75 and

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60 TJ of heat are 1.5 M € and 1 M €, respectively. These costs are lower than those needed to supply that same amount of heat with a gas fired boiler (2.5 M € and 2 M €, resp.).

If the CO_2 emissions costs savings are excluded, the direct costs for gas purchase are still higher than installing and operating an HT-ATES would be. The relative savings are better for scenario 2 because that set-up would require a considerably lower flow rate, and with that also lower required investment for the HT-ATES wells.

The costs to provide the 75 and 60 TJ result in a heat price of around 20 and 15 €/GJ, respectively.

Policy and Permit

The targeted reservoirs within this study do not reach deeper than 500 meters, which is within scope of the Water Law regime, with “Gedeputeerde Staten” of the province as the competent authority. As the infiltration temperature exceeds 25 °C and the long-term heat surplus in the soil will occur HT-ATES does not fit standard ATES regulations. It is possible to deviate from these in case systems are implemented as a research project, which also account for HT-ATES projects. To make sure other interest are not harmed, the effects of the ATES system must be quantified by doing in an impact study. Provinces may grant licenses for HT-ATES pilot projects if no other interests are harmed.

Comparison of baseline situation with HT-ATES system: CO_2 saving, cost and benefits

The financial benefits arise from both the reduction of both natural gas purchases as well as reduction in CO_2 emission rights purchases, both quantified in Table 6.

Please note that:

- In this case it is not clear who saves the CO_2 emission rights and can account for these costs (the system operator, or the users of heat (greenhouses))
- Any additional revenues related to the increased subsidy from the geothermal well (SDE+) are not considered.
- Pre-Ukrainian war price levels for electricity and gas are used
- CAPEX for gas fired boilers or combined heat and power systems (CHP) in the case of no HT-ATES are not considered.

The costs used originate from pre-Ukrainian war levels. The energy costs levels are likely to remain much higher than were applied in this study, and will most certainly vary stronger. Which would be a good argument to be as self-sufficient as possible.
When applying energy costs for both electricity and gas twice as high compared to pre-Ukrainian war, the yearly profits double. Hence, this is beneficial for the financial feasibility of HT-ATES.

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Table 6 Benefits (financial + emission reduction) of HT-ATES system installation

	Scenario 1	Scenario 2	
Natural gas reduction	2,380,952	1,904,762	*m^3*
Emission reduction of CO_2	4,229	3,383	*ton CO_2*
Cost per tonne CO_2 emitted with tax (emission rights)	25	25	*€/ton CO_2*
Cost per m^3 of natural gas with tax	1	1	*€/m^3*
Total emission reduction savings	106	85	*k€/year*
Total natural gas purchase reduction savings	2,381	1,905	*k€/year*
Total savings due to HT-ATES installation	**2,487**	**1,989**	***k€**/year*

2.1.3. Conclusions and recommendations

Key performance indicators

The technical and financial feasibility shows that there is potential to cost efficiently increase sustainable heat delivery from the geothermal wells of the TRIAS Westland site by applying an HT-ATES. The yearly total costs of the HT-ATES are considerably smaller than they would be if the same amount of heat would be delivered by gas fired boilers. The results of this feasibility study are summarised using the ULTIMATE KPI's in Table 7.

Table 7 Overview of the ULTIMATE KPI's and the scales of the TRIAS Westland project

Objective	How it will be measured/determined?	Scale: full-scale
HT Aquifer thermal energy storage and recovery	Heat recovery factor [-], Delivered heat cost [€/GJ], CO_2 reduction [t/a]	65 to 80 % 15 to 20 €/GJ 3 to 4 kton CO_2/y
Showing the success of the implemented circular economy systems	Substitution of fossil fuels by green energy [%]	5 to 6%*

* For the TRIAS Westland site, the heat storage and fossil substitution is 75-60 TJ. Because the system is very large (>1300 TJ) and has a high base-load heat demand, the contribution of HT-ATES to the total is limited. In other supply-demand conditions HT-ATES systems are more likely to facilitates 20 to 30% of the total heat demand.

Best practices and recommendations for technology implementation

Heat availability and demand

Due to the relatively high overall heat demand in the connected district heating network, there is a relatively limited (projected) over capacity (approx. 5% of the total capacity). Due to the large total capacity of the heat source, this still results in a considerable amount of heat for storage (75-60 TJ/year).

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Recommendations:

- The amount of heat available in summer should be further analysed, to obtain better confidence in the amount of heat that can be stored over multiple years. This is important, because the performance of the HT-ATES and potential extra heat delivery depends on this. Given the large demand, additional sources of heat could also be considered.
- The exact concept for (hydraulic) integration should be further analysed to ensure the supply temperature will match production temperatures, and to maximise heat delivery from the HT-ATES.

Subsurface

The deepest aquifer in Maassluis formation is very suitable for installation of HT-ATES wells. The top of the projected aquifer is at 210 m depth and the thickness is around 30m. The additional screening and logging proved to be key to identify available well screen depths. Exploratory simulations showed that the recovery efficiency of the 60 TJ storage capacity would be 65 to 80% depending on geological conditions.

Recommendations:

- The exact location of the HT-ATES wells is to be identified based on optimal integration in the district heating network and in coordination with the assessment of impact on other subsurface interests.

Requirement for seasonal storage

Greenhouses often exhibit a high base-load heat demand, resulting in limited heat availability in summer months for storage. Hence, the need for heat storage is not always likely when greenhouses use geothermal heat. In the case of TRIAS Westland, the size of the heat source resulted in the situation that with an availability of only ~5% of the total heat supply, it still resulted in a reasonably large heat storage system of about 60-75 TJ. Given the high peak demand, there is potential for much more heat delivery when additional sources of heat could be utilised. This would also increase the added value of the seasonal storage. Hence, the need for seasonal heat storage for greenhouses that use geothermal as a source for heat, strongly depends on the local conditions regarding the heat demand and supply profiles. Also the size of the source of heat relative to the total yearly demand affects to what extend heat storage has an added value.

Uncertainty reduction

Various HT-ATES feasibility studies have shown that prior detailed knowledge on the composition of the subsurface is key to correctly assess the feasibility. While drilling a geothermal well, the potential layers for HT-ATES are penetrated, which creates a window of opportunity to screen them to obtain this detailed insight. Logging/screening these shallow layers while targeting a (much) deeper aquifer, is a cost-effective method to gather valuable information to reduce uncertainty for the application of HT-ATES.

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In this study it was demonstrated that data acquisition for shallow layers during drilling activities for geothermal systems, can cost effectively and successfully be implemented. The obtained data provided great insight in potential layers at reasonable costs. The approach followed in this study could easily be used in other projects. This approach consisted of deepening the conductor drilling (usually around 100m depth) which in NL are generally made by smaller rigs. This has 2 main advantages:

1. The daily rate of such rigs is much lower than for the large rig drilling to several km depth.
2. Such rigs allow for reverse circulation flush drilling, providing very accurate cutting samples along the borehole depth.

In the case for TRIAS the smaller rig could be utilised, resulting in an additional cost of 30 k€ to get insights via cuttings, logging and cores. In case a small rig cannot be used the costs will be at least 2-3 times larger. In any case the costs are a small percentage (<<1%) of the total drilling costs needed for the geothermal doublet.

Permitting

HT-ATES is allowed to be applied, however, no standard policy framework for permitting of these systems exists at this moment. The issuing of a permit requires a dedicated decision of the 'Gedeputeerde Staten' of the province.

Recommendations:

- If HT-ATES is further explored / elaborated, it is key to initiate contact with the province to coordinate the permitting procedure.
- For future replication, it is recommended that a legal framework for licensing underground thermal storage is developed and implemented. Currently, the licensing of HT-ATES systems is legally possible, provided that "the interests of soil protection do not oppose it." However, no assessment criteria and permit regulations were yet available for HT-ATES, to assess permit can be granted. A legal framework would allow the responsible authorities to consider HT-ATES permit applications in a consistent manner. For the initiator of an HT-ATES system, the framework provides clarity about the boundary conditions obtaining a license.

Implementation in a symbiotic frame

The economic feasibility of implementing an HT-ATES heat storage system depends on a number of factors. The ATES is used to store surplus heat and make it available during a period when there is a shortage for a certain application. An ATES therefore, is a feasible solution when there is a party with a demand and a party that can offer a surplus and the demand and surplus are not simultaneous. One party could be both user and supplier of the heat.

In the case of the greenhouse sector, the greenhouses are the parties in need of heat. The supplier of the heat could be any sector that has excess thermal energy available. Examples include geothermal plants (this case study), but could also be industries with

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residual waste, such as incineration plants, refineries, etc. This heat may be available free of charge (i.e. excess capacity, use of the heat actually incurs cost savings for the party as it saves in e.g. cooling costs). However, in some cases, there might be costs charges per Joule of heat delivered.

Not included in the feasibility study performed are the costs for implementing and operating a district heating network to provide the heat from the HT-ATES to the customers (greenhouses). The construction and operation of both the ATES and the network require specialised technical expertise.

The operation of the HT-ATES and the heat distribution network to the user’s needs to be operated and maintained. Various models are feasible for organising this responsibility. Options include: 1) setting up a cooperative with the specific task of providing the service, with cooperative members being the end-users of the heat (greenhouses in this case study), with as further possible members other parties, such as the heat supplier and/or an service provider 2) setting up a separate company that is responsible for managing the HT-ATES and all associated activities, 3) delegating the work to an existing service provider, e.g. the company in charge of district heating network in this case study.

Because of the specific expertise required, option 3 is to be recommended, but the other options are also feasible if the required expertise is hired/contracted. An example of this model is the wastewater treatment plant at de Vlot (CS2 – water and resource recovery activities covered in D1.3 and D1.5), where a cooperative of greenhouse owners is responsible for the operation of the treatment plant with the assistance of a specialised third party, contracted for consulting services.

Crucial factors for the implementation of an HT-ATES

- A suitable heat source to match (part of) the demand and that provides the right conditions for storage
- Sufficiently high supply quantities to make the storage cost effective
- Suitable hydrogeological conditions for storage of thermal energy with a sufficiently high recovery factor for economic operation
- Obtaining the permits for drilling and establishing the HT-ATES

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2.2. Anaerobic treatment of brewery and food industry wastewater to recover biogas in Lleida (ES)

Antonio Gimenez Lorang (AQUALIA), Victor Monsalvo (AQUALIA)

2.2.1. Case study and ULTIMATE concept

Case study description

In Lleida, the water smart industrial symbiosis exists since 2009 and interlinks the Mahou San Miguel (MSM) brewery, one of the most important one's in Spain, with a multinational utility Aqualia as well as the local municipal utility of Lleida and the Catalan Water Agency. The brewery has its own wastewater treatment plant. However, until the beginning of ULTIMATE, there was no water reclaimed, no energy recovered, and no circular-economy based approach on this WWTP. Due to the biodegradability of the wastewater, energy can be recovered in form of biogas and be converted efficiently to electricity and heat, by means of some anaerobic-based solution. Additionally, the carbon footprint can be also reduced due to Mahou San Miguel´s commitment to green energy and self-sufficiency. Therefore, in ULTIMATE the first industrial-scale bioelectrostimulated anaerobic reactor (ELSAR) for anaerobic wastewater treatment was demonstrated (Figure 12).

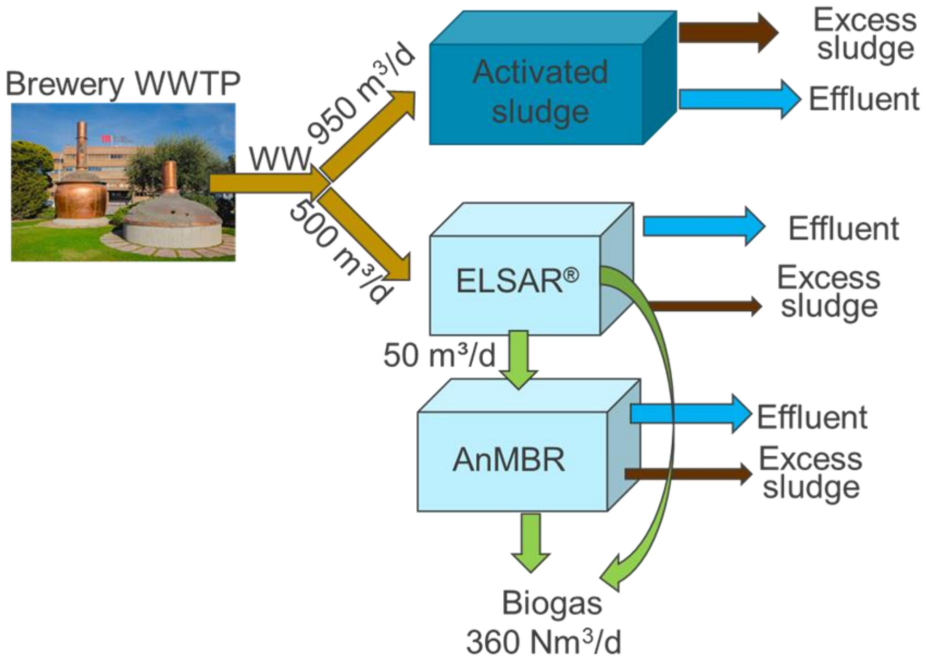

Figure 12 Flow scheme of the existing system: activated sludge system and the ULTIMATE solutions: electrostimulated anaerobic reactor (ELSAR) and anaerobic membrane bioreactor (AnMBR)

First the anaerobic biodegradability of the wastewater was confirmed using standard biochemical methane potential tests and a comprehensive biochemical characterisation of the waters and a geotechnical study were carried out to assess the civil engineering requirements estimation. This was followed by an initial construction

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project and a detailed engineering project. After 12 months, the building permit was obtained and the construction of ELSAR® required one year.
An innovative anaerobic membrane bioreactor (AnMBR) schema has been included in the same CS, in order to validate additional advantages, like optimal effluent quality and improvement of biomass retention. Organic matter is converted to a high-calorific-value biogas by means of fermentative and methanogenic microorganisms, with no need of aeration and a low extra sludge production.

Technology description
ELSAR® is basically a combination of an upflow anaerobic sludge blanket reactor (UASB) with integrated electrodes (Figure 13). On the one hand, organic matter is converted to biogas by fermentative and methanogenic microorganisms. But due to the integrated bioelectrical system, electroactive microorganisms oxidize organic matter and release electrons to the anode, hydrogen ions and CO_2. The different pathways occurring in the reactor enable a high flexibility and a stable biogas formation process.

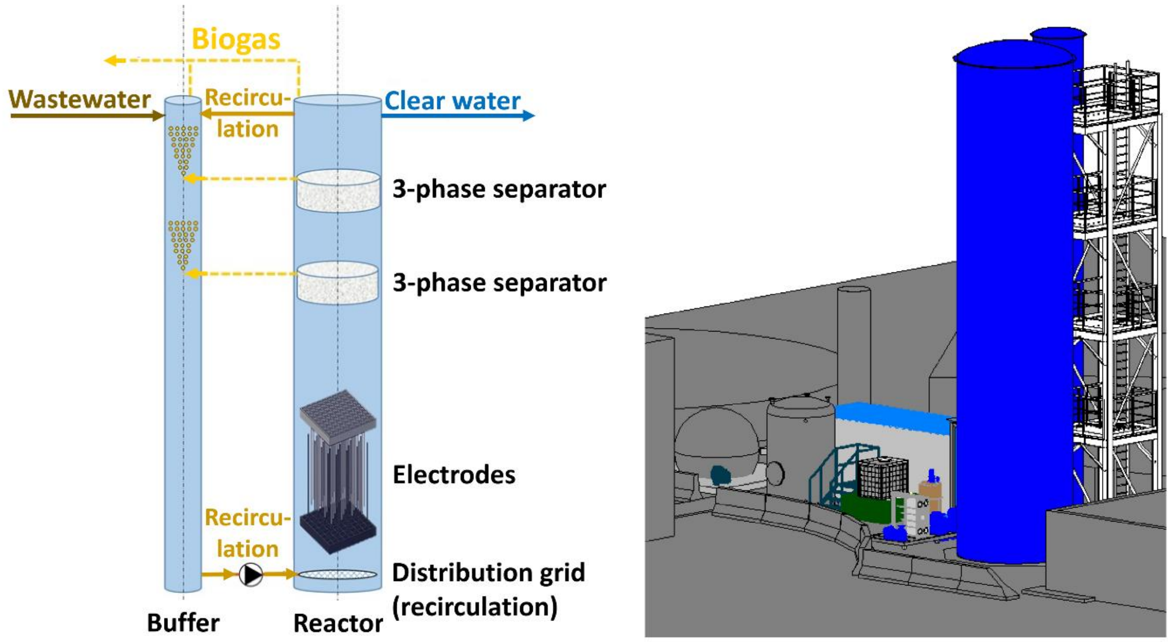

Figure 13 Scheme of the ELSAR reactor connected to a buffer reactor

Like any other high-rate anaerobic reactor, it is operated at mesophilic range and requires a buffer tank, where the wastewater is pH-buffered and heated. ELSAR® in CS5 can treat up to 20 m^3/h of wastewater or an equivalent organic loading rate (OLR) of 2,000 kg COD/d, producing 30 Nm^3 biogas/h. Expected total COD and soluble removal is 90% and 96%, respectively. Biogas treatment includes gasometer, flare and boiler (with the purpose of heating the incoming wastewater). The electroconductive anode consists of the fluidized bed made of activated carbon particles. This anode transfers the electrons via collision to a static graphite electrode with a polarized structure.

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The AnMBR is usually applied as pre-treatment for wastewater with high organic loads. As in ELSAR®, organic carbon compounds are biodegraded and biogas, mainly consisting of methane (CH_4) and CO_2, is produced by microorganisms. AnMBR is a system with biomass accumulation, meaning, that the hydraulic retention time is decoupled from the solids retention time and thus, allows anaerobic microorganisms to proliferate without being washed out of the system. During CS5 runtime, the optimal option for AnMBR was chosen (Figure 14): the direct coupling with ELSAR by means of its effluent, similar as done in one of the seldom cases of industrial-scale AnMBR treating municipal wastewater (Spernal, UK).

Unique selling points of the combination ELSAR with AnMBR

- No aeration energy for removal of organic carbon compounds
- Low sludge production and associated treatment efforts
- Higher methane yield compared to conventional anaerobic digestion
- Higher organic loading rates possible compared to conventional anaerobic digestion
- Increased process stability
- Short stabilisation periods after shock loads
- Higher calorific value of the biogas due to higher H_2 content
- Pathogen and solids free effluent which can be re-used in a number of applications (e.g. farming and industrial use)
- Compact equipment with low carbon footprint and low operation costs

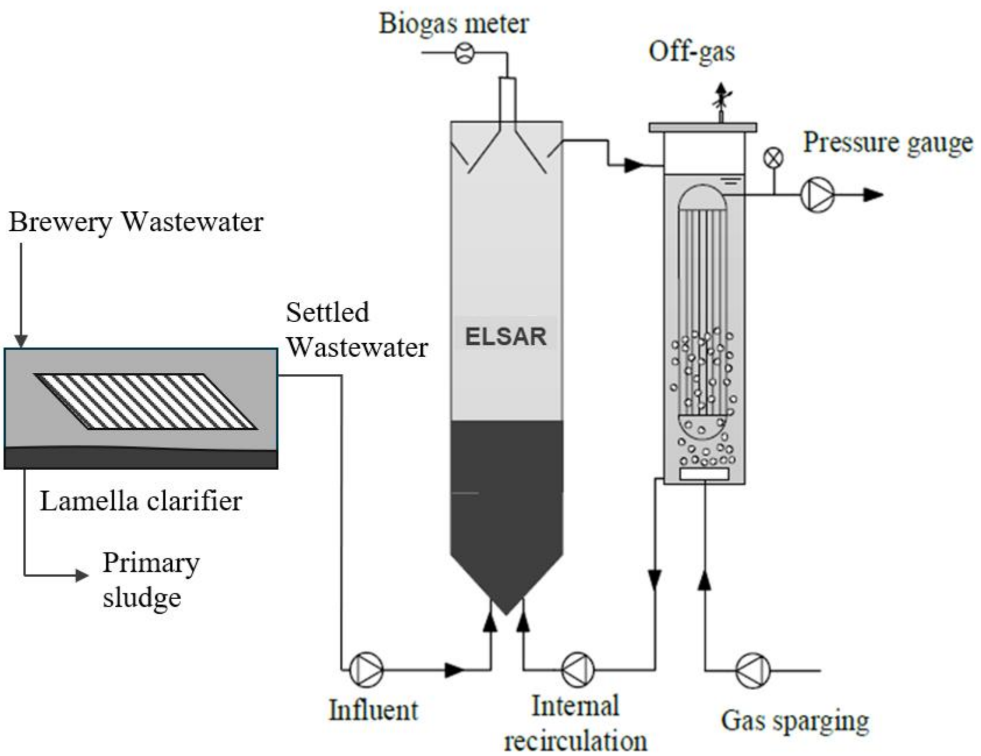

Figure 14 ELSAR combined with an AnMBR

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Technical requirements for the implementation and operating conditions

Wastewater requirements

- Biodegradable COD > 2 kg/m^3 with a minimum organic load of 2000 kg COD/d[1]
- (Only ELSAR) TSS < 300 mg/L (or include a primary treatment) Granular sludge doesn't tolerate wastewater with high suspended matter, that may damage the granules or interfere in the hydraulic performance.
- Ideally, wastewater temperature 30-37ºC (or include boiler) and pH 6-9 (or include acid/alkali chemicals).

Other inputs (besides wastewater)

- (Only ELSAR) Although power requirements are low (only for pumping water), during start-up there may be a need for heat for increasing the wastewater temperature, depending on WW temperature.
- Other regular requirements: tap water, compressed air, drainage points, etc.
- (Only ELSAR) Because the ELSAR is a compact, tall and slim solution, the water column can be very high (up to 20 m), providing a high weight / pressure load to the floor. Therefore, correct civil works are important. Because of this height, there must be vertical space available (careful with electric towers, wires, etc).
- Granular sludge: due to the high acceptance of high-rate anaerobic reactors in industrial WW, granular sludge (needed to inoculate the ELSAR) is generally available in Europe. However, big distances to a source of such granular sludge can make inoculation an expensive operation and this distance shall be considered when assessing the viability of implementing ELSAR as a treatment solution.

Outputs

- Discharge requirements will determine the need of post-treatment after ELSAR and AnMBR. In Spain, for example, both solutions should be enough to meet the usual COD and TSS requirements for discharge in industrial contexts (< 1500 mg COD/L). However, if the nutrients content has to be reduced, additional polishing treatments may be needed.
- Biogas use is relevant and can influence on the business case. Gas injection is usually reserved for big methane production sites (> 50 m^3 CH_4/h) and implies some complexity (upgrading, connection to the grid, administrative formalities, etc.); a boiler may be used as an alternative for self-consumption for different sizes; upgrading is less strict for boilers. CHP is an option but limited to medium sizes (>250 kW). A flare is mandatory for burning excess biogas.

[1] Usually 2000 kg COD/d is considered as edge for economic viability in anaerobic reactors (considering the extra CAPEX needed for biogas storage & flare & boiler) vs. aerobic systems. Moreover, low-strength wastewater may bring insufficient feeding conditions for granular sludge.

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2.2.2. Results of new approaches

Technology performance

The aim in ULTIMATE was to construct a full-scale ELSAR and to commission it during the project's lifetime. In the first four months of commissioning, the ELSAR is still under an initial running phase: Organic loading rates (OLR) up to 12.5 kg total COD/(m^3*d) were achieved in the ELSAR reactor with no signs of instability of the process or decrease in performance, while the expected OLR capacity is 25 kg total COD/(m^3*d). Therefore, it can be stated that the 50% of its treatment capacity has been achieved.

The average performance has been 89,0±7,6% and 93,0±4,5% in terms of total COD removal and soluble COD removal, respectively; this performance is calculated vs. the settled wastewater (i.e., after lamella clarifier) and is close to the estimated COD removal rate during design (90% COD removal).

The energetic consumption of ELSAR according to onsite monitoring is 0.1 kWh per treated m^3 WW, while the current aerobic treatment consumes more than 3 kWh/treated m^3 WW. ELSAR electricity needs are mainly required for pumping wastewater.

Considering that the nominal capacity of ELSAR is 35% (500 m^3/d from 1450m^3/d) of the average incoming wastewater, ELSAR at full capacity could potentially reduce about 33% of the electrical consumption (Table 8). Even considering the above mentioned achieved performance (50%), the reduction in terms of electrical consumption in the WWTP is above the KPI goal of 10% energy demand reduction.

Table 8 Energy consumption before and after ELSAR implementation

	Conventional activated Sludge (CAS) without ELSAR	CAS with ELSAR at 100% of its capacity	CAS with ELSAR at 50% of its capacity
Incoming wastewater	1450 m^3/d	(950 + 500) m^3/d	(1200 + 250) m^3/d
Energy consumption	· CAS: 3 kWh/m^3	· CAS: 3 kWh/m^3 · ELSAR: 0,1 kWh/m^3	· CAS: 3 kWh/m^3 · ELSAR: 0,1 kWh/m^3
Energy consumption	4350 kWh/d	(2850+50) kWh/d	(3600+25) kWh/d
Difference vs. CAS (without ELSAR)	-	-33%	-17%

Sulphates are present but don't represent an issue for methanogenic competence, since the ratio S-SO_4/COD is low enough. The only problem of the sulphate content is the high H_2S content in biogas, that (1) provokes corrosion in sensitive materials, and (2) represents a health risk because of its toxicity, especially in closed areas (which are minimum in the ELSAR® of Lleida). Besides of H_2S, CH_4 content is rather constant (70-75% v:v; Figure 15).

So far, the lamella clarifier managed to achieve a constant TSS content below the maximum recommended TSS content of 300 mg/L in the input wastewater (Figure 16).

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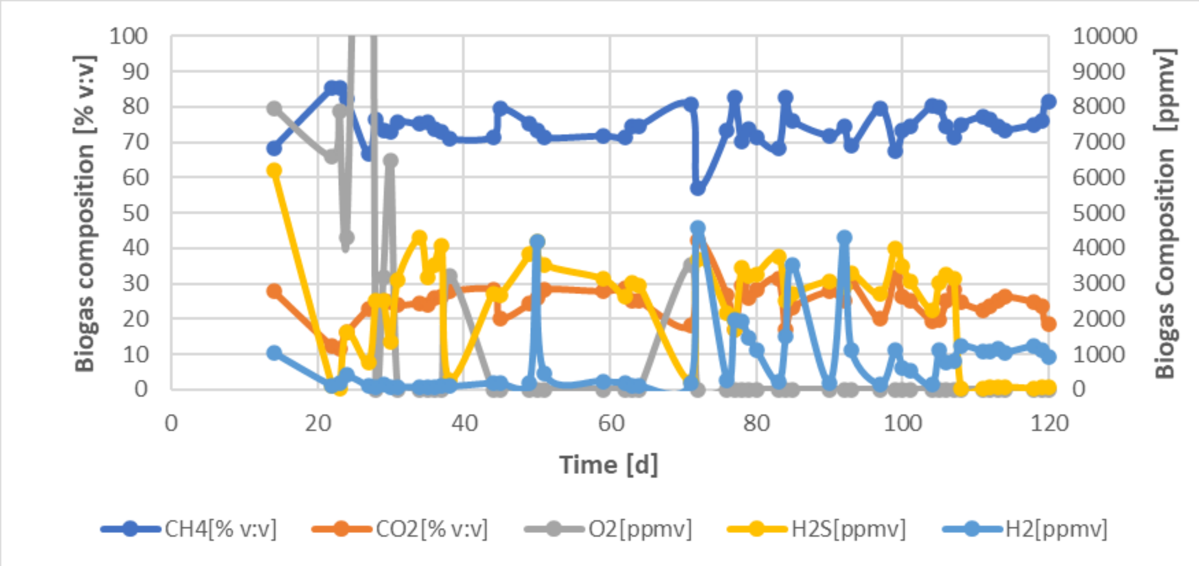

Figure 15 Methane, CO_2 and H_2S contents in the produced biogas

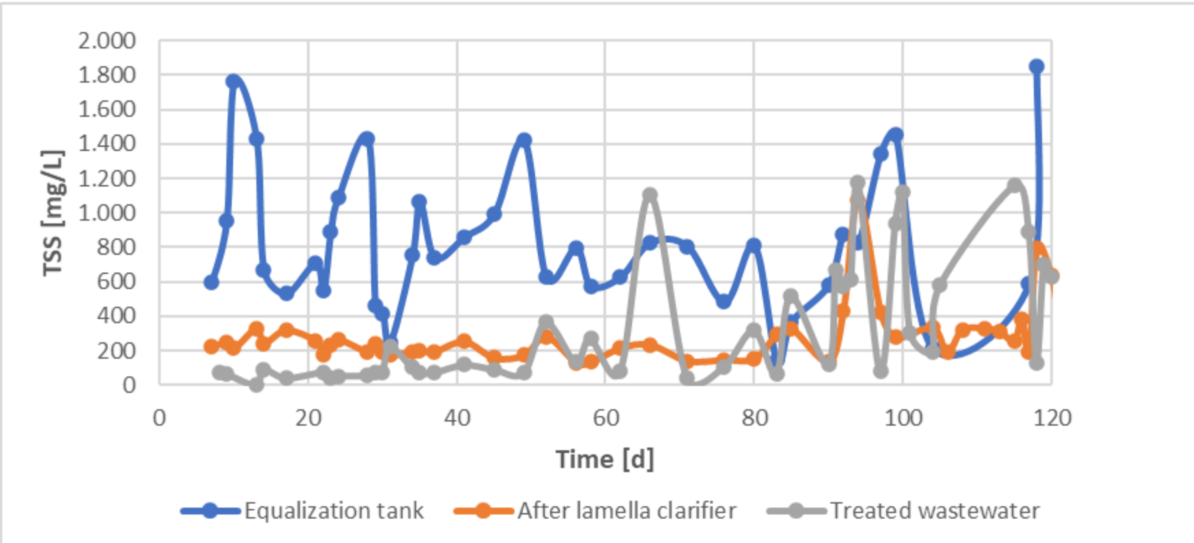

Figure 16 Total suspended solid (TSS) content in the equalization tank, after the lamella clarifier and after the ELSAR treatment

On average, referring to settled wastewater, total COD (Figure 17) and soluble COD removal in the reactor have been 93.4% and 95.7%, respectively. In the first four months, the ELSAR has not produced excess sludge. According to sludge balance, once inoculated in ELSAR and fed with the brewery's wastewater, the original sludge suffers a significant loss, even if biomass was kept at constant conditions and was fed with the same wastewater. This loss is in accordance with other known start-up experiences, among the granular high-rate anaerobic reactors' sector. Interestingly, a drop in the nominal size of the granules has been observed since its inoculation, indicating sludge deterioration or breakdown. However, sludge settleability did not increase, since the sludge volume index is kept still in optimal values (<20 mL/g).

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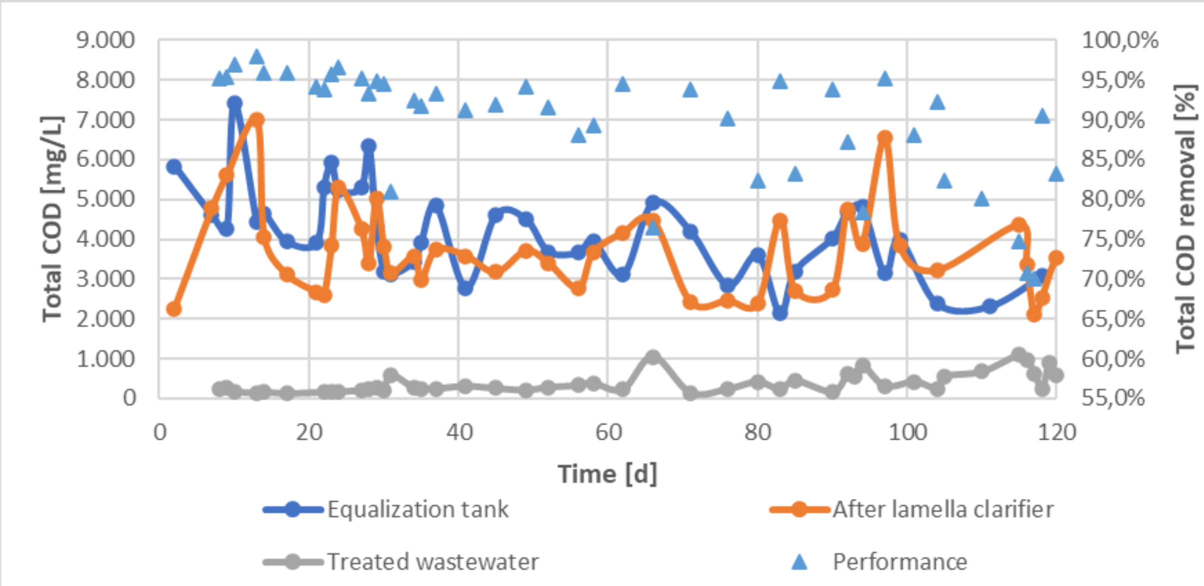

Figure 17 Total chemical oxygen demand (COD) concentrations in the equalisation tank, after the lamella clarifier and after the ELSAR treatment as well as the COD removal rate

Overall, the combination of ELSAR and AnMBR provided a constant TSS content in the AnMBR's permeate (below the analytical limit of detection, i.e. below 2 mg/L). However, so far AnMBR results in terms of operability are not sound, with big fluctuations in permeability, probably due to high soluble COD concentration that was not degraded in the ELSAR and needing a stronger polishing, i.e., higher COD degradation.

Comparison of ELSAR and AnMBR

It doesn't seem that the better effluent quality provided by the AnMBR compensates the increase in OPEX (due to gas demand for sparging, chemicals for cleaning membranes, etc.) and CAPEX (due to membranes, tank for membranes, pipelines including recirculation, etc). The 3-phase separators included in ELSAR (Figure 13) are enough to remove granular sludge, in which the biomass is mostly concentrated. Moreover, soluble COD after ELSAR might still be too high for membranes in the following AnMBR polishing.

Comparison of baseline situation with ELSAR and AnMBR system

In the first four months of commissioning, the ELSAR removed up to 30 000 kg COD and treated up to 10.000 m^3 of wastewater

Despite not having achieved yet the full capacity, the ELSAR behaviour has been good and the demo-site has showed promising and consistent results that allow to validate the solution, at least up to the achieved OLR. This plant's magnitude immediately attracted the attention of the brewery, which is considering the ELSAR as an option to revamp the current WWTP. So far, the ELSAR has not produced excess sludge.

Several biochemical methane potential lab tests indicated that 0.31 Nm^3 CH_4 (with no electrostimulation) can be produced per removed kg COD. Assuming the 2000 kg

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COD/d nominal capacity, and 90% of COD removal, ELSAR could potentially produce up to 558 Nm³ CH_4/d, replacing the same amount of fossil natural gas (which is mostly methane).

2.2.3. Conclusion und recommendations

Lessons learned from technology operation and symbiotic relationship

According to the COD removal, to the biogas production, to the biogas quality and to the absence of instability indicators (volatile fatty acids, VFA), as well as to the low energetic consumption, ELSAR showed to be a suitable, effective, compact and competitive solution for the treatment of food and beverage wastewaters. Special attention should be paid for choosing enough and appropriate inoculum (granular sludge), which is the biomass required to drive the anaerobic process. A start-up procedure like the ones of traditional high-rate anaerobic reactors (based on gradual increases of OLR and VFA monitoring) was successful.

A primary treatment upstream of the ELSAR is required, to achieve levels below the maximum suspended matter contents in the wastewater tolerated by ELSAR. Up to 12.5 kg/m^3/d in batch mode showed that no chemicals were needed for TSS removal. Sludge adaptation is critical and re-inoculation can be required.

AnMBR coupled to ELSAR or to any anaerobic high-rate anaerobic reactor is an interesting idea to cover process needs (biomass retention and effluent quality), but it needs further research for being validated as a reliable solution, since adding AnMBR to ELSAR means adding infrastructure (CAPEX) and operation and maintenance (OPEX).

Best practices and recommendations for technology design and operation in the symbiotic frame

Granular sludge and methanogenic cultures are rather delicate and intolerant to fluctuations in water composition, especially in pH, TSS or temperature. Therefore, pre-treatments or big enough pre-equalization steps are essential for the success of anaerobic processes like ELSAR or AnMBR. Since ELSAR or AnMBR are not only COD eaters, but biogas producers, a plan for taking profit of biogas is required to make attractive the idea anaerobic processes to potential industrial end-users like the brewery in CS5. Both proposed systems are compact, being of interest in industrial areas, where usually space is an issue.

Crucial factors for technology implementation and its optimal performance

- The higher the content in biodegradable COD (> 2 g COD/L) in your wastewater, the higher the benefits vs. traditional aerated alternatives, especially in terms of OPEX and benefits due to biogas profits.
- The higher the prices in electricity, in gas (or in heat) or in sludge treatment, the more attractive the anaerobic processes like ELSAR or AnMBR.

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- Equalised, between pH 6 and 8, warm, sulphate-light, biodegradable wastewaters are essential for anaerobic processes.

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2.3. Biogas valorisation for electricity production using a solid oxide fuel cell in Lleida (ES)

Antonio Gimenez Lorang (AQUALIA), Victor Monsalvo (AQUALIA)

2.3.1. Case study and ULTIMATE concept

Case study description

A domestic-scale (<5 kW) solid oxide full cell (SOFC) is used at the WWTP valorising the cleaned biogas from the sludge treatment facility (Figure 18, Figure 19). There, Aqualia uses a self-designed pre-treatment and the commercial existing BlueGEN system, developed by Solydera (formerly Solidpower). With a gas input of 2.5 kW, the electrical power is up to 1.5 kW and the usable heat is 0.54 kW. To the author's knowledge, it will be the first SOFC operated with WWTP biogas in Spain. Also, for the SOFC provider this study has been the first time where his SOFC product was fed with biogas. The goal of this demonstration site was to introduce and validate the SOFC technology as an energy recovery solution and its potential in a WWTP environment compared to traditional solutions such as a CHP unit.

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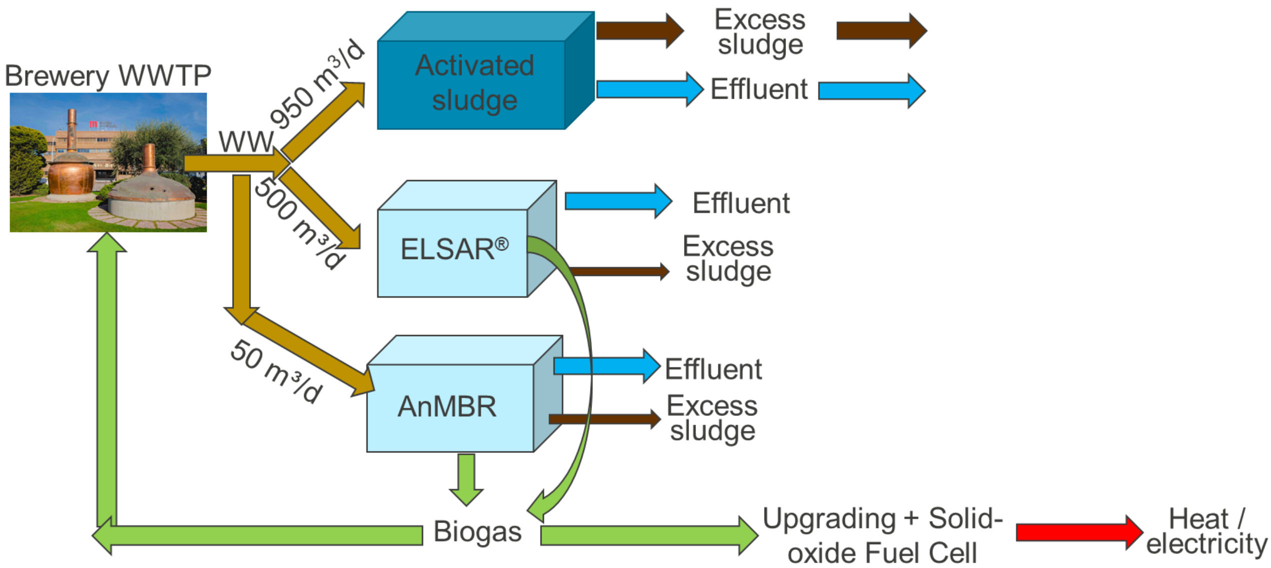

Figure 18 Flow scheme of the existing system: activated sludge system and the ULTIMATE solutions: ELSAR and AnMBR including the solid oxide fuel cell for biogas valorisation

Technology description

The SOFC (TRL 9) model BG15 of Solydera uses chemical energy bound in gases such as hydrogen, carbon monoxide or upgraded biogas to produce electricity via electrochemical reactions, supplying also heat as by-product. In the case biogas is used, methane (CH_4) must be converted first into hydrogen (H_2) and carbon monoxide (CO) in a reforming process.

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Using biogas as an alternative SOFC fuel to H_2 or CO was proven to be viable. Therefore, the SOFC can be considered as a substitute of a combined heat and power plant (CHP) in WWTP with anaerobic digestion of sludge. The most interesting point here is the electrical conversion efficiency: in SOFC this is between 50% and 60%, which is higher than CHP electricity producing processes (ranging between 28% and 40%, according to Riley et al., 2020).

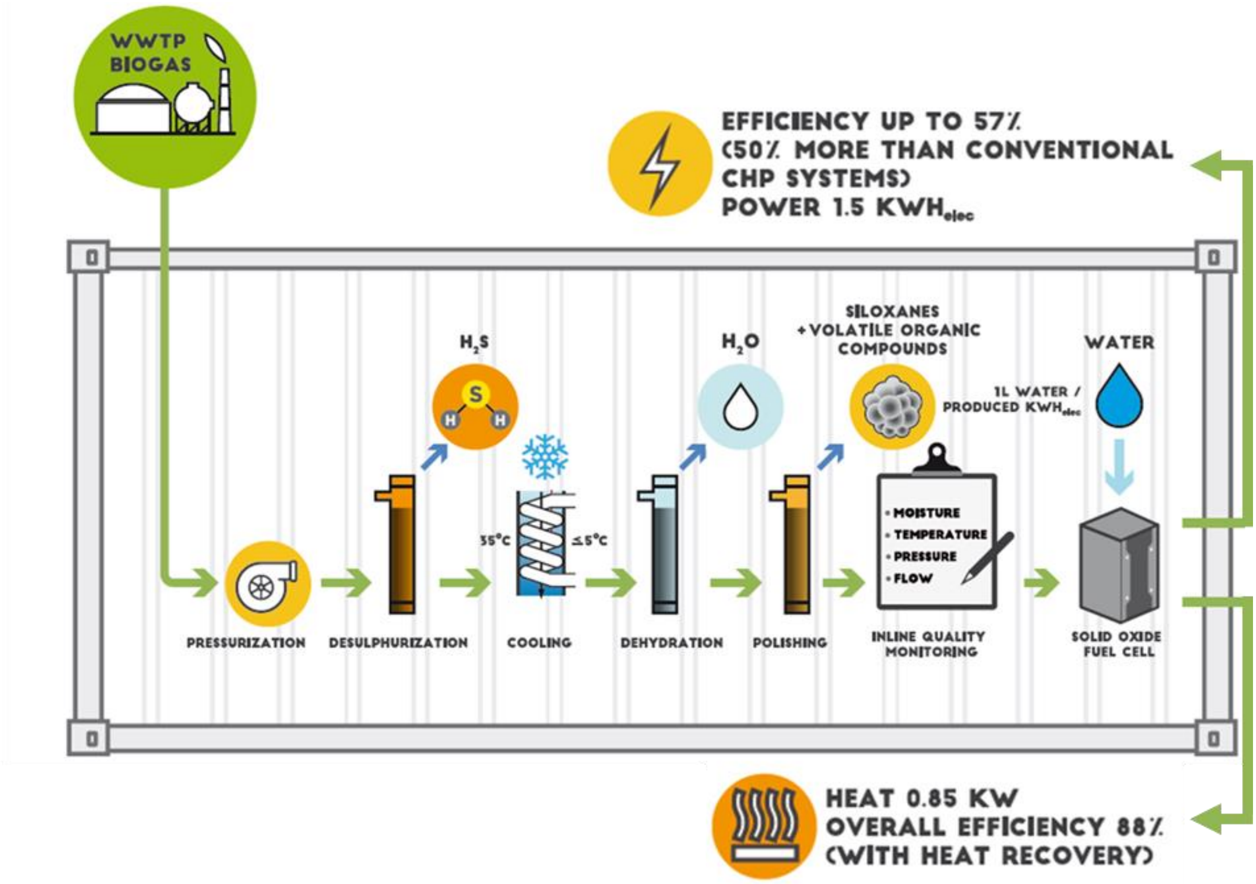

Figure 19 Solid oxide full cell with biogas upgrading treatment units

Unique selling points

- High electrical conversion efficiency (60%)
- Low environmental impact due to biogas valorisation

Technical requirements for the SOFC implementation and operating conditions

Raw biogas needs to be cleaned prior to the valorisation in a SOFC, since it usually contains H_2S, siloxanes, volatile organic compounds (VOC) and vapour condensates which can harm the SOFC. Therefore, biogas pre-treatment was required, although there were no established criteria, neither from the supplier nor from literature. The chosen pre-treatment was based on several absorbents for removing the mentioned pollutants until non-detectable limits. General ATEX and safety measures were considered in the design and operation of the unit.

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2.3.2. Results of SOFC demonstration

Technology performance

After the first year of operation, a constant output's behaviour was achieved, fitting with the SOFC specifications (Figure 21, Table 9):

- Electrical efficiency: between 55.1±0,5% and 55.6±0,5%, being ca. +50% higher than conventional CHP. A KPI was set for an Energy recovery >30%. Because electrical efficiency was above 30%, it can be concluded that this KPI has been widely reached.
- Produced power: between 1.226±0.018 kW and 1.298±0.018 kW, confirming nominal capacity (1.3 kW)
- Net thermal efficiency: in case of heat reuse, up to 0.75 kW would have been produced at 30 °C return temperature and 1.3 kW_{el} (heat was not reused in ULTIMATE)

The biogas pre-treatment was validated, since impurities in pre-treated biogas were not present. The produced energy was injected into the local electricity grid. Up to 6 MWh were produced and an electrical bicycle (Figure 20) was fed with the produced energy.

Figure 20 ULTIMATE electrical bicycle for transport of samples etc. from the plants to the laboratory in CS5

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Comparison of the baseline situation with the SOFC integrated system

The SOFC demo-site produced net 1.3 kW and consumed 10 m^3 of biogas/d (Figure 21, Table 9). This is a negligible fraction of the biogas produced in the ELSAR (30 m^3 biogas/h) or in a WWTP like the one in Lleida (ca. 3000-4000 m^3 biogas/d). Thus, the impact on an industrial scale was negligible.

However, the interest of SOFC as a reliable solution with energetic purposes for biogas was seeded and has attracted the attention of engineers and developers in Aqualia. Moreover, external contacts have contacted Aqualia to get insights of the CS5 SOFC experience. Aqualia promoted the SOFC experience among local water entities.

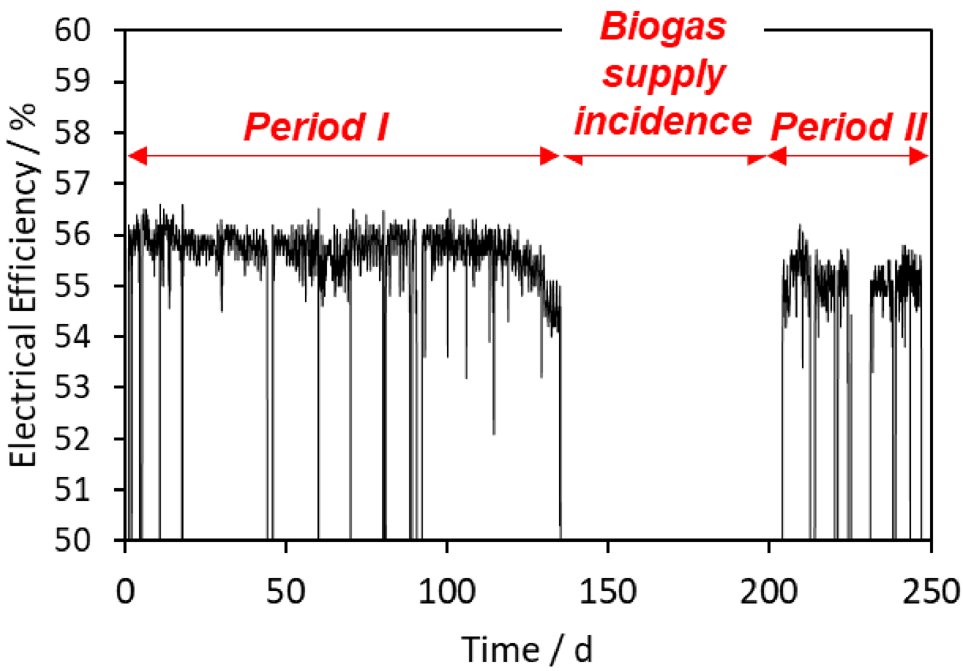

Figure 21 Electrical efficiency of the SOFC after the first year of operation

Table 9 Average values of the electrical efficiency, power output, water consumption and produced energy of the SOFC in two periods after the first year of operation

Parameter	Period I	Period II	Supplier specifications
Electrical efficiency	55,6 ± 0,5 %	55,1 ± 0,5 %	57,0 %
Power output	1298 ± 18 W	1226 ± 18 W	1300 W
Water consumption	18 ± 8 L/d	16 ± 7 L/d	Up to 32 L/d
Produced energy	4 MWh	2 MWh	-

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2.3.3. Conclusions and recommendations

Lessons learned from technology operation and symbiotic relationship

- Shutdowns of SOFC must be minimised, to maximise the lifespan of the SOFC stack and components.
- No dehydration (total removal of water) of biogas before entering the SOFC is really needed; thus, this step can be removed from the design.
- The more mature the SOFC market, the more understanding of boundary conditions of the solution. For example, biogas quality requirements were not known from the side of the SOFC supplier, since this was his first experience using biogas as fuel.

Best practices and recommendations for technology design and operation in the symbiotic frame

FC market seems still to be immature. However, there are already singular industry-scale references that validate the feasibility of the SOFC technology, paving the way to a revamping era for old biogas-fed CHP in WWTP, gaining electrical efficiency. Additionally, SOFCs might bring easier O&M than traditional CHP, because core equipment in SOFCs (stacks) is modular and therefore probably more easily to be replaced than internal combustion engines, which are a multicomponent equipment. Production development is still needed in the SOFC industry to achieve competitive prices. Water entities and water utilities shall be aware of the FC market development and detect opportunities as early adopters for FC in WWTP producing biogas.

Crucial factors for technology implementation and its optimal performance

- A techno-economic market study for 60-250 kW FC is required to understand better the potential of SOFC solution.
- SOFCs are, as CHPs, solutions which intend to produce electricity and heat from biogas. It seems reasonable to suggest that public support for grid injection of biogas (in the form of biomethane) could influence the promotion of SOFC or CHP systems, potentially displacing them and promoting instead the upgrading of existing plants.
- Nevertheless, it is important to remark that injection of biogas is usually linked to landfills or to agri-food waste, and seldom to WWTP, where the biogas production potential is lower. Moreover, energetic self-sufficiency of large WWTPs is one of the mandatory requirements stated in the new draft WW EU directive. In such a context, self-consumption of biogas is a coherent and interesting strategy for WWTP operators. Therefore, SOFCs represent an opportunity for efficient energy obtention, energy that can be used in the WWTP processes, either in form of heat or in form of electricity.

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2.4. Biogas production from anaerobic pre-treatment of municipal and/or industrial wastewater in Karmiel (IL)

Katie Baransi Karkaby (GSR), Nedal Massalha (GSR), Mahdi Hassanin (GSR), Isam Sabbah (GSR)

The immobilised high-rate anaerobic reactor, also known as advanced anaerobic technology (AAT), can be applied in wastewater treatment plants (WWTP) as a pre-treatment. It reduces the organic load, which leads to savings in energy demand/costs in the downstream aerated tank. Due to the anaerobic conditions in the reactor, biogas is formed and can be recovered. The recovered biogas is a renewable energy source that can be reused at the wastewater treatment plant.

2.4.1. Case study and ULTIMATE concept

Case study description

The Symbiosis in Karmiel interconnects two SMEs (AgRobics and GtG) from the agro-food sector with a public wastewater utility, linking an industrial wastewater combined with a municipal wastewater treatment plant of Karmiel (WWTP). The agro-industrial sector includes agriculture, food industry, olive oil mills and water treatment. The symbiosis enables protecting the Karmiel's WWTP that is usually exposed to sudden shocks of strong and problematic agro-industrial wastewater (i.e, olive mill wastewater, slaughterhouse, winery). Karmiel municipal WWTP faces problems due to illegal discharge of agro-industrial wastewater, mainly olive mill wastewater (OMW) during the harvest season as well as illegal discharges from slaughterhouses. No solution has been found yet for upstream and on-site wastewater pre-treatment that is technically feasible, economically viable and socially acceptable. Thus, when such shock loads happen, the wastewater is discharged without adequate treatment, leading to almost total collapse of the biological process.

The Karmiel municipal WWTP (Northern Israel) includes pre-treatment, physical settling, biological treatment (activated sludge-based) and tertiary treatment (sand filtration). The immobilised high-rate AAT (AgRobics) system provides protection for the next downstream process of high load organic matter (high shock COD). The AAT pilot in ULTIMATE receives 100 m^3/d of wastewater by a centrifugal pump. During the operation, OMW was discharged (for the experiments tagged as "with OMW") into the system using a peristaltic pump. Using a 1.5 m^3 mixing (equalization) tank, 99.5% municipal wastewater (mWW) was mixed with 0.5% olive mill wastewater. The mixed stream enters the AAT pilot for high-rate anaerobic treatment of about 5 hours of hydraulic retention time (HRT) and production of biogas.

Technology description

In the AAT, the microorganisms are immobilised in a "bio-stabilised" polyurethane-based matrix. This matrix has a large surface area for biofilm fixation and for new growth formation. This structure protects the microorganisms from washout leading to

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a much more stable process operation. This stable process insures sustained production of biogas by reducing the organic load (relatively high as a result of the mixture of OMW and mWW). More important than the production of biogas and reduction of the energy demand in the successive aerobic step, is the high potential of decreasing the sludge production. This reduction leads to significant decrease of the treatment and transportation of the sludge, which is usually used for soil amendment after composting. The TRL of the system is 8. AAT has the capacity to treat high organic loads (9-11 kg COD/(m^3*d)) resulting from the OMW discharge and protecting the subsequent activated sludge process. This system enables recovery of a significant part of the organic load by anaerobic biodegradation to produce biogas (up to 12.5 m^3 biogas/d corresponding to 0.016-0.08 m^3 biogas/(kg COD_T)), shown to be highly dependent on the temperature in the bioreactor and partly on the organic loading rate. AAT can tolerate an addition of up to 0.5% OMW to mWW by removing more than 50% of the total chemical oxygen demand and 18-47% of polyphenols. The points of application driven by this work are AAT systems applied for pretreating municipal mixed with agro-industrial wastewater, increasing the biogas production, decreasing energy demand, reducing the sludge production and protecting small-medium WWTPs by any agro-industrial discharges.

Unique selling points

- Reduction of high organic loading rates in an anaerobic pre-treatment prior to an activated sludge system; this solution contributes to an extra biogas production from the inlet wastewater
- High process stability due to the immobilised biofilm matrix

Technical requirements for its implementation and operating conditions

For the anaerobic high-rate reactor, a polymer-based foam is used to enable a stable microbial activity and hence, a robust biogas formation process. A storage tank is also important for OMW storage and discharge. The typical ranges for operating parameters are given in Table 10.

Table 10 Typical ranges of selected parameters for operating conditions

Parameter	Units	Min	Max
pH	-	6.8	8.5
Temperature in bioreactor	°C	15	40
Hydraulic retention time	h	2.4	
Organic loading rate	kg COD/(m^3*d)	1.5	9-11
%OMW	%Volume	0	0.5

2.4.2. Results of new approaches

Technology performance

The results from the Karmiel system performance are presented in Figure 22-Figure 29. The degradation of total and soluble COD is an important parameter for the

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operation of the system. Figure 22 presents the total COD of the influent and the effluent (Figure 22a) along with the removal efficiency as a function of temperature (Figure 22b).

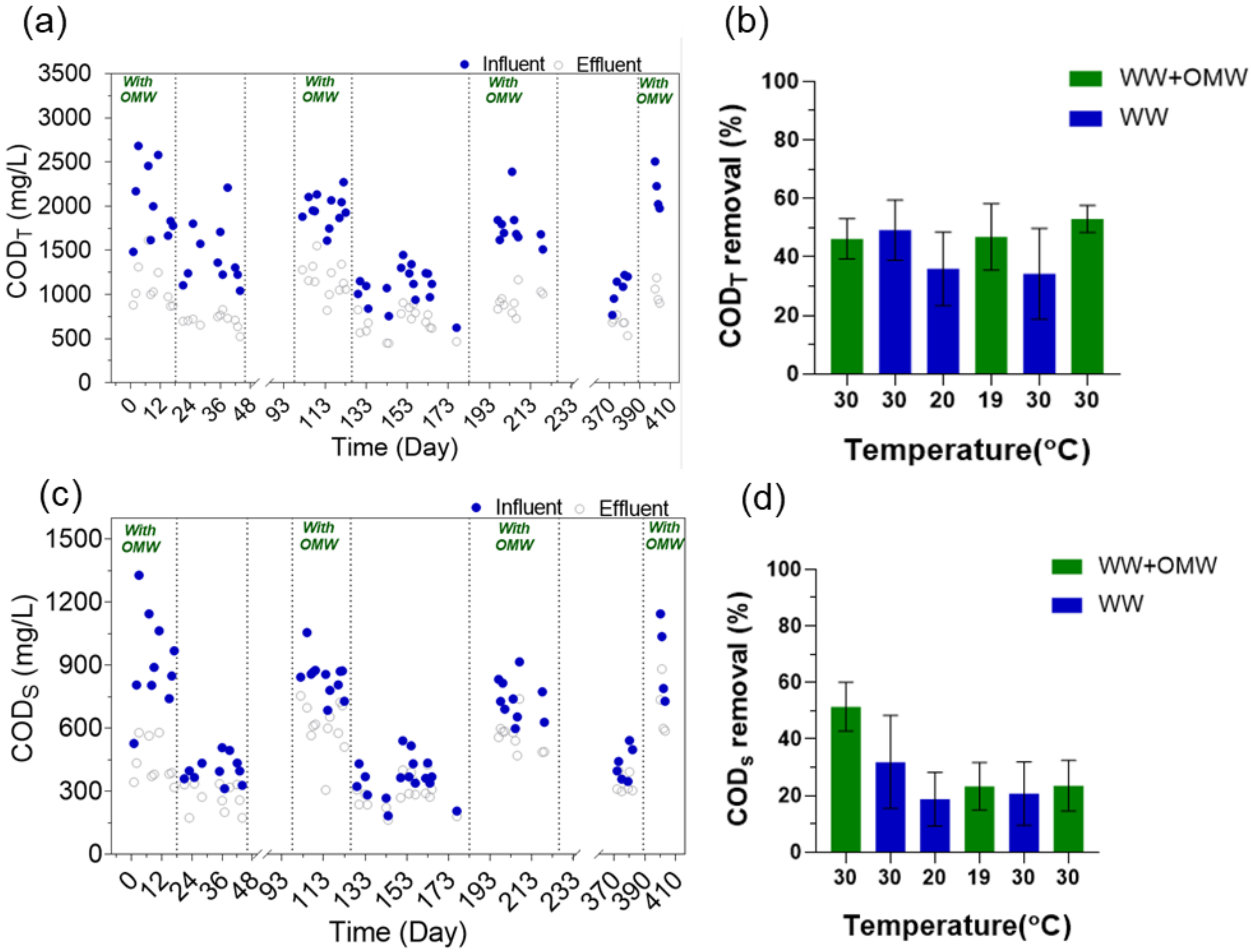

Figure 22 *(a) Total COD as a function of time for the influent AAT and the effluent at the Karmiel system and (b) total COD removal as a function of temperature for the influent AAT and the effluent at the Karmiel system; (c) soluble COD as a function of time for the influent AAT and the effluent at the Karmiel system; (d) soluble COD removal as a function of temperature for the influent AAT and the effluent at the Karmiel system.*

Figure 22a shows that the influent total (COD_T) increases when OMW was combined with mWW, however, the effluent total (COD_T) was stable at a value of about 900 mg/L. It is clearly shown that the high organic peaks observed as a result of the mixed OMW were shaved and eliminated; this demonstrates a future potential for protecting WWTPs from sudden agro-industrial discharges. Moreover, during the summer period (hot weather with an average temperature around 30 °C), a COD removal efficiency of 46% was achieved (Figure 22b) for an inlet COD_{in} of 2,280 mg/L (WW+OMW), while a removal efficiency of 49% was achieved (Figure 22b) for a COD_{in} of 1,430 mg/L (without OMW). In the winter period (warm period with average temperatures of 19-20° C), a COD removal efficiency of 47% was obtained for a COD_{in} of 1,770 mg/L (WW+OMW), while the removal efficiency was slightly decreased to about 36% (Figure 22b) for a COD_{in} of 1,088 mg/L (without OMW). The soluble COD_S was lower than the

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total COD_T, 33% of COD_T for WW, and 43% of COD_T for WW+OMW (Figure 22c). The removal efficiencies were lower as well (Figure 22d).

Figure 23 shows the AAT performance efficiency of total COD removal as a function of the OLR during the performance period. As can be seen from this figure, the OLR with added OMW was higher than without OMW in the feed. The addition of OMW at 0.5% has increased the OLR to 9–11 kg COD/(m^3*d), where the corresponding COD removal was between 40% and 55%. It is important to mention that these applied OLR values are very high for mWW systems, where they are comparable to operational conditions of the challenging high-rate anaerobic treatment of agro-industrial wastewater. The main outcome of this long operation period (4 seasons) shows the removal efficiency was relatively stable throughout the operation of AAT. A slight decrease in the removal efficiency was observed in days 133-183, which may be mainly due to relatively low temperatures (around 20 °C).

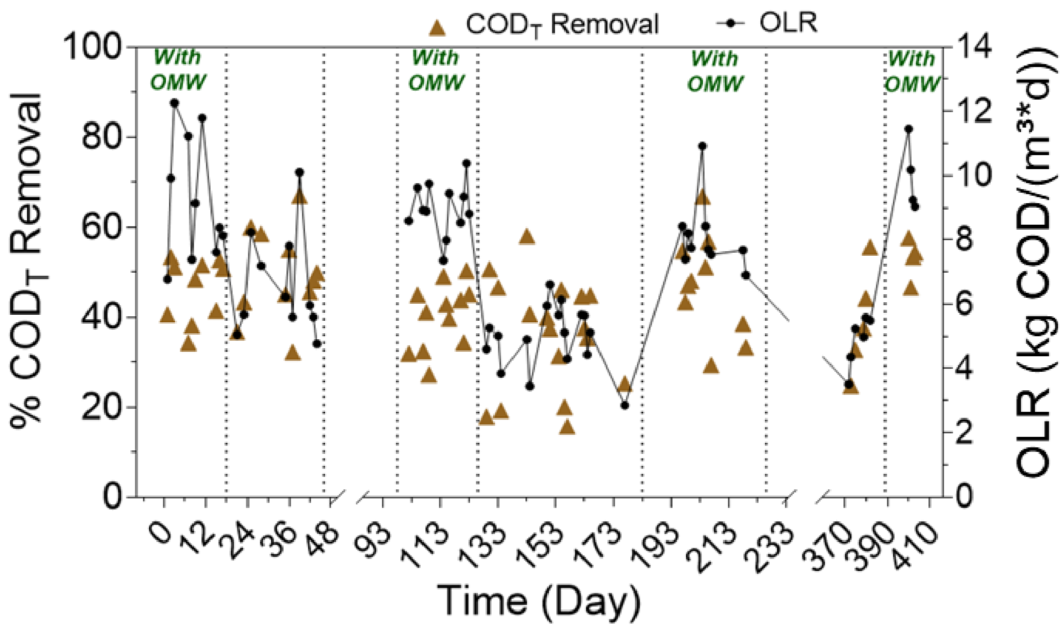

Figure 23 *OLR and %COD_T removal as a function of time for the influent AAT and the effluent at the Karmiel system.*

Anaerobic biodegradation results in biogas production, which is an important aspect for energy recovery. Figure 24 presents biogas production (m^3/d) throughout the AAT's operation time; the average OLR of each operational period is also presented at the upper part of the figure. From the figure, it is clear that the biogas production was highly dependent on both temperature and OLR. In all cases, the addition of OMW resulted in a 10% increase in the biogas production. In particular, the first two operational periods were the best for comparison, as they were operated under almost the same temperature (30 °C). In these periods, the addition of OMW resulted in an average increase of about 10%; from 8.7 m^3/d (mWW without OMW) to 9.6 m^3/d when OMW was added. This increase corresponds to the change in OLR, where the high OLR of 9.3 kg COD/(m^3*d) (mWW mixed with OMW) resulted in higher biogas production rate than the lower OLR of 6.57 kg COD/(m^3*d) (without OMW). A similar increase in the

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biogas production rate was also observed for the period at a low temperature of 20 °C (days 133-233), where a biogas production rate of 3.7 m^3/d was obtained with the addition of OMW (OLR=8.2 kg COD/(m^3*d)) compared to 3.4 m^3/d without the addition of OMW (OLR=5 kg COD/(m^3*d)). Comparison of the biogas production at the different temperature ranges indicates the strong effect of temperature on biogas production, as biogas production was two and a half times higher at 30 °C than at 19.5 °C despite comparable OLR of 9.3 kg COD/(m^3*d) and 8.2 kg COD/(m^3*d).

The proposed biogas recovery (KPI) at the beginning of the project was 8-15 m^3/d, as mentioned above, 9.6 m^3/d of biogas was achieved when mWW was mixed with OMW corresponding to high OLR of 9.3 kg COD/(m^3*d). This result is in line with the proposed KPI.

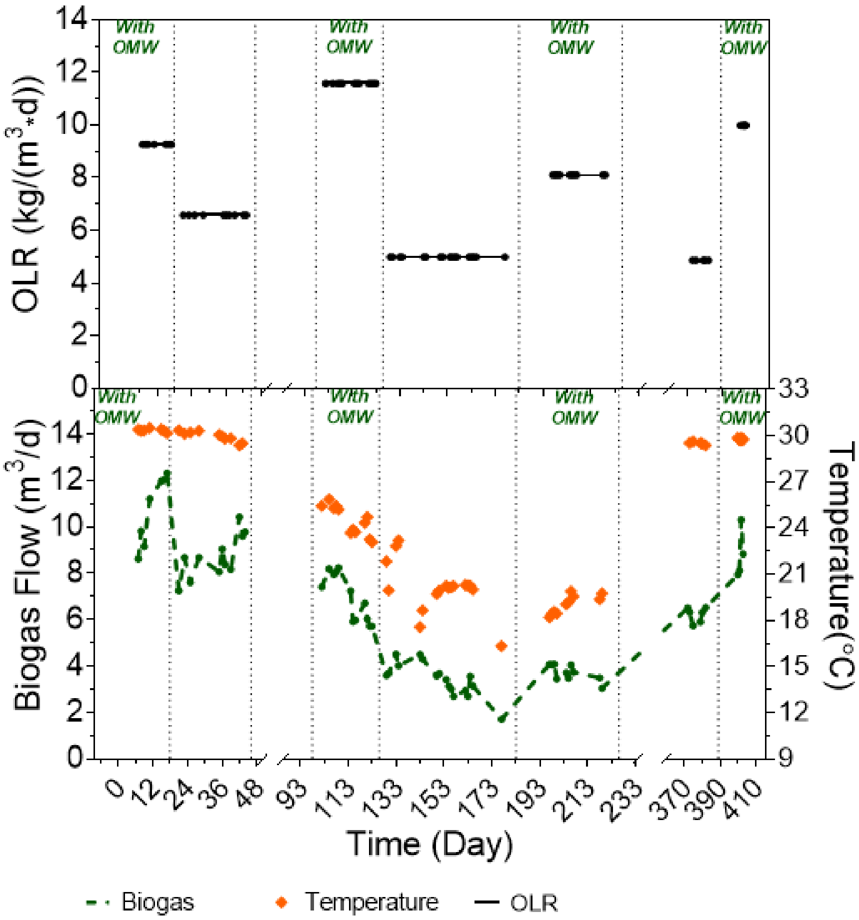

Figure 24 *Biogas flow and temperature as a function of time from the AAT at Karmiel system, the average OLR of each operational period is presented at the upper part of the figure.*

Comparison of baseline situation with ULTIMATE solution

The proposed energy recovery (KPI) was 20%, 20% is achievable according to BioWin simulation due to the combination of reduction of the organic matter by an anaerobic process and additional biogas production. The redaction of organic load by the AAT led to a less need for oxygen in the successive activated sludge aeration unit.

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The proposed reduction in energy demand (KPI) was 20-25%, however only 8–15% can be achieved beyond the project according to BioWin simulation. This is due the oxygen (energy) needed for the nitrification process and the organic matter we need to leave for the denitrification. However, in case there is no need to remove the nutrients in the following activated sludge (aerobic) system (which is correct for the case of Karmiel system), we might reach more than 20% saving of the energy.

The methane production rate over OLR as a function of time and temperature is presented in Figure 25. In this figure, it is clear that the normalised methane per OLR was lower when applying OMW relatively to the scenario without OMW addition at a similar temperature. This can be attributed to the inhibiting effect of the OMW constituents (i.e., polyphenols and tannins). Regardless of the different operational conditions, it can be clearly seen that methane was produced throughout the AAT operation.

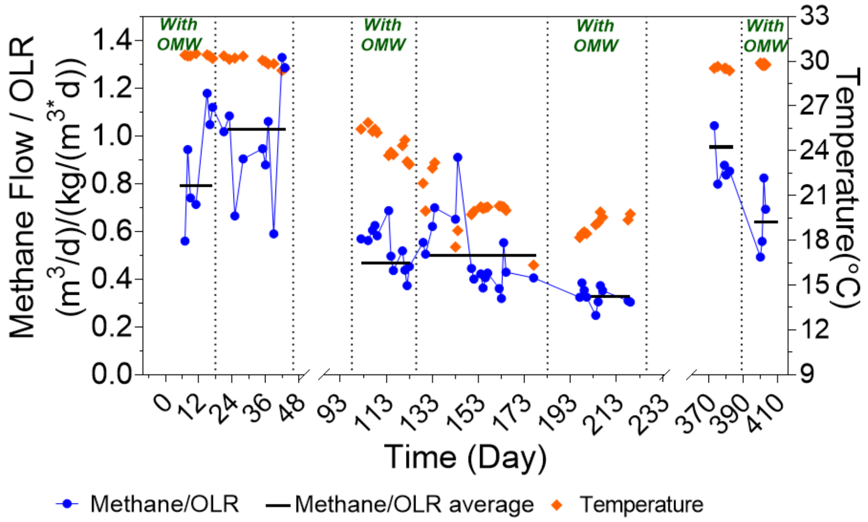

Figure 25 *Methane flow rate over average OLR as a function of time and temperature of the AAT system at Karmiel*

The estimated methane yield (KPI) at the beginning of the project was 0.12-0.15 m³ CH_4/(kg CODs). CODs corresponds to the inlet dissolved organic matter.

Figure 26 (a) shows that the achieved methane yield was between 0.01-0.06 m³ CH_4/(kg COD_t); the kg COD in this case corresponds to the total COD in the inlet. From Figure 26 (a) it can be seen the average methane yield was 0.037 m³ CH_4/(kg COD_t) that corresponds to a high OLR of 9.3 kg COD/(m^3*d) when mWW was mixed with OMW (at high temperature). However, the methane yield range is 0.03-0.197 m³ CH_4/(kg COD_s) as can be seen in Figure 26 (b) if calculated based on the inlet soluble COD (COD_s), the average values for methane yield based on the inlet soluble COD are shown in Figure 26(c). The yields are lower than the methane yields of typical anaerobic digestion system that work in the optimal temperature of 37 °C, where in our case the temperature is much lower (15-27 °C), also the HRT is 5 hours, which is very low (typical for high rate systems). Figure 26(d) shows the methane yield based on the

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removed soluble COD, in this case the yields are higher and much closer to the theoretical values of the production of methane.

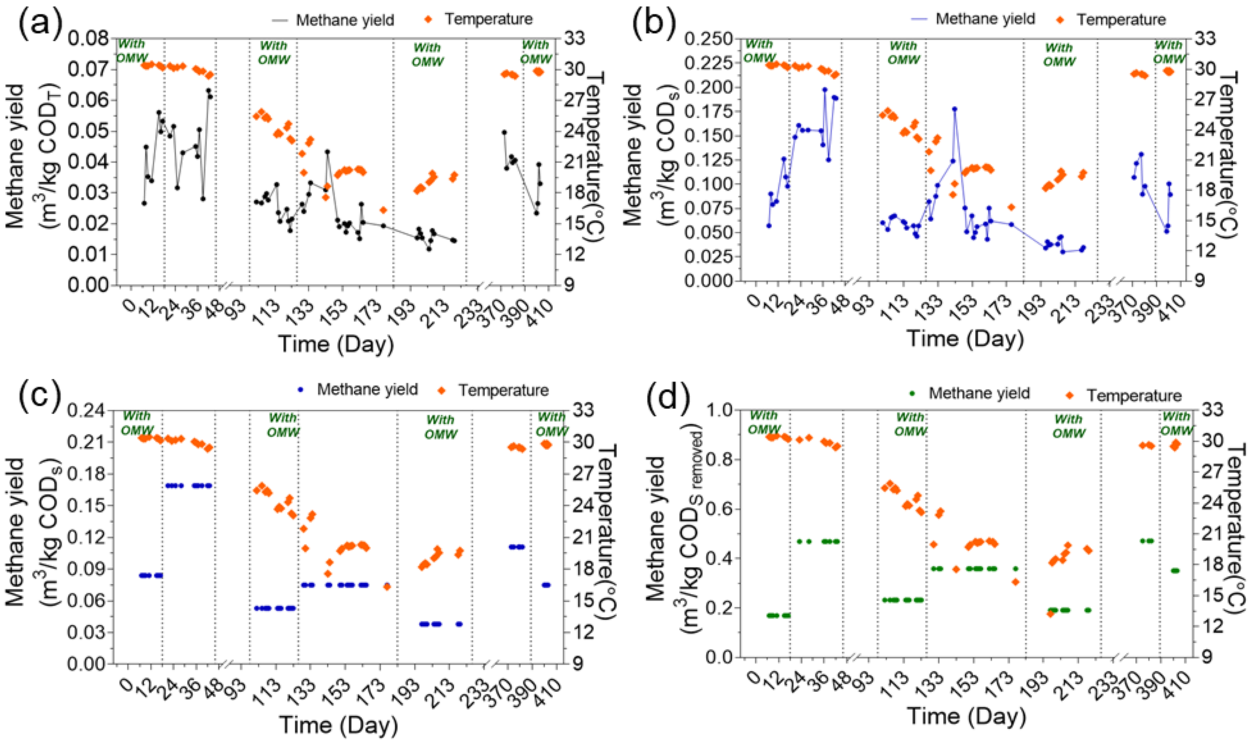

Figure 26 *(a) Methane yield based on COD_t as a function of time and temperature of the AAT system at Karmiel; (b) methane yield based on COD_S as a function of time and temperature of the AAT system at Karmiel*

In the second period of operation where only mWW fed the AAT (at high temperature), the average methane yield achieved was 0.049 m³ CH4/(kg COD), apparently due to less inhibition effect caused by the OMW mixed with mWW in the first operational period.

Figure 27 presents methane production rate as a function of OLR and temperature. This 3D presentation visually illustrates the relatively combined impact of OLR and temperature on methane production. As can be seen in the figure, higher methane yields were achieved at higher temperatures regardless of the changes in OLR. As anticipated, OLR has a much lower effect on methane production than the temperature in anaerobic process. It is clear that, for the same temperatures, higher OLRs did not lead to increased methane production.

The polyphenol concentrations during the AAT operation are shown in Figure 28. It is clear that the OMW discharge increased the polyphenols concentration in the inlet (45 mg/L on average). However, the AAT was able to tolerate these concentrations, achieving removal efficiencies ranging between 18% and 47%.

Another important aspect for achieving a “healthy” anaerobic digestion process is pH. The ideal pH for anaerobic digestion is 6.8–7.2, while the process can be functional without inhibition at pH values of 6.5–8. As shown in Figure 29, the AAT effluent pH

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generally remained within these permissible values. Specifically, the pH dropped to 6.6 when OMW was added to the system. Therefore, only 0.5 m³/d of OMW per 100 m³/d of mWW was applied to avoid rapid acidification. It is important to indicate that the VFAs levels remained very low in the AAT outlet. This demonstrates that the methanogenic stage was not disturbed, and the methane was easily formed from these intermediates.

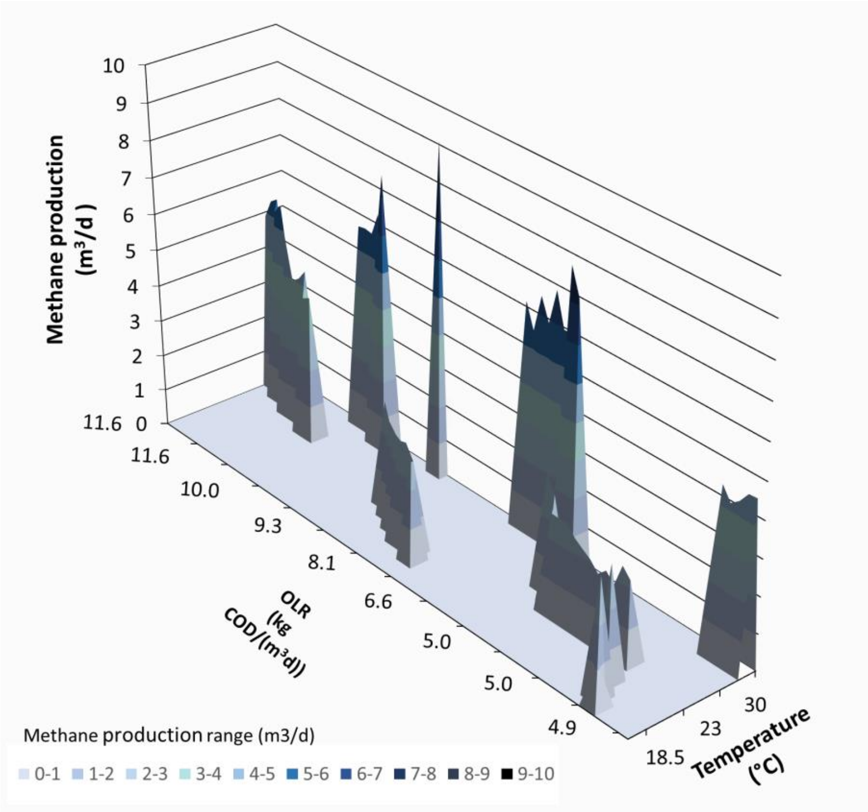

Figure 27 Methane flow rate of the AAT system as a function of OLR and temperature

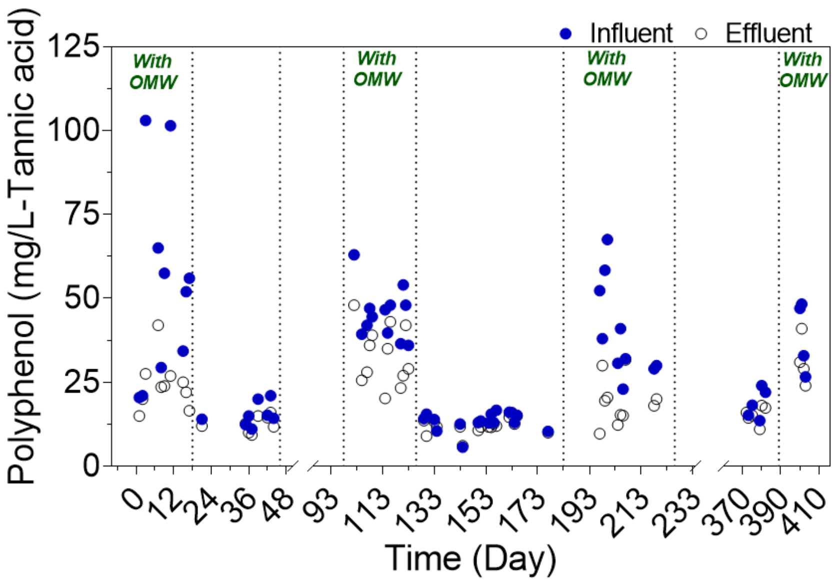

Figure 28 Total polyphenols concentration as a function of time for the influent AAT and the effluent at Karmiel system

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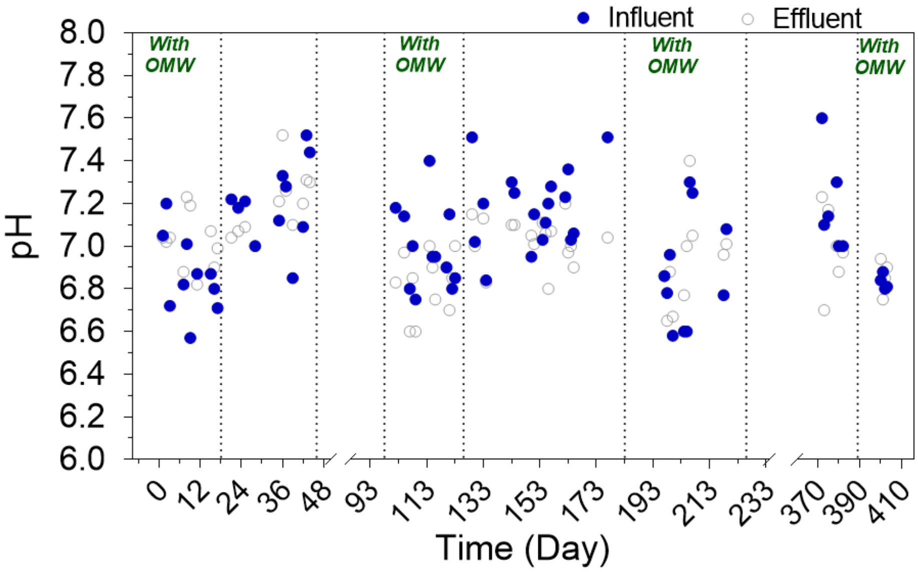

Figure 29 pH changes during the AAT operation

2.4.3. Conclusion

Lessons learned from technology operation and symbiotic relationship

No appropriate treatment or management solution has yet been developed for an upstream and on-site treatment of olive mill wastewater, that can be considered technically feasible, economically viable and socially acceptable. Thus, most of this challenging wastewater is discharged without adequate treatment, in the worst-case scenarios, or through land spreading, if available, in the relatively better scenarios.

In this current study, we simulated the scenario of the illegal discharge of agro-industrial wastewater and showed that OMW mixed with mWW could be successfully treated and partially biodegraded without harming the downstream process in any WWTP. However, this can be achieved under limited and controlled conditions. More specifically, we have shown in this study that, when our developed AAT technology is applied and operates well, the system can tolerate the addition of up to 0.5 m^3/d of OMW per 100 m^3/d of mWW (0.5% OMW), which corresponds to an additional OLR of 2.7-3.3 kg COD $m^{-3}d^{-1}$ to the baseline of the mWW. The system shows a COD reduction of about 50%, a polyphenol reduction of 18%-47% with a stable performance, as well a decent increase of biogas production of 8-41%. A ratio of OMW/WW exceeding 0.5% increases the organic loading rate and decreases pH levels leading to reduction of the biological anaerobic activity (limitation in achieving our goal of reaching a 2% OMW).

Moreover, AAT enabled treating high organic loads (9-11 kg COD $m^{-3}d^{-1}$) resulting from OMW discharge, by shaving the high peaks of the organic content, leading to a protection of the subsequent activated sludge process. The AAT system allows the recovery of a significant part of the organic load through the production of biogas, the main product of anaerobic biodegradation, which was shown to be highly dependent

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on temperature and partly on the OLR. However, biogas production in cold weather was below the promised 8 m^3 biogas/d.
This work shows that the AAT system has the potential for pretreating mWW, increasing the energy efficiency of the plant, and protecting small-medium WWTPs of sudden agro-industrial discharges.

Best practices and recommendations for technology design and operation in the symbiotic frame

Combining OMW with mWW based on the above optimal operation ratio as was shown in the R&D section, will be the recommendation for the symbiotic frame of best practice of management the very problematic stream of olive mill wastewater at the first step. This symbiotic solution comes with other advantages:

1) Increase of the total production of biogas as well as decrease of the energy demand for the following aerobic process.
2) Significant decrease of the sludge production leading to a significant saving of the operational cost
3) Potential of material recovery (polyphenol; D1.5)

Crucial factors for technology implementation and its optimal performance

- Low temperature (around 20 °C) for a long period (in the wintertime) would negatively affect the implementation of the AAT technology. In our three years of operation of the pilot system, we have shown that anaerobic activity is highly dependent on the temperature of the water. From our results the combination of high organic load and temperature, we can summarize that a temperature of below 18 °C for more than 4-5 months will be a crucial factor to obtain optimal performance of the AAT process.
- The acceptance of stakeholder (for the Israeli case it is the Ministry of Environmental Protection and the Water Authority) is the main and crucial factor for the implementation of this technology.
- A higher ratio of OMW to mWW than 0.5 vol.-% is a limiting factor for the performance of the AAT system.
- The collection and adequate storage of the OMW (proper and accessible storage tank) is essential.

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2.5. Combining anaerobic biofilm treatment with membrane filtration and activated carbon in Shafdan (IL)

Katie Baransi Karkaby (GSR), Nedal Massalha (GSR), Mahdi Hassanin (GSR), Isam Sabbah (GSR)

The immobilised high-rate anaerobic reactor (advanced anaerobic technology "AAT") was, similarly to the Karmiel system, applied in the Shafdan pilot, but in this system it was combined with membrane filtration and activated carbon for higher biogas production (biofouling reduction/optimal operation) and for improving effluent water quality.

2.5.1. Case study and ULTIMATE concept

Case study description

The Symbiosis in Shafdan interconnects one SME (AgRobics) from the agro-food sector with a public wastewater utility, linking an industrial wastewater treatment plant (WWTP) with a municipal WWTP. Shafdan is the largest WWTP (400,000 m^3/d) of Tel-Aviv and in the center of Israel region. The applied symbiosis is suggested in order to examine in a large WWTP the combination of agro-industrial wastewater with mWW as a potential for better solution of such agro-industrial effluent and for potential energy recovery by biogas production. Suitable pre-treatment of agro-industrial wastewater at the Shafdan WWTP enables the continuation of the current nature-based reuse system and water supply for agricultural activity in the Negev desert, even when receiving more agro-industrial wastewater in the future. At the same time increasing the production of biogas (for decreasing the energy demand) and decreasing the sludge production.

Technology description

Integrated in the Shafdan WWTP, the pilot system consists of an AAT reactor combined with a novel activated carbon anaerobic membrane bioreactor (AC/AnMBR) that is positioned downstream to the AAT (Figure 30, Figure 31). Where, the immobilised biomass instead of granular biomass and the addition of activated carbon offers a promising approach for fouling reduction, which is unexplored yet within AnMBR technologies. The AAT combined with AC/AnMBR contributes to partially reducing the energy demand, decreasing sludge production as well as increasing biogas production. The TRL of the system is 6 (prototype system verified).

The system was delivered in August 2022, where the operation has started just around mid of November 2022 because of some technical trouble shooting and different technical problems of the start-up of the system. Then after a few months of problems, mainly because the instability in providing raw wastewater to the system, the technical staff could solve most of them and the sampling plan started in May, 2023. However, in August 2023, once again it was observed that the inlet COD was very low (below 200 mg/L) as can be seen in Figure 32.

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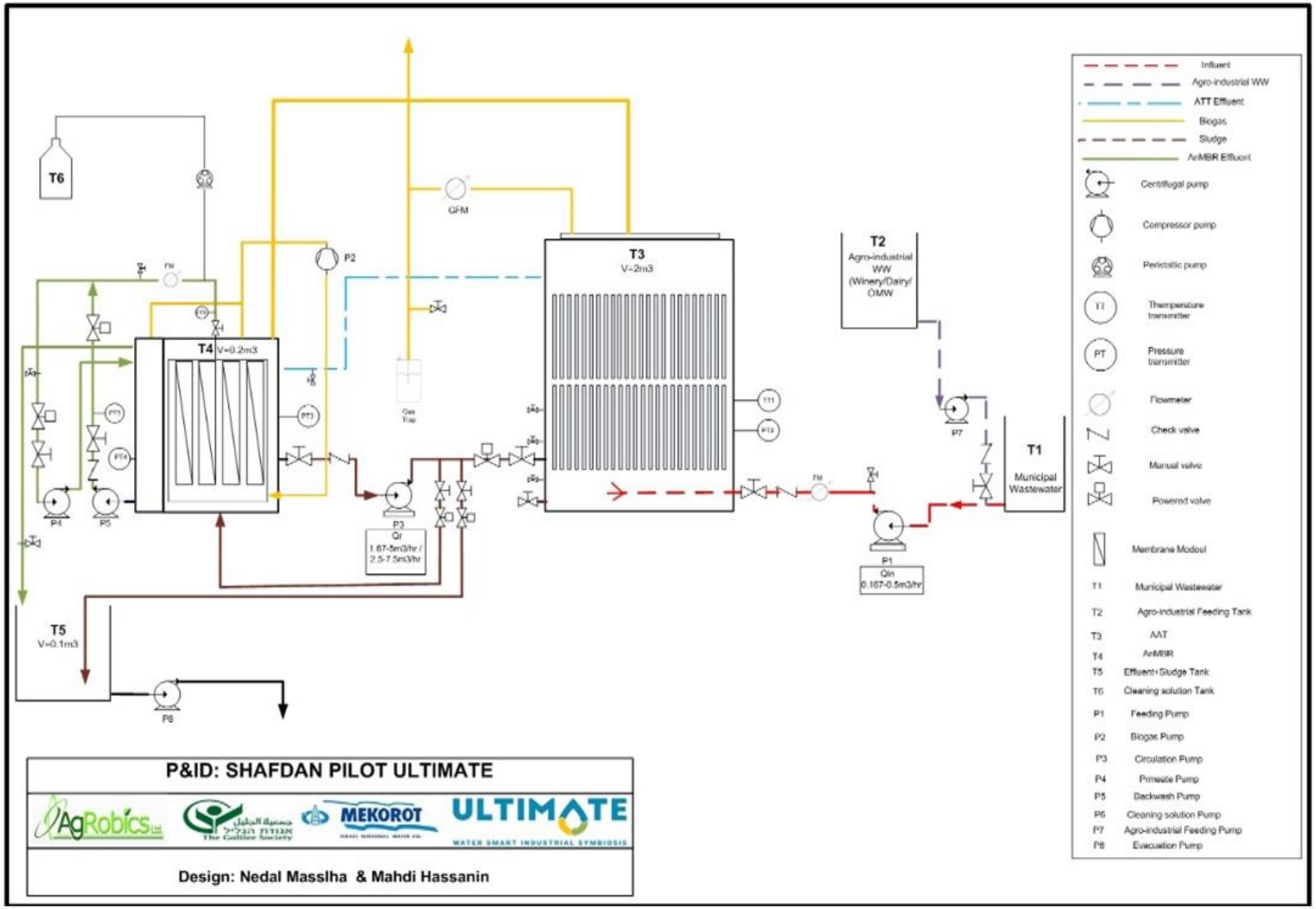

Figure 30 *PI&D description of the AAT combined with AnMBR*

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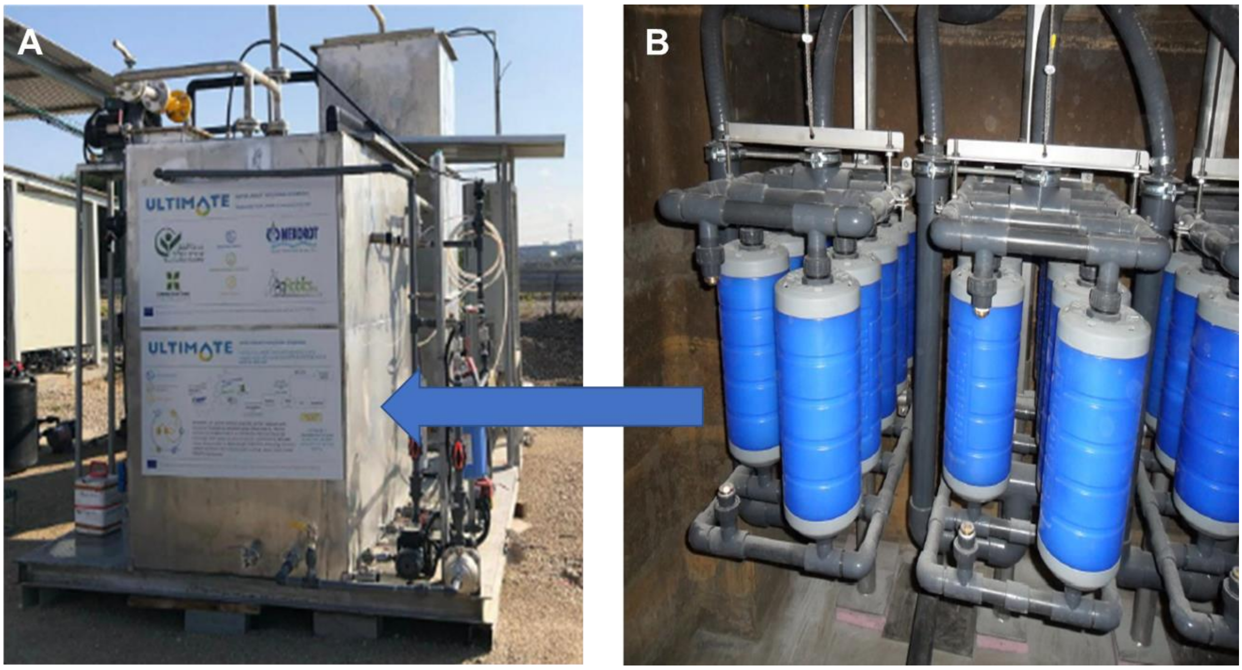

Figure 31 *Picture of the A) Shafdan system with the B) membrane units*

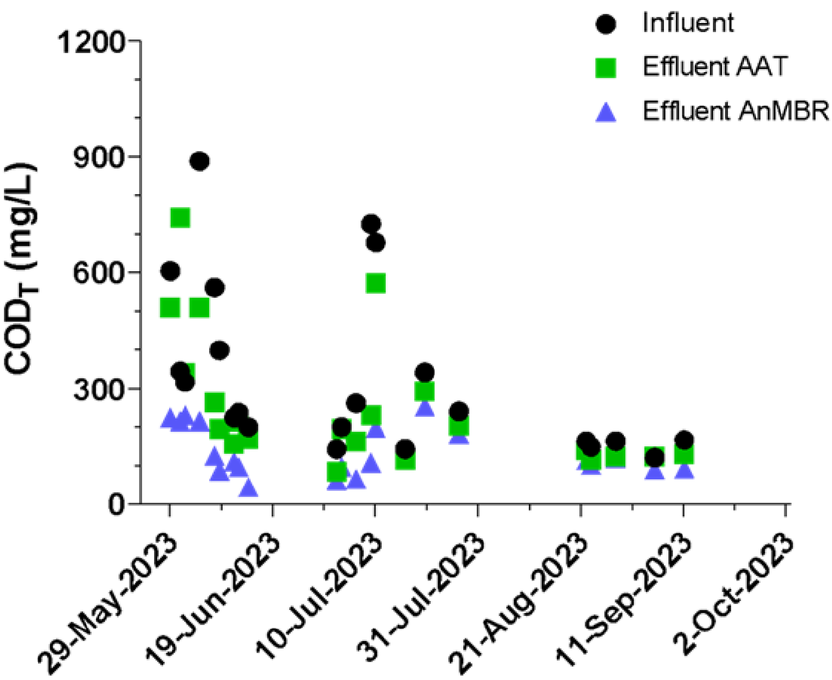

Figure 32 *Total COD in the influent and effluent of the Shafdan demonstration plant*

The plan was to make a change in the inlet line in order to provide more representative raw wastewater (typically with COD of 600-800 mg/L). However, the event of October 7th 2023 prevented us from of doing this work for few months because of:

1. The site is southern of Tel-Aviv, where in the first 2 months after October 7th, the GSR and Agrobics staff couldn't attend and operate the system.

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2. The system was shut down for three months, and everything needed to be restarted from the beginning.
3. After GSR and Agrobics staff was allowed to return to the site, the technical staff of Mekorot (who were supposed to monitor and operate the system on the daily basis) was not sufficient (cut) as well as was not available most of time because the priority was given to more urgent work.

In addition, we figured out that shutting down the system led to other technical problems in the system, which required maintenance and repairs lasting for about 1-2 months. All the maintenance work was completed by the end of March 2024, but unfortunately, the issue of providing a stable and continuous flow of representative raw wastewater still persists.

Because of all the above circumstances (technical and security-based because of the situation in the Tel-Aviv region), we have decided to go for plan B and conduct the workplan using our bench-scale pilot system (in the labs of the GSR), see Figure 33.

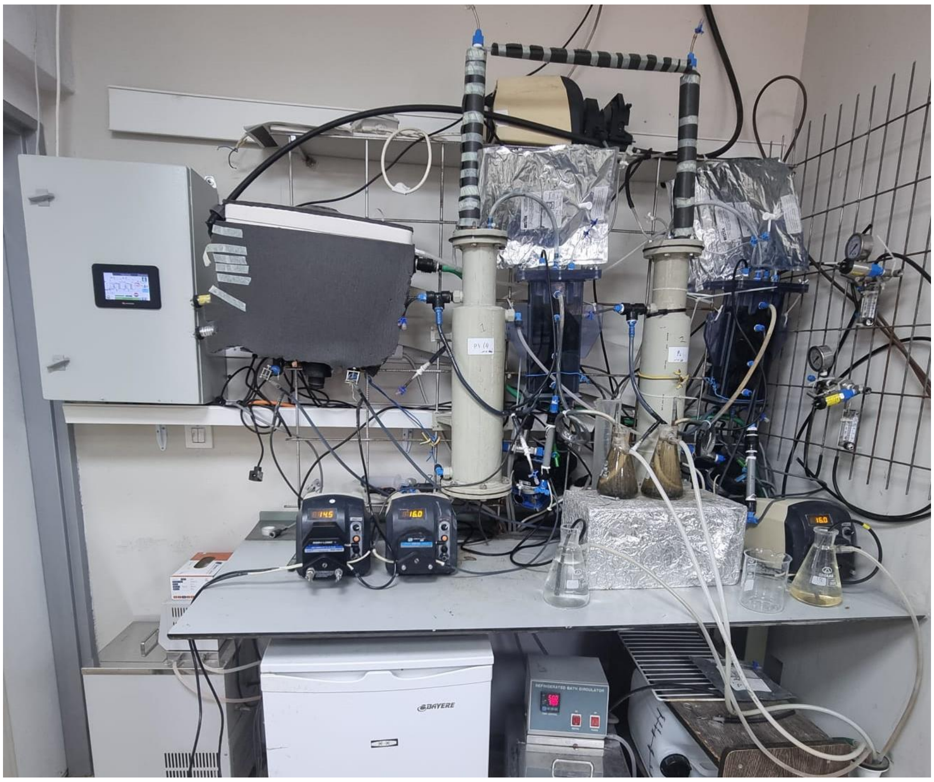

Figure 33 Picture of the lab scale AnMBR systems

The capacity of the technology was demonstrated in ex-situ bench-scale system. The system consists of an anaerobic digester (1.8 L) and a membrane chamber (2 L) (ex-situ configuration), activated carbon was added to the membrane chamber in the form of carbon cloth (CC) thereafter it was replaced with granular activated carbon (GAC) within a column that was circulated with the membrane chamber. The system was operated under different conditions of OLR and filtration flux at a temperature of 32 °C and recovery of 65-70%. The modules contained two polyether sulphone (PES)

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(MWCO 300 kDa) membranes each were integrated after achieving a stable anaerobic activity. Peristaltic pumps were used to control (connected to a control system) a constant flux and operated at a filtration–relaxation mode, namely, filtration of 10 minutes followed by 1 min backwash and 1 min of accelerated filtration step.1% of OMW was added to synthetic wastewater achieving an additional OLR of 2-3 kg COD/m³/d while working with a hydraulic retention time (HRT) of 18 h. On average, the total COD removal of the AAT combined with AC/AnMBR was around 83-86% ($COD_{T,in}$ of about 1900 mg/L). The methane yield was around 0.29 m³ CH_4/(kg COD). With 52% average removal of polyphenols. The points of application for AAT combined with AC/AnMBR systems can be for pre-treating domestic mixed with agro-industrial wastewater, increasing the energy efficiency of the plant and protecting small-medium WWTPs from sudden agro-industrial discharges.

Technical requirements for the implementation of the AAT-AnMBR and operating conditions

For the immobilised anaerobic high-rate reactor, a polymer-based foam is used to enable a stable microbial activity and hence, a robust biogas formation process. The typical ranges for operating the AAT parameters are given in Table 11. In order to protect the membranes within the AnMBR two suspended solids filters of 6 mm followed by 1.5 mm was installed before the AAT feed.

Table 11 Typical ranges for selected parameters during operation

Parameter	Units	Min	Max
pH	-	**6.8**	**8.5**
Temperature in reactor	°C	**15**	**40**
Hydraulic retention time	h	**2.4**	**18**
Organic loading rate	kg COD/(m³*d)	**1.5**	**11**
%OMW	% volume	**0**	**1**

2.5.2. Results of new approaches

Technology performance

Results from the lab scale AnMBR system are shown below. Figure 34A shows the COD total of the influent and effluents of the anaerobic system (without membrane operation). The inlet COD was elevated until getting an OLR of 2.1 kg COD/m³/d and an HRT of 18 h. The methane production rate can be seen in Figure 34B. After reaching a steady-state, specifically on day 285, 6 g of CC was added to the first membrane chamber, thereafter, on day 340 PES flat sheet membrane modules were inserted and operated. The average COD of the system, including the AnMBR can be seen in Figure 35, where no significant differences were observed between the two ex-situ AnMBR configurations in terms of COD removal and in terms of methane production. In average the total COD removal of the AnMBR was around 83%.

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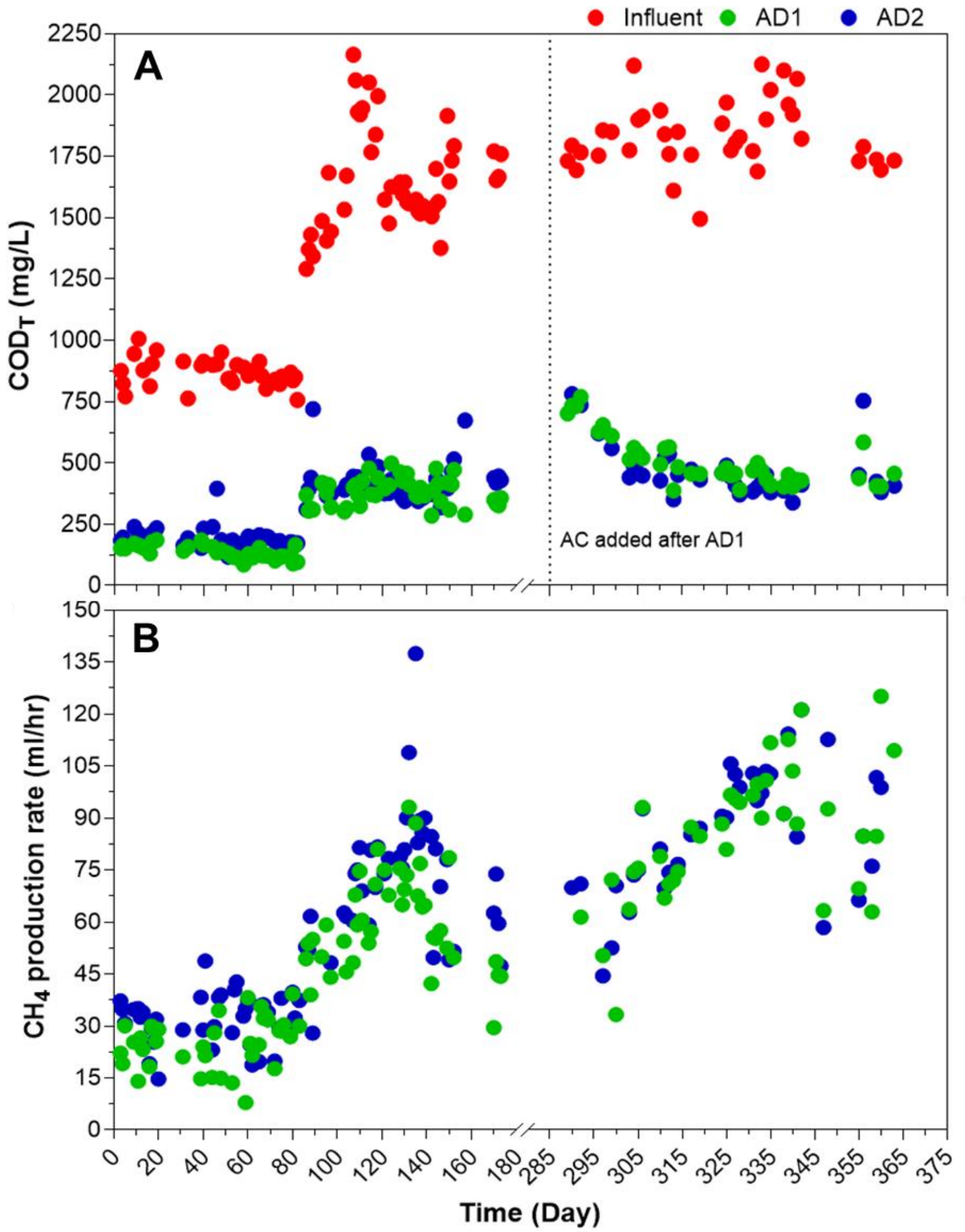

Figure 34 *(A) COD total over the time (days) (B) methane production rate over time of the anaerobic digestion (AD) chambers for the new Ex-situ configuration at GS.*

After this set of experiments, another set was conducted using GAC instead of CC. The amount of GAC that was added into the first system was 6.5 g. 20 g of GAC was added into the second system. Both systems operated for five months before inserting the membranes. Results of both systems performance (only AAT before membrane filtration, named AD) in terms of COD concentration, polyphenols concentration, biogas yield and methane yield are given in Figure 36-Figure 39, respectively. Figure 36 shows that there is a slight difference in the COD removal efficiencies of both anaerobic digestion (AD) systems, apparently due to oxygen exposure of the first system, however, the COD of the effluent after exposure to 20 g of GAC was lower than for the first system (6.5 g GAC).

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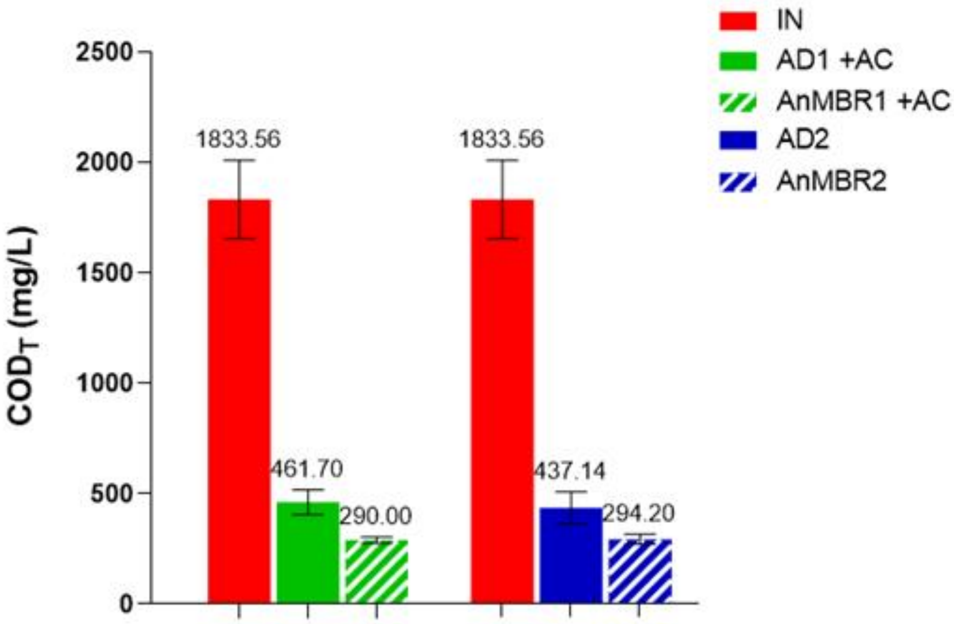

Figure 35 *Average COD total of the ex-situ lab systems, including the inlet, the anaerobic digestion (AD) chambers and the AnMBRs.*

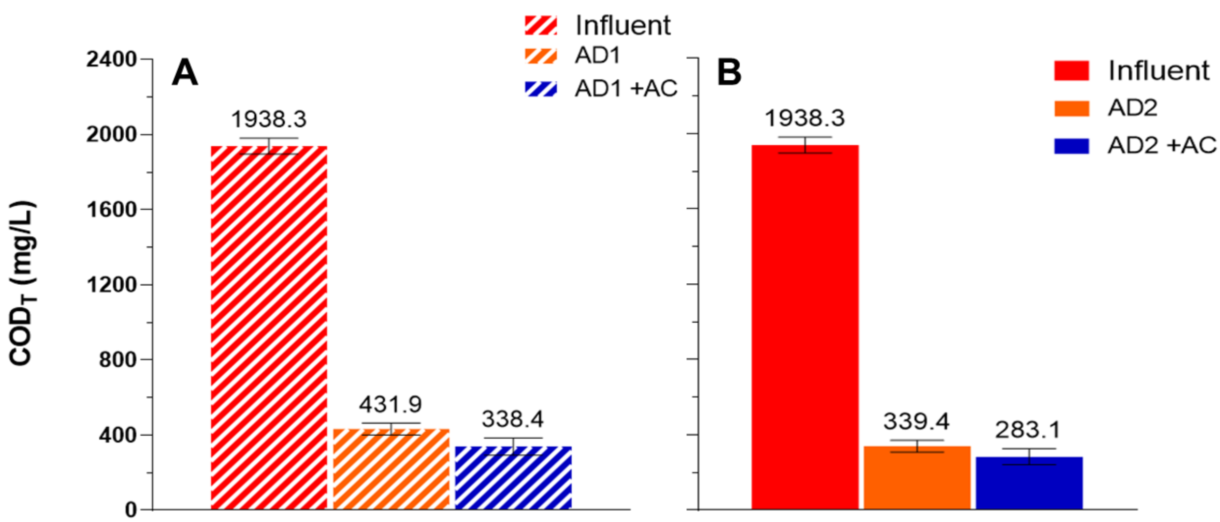

Figure 36 *(A) Average COD total of the ex-situ lab system1 containing 6.5 gr GAC, including the inlet, the anaerobic digestion (AD1) chambers and GAC. (B) Average COD total of the ex-situ lab system2 containing 20 gr GAC, including the inlet, the anaerobic digestion (AD2) chambers and GAC.*

Figure 37 shows that there is a difference in the polyphenols removal efficiencies of both anaerobic digestion (AD) systems. However, the polyphenols concentration in the effluent after exposure to 20 g of GAC was lower than for the first system containing only 6.5 g GAC.

In terms of biogas yield, Figure 38 shows a slight increase in the biogas yield in the system containing a higher concentration of activated carbon. A similar trend is also shown for the methane yield in Figure 39, this might be attributed to the direct interspecies electron transfer mechanism as it can be seen in our recent publication

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(Shimshoni et al. 2024). The methane yield of the AAT in the bench-scale system is an order of magnitude higher than the methane yield of Karmiel's system. This might be due to the higher HRT of 18 h relatively to 5 h, and also to the higher operational temperature of the lab scale system.

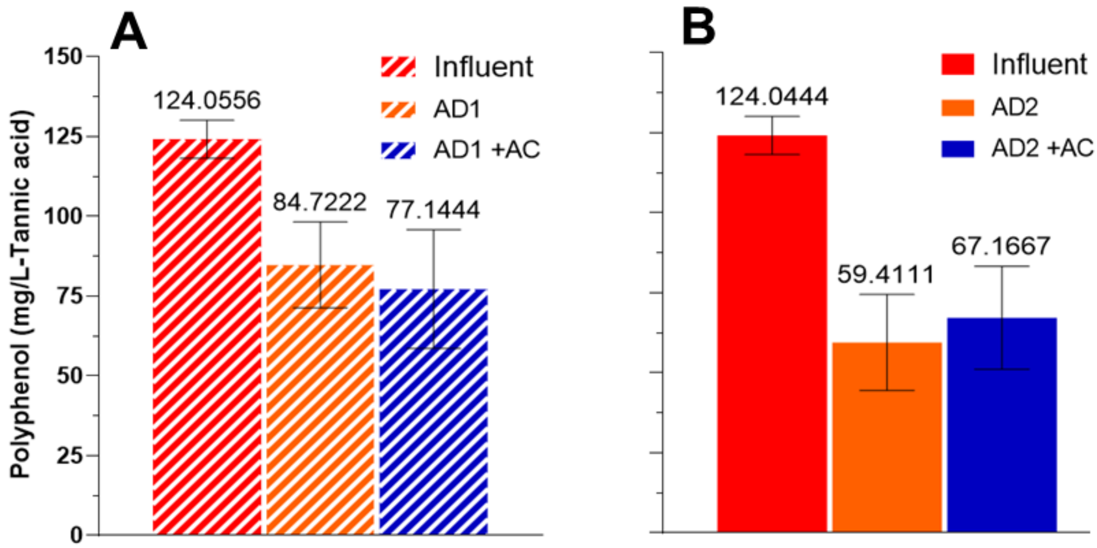

Figure 37 *(A) Average polyphenols concentrations of the ex-situ lab system1 containing 6.5 g GAC, including the inlet, the anaerobic digestion (AD1) chambers and GAC. (B) Average polyphenols concentrations of the ex-situ lab system2 containing 20 g GAC, including the inlet, the anaerobic digestion (AD2) chambers and GAC.*

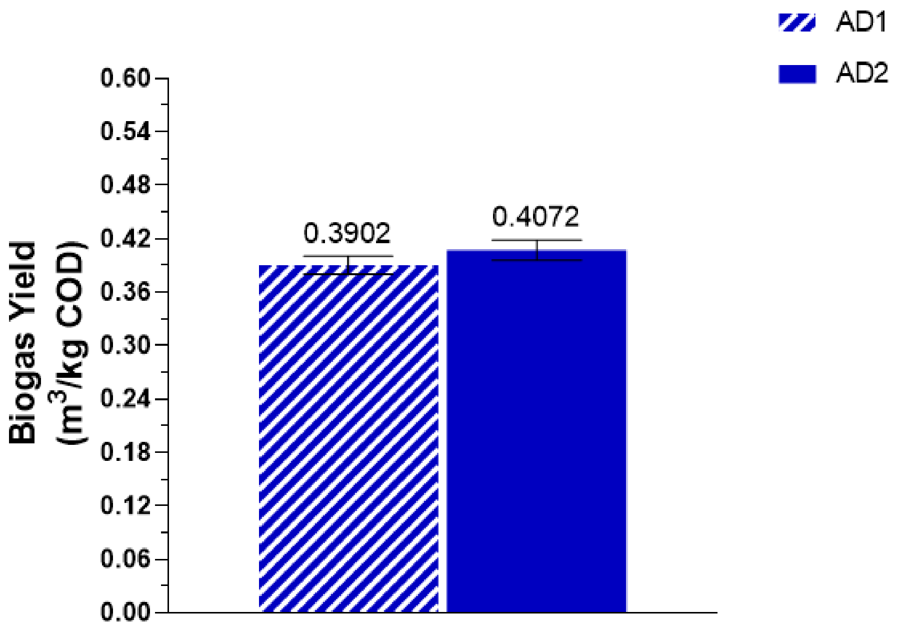

Figure 38 *Biogas yield of the first lab scale AAT system containing 6.5 g GAC named AD1 and biogas yield of the second lab scale AAT system containing 20 g GAC named AD2.*

After the system has reached a steady-state in terms of removal efficiencies and methane production, the membrane modules were inserted into the membrane chamber. The typical membrane fouling profile was monitored by a pressure

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transmitter indicated by the deferential trans-membrane pressure (TMP) of the two membrane modules.

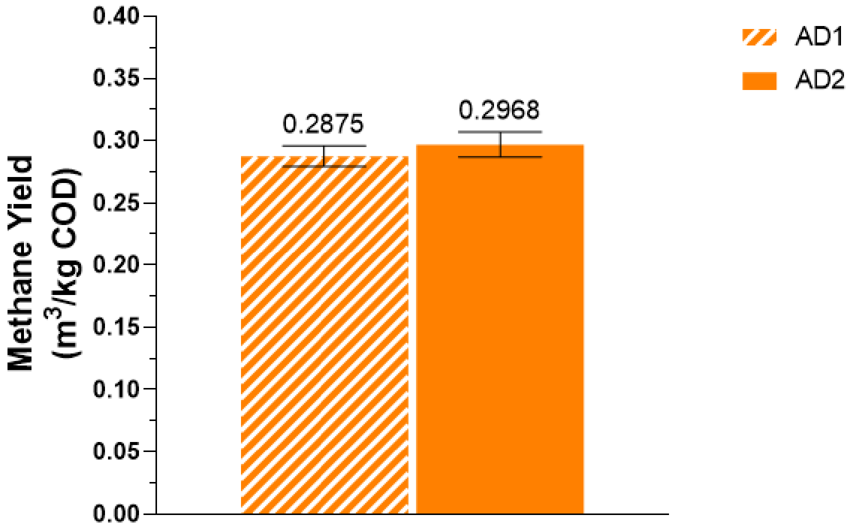

Figure 39 *Methane yield of the first lab scale AAT system containing 6.5 g GAC named AD1 and methane yield of the second lab scale AAT system containing 20 g GAC named AD2.*

Firstly, the TMP profile during filtration time was recorded at a flux of 10 LMH (litres of permeate per square meter of membrane area per hour) while applying biogas circulation and sparging under the membrane modules. This operation regime was compared with a similar one by changing the GAC to a new one (same amounts were added after intensive washing procedure). The results of the TMP profile are presented in Figure 40.

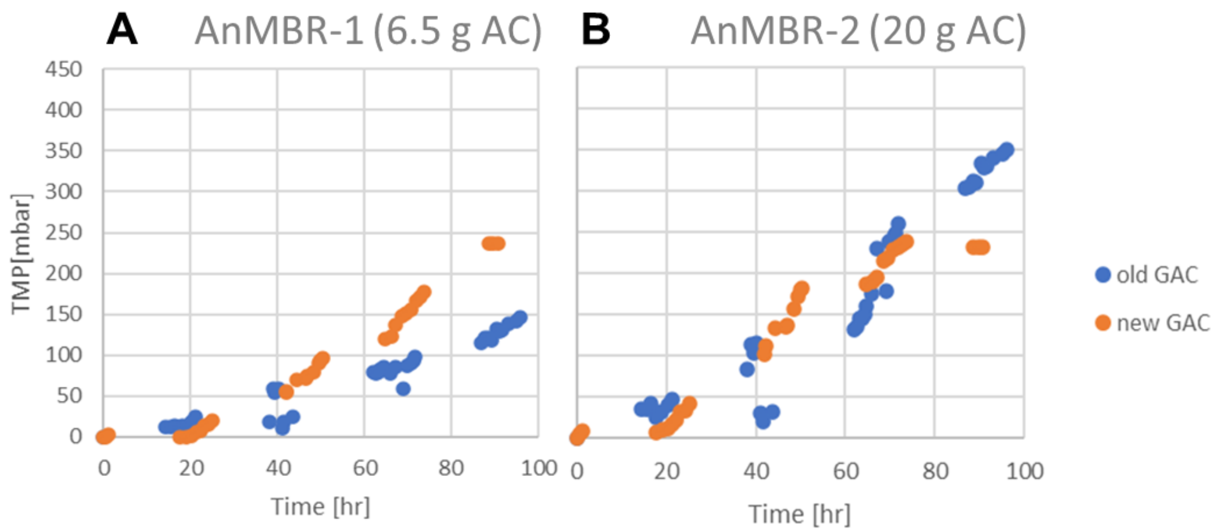

Figure 40 *TMP profile of PES membranes (A) 6.5 g GAC was added to AnMBR1. (B) 20 g GAC was added to AnMBR2. Operational conditions: HRT= 18 h,10 LMH, working with gas circulation.*

Here it can be seen that for the higher concentration of GAC there was a rapid fouling development for both old and new GAC addition. On the other hand, AnMBR

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containing lower GAC concentration showed moderate fouling development, interestingly the AnMBR with the new GAC showed higher TMP values, possibly due to suspended particles washout.

The effect of flux on fouling was also tested in both AnMBRs, results are presented in Figure 41, where it can be seen that a higher flux contributed to higher fouling formation in both systems, probably due to higher concentration polarization that accelerates fouling formation. Specifically, for the flux of 15 LMH the TMP profile looked similar in both systems, however there was a significant difference in TMP profiles for the lower fluxes of 10 and 14 LMH in AnMBR1 relatively to AnMBR2 indicating that lower GAC addition enhances better fouling control.

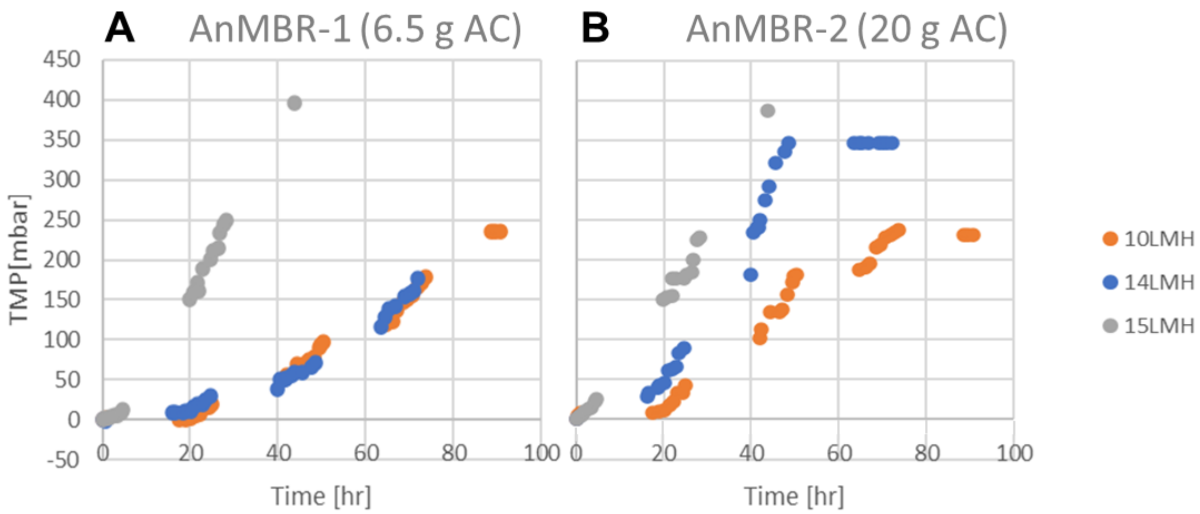

Figure 41 *TMP profile of PES membranes (A) 6.5 g GAC was added to AnMBR1. (B) 20 g GAC was added to AnMBR2. Operational conditions: fluxes of 10, 14 and 15 LMH, working with gas circulation.*

The effect of applying biogas circulation and sparging (at a flow of 0.6 L/min) was tested for both systems under 10 LMH. The results are presented in Figure 42, where significant differences in TMP profiles are shown between the AnMBRs working with and without gas sparging. Interestingly, an intensive acceleration in TMP was recorded for the first system containing lower GAC concentration when no biogas sparging was applied.

The effect of fouling formation without applying biogas circulation was also tested for the lower flux of 6 LMH, results of the TMP presented in Figure 43 indicate a slower fouling formation for the lower flux of 6 LMH relatively 10 LMH. Still, also in this case the first system containing lower GAC concentration showed higher fouling propensity than the second system with the high GAC concentration.

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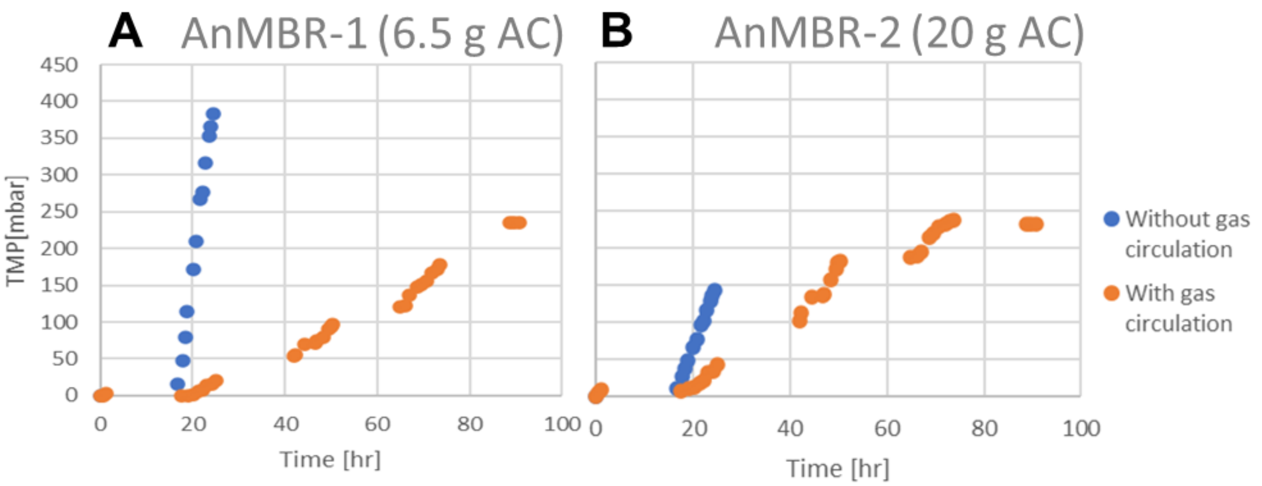

Figure 42 *TMP profile of PES membranes (A) 6.5 g GAC was added to AnMBR1. (B) 20 g GAC was added to AnMBR2. Operational conditions: fluxes of 10 LMH, working with and without biogas circulation*

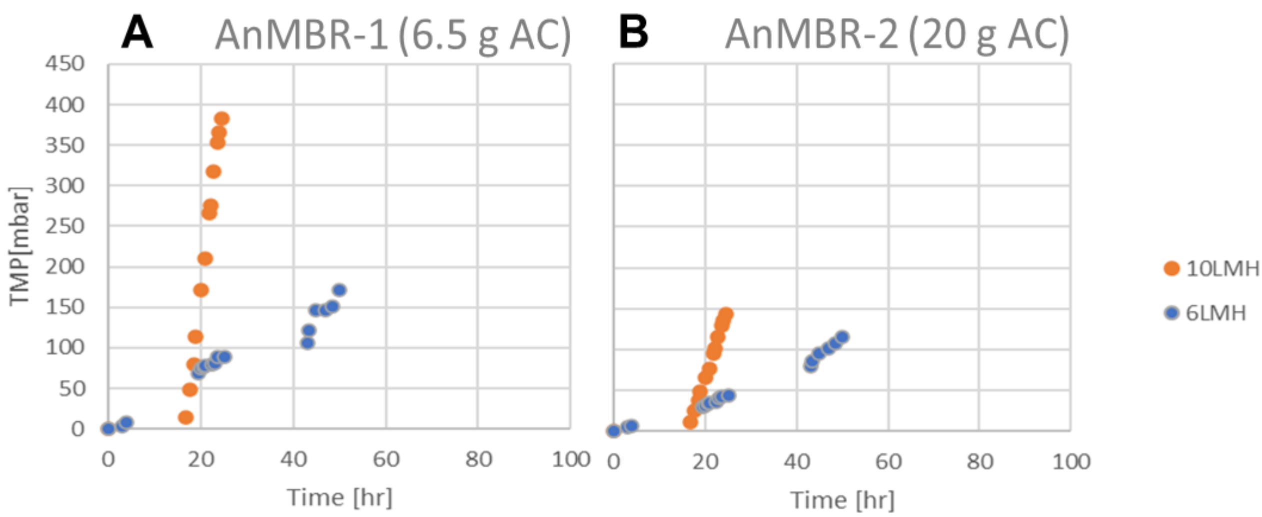

Figure 43 *TMP profile of PES membranes (A) 6.5 g GAC was added to AnMBR1. (B) 20 g GAC was added to AnMBR2. Operational conditions: fluxes of 6 and 10 LMH, working without biogas circulation.*

Results of both AnMBRs performance in terms of COD concentration, polyphenols concentration, biogas yield and methane yield are given in Figure 44-Figure 47, respectively. Figure 44 shows that there is no clear difference in the COD removal efficiencies of both anaerobic digestion (AD) systems.

Figure 45 shows polyphenols concentration at the different sampling points in the system. These concentrations were similar to the results presented in Figure 37 (before membrane filtration). However, in this case lower concentrations were achieved when applying GAC due to adsorption process. The reason might be the higher adsorption capacity of the “new” GAC (operating for 3 months). Surprisingly, concentration of polyphenols in the permeate was slightly higher than before filtration, this might be due to the concentration polarization effect.

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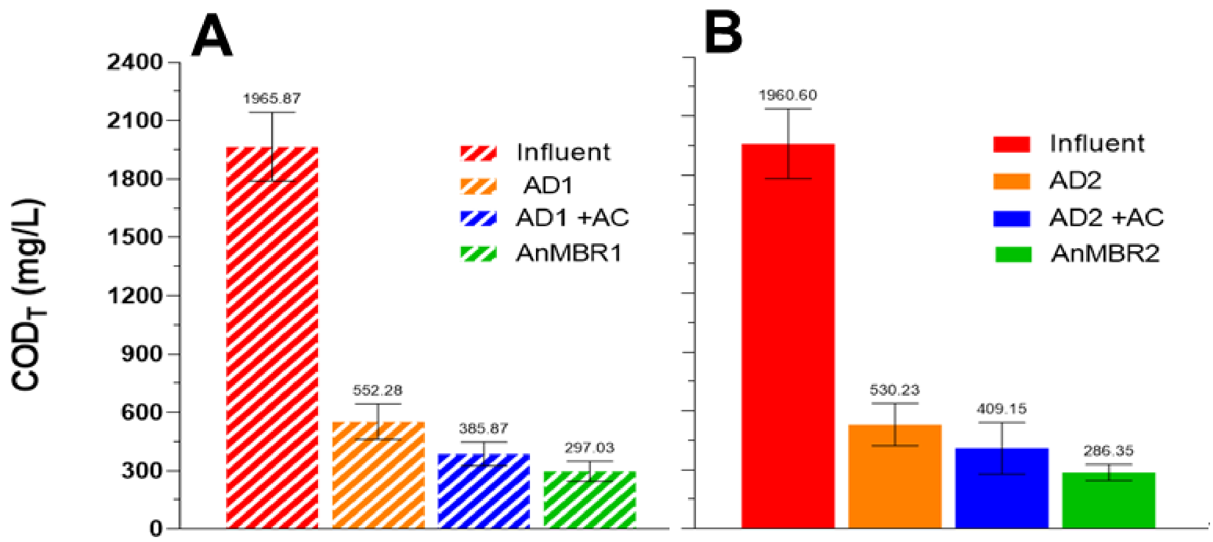

Figure 44 (A) Average total COD of the AnMBR1 containing 6.5 g GAC, including the inlet, the anaerobic digestion (AD1) chamber, GAC addition after AD1 and permeate of the AnMBR1. (B) Average COD total of AnMBR2 containing 20 g GAC, including the inlet, the anaerobic digestion (AD2) chamber, GAC addition after AD2 and permeate of the AnMBR2.

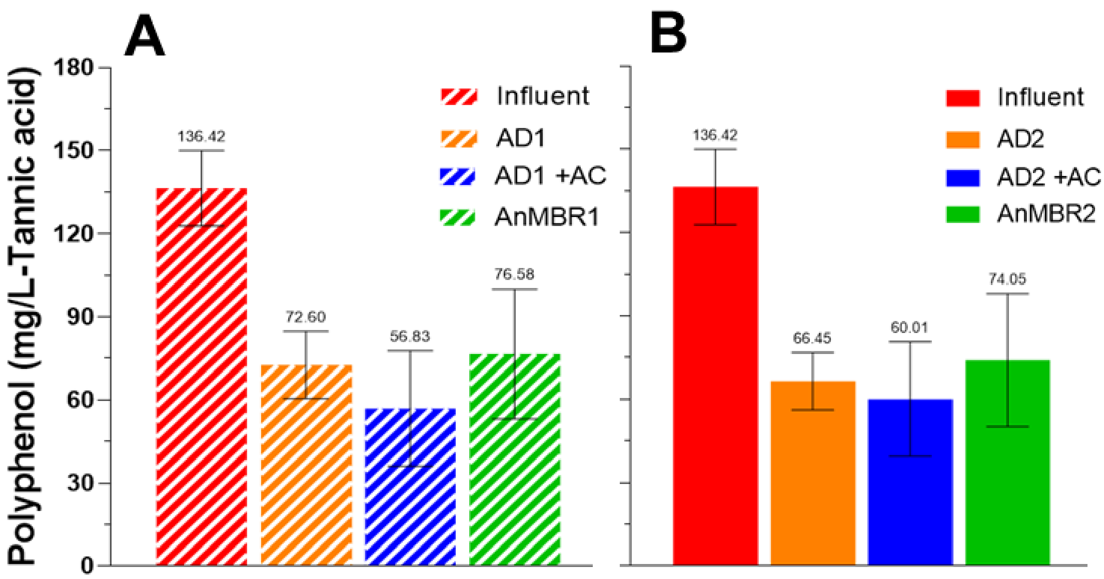

Figure 45 (A) Average polyphenols concentrations of the AnMBR1 containing 6.5 g GAC, including the inlet, the anaerobic digestion (AD1) chamber, GAC addition after AD1 and permeate of the AnMBR1. (B) Average polyphenols concentrations of AnMBR2 containing 20 g GAC, including the inlet, the anaerobic digestion (AD2) chamber, GAC addition after AD2 and permeate of the AnMBR2.

In terms of biogas yield, Figure 46 shows the yields of both AnMBRs with no apparent change in the yields, similarly to the results of the AD systems presented in Figure 38. A similar trend is also shown for the methane yield in Figure 47. With a slight decrease (not significant) in the methane yield for AnMBR2 containing the higher concentration of GAC.

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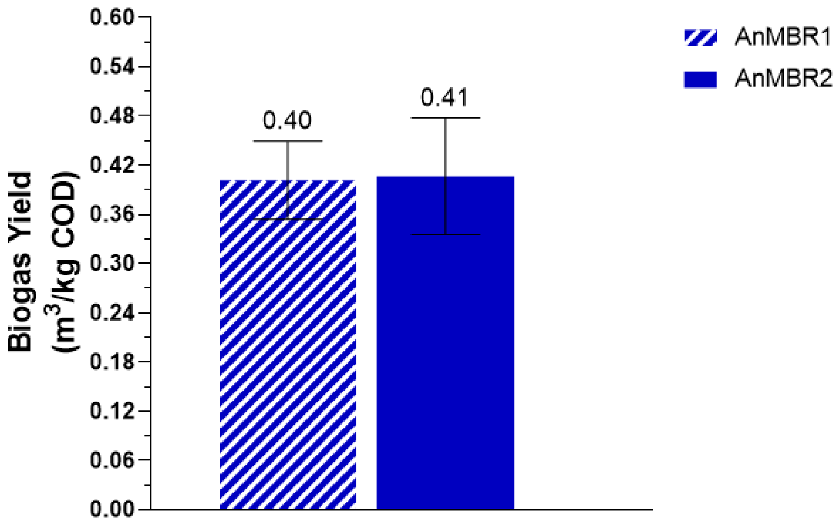

Figure 46 *Biogas yield of the first lab scale AnMBR system containing 6.5 g GAC named AnMBR1 and biogas yield of the second lab scale AAT system containing 20 g GAC named AnMBR 2.*

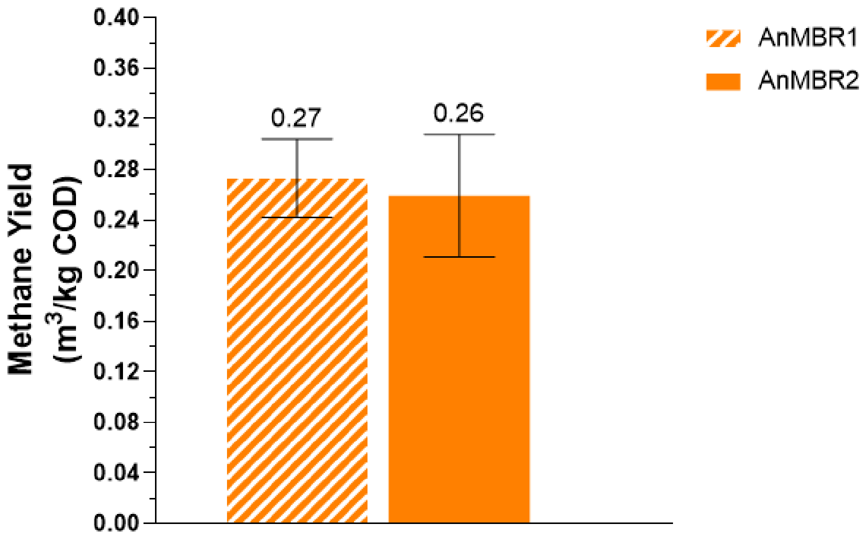

Figure 47 *Methane yield of the first lab scale AnMBR system containing 6.5 g GAC named AnMBR1 and biogas yield of the second lab scale AAT system containing 20 g GAC named AnMBR 2.*

Comparison of baseline situation with ULTIMATE solution

The (AAT-AnMBR) technology enhances biogas production/recovery. It is also considered as a suitable solution for agro/industrial wastewater treatment, that produces high quality of secondary effluent. Based on the COD removal and biogas yields in the lab-scale experiments, a reduction of 30-50% in the energy demand is roughly expected for a full-scale system.

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2.5.3. Conclusion

Lessons learned from technology operation

AAT system needs time and preferably high temperatures in order to reach a steady state of the anerobic unit (fixed foam-based AAT system) before connecting it to the filtration (membrane unit).

Moreover, the two AAT-AnMBR lab-scale systems were compared and showed a reducted fouling propensity when adding AC to the system without applying biogas sparging onto the membrane modules. However, when applying gas sparging, the system containing higher concentration of GAC had higher propensity of fouling formation and membrane blockage.

Best practices and recommendations

In terms of the symbiotic frame, the combination between the AAT and AnMBR with the addition of activated carbon confirms the main hypothesis that this new engineering paradigm can be applied for better management of small and seasonal ago-industrial wastewater (i.e., OMW, winery, etc.), leading to an increase (8-40%) in the biogas production. Because of the anaerobic treatment of most of the organic matter, a significant reduction of the sludge production is anticipated, based on the simulation of the AAT performance in Karmiel pilot-scale system. Still the issue of biofouling of the membrane requires more investigations under real conditions for optimal performance.

Crucial factors for technology implementation and its optimal performance

In addition to all factors for the AAT system (Karmiel pilot), in the Shafdan systems some other factors are crucial and need more attention to ensure adequate performance. Within these factors:

- Stable connection of the system with wastewater inlet
- Separation between the two units (AAT and AnMBR) is essential to ensure adequate performance and protection of the membrane unit from the anaerobic biomass and solids
- High TSS of the agro-industrial wastewater (i.e., OMW) is one of the limiting factors that can significantly damage the membranes.
- Also, the accumulation of inhibitory compounds (i.e., polyphenols) can affect anaerobic activity.

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2.6. Heat recovery and reuse from treated (AnMBR) distillery wastewater in Tain (UK)

Marc Pidou, Celeste Gritti

2.6.1. Case study and ULTIMATE concept

Case study description

Case Study 7 is the Glenmorangie whisky distillery located in Tain, in the north-east of Scotland. The current effluent treatment plant, at the start of the symbiosis between the distillery, the water sector and farmers, was designed and installed by Aquabio, partner in the ULTIMATE project, and consists of screens followed by an anaerobic membrane bioreactor (AnMBR) to treat the wastewater generated during the whisky making processes. The treated effluent is then discharged in the local estuary, the Dornoch Firth. The main target for the current treatment train is to remove the organic content, achieving over 98% removal of the 10.7 t/d COD load. In the AnMBR, the COD is biodegraded to produce a biogas with a methane yield of 0.27±0.05 Nm^3 CH_4/(kg COD). The biogas is converted to heat in a boiler and then reused to heat the stills. Based on the methane content of the raw biogas, the potential for onsite energy production is on average 28.8 MWh/d, however a fraction of the treated biogas can be flared (5% on average daily), depending on the demand on site. Overall, this reduces the dependence on fossil fuels of the distillery by 15%.

It should however be noted that the effluent for discharge still contains concentrations of ammonium and phosphorus of about 700 mg N/L and 250 mg P/L, respectively, offering potential for recovery as fertiliser for example. Also, the AnMBR is operated in the mesophilic range; thus, its effluent has a temperature between 35 and 40 °C which provides an opportunity for residual heat utilisation within the treatment facilities, reducing the overall energy demands of the additional technologies being considered. Finally, the effluent can be further treated to produce high quality water that can then be reused at the distillery for cleaning or cooling purposes. This would then lead to a significant reduction in tap water demand for these uses. As part of the ULTIMATE project, Aquabio and Cranfield University (partners in the project) are collaborating with the Glenmorangie distillery and Alpheus, the current operator of the treatment site, to evaluate options to expand the circular economy approach at distilleries with residual heat utilisation, nutrients recovery and water recycling.

Heat recovery and reuse concept and trials

As stated above, the distillery has already established an energy recovery approach through the production of biogas in the anaerobic system and conversion to steam for heating the stills. As part of this project, we then investigated the potential to utilise residual heat from the AnMBR effluent to further extend this approach and maintain or possibly even expand the reduction in energy use from fossil fuels. It then becomes critical to understand where heat might be recovered and utilized and how it may affect, positively or negatively, the systems used. Three key treatment systems have been

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investigated for nutrients recovery with struvite precipitation and ammonia stripping (Gonzalez Camejo et al. 2024, D1.5) and reverse osmosis (RO) membranes (Naves Arnaldos et al. 2024, D1.3) for the production of high-quality water for reuse. If implemented, these systems would provide environmental (resource recovery and reduction of pollutant in discharge effluent) and economical (reduction in water bill and income from products formed) benefits but would also increase the energy usage of the distillery which can be partly alleviated through the additional recovery and use of residual heat. The AnMBR effluent which will be further treated through these systems has a temperature of 35 to 40 °C which is actually expected to have different effects on the different technologies. Indeed, a higher water temperature is known to increase the solubility of struvite which would impair its formation and hence possibly affect recovery efficiencies. Alternatively, higher temperatures are known to be beneficial to the ammonia stripping process as it favours the conversion of ammonium into ammonia leading greater volatilisaiton and ultimately recovery. Finally, both negative and positive impacts can be potentially observed in RO membranes from increased temperatures. Indeed, higher temperatures lead to a reduction in the viscosity of water then improving the filterability but they also increase ions mobility and hence diffusion through the RO membrane potentially leading to a poorer quality permeate. In view of establishing beneficial residual heat utilisation within the treatment train studied, this work first focused on the impact of temperature on the treatment technologies performance. This was then complemented with energy balance exercise to determine the best approach to residual heat utilisation within the treatment train studied in this case study.

For practical reasons and control of the temperature during the trials some of the experiments were carried out in the lab environment. All trials were performed with the real distillery wastewater. As such for the struvite precipitation, the trials were carried out with a multiple jar tester (Phipps & Bird's), with a sequence of fast mixing for 5 min at 150 rpm during which magnesium chloride was dosed to obtain a P:Mg ratio of 1:1.3 and the pH was adjusted to 8.3 with caustic. Mixing was then reduced to 60 rpm for 55 min to allow for the precipitation reaction to occur. The mixture was then left to settle for 30 min to separate the precipitate from the water for analysis. For the RO membrane, the trials were carried out in a dead-end filtration cell (Sterlitech HP4750) under 10 bar pressure. As for the pilot trials (Naves Arnalods et al. 2024, D1.3), a hydrophilic polyamide-urea thin film composite reverse osmosis membrane (TriSep X201) was used. For the lab-based trials, the wastewater was heated up to the wanted temperature and then transferred into the testing apparatus with regular measurements of the temperature as validation over the duration of the trials. For the stripping, the trials were carried out in the demonstration systems trial on site as part of this project. The ammonium present in the water was first converted to ammonia which is volatile. This was achieved by increasing the pH (caustic dosing) and/or the temperature of the water. The temperature of the water was controlled through an electric heater located in the feed tank of the stripping unit (after the struvite precipitation unit). The water was then pumped (0.5 m^3/h) at the top of a packed

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stripping column and flows down while an air blower sent air (2500 m^3 air/h) upwards in the column (see Gonzalez Camejo et al. 2024, D1.5 for details). The packing media in the column provided increased surface area for a better mass transfer of the ammonia from the liquid to the gas. The treated effluent flows out at the bottom of the column and the ammonia rich air is sent into a scrubber, where it comes into contact with a sulphuric acid solution. The ammonia is then transferred from the air to the water producing an ammonium sulphate solution.

The technologies evaluated here are all already commercially available but their application for distillery wastewater had, to our knowledge, not yet been done with also no reports of their integration for such industrial applications. Based on this, the systems were at a TRL of 5 at the start of the project and through the trials carried out here with real wastewater that increased to TRLs of 6 to 7 depending on the scale of the trials (lab or demonstration).

2.6.2. Results of new approaches

Heat utilisation to increase filterability in RO membranes

As mentioned above, temperature could have a negative impact on the permeate quality of the RO membranes but in parallel improve filtration performance. The results confirmed an improvement of the filterability of the water with increased temperature as the average flux increased for the trials increased from 7.3 ± 0.3 L/(m^2*h) at 20 ºC to 8.0 ± 0.3 L/(m^2*h) and then 8.2 ± 0.6 L/(m^2*h) at 30 and 40 ºC, respectively. Interestingly, no clear impact could be seen on the treatment performance (Table 12).

Table 12 Characteristics of the concentrates and permeates obtained from the RO membrane trials with the real distillery AnMBR effluent at temperatures of 20, 30 and 40 ºC.

	COD mg/L	TAN mg/L	PO4-P mg/L	TN mg/L	pH -	EC mS/cm
AnMBR effluent	523	920	193	900	7.87	2.1
Concentrate						
T = 20°C	1044 ± 174	1433 ± 86	343 ± 29	1460 ±139	8.29 ± 0.16	11.3 ± 2.7
T = 30°C	1157 ± 210	1493 ± 110	379 ± 26	1540 ±180	8.53 ± 0.02	13.7 ± 1.4
T = 40°C	985 ± 165	1393 ± 27	342 ± 8	1450 ± 50	8.52 ± 0.11	12.6
Permeate						
T = 20°C	20 ± 6	101 ± 5	4 ± 0.2	119 ± 25	8.56 ± 0.55	0.72 ± 0.4
T = 30°C	46 ± 40	147 ± 17	6 ± 1.3	151 ± 22	9.08 ± 0.1	1.1 ± 0.1
T = 40°C	31 ± 15	137 ± 29	5 ± 1.8	96 ± 54	9.10 ± 0.22	1.0

Although some differences can be observed in the permeates in terms for example of the organics (as COD) and ammonia, it can't be correlated to the temperature in these trials. The complex matrix of the distillery wastewater with initially very high concentrations of the nutrients in particular may explain that limited impact of the temperature was observed in the permeate quality as the diffusion mechanism may be heavily dominated by the concentration polarisation at the surface of the membrane. Overall, these results highlight that the increased temperature available in the AnMBR effluent at 35 to 40 ºC when compared to more typical conditions (e. g. 20 ºC) would

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be beneficial for the RO membranes and assuming the increase in flux of about 11% observed here, a significant saving could be made in terms of either capital cost by reducing the overall surface area of membrane required to treat a fixed flow or operational expenditure as reduced pressure would be required at the higher temperature to achieve a set flux.

Effect of a higher temperature on struvite precipitation

The results of the tests carried out on struvite precipitation from the AnMBR effluent from the distillery suggest that there will no significant impact of the increased temperature available in the wastewater in this specific case. To illustrate, phosphorus removal and recovery did decrease from about 95% at 20 ºC to just over 93% at 30 ºC and 40 ºC but this difference is not expected to affect the process significantly (Figure 48). The ammonia removal efficiency varied between 13 and 15% for these temperatures. The very high supersaturation achieved within the wastewater driving the struvite reaction may explain the limited impact of the temperature in this context. Overall, this shows that the integrated system design is not expected to be affected and the sequence of technologies can remain the same without the need to implement a reduction in temperature at this stage.

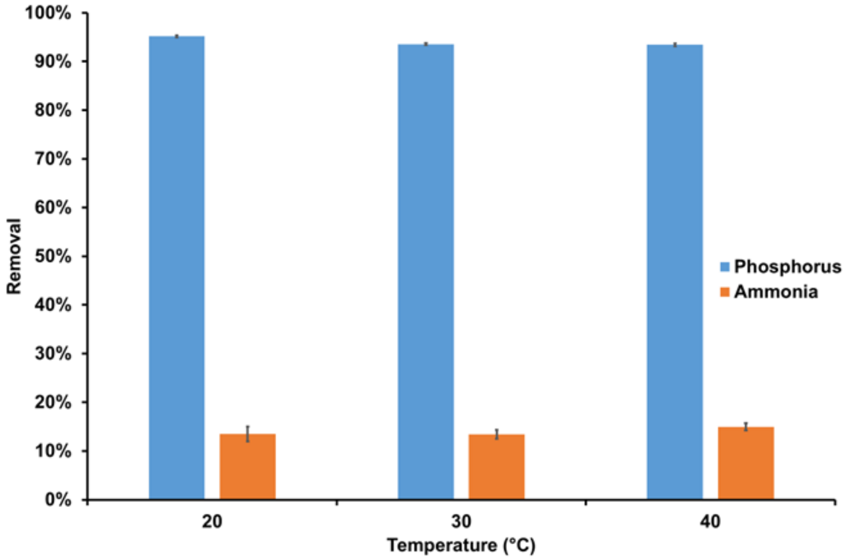

Figure 48 Impact of temperature on the removal efficiencies of the phosphorus (as PO_4-P) and the ammonia (as NH_4-N) by struvite precipitation from the real distillery wastewater

Heat utilisation for ammonia stripping

Finally, the impact of temperature was tested in the demonstration scale stripping unit. In this case, the impact of both temperature and pH was evaluated as they can both be used to control the conversion of ammonium to the more volatile ammonia as part of the process. Very surprisingly, no impact of either the temperature or the pH was observed here as the ammonia removal efficiency remained relatively stable between 68 and 72% for all conditions tested (Figure 49). Based on the theory, at pH 9, only 45 and 54% of the nitrogen should be in the form of free ammonia at 30 and 35 °C, respectively, while it increases to 89 and 92% at pH 10. At this stage, there is no clear explanation of the significant differences observed between the practice and the theory. It should however be noted that these specific trials were conducted only over

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a few days which may have influenced the performance as conditions were changed in relatively short succession. Trials carried out in parallel at lab scale with the real wastewater did however demonstrate the expected impact of temperature with ammonia removal efficiencies with over 90% achieved at 60 °C and pH 11. Based on this, trade-offs can be explored between pH adjustment (chemical use) and temperature. Indeed, assuming a pH of 9 as required for optimum phosphorus removal in the struvite system (Gonzalez Camejo et al. 2024, D1.5) a temperature of 60 to 65 °C is required to obtain 90% of free ammonia. At a more typical operational temperature of 20 °C, a pH of 10.5 would be needed and at the temperature of the AnMBR effluent (35 °C) a pH of 10 is needed. Overall, this shows that the residual temperature available in the AnMBR is beneficial and leads to a reduction in the chemical demand for pH adjustment in the stripping unit.

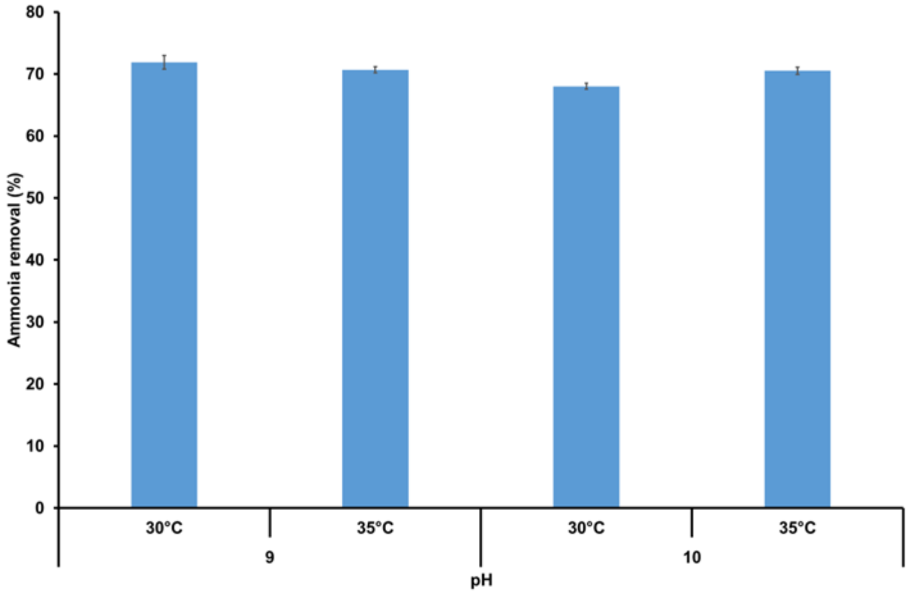

Figure 49 Impact of temperature and pH on the ammonia removal efficiency by stripping of the real distillery wastewater in the demonstration scale unit.

Comparison with baseline situation

The trial results obtained here have shown that there generally is a benefit in having the AnMBR effluent at a temperature of 35 to 40 ºC, in particular for the RO membrane and stripping systems and hence the most sensible approach in an integrated system combining these different stages is in fact not to alter water temperature in the sequence. However, further benefits can be obtained if the temperature was increased to even higher temperatures, 60 to 65 °C, for the stripping system. If this was to be implemented through an electric heater in the system, it would be at a huge energetic and economic cost. This would only be viable if heat could be obtained from other sources on site. Interestingly, as briefly mentioned earlier, the biogas from the AnMBR is converted to steam to heat the stills, so some of that steam could be used for the stripping, but this would be of no benefit for the distillery. However, an average of 5% of the biogas is actually flared on site due to the somewhat lower demand when

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compared to what is produced. It would then be a major saving to use this biogas surplus for heat production for the stripping unit, amounting to 1.4 MWh/d.

An assessment of the energy demand of each the technologies in the treatment based on design and literature data suggests that the additional units being considered here, struvite precipitation and stripping for nutrients recovery and reverse osmosis membrane for water reuse, would have a total energy demand of about 6 kWh/m^3 (Figure 50). Considering the current treatment flow of 322 m^3/d, an additional energy use of about 1.9 MWh/d would be required. As stated above, there is a spare energy capacity of about 1.4 MWh/d from the biogas surplus which could be converted to heat and electricity in a combined heat and power engine to provide part of the required energy for these systems. In terms of the heat utilisation for the stripping unit, heat transfer rate of about 467 kW would require heating the water from 35 to 65 °C. Some savings could be achieved by pre-heating the feed to the stripping unit using a heat exchanger with its effluent.

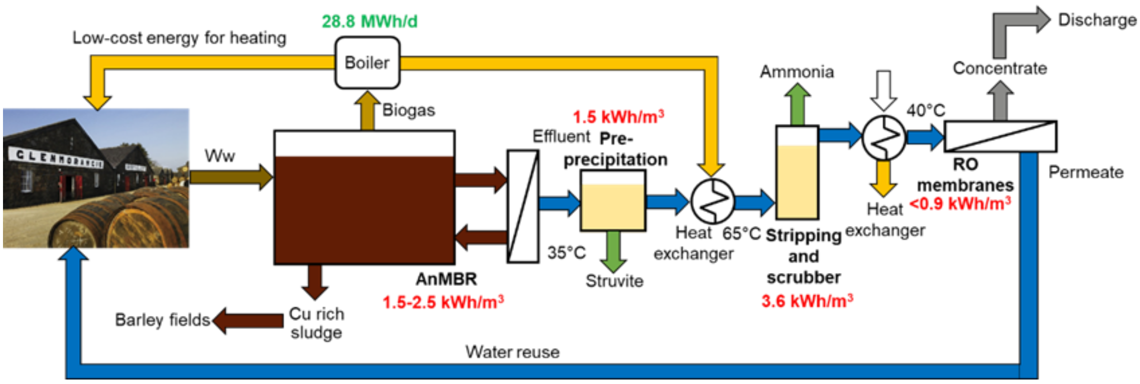

Figure 50 Energy demand of the integrated treatment train

As part of this project, the KPI for energy was to maintain the 15% reduction in fossil fuel currently achieved by the distillery even after implementation of the resource recovery technologies. Although, a significant fraction of the additional energy demand (about 74%) can be covered by the use of the residual heat in the effluent and the biogas surplus, based on current estimates, it is not possible to balance availability and demand. Further savings are possible through the optimisation of the processes. It should also be noted that the current values are based on conservative estimates and a more accurate estimate can be obtained from a detailed design of the systems.

2.6.3. Conclusion

Lessons learned from the trials for heat utilisation

The results from this work demonstrated that an increase in temperature of the water to up to 40 °C did not seem to negatively impact the processes implemented. On the contrary, the increased temperature was found to be beneficial for the RO membranes by increasing the flux at a given pressure. This would then lead to possible reductions

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in capital and operational cost when compared to operation at lower temperatures. The higher temperature in the AnMBR effluent when again compared to other applications is also expected to help reducing the demand in chemicals for pH adjustment in the stripping unit.

Best practices and recommendations

Overall, the results simply suggested to keep the wastewater at the increased temperature for all technologies, reducing the need to implement additional systems such as heat exchangers. However, a further increase in temperature up to 65 °C would help optimise the stripping process to achieve up to 90% removal and recovery of the ammonia, while minimising the need for more chemical dosing for pH control. In this case, additional systems such as heat exchangers would be needed.

In this current case study, there is a biogas surplus, with 5% of the production being flared on average. This could then be used to provide heat to increase the temperature of the water in the stripping unit as well as some renewable electricity, if using a combined heat and power engine. Despite these benefits and the current biogas surplus, the energy demand of the new approach, combining struvite precipitation, ammonia stripping and reverse osmosis membranes, is still expected to be higher so full-scale implementation would lead to an increase in energy cost at the distillery.

Crucial factors for technology implementation and its optimal performance

- Minimise distances between systems to avoid heat losses and maximise the benefit of increased temperature in each of the systems.
- Pipe and system lagging will be critical to also avoid losses in colder climates.
- Biogas or waste heat available on site or from other industries within a symbiosis system to be utilised within the system to increase the temperature of the water

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2.7. Feasibility study for heat recovery from flue gas washing water at the Chemical Platform Roussillon (FR)

Anne Reguer (SUEZ RR), Stéphane Deveughèle (3S)

2.7.1. Case study and ULTIMATE concept

Case study description

The Roches-Roussillon chemical platform exists since 1915 and brings together 19 companies specialised in the chemical industry on the same site, including several giants of the sector such as Seqens, BASF, Adisseo and Elkem. SUEZ RR IWS Chemicals (SUEZ RR) operates on this platform two hazardous waste incinerators (Aqueris) that treat a significant proportion of the chemical platform waste and a biomass recovery unit (ROBIN) that provides 15% of the chemical platform steam requirement.

On the Roches-Roussillon site, SUEZ RR activity focuses on three areas:

- Aqueris: Two high temperature incineration lines for industrial liquid hazardous waste (aqueous and organic), named L4000 and L5000 and specialised in:
  - Aqueous waste with strong salt content
  - Sulphurous waste (mercaptan type)
  - Very dangerous waste (cyanide, acetonitrile, etc.)
- EvapoRON: evapo-incineration (concentrate is incinerated at Aqueris plant), for waste with a low pollutant load
- Robin: hazardous and non-hazardous biomass valorisation, with steam production distributed to the platform industrials.

Among these, the ULTIMATE project is involved in the Aqueris application (Figure 51).

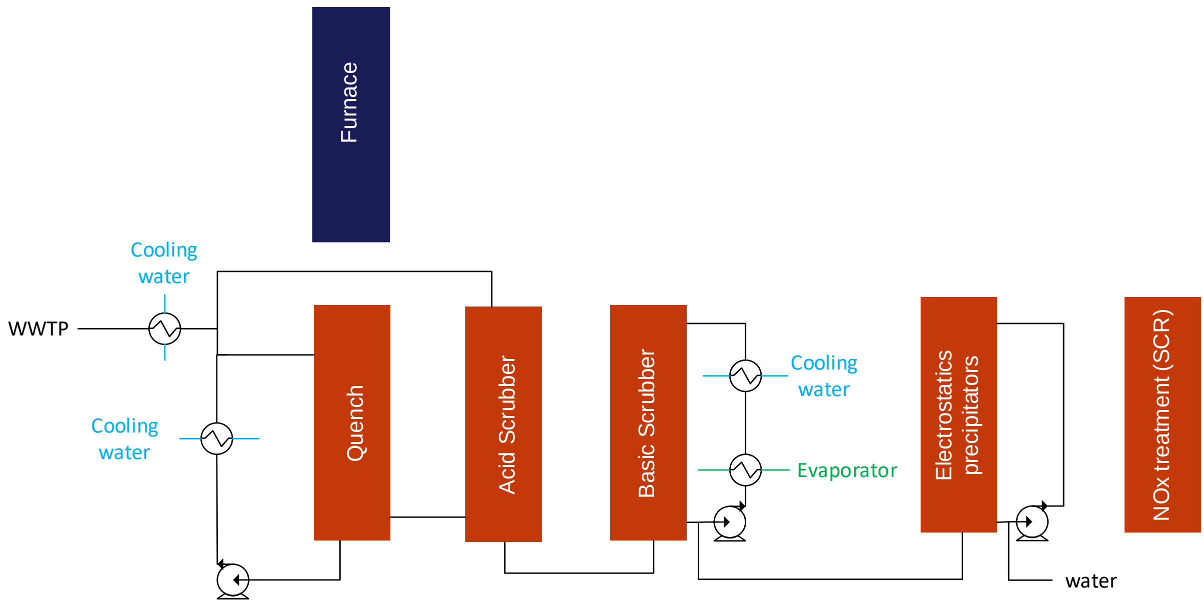

Figure 51 Simplified diagram of an incineration line of Aqueris plant with cooling and energy recovery

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The plant is specialised in the treatment of high-salt waste, which represents around 80% of the tonnage incinerated. Because salts are present in high content in the flue gas, and above all because some salts are liquid and potentially sticky at furnace temperature (1100 °C), it is impossible to separate them at the furnace outlet. Consequently, the plant has been designed to solubilise the salts immediately after thermal combustion, by means of a quench, which excludes any energy recovery by a boiler from the flue gas, whose temperature is rapidly dropped to 90 °C.
The only energy recovery currently in place is the use of a small fraction of the heat contained in the washing water (~5%) to heat a vacuum evaporator, which replaced a steam-powered evaporator in 2014.

Description of the heat recovery concept
An incineration plant consumes relatively few energies compared to the energy it generates through the self-combustion of waste. The approach applied was therefore the following:

- determine the amount of residual heat on the incineration plant and the potential sources for energy recovery,
- set an energy recovery target in line with relevant regulations applicable to hazardous waste incineration,
- list the different forms of energy used by the incineration plant,
- study the applicability of technologies able to produce a form of energy used by the site from heat sources available on site.

Sources for energy recovery
Heat is currently dissipated as follows:

- through the furnace walls,
- by two liquid/liquid heat exchangers on each incineration line: one on the quench recirculation (E41 for L4000 and E51 for L5000), and one on the basic scrubber recirculation (E42 for L4000 and E52 for L5000),
- by two heat exchangers at the physico-chemical WWTP inlet,
- in the flue gas emitted from the stack.

Heat recovery from the furnace walls is of limited interest in terms of recovery rates and presents a major technical risk: external cooling of the kiln could lead to condensation of acid gas behind the refractory bricks, damaging the metal linings. This source has therefore been excluded.

Concerning recovery on heat exchangers, the plant is equipped with several flow and temperature measurement points, which enable an assessment, for each of the two lines and over a period of more than a year, of the heat dissipated at each of the three washing water cooling points described above. Results for the two main heat exchangers are shown in Figure 52. The large amount of heat dissipated on this

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equipment (10 MW for each line) led to the selection of these sources as potentially eligible for energy recovery (Figure 53).

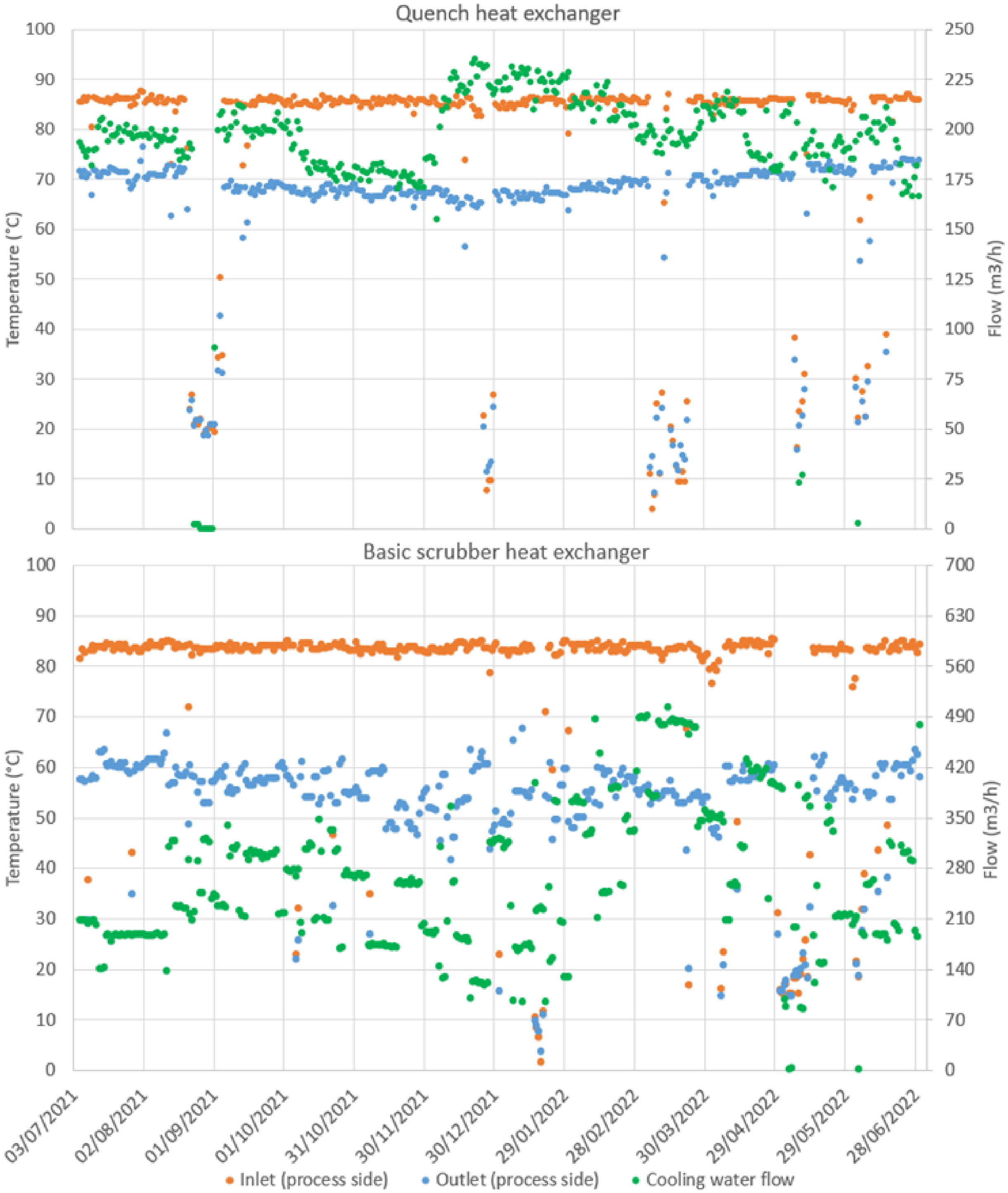

Figure 52 Typical curves of Aqueris heat exchangers

The heat dissipated on the WWTP heat exchangers represents less than 10% of the heat dissipated on all Aqueris heat exchangers. This source was therefore not considered relevant for energy recovery.

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The characteristics of the flue gases emitted through the chimney (30 000 Nm^3/h on each line and a temperature around 100-110 °C) make them an interesting source to study for energy recovery.

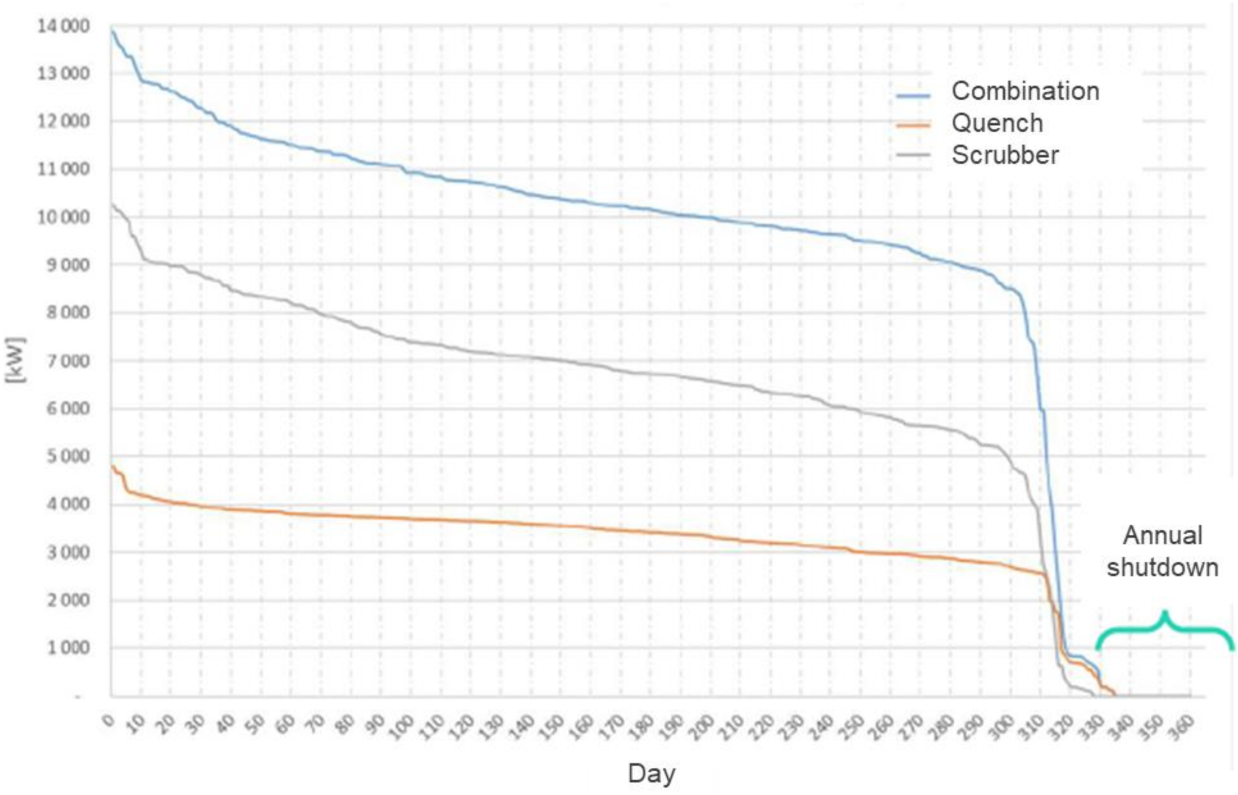

Figure 53 Monotonic of heat sources of one incineration line of Aqueris plant

Energy recovery target

As mentioned above, incineration requires relatively little energy compared to the energy produced by combustion. In this context, the driving force behind investment in energy recovery solutions cannot be savings in energy costs. On the other hand, achieving energy recovery can have a significant commercial impact, and this is directly linked to the regulations governing waste treatment.

The United Nations, with the aim to standardize waste treatment operations, defines at global level by the Basel Convention, which came into effect on the 5th of May 1992, 13 recovery operations and 15 disposal operations. Commonly, an incineration unit which produces steam is considered as a recovery unit and is assigned R1 code (*Use as fuel (use principally as a fuel or other means to generate energy)*). An incineration unit which doesn't produce steam is considered as a disposal unit and is assigned D10 code (*Incineration on land (covers the incineration of waste where the main purpose of the incineration is the thermal treatment of waste in order to reduce the volume and the hazardousness of the waste, and to obtain an inert product that can be disposed of)*). This difference is of great importance for our customers, who are more and more interested in waste recovery solutions. Although the recovery or disposal codes are defined internationally, the attribution criteria are national. In France, the criteria to

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obtain the R1 code for hazardous waste incineration unit is defined in a ministerial decree (*Arrêté du 20 septembre 2002 relatif aux installations d'incinération et de co-incinération de déchets dangereux*). This decree requires to recover 25% of the heat dissipated to obtain an energy recovery code, with the following calculation:

$$P_e = (E_{th} + 2.6 \times E_{élec}) / E_p \qquad \text{Eq. 1}$$

with,

P_e: Energy recovery yield
E_{th} : thermal energy used for on-site and off-site use
$E_{élec}$: generated power
E_p : total heat energy produced by the exchanger

With the vacuum evaporator, we are currently around 5%. The aim is then to valorize at least 20.4 GWh_{th}/year or to produce about 7.8 GWh_{el}/year.

Energy used by the incineration plant
Electricity (1.8 MW) is used for equipment (pumps, fans, etc.). The second source of energy is 6-bar steam (1.6 MW) used for:

- Air combustion preheating (1.3 MW)
- Injection of vent (gas)
- Temperature control of some storages
- Occasionally, for pipe tracing and maintaining of tank temperatures during unloading, after expansion to 2 bar

Technologies studied
The technologies evaluated for producing "useful" energy from the incinerator's residual heat are:

- An ORC (Organic Rankine Cycle), for electricity generation
- A heat pump for steam generation

The ORC technology can be applied to hot water, ideally above 85 °C, or to flue gas. Incinerator flue gas cleaning water is no more than 85 °C, and its high salt content excludes its direct use in an ORC, due to clogging and corrosion risks. It is so necessary to recover heat from the cooling water. Today, the cooling network operates on an open cooling tower, and is therefore at a maximum of 40 °C. A modification of the process is therefore required to raise the cooling water temperature level. Nevertheless, as a first approach, a temperature of 85 °C has been considered in order to assess the relevance of going further.

Steam generation from hot water, with a heat pump, at a pressure higher than 2 bar, and in particular of the order of 6 bar (which is the pressure level used on site), are technologies currently under development.

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2.7.2. Results of the feasibility study

2.7.2.1. Results of the feasibility study and expected technology performance

Organic Rankine Cycle applied to cooling water

An Organic Rankine Cycle (ORC) plant can produce electricity from energy contained in hot water. On our incineration plant, an ORC could be implemented on the cooling water network (Figure 54). For this feasibility study, we considered the following favourable assumptions (Table 13).

Table 13 Assumptions for feasibility study

Incineration line	L4000		L5000	
Heat exchanger	E41	E42	E51	E52
Cooling water flow (m^3/h)	190	230	190	230
Wastewater temperature	86 °C	84 °C	86 °C	84 °C
Cooling water temperature assumption for feasibility study	85 °C			

A technical solution, able to produce 40 kW from 83 t/h of water at 85 °C has been identified. Considering the low temperature level, a very low yield of around 2 to 3% is expected. With the thermal energy potentially available in the cooling water, and considering 8,000 h/a of operating time, such a solution would thus be possible to generate 3,2 GWh_{el}/a, which is still insufficient to obtain the energy recovery code. In fact, the energy recovery yield is about 5% for the Aqueris plant in this case.

A quick economic estimation was nevertheless made (Table 14). From an economic point of view, this solution provides an insufficient return on investment.

Table 14 Economic estimation for return on investment

CAPEX (Equipment only, without implementation)			
	Number	**Unit cost**	**Total cost**
ORC	10	400 k€	4 M€
Expected profit on sale or use of electricity			
	Power generation	**Sales price**	**Total profit**
Electricity	3,2 GWh_{el}/a	80 €/MWh_{el}	256 k€

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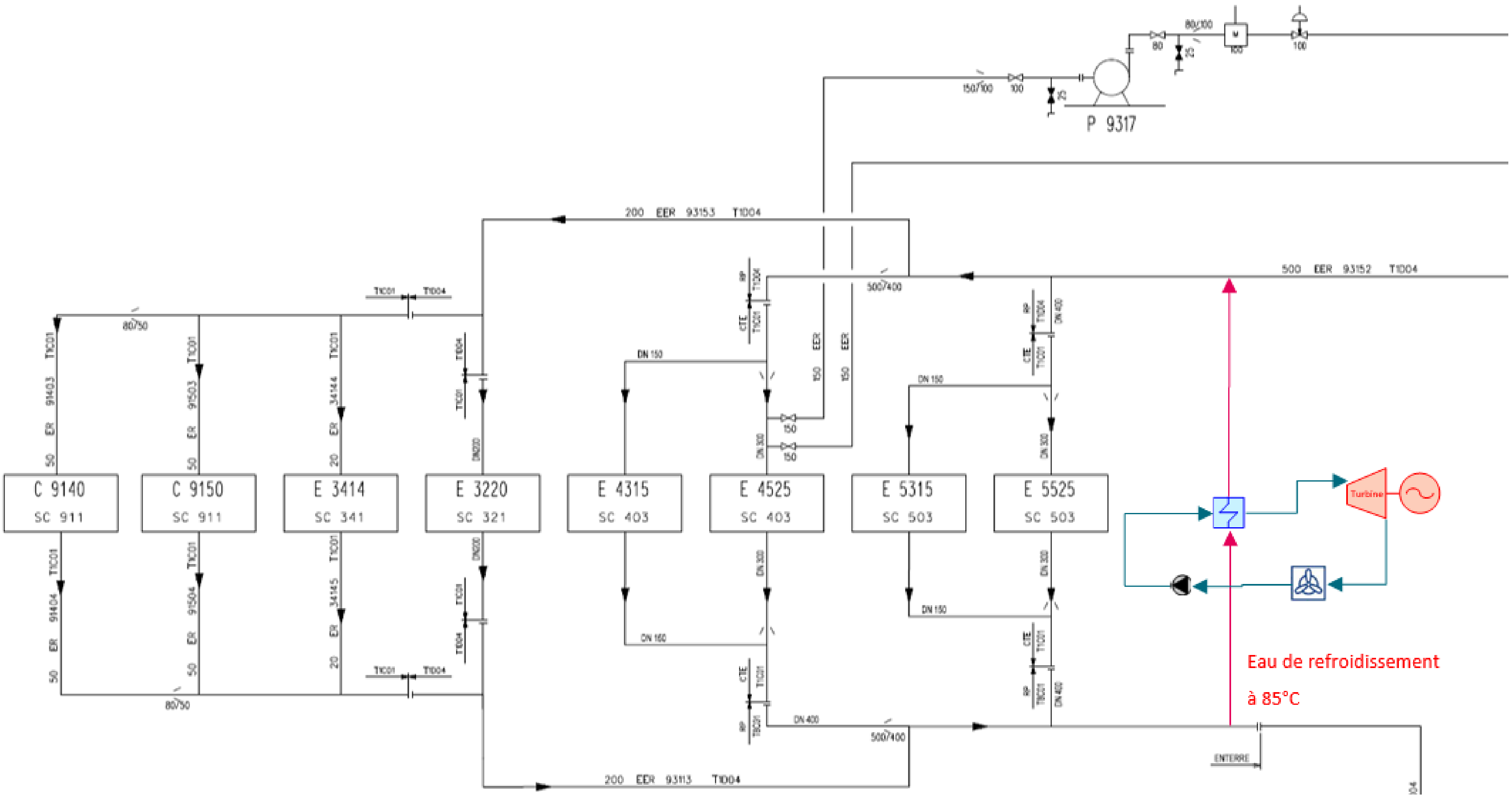

Figure 54 Schematic layout of the ORC for heat recovery on water

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Organic Rankine Cycle applied to flue gas at the chimney

Considering the conclusions of the feasibility study for the installation of an ORC to produce electricity from cooling water, another option was investigated: recovery of the heat contained in the flue gases in the chimney.

The solution (Figure 55) consists in the implementation of a heat exchanger on the flue gas at the outlet of the flue gas treatment system, to produce superheated water at 95 °C. Then the ORC system recovers energy contained in the heated water and produces electricity. Calculations were made with the following assumptions:

- Flue gas temperature is about 110 °C
- Flue gas flow (for the 2 incineration lines) is about 60 000 Nm^3/h

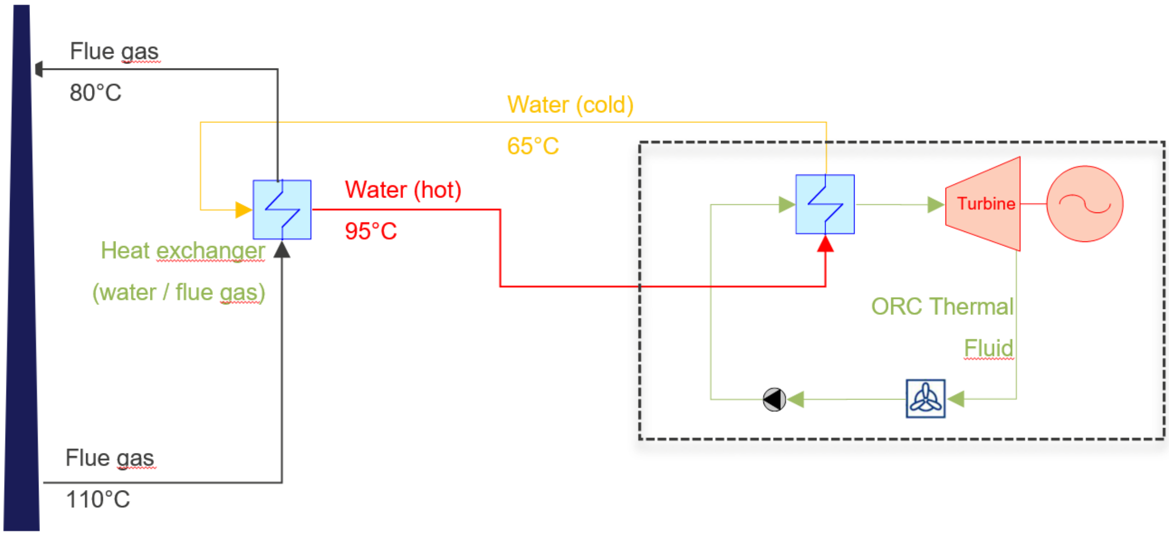

Figure 55 Schematic layout of the ORC for heat recovery on flue gas

The heat power available in the flue gas was estimated at 700 kW for Aqueris plant, giving a total energy output of 5.6 GWh_{el}/a. An efficiency of 7% is assumed for the ORC, corresponding to the production of about 0.4 GWh. The energy yield is therefore about 0.6%.

Heat pump on cooling water

The technical solution studied consisted in using, as shown in Figure 56, two technologies in series:

- A heat pump for simultaneous heating and cooling;
- A vapor-compression heat pump to produce steam.

The study considered different heat sources:

- Recovery on 1 or 2 heat exchangers (EX1 or EX2 or EX1+EX2)
- Recovery on 1 or 2 incineration lines (L4000 or L5000 or L4000+L5000)

Regarding the type of energy consumed on site, the study looked at three different qualities of steam to produce: 6 bar steam, 4 bar steam and 2 bar steam.

Indeed, the production of 6 bar steam, which is the platform's standard low pressure, from our hot water remains uncertain from a technical point of view and will inevitably

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be very costly. As this steam is certainly expanded by some manufacturers, there may be an interest in producing lower-pressure steam. The results are presented in Table 15.

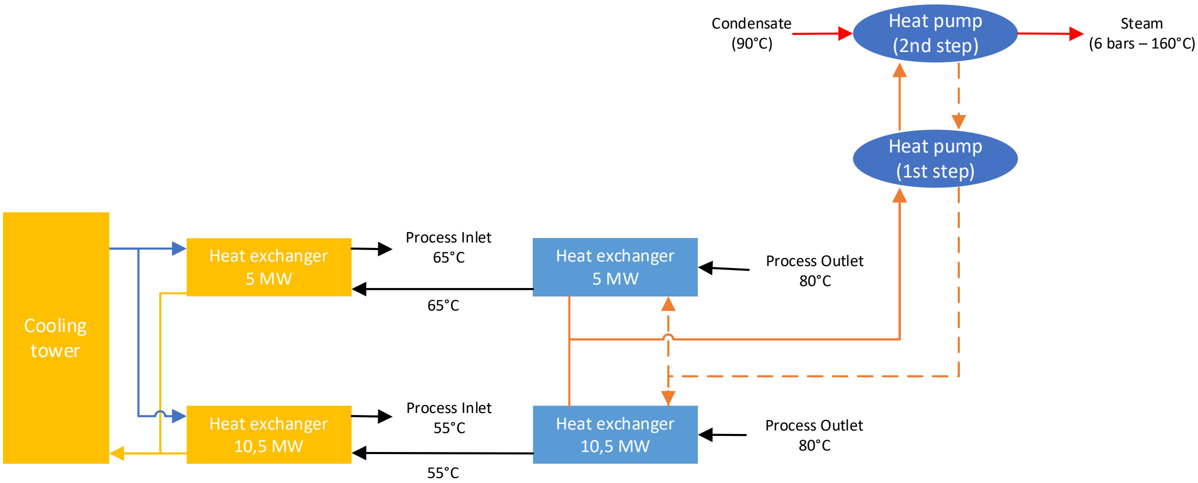

Figure 56 Schematic diagram for the installation of a heat pump solution

Table 15 Results of study "heat pump on cooling water"

Heat source	Steam pressure target	Residual heat recovered (MWh)	Pe (Energy recovery yield)	Steam production (t/y)	Power consumption (MWh)	Ratio Power consumption / Energy recovered (MWh_{el}/MWh)
E41 or E51	6 bar steam	27 000	16%	51 000	19 227	0,7
E41 or E51	6 bar steam	27 000	16%	69 000	25 973	1,0
E41 or E51	4 bar steam	27 000	16%	60 000	21 933	0,8
E41 or E51	4 bar steam	27 000	16%	63 000	20 130	0,7
E41 or E51	2 bar steam	27 000	16%	57 000	17 747	0,7
E41 or E51	2 bar steam	27 000	16%	53 000	11 987	0,4
E42 or E52	6 bar steam	53 000	32%	130 000	51 733	1,0
E42 or E52	6 bar steam	53 000	32%	107 000	32 693	0,6
E42 or E52	4 bar steam	53 000	32%	126 000	46 700	0,9
E42 or E52	4 bar steam	53 000	32%	144 000	48 133	0,9
E42 or E52	2 bar steam	53 000	32%	120 000	38 133	0,7
E42 or E52	2 bar steam	53 000	32%	123 000	31 970	0,6
(E41+E42) or (E51+E52)	6 bar steam	80 000	49%	193 000	74 640	0,9
(E41+E42) or (E51+E52)	6 bar steam	80 000	49%	158 000	49 840	0,6
(E41+E42) or (E51+E52)	4 bar steam	80 000	49%	185 000	66 583	0,8
(E41+E42) or (E51+E52)	4 bar steam	80 000	49%	158 000	45 100	0,6
(E41+E42) or (E51+E52)	2 bar steam	80 000	49%	177 000	55 030	0,7
(E41+E42) or (E51+E52)	2 bar steam	80 000	49%	176 000	41 307	0,5

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To reach the energy recovery target, energy recovery from the quench exchanger is insufficient. On the other hand, recovering energy from the two exchangers would result in steam production too high for easy distribution. Energy recovery on the basic column exchanger offers a compromise between both parameters, even if steam production remains significant.
The estimated Class 5 CAPEX for this type of technical solution has been estimated at 19 M€ (-30%/+50%). While the revenue generated by the sale of steam is interesting, the electrical costs generated by the production of this steam represent 60 to 80% of the revenue, making the investment economically unacceptable.

Design, IT development, configuration and test of a monitoring and control application (ULTIMATE IT application)

The ULTIMATE IT application was developed using WasteAdvanced®, a market software product developed by SUEZ Smart Solutions (3S). WasteAdvanced® is a digital solution for optimising the performance of waste-to-energy plants. Three technical objectives were associated with the ULTIMATE IT application:

a. Collect measurements from various information sources on the site
b. Create and configure business indicators based on these measurements and the business calculation formulas supplied by SUEZ RR
c. Create and configure widgets to display the measurements collected and the indicators calculated, in accordance with the display requirements expressed by SUEZ RR
d. Test of the ULTIMATE IT application

a. Collect measurements

Table 16 shows the source of measurements that feed the ULTIMATE application for the CS8 “Energy recovery” study. The data source (Foxboro SCADA) provides real-time data.

Table 16 Number of measurements configured in the ULTIMATE application by type of data source

Measurements origin	Measurements device	Measurements source	Number of measurements
Aqueris process (see subsection “Results of feasibility study” of section 2.7.2)	Sensors	Foxboro SCADA (publisher: Schneider Electric)	22

For cybersecurity reasons specific to the CS8 site, no IT communication is possible between their industrial network and the SUEZ office network, and vice versa. As part of the ULTIMATE project, this technical impossibility meant that it was not possible to automatically collect measurements from the source of real-time information at the CS8 site. Figure 57 illustrates the alternative technical solution based on the manual transfer of data files.

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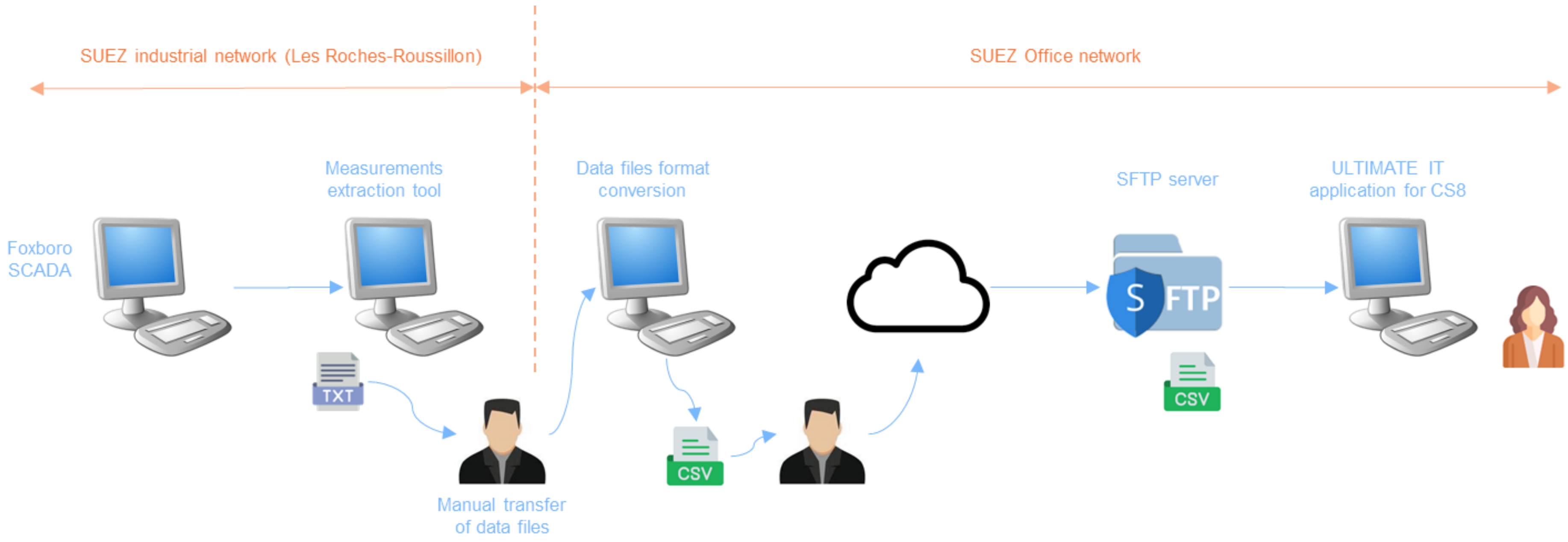

Figure 57 IT architecture for CS8

Process – acquisition of real-time measurements until their consultation:

- The operator manually extracts the real-time measurements of the existing Aqueris process, available in the Foxboro SCADA installed on the industrial network, and stores them in TXT format files on a USB key.
- The operator connects the USB key to a computer located on the SUEZ office network, transfers the measurement files to this computer and converts the two types of data file formats (TXT from Foxboro SCADA) to CSV format.
- The operator uploads these CSV files manually on a secure SFTP server created and configured by SUEZ Smart Solutions on SUEZ's Microsoft Azure cloud.
- The ULTIMATE IT application regularly scans this SFTP server, automatically transfers the new measurements and stores them in its database, which are then available for consultation via the application's graphical interface.

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b. Create and configure business indicators

Business indicators have been configured in the ULTIMATE application, in accordance with the CS8 requirements for the heat recovery study. Therefore, CS8 provided the following information required to configure the business indicators in the ULTIMATE application (Figure 58, Table 17, Table 18):

- Information characterising each business indicator $\boldsymbol{y}$ (name, unit, calculation formula, etc.)
- Information (name, unit, etc.) characterising each of the measurements $\boldsymbol{x_k}$ collected on site and used as input for the calculation formula $\boldsymbol{F}(\boldsymbol{x_1}, \boldsymbol{x_2}, \cdots, \boldsymbol{x_k}, \cdots, \boldsymbol{x_n})$ for the business indicator. See subsection "*a. Collect measurements*".

A large Excel spreadsheet was edited to store the information transmitted by CS8; this spreadsheet acted as a specification and exchange document between the CS8 partners throughout the ULTIMATE project, and to which numerous revisions were made.

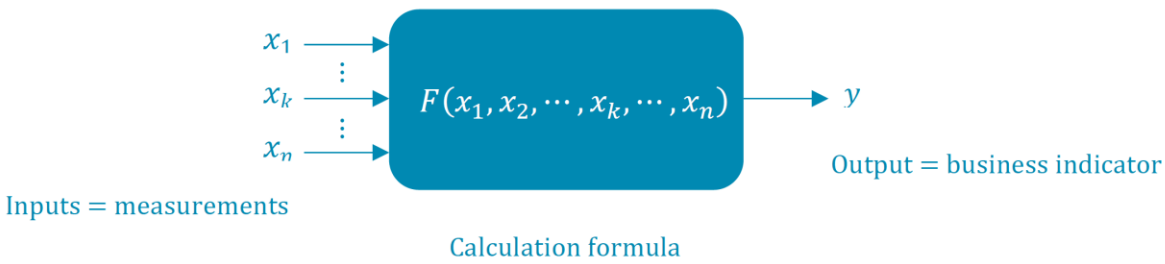

Figure 58 Information characterising each characterising each of the measurements

Table 17 Information required by the ULTIMATE application to configure a business indicator

Information required	Comments
Name	Name of the business indicator
Parent	The node in the application tree to which the business indicator is attached
Quantity	Unit of the business indicator (concentration, power, flow, etc.) and associated unit
Expression	Mathematical formula allowing the calculation of the values of the business indicator based on the values of its inputs
Input variables	Inputs required for calculating the business indicator

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Table 18 Information required by the ULTIMATE application to configure an input used in the formula for calculating a business indicator

Information required	Comments
Quantity	Unit of the input (concentration, power, flow, etc) and associated unit
Decimal separator	Comma or dot for instance
Data connector	Name of the connector to the information source. Various types of connector exist in the WasteAdvanced® product: databases, OPC, TXT or CSV files, etc.
Column name	In a text file containing several columns, ID to identify the column to be considered for entry
File name	Name of the file (here for a text file)
Quantity	Unit of the input (concentration, power, flow, etc) and associated unit
Decimal separator	Comma or dot for instance

In the Annex, screenshots of the application, in which the required information can be entered to configure a business indicator (Figure 68-Figure 72) and an input (Figure 73-Figure 75) are shown.

c. Create and configure widgets

In addition to the site measurements and business indicators, widgets have been configured in the ULTIMATE application, in accordance with the CS8 requirements. Two types of information are distinguished:

- Information characterising the content of each widget: inputs and/or business indicators to be displayed.
- Information characterising the display of the content of each widget: time series, bar chart, pie chart, gauge, etc.

The specifications associated with the widgets have also been added to the Excel sheet for business indicators, mentioned in the previous subsection "*b. Create and configure business indicators*".

d. Test of the ULTIMATE application

The ULTIMATE IT application is operational and was accessed online by the CS8 users. Figure 59 shows the authentication page of the ULTIMATE IT application as it is accessible by the case study partners. Examples of the output of the application such as the display of different process parameters are shown in the Annex (Figure 76-Figure 79).

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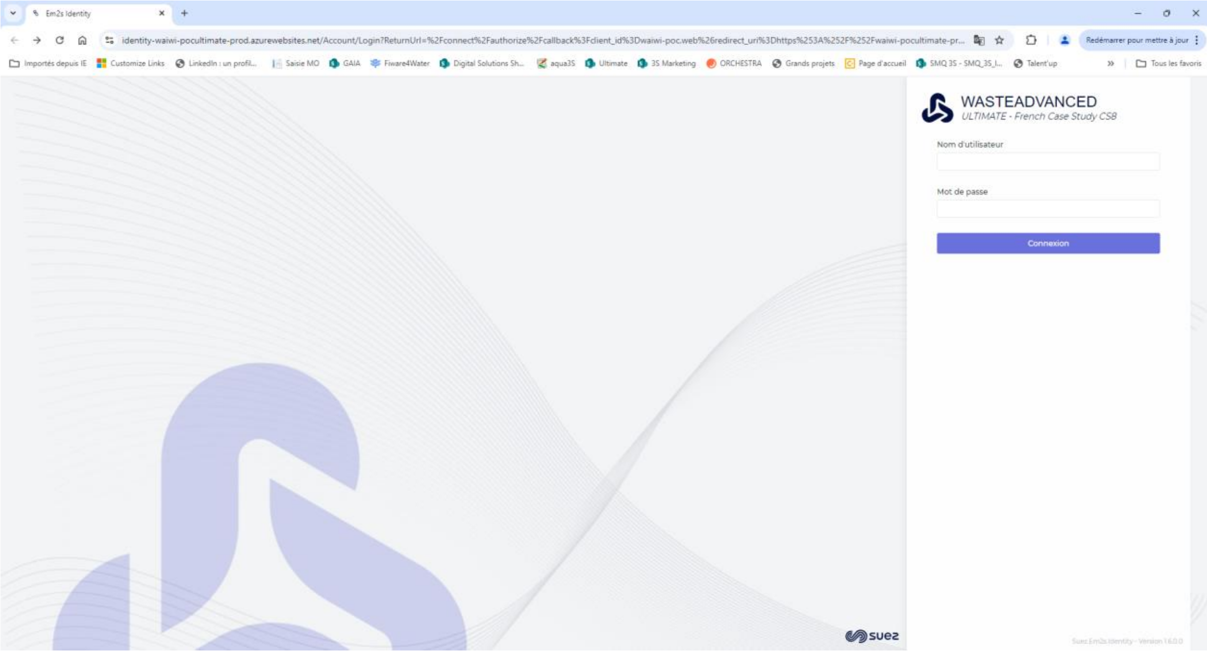

Figure 59 Authentication screen (login and password) to access the ULTIMATE IT application

The test of the application showed, that the KPIs calculated by the ULTIMATE application were consistent with the results of the feasibility study. Furthermore, the possibility of calculating the KPIs automatically, without having to extract and process the measurements, represents a considerable time saving. In addition, the use of visual indicators (widgets), in a format meeting the needs of the operator, is also a strong advantage, allowing a rapid interpretation of the results.
Because the ULTIMATE IT application was used successfully in the context of a pilot test, its functionalities are considered interesting for full-scale operational use.

2.7.3. Conclusion

Lessons learned
The regulatory context is a key aspect to analyse the concept study on energy recovery on the incineration plant of Roussillon. In fact, this site is considered as a hazardous waste disposal site (D10 code) because there is no steam production from, due to the very high salt content in, the flue gas. Being recognised in the future as a recovery unit is a major challenge for the site. To achieve this, the target of 25% recovery of residual energy from heat exchangers must be reached.

However, the technologies studied for energy recovery from washing water either:

- do not meet the recovery target
- have a too high return on investment time
- are highly energy demanding to achieve a usable form of energy.

Even though the heat recovery concepts were not feasible, the ULTIMATE IT application was successfully developed and tested on-site. The ULTIMATE

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IT application was designed to be easily adaptable to other heat recovery concepts and to serve as a basis for future concepts.

Crucial factors for the implementation of a heat recovery system

- Identify potential external customers for the energy produced by the recovery system and ensure that the form of energy produced matches the demand.
- Evaluate the carbon impact of the solution implemented to ensure its overall energy efficiency.

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2.8. Increase energy efficiency through a symbiotic and joint controlled operation of two WWTPs in Kalundborg (DK)

Anne Kleyböcker (KWB), Jan Schütz (KWB), Sille Bendix Larsen (NOVO), Malene Kristensen (KALUND)

2.8.1. Case study and ULTIMATE concept

Case study description

The Kalundborg Industrial Symbiosis Association exists since 1972 and interlinks seventeen private and public companies. The local industrial sector includes petrochemical, light building construction material, food, pharma, biotech, energy and bioenergy as well as waste processing. Different circular economy approaches for water, energy and materials are already implemented, e.g. the reuse of cooling water for steam production, the reuse of gypsum from exhaust gas cleaning to produce plasterboards, integrated heat management and the transfer between the industries and the district heating network as well as heat recovery from process water for district heating. Even though the Kalundborg Industrial Symbiosis already recovers and reuses certain materials, water and energy, there are still options to intensify and extend the circular economy related strategies. One aspect is the treatment of wastewaters, which is done by two companies Novozymes and Kalundborg Utility.
ULTIMATE focuses on the optimisation of two WWTPs aiming at developing and implementing a joint control system for both plants, the recovery of the WWTP effluent as fit-for-purpose water (Naves Arnaldos et al. 2024, D1.3) and to explore the potential for the recovery of valuable compounds from the industrial wastewater as well as on identifying options to reuse thermal energy recovered from wastewater (Gonzalez Camejo et al. 2024, D1.5). Therefore, the symbiotic relationship between Novozymes and Kalundborg utility is extended in the frame of ULTIMATE to create a win-win situation for both.

Technology description

In this deliverable, we focus on the joint control system. Especially, when two wastewater treatment plants (WWTPs) are located next to each other, but controlled separately, a joint control system can enhance their performance, increase their energy efficiency and lower their environmental impact. Usually adjacent WWTPs are operated by different companies. This is also the case in Kalundborg (DK), where the effluent of an industrial WWTP is discharged to a municipal WWTP. Both WWTPs are operated separately and owned by different companies.

The joint control system connects two separate control systems as shown in Figure 60 and has a TRL of 8. The industrial WWTP has its own control system consisting of a programmable logic controller (PLC) and a supervisory control and data acquisition (SCADA) system. The PLC uses real time data measured in the WWTP and controls the wastewater treatment process. The SCADA system displays and stores those data

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in a database. A remote terminal unit (RTU) of the industrial WWTP is used to send data to the RTU of the municipal WWTP. The municipal RTU receives those data and transfers them to the municipal PLC. Here, the industrial real-time data are used together with the real-time data from the municipal WWTP to control the set-point for the dissolved oxygen (DO) concentration in the aerated tanks. The DO concentration is crucial for a successful and energy efficient wastewater treatment process.

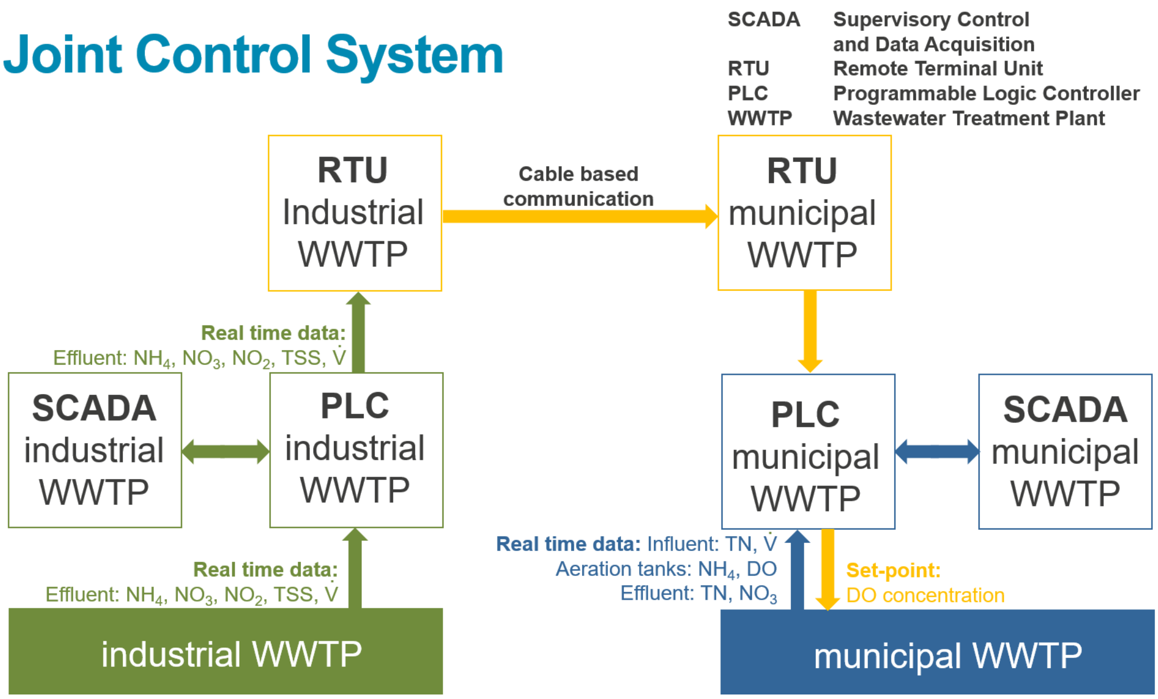

Figure 60 *Joint control system using remote terminal units at both WWTPs to deliver real time data from the industrial WWTP to the municipal WWTP in order to predict organic and nitrogen loads*

Unique selling point and motivation to implement the technology

- ✓ **Reduction of energy consumption**

The joint control system allows for a synergetic wastewater treatment management of both WWTPs. Especially energy can be saved due to a new predictive controlled nitrogen elimination and thus, the avoidance of over-aeration. Using an advanced control strategy, Bertanza et al. (2021) showed for their WWTP located in Italy, a reduction of 25% of the power requirement for aeration in a nitrification reactor by implementing a fuzzy control system.

Requirements for its implementation and operating conditions

A control system can only be as reliable as the real time data are. Therefore, reliable sensors and strategies are needed to control and maintain them. For example, Fragkoulis et al. (2011) and Gerneay et al. (2020) show different approaches and models to evaluate the monitoring performance of a WWTP and detect faults in sensors and actuators. In Kalundborg at the iWWTP, the sensors were maintained once a week and calibrated, when a drift occurred. At the mWWTP, the ammonium

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sensors were automatically calibrated every day and they were normally cleaned every 4 weeks and earlier, if a drift occurred. In addition, grab samples were taken and analysed in the laboratory to confirm the online measurements. In the case of the two WWTPs in Kalundborg, the following parameters are measured as shown in Figure 60:

- Flowrates (municipal influent and industrial effluent, both entering the municipal WWTP)
- In aeration tanks of iWWTP: ammonium (NH_4-N), nitrate (NO_3-N), nitrite (NO_2-N)
- Industrial effluent: total suspended solids (TSS)
- Municipal influent: total nitrogen (TN)
- In aeration tanks of mWWTP: NH_4-N, NO_3-N; DO concentration
- Effluent of mWWTP: TN; NH_4-N, NO_3-N
- Energy consumption of mWWTP

2.8.2. Results of new approaches

Equation to predict the nitrogen load from the iWWTP to the mWWTP

In order to optimise the biological nitrogen elimination in the municipal WWTP, a predictive empirical equation for the TN load coming from the industrial WWTP was developed. Therefore, different parameters were continuously measured and evaluated as shown in Figure 61.

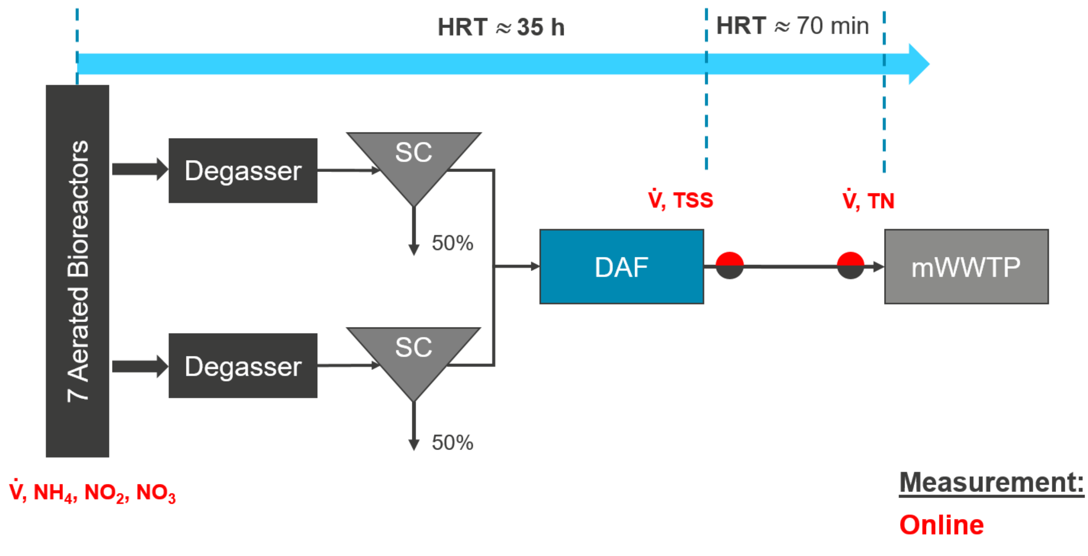

Figure 61 Flow scheme showing the measurements for the early warning indicator regarding the nitrogen load coming from the industrial WWTP to the municipal WWTP

Figure 61 shows the seven intermittent aerated bioreactors of the industrial WWTP. In the effluent of each reactor, the flow rate and the concentrations of ammonium, nitrite and nitrate were measured. The concentrations have a high variation due to the intermittent aeration of the bioreactors. For determining the resulting concentrations of ammonium, nitrate and nitrite, a mix calculation was used for each parameter (Eq. 2).

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Eq. 2 $$c_{NX-N,mix} = \frac{\sum_{k=1}^{7}(\dot{V}_k * c_{NX-N,mix})}{\sum_{k=1}^{7}\dot{V}_k}$$

After the dissolved air flotation system, the total suspended solids (TSS) were measured and used as an indicator to estimate the organic fraction of the nitrogen load being released to the municipal WWTP, because former measurements (before ULTIMATE) showed, that the organic fraction of the nitrogen was mainly contained the solid fraction of the effluent being around 6%. Furthermore, at the municipal WWTP, a new sensor (BioTector B7000 from HACH) was implemented in the influent of the mWWTP to determine the TN concentration. The BioTector was positioned roughly 37 h later in flow direction than the measurement in the effluent of the bioreactors and 70 min later than the TSS sensor.

To investigate, whether a predictive equation for the TN load to the mWWTP can be derived from the measurements of the aerated bioreactors and the TSS sensor in the DAF system, Eq. 3 was used to develop this equation using correlation coefficients.

Eq. 3 $$c_{TN} = x * c_{NH_4-N,mix} + y * c_{NO_2-N,mix} + z * c_{NO_3-N,mix} + 0.06 * c_{TSS}$$

with

- mix c_{NH4-N} calculated mix concentration of NH_4-N in effluent of bioreactors
- mix c_{NO2-N} calculated mix concentration of NO_2-N in effluent of bioreactors
- mix c_{NO3-N} calculated mix concentration of NO_3-N in effluent of bioreactors
- c_{TSS} concentration of TSS in effluent of DAF tank
- x, y, z factors to compensate measurement inaccuracies and/or reduction/ oxidation reactions of the N fractions during the 37 h, before the wastewater reaches the BioTector.

The factors x, y and z were determined according to the best correlation results for the running averages of Eq. 2 and the BioTector results. The running averages were chosen, because of the high variation of the concentrations in the effluent of the intermittent aerated bioreactors. For the correlation analysis, different coefficients were used such as the coefficient of determination (R^2), the Nash-Sutcliffe efficiency coefficient (NSE), the likelihood (Λ) and the root mean square error (RMSE). The correlation coefficients were determined according to Ahnert et al. (2007), Mannina et al. (2011), Guo et al. (2015) and Carreres-Prieto et al. (2023).

Figure 62 and Table 19 show the summary of selected results. The best fit considering high and low concentrations was reached for x; y; z = 0.6; 1.8; 2.3 with correlation coefficients between 0.68 and 0.77 and a RMSE of 0.3 mg L^{-1}. However, especially for smaller concentrations below 25 mg L^{-1}, the correlation was not as good as for peak concentrations. For concentrations of 25 mg L^{-1} and lower, the best combination of x; y; z was 2.0; 0.5; 2.0, for which the correlation coefficients were between 0.54 and 0.63 with an RMSE of 1.8 mg L^{-1}.

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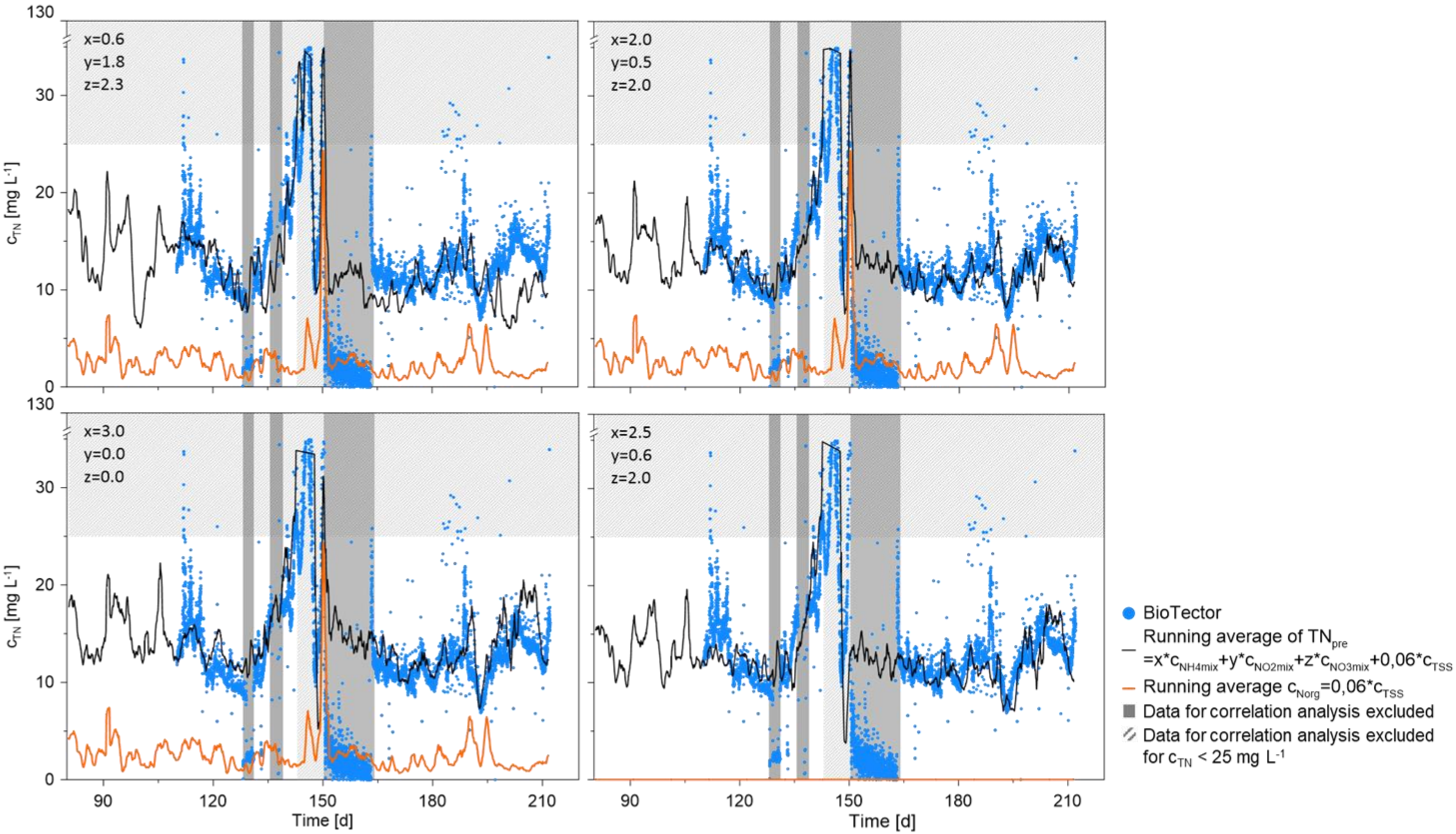

Figure 62 Data from BioTector for TN concentration (•), the running average of Eq.2 (—) and organic nitrogen fraction (—): the grey coloured ranges were not used for correlation, because the BioTector was not in regular operation. For the correlation of TN concentrations below 25 mg/L, data in the grey hatched areas were excluded.

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Table 19 Results for correlation coefficients using the time periods without sensor failure (time periods of 128-131; 135-139; 151-164 were not considered) and for TN concentrations ≤ 25 mg/L

x; y; z	$c_{N,org}$	focus	R^2 [-]	NSE [-]	Λ [-]	RMSE [mg/L]
0.6; 1.8; 2.3	0.06*c_{TSS}	$c_{TN} \leq$ max	0.77	0.68	0.72	0.3
0.6; 1.8; 2.3	0.06*c_{TSS}	$c_{TN} \leq 25$ mg L^{-1}	0.25	-0.25	0.29	2.9
0.6; 1.8; 2.5	0	$c_{TN} \leq$ max	0.66	0.31	0.50	4.7
1.0; 1.0; 1.0	0.06*c_{TSS}	$c_{TN} \leq$ max	0.75	0.47	0.59	4.1
1.0; 1.0; 1.0	0.06*c_{TSS}	$c_{TN} \leq 25$ mg L^{-1}	0.42	-0.57	0.21	3.3
2.0; 0.5; 2.0	0.06*c_{TSS}	$c_{TN} \leq$ max	0.69	-1.08	0.13	8.1
2.0; 0.5; 2.0	0.06*c_{TSS}	$c_{TN} \leq 25$ mg L^{-1}	0.59	0.54	0.63	1.8
2.5; 0.6; 2.0	0	$c_{TN} \leq 25$ mg L^{-1}	0.51	0.26	0.48	2.2
3.0; 0.0; 0.0	0.06*c_{TSS}	$c_{TN} \leq$ max	0.59	-3.87	0.01	12.4
3.0; 0.0; 0.0	0.06*c_{TSS}	$c_{TN} \leq 25$ mg L^{-1}	0.56	0.08	0.40	2.5

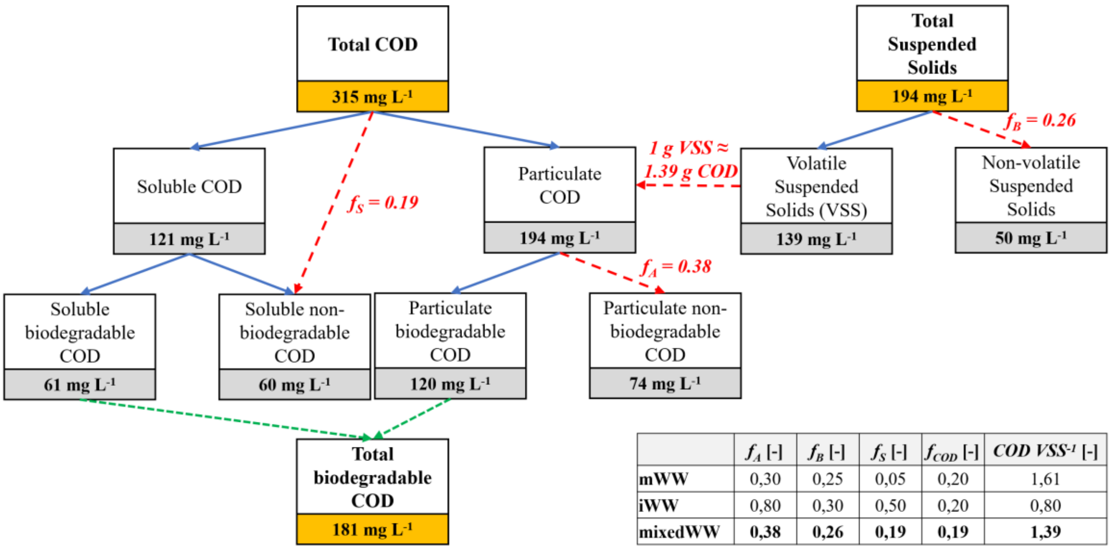
Aiming at simplifying Eq. 3 by neglecting either the organic nitrogen concentration or nitrite and nitrate concentrations, the combinations 2.5; 0.6; 2.0 as well as 3.0; 0.0; 0.0 resulted in a still useful replication of the TN concentrations, even though the correlation coefficients were less good than for the other combinations. Also, neglecting the organic nitrogen concentration resulted in the loss of the TN peak at day 40. Nevertheless, it has the advantage, that the TN concentration can be predicted 36 h earlier than using an equation involving the TSS content for the organic nitrogen concentration. Neglecting the nitrite and nitrate concentrations has the advantage, that only 16 sensors (7 flow, 7 ammonium and 2 TSS sensors) are needed instead of 23 sensors. Considering the time benefit of the combination that neglects the TSS content for the organic nitrogen concentration, it makes sense to use it as an early warning signal.
In a second step, the combinations 2.0; 0.5; 2.0 and/or 3.0; 0.0; 0.0 can be used to confirm and/or revise the warning, because they also involve the TSS as indicator for the organic nitrogen and they correlate better. Finally, in the third step, the BioTector can confirm/revise both signals.

Even though the correlation coefficients for the best fit were far from 1.0, indicating an identical fit, the accuracy is good enough to at least provide a first warning. Considering the high number of sensors (23 and 16) on which the correlation depends on, a correlation factors of higher than 0.5 are quite a good result and also show the good data quality due to the regular maintenance of the sensors. Furthermore, the RMSE of 1.8 mg N L^{-1} is still in an acceptable range. Mannina et al. (2011) for example reached with 0.65 and 0.54 similar ranges for the likelihood for the best fit of the ammonium concentration in a calibrated WWTP model, while the RMSE ranged between 5.18 and 7.33 mg NH_4 L^{-1}. Guo et al. (2015) determined the R^2 and NSE for two machine learning models to predict the TN concentration and reached values of 0.47 and 0.46

as well as 0.45 and 0.46, respectively, which was below the results of our best fits. Hence, our results seem to be in a typical range for prediction models and the empirical equation is good enough to be used as an early warning indicator.

Model in Simba#

For Activated Sludge Modelling (ASM) the EAWAG ASM3+BioP (Siegrist et al. 2002) with the HSG parameter set according to Alex et al. (2015) was used to simulate the processes of the investigated full-scale WWTP. The developed model can describe the nitrogen and phosphorus removal processes and was implemented into the simulation environment of SIMBA# version 5.0 (SIMBA#, ifak, Magdeburg Germany). As model outputs the effluent parameters COD, TSS, TN, NH_x-N, NO_x-N, TP and PO_4-P were selected. In order to convert the influent measurements for COD and TSS into model state variables, a fraction-based approach according to DWA A-131 (2016) was applied. Figure 63 gives an overview of the calibrated fractions for the COD and TSS concentrations of the mixed WW entering the aeration tanks of the mWWTP.



	f_A [-]	f_B [-]	f_S [-]	f_{COD} [-]	$COD\ VSS^{-1}$ [-]
mWW	0,30	0,25	0,05	0,20	1,61
iWW	0,80	0,30	0,50	0,20	0,80
mixedWW	**0,38**	**0,26**	**0,19**	**0,19**	**1,39**

Figure 63 Detailed overview of the COD and TSS fractions entering the activated sludge tanks at the mWWTP

The calibration of the dynamic model focused mainly on the sludge production parameters and the fractionation parameters f_A, f_B, f_S, f_{COD} and VSS to COD ratio, because those had a greater influence on the model results than the other model parameters. For closing the sludge balance, the content MLSS, the SVI and the ratio of RAS and WAS were manipulated. To calibrate the nitrification and denitrification processes in the model, the maximum growth rate for autotrophic microorganisms (μ_{AUT} = 1.8) was used instead of the default growth rate of 1.12.

To interpret the model results and to determine the predictability of the model and its corresponding accuracy under real-time conditions correlation analyses were performed. Table 20 presents the correlation coefficients (R^2, NSE and likelyhood) for the selected model outputs. R^2 is greater than 0.7 for almost all parameters except for the NO_x-N load (0.29). The NSE coefficient is also greater than 0.7 for almost all

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parameters expect for the TSS and NO_x-N loads. This indicates that the model fits well to the actual measured loads of COD, TN, NH_x-N, TP and PO_4-P. For TSS, R^2 is higher than 0.5 and the NSE is still positive but lower than 0.5 which implies that the model has some relevance with the reality in terms of variation, but it fails to reproduce the mean. One reason for this issue is the three-layer model of the secondary clarifier used and the different settling abilities between the real conditions and the simulated model results. Calibration trials to improve the settling ability did not lead to satisfactory results. Only the SVI had a major impact on the goodness of fit. For the NO_x-N load, the NSE was negative and R^2 was lower than 0.5 (0.29).

Table 20 *Correlation analysis (R^2, NSE, L) between the model outputs of COD, TSS, TN, NH_X-N, NO_X-N, TP, PO_4-P under steady state conditions and concentrations determined in 24h-mixed samples*

	R^2 [-]	NSE [-]	Λ [-]	a_i [-]
COD	0.91	0.90	0.91	0.19
TSS	0.70	0.41	0.56	0.12
TN	0.90	0.71	0.75	0.15
NH_x-N	0.72	0.71	0.75	0.15
NO_x-N	0.29	-0.06	0.35	0.07
TP	0.81	0.75	0.78	0.16
PO_4-P	0.78	0.70	0.74	0.15
Overall Model-Efficiency: $E_i = \sum_{j=0}^{n} \alpha_j \times \Lambda\left(\frac{\theta_i}{Y_j}\right)$				**0.73**

This implies that this parameter is not adequately predicted by the dynamic model. However, the small concentrations of the nitrite and nitrate should be noted in this context ranging from 1.0 mg L^{-1} to 1.2 mg $L^{-1}$with an average concentration of 1.1 mg L^{-1}. Already small deviations in their concentrations can lead to quite poor correlation results. Similar observations were made by Mannina et al. (2011) and Solís et al. (2022), who also simulated a full-scale WWTP.

In order to calculate the overall model efficiency, the likelihood measure (Λ) was also determined for each parameter. As with NSE, Λ is used for parameter calibration of hydrological and hydrogeological models (Molin et al. 2020). The results for Λ are on a similar level as those for the NSE and vary for this model between 0.35 for NO_x-N and 0.91 for COD. Besides for NO_x-N, the results indicate a good fit between the simulation outcomes and the observed data. For comparison, Mannina et al. (2011) achieved results for Λ between 0.12 for TP and 0.7 for TSS for the same selection of parameters and categorize their results as satisfactory. Hence, our results were as good as and for some parameters even better as the results of Mannina et al. (2011). The overall model efficiency was 0.73, indicating that the model predicted 73% accurately the real-environment conditions of the mWWTP.

To give an indication of how well the model fits in terms of numerical deviation, the root-mean-square-error (RMSE) was also calculated for each individual model output. In Table 21 the average concentrations for the measured and simulated concentrations along with the RMSE are highlighted.

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Table 21 *Comparisson of measured and simulated mean concentrations for the selected model outputs (COD, TSS, TN, NH_x-N, NO_x– N, TP and PO_4-P)*

	COD [mg L^{-1}]	TSS [mg L^{-1}]	TN [mg L^{-1}]	NH_x-N [mg L^{-1}]	NO_x-N [mg L^{-1}]	TP [mg L^{-1}]	PO_4-P [mg L^{-1}]
Measured	67.1	10.1	6.3	0.4	1.4	0.8	0.8
Simulated	65.4	7.2	5.3	0.4	1.1	0.9	0.7
RMSE	7.15	4.01	1.27	0.12	0.69	0.18	0.18

The calibrated model was used for scenario analysis in order to define the set points for the JCS. For this investigation, the simulation was run until a steady state was achieved for at least 60 days, corresponding to approximately two sludge ages (SRT ≈ 27 d), before the results were generated.

Scenario testing for set-point definition

Within the scenario analysis, the behaviour of the simulated mWWTP was investigated with respect to the significance of high TN concentrations originating from the iWWTP. The JCS exerts a direct influence on the aeration controller. The intermittent aeration of the mWWTP is controlled by the measured ammonium concentration in the aeration tanks. The relationship between the ammonium concentration and the calculated DO set-point within the controller is linear (Figure 64).

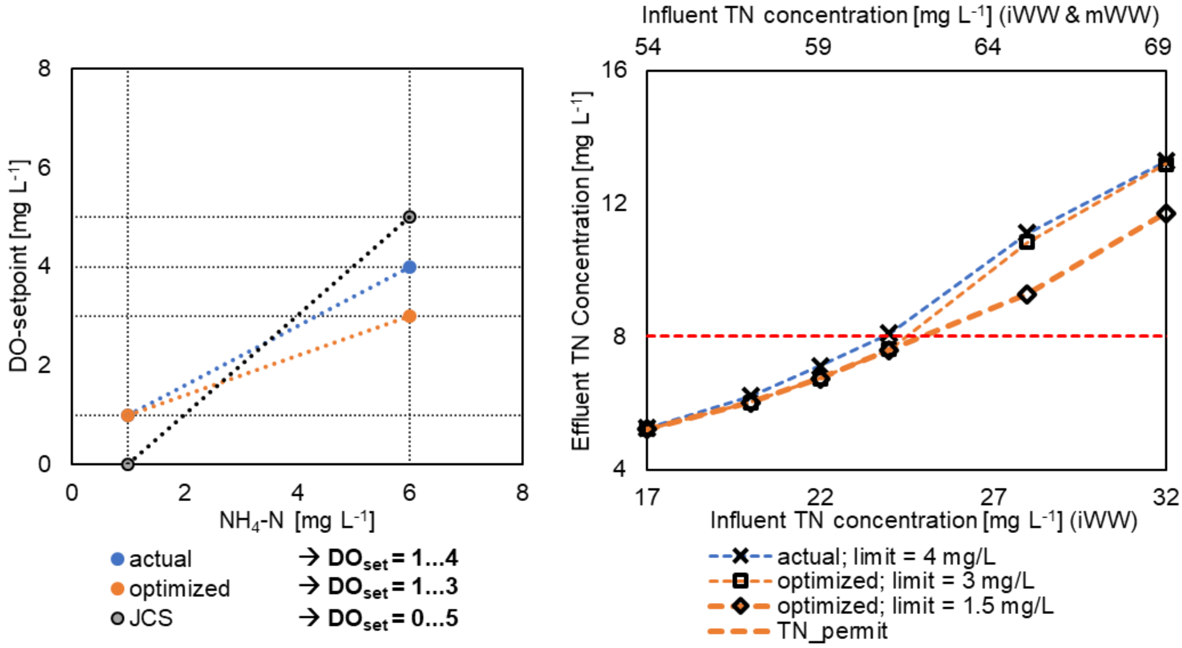

Figure 64 *Left: linear equations for the interpolation of the oxygen setpoint within the aeration controller. Linear eq. TN normal = actual settings for controller in real world. Linear eq. TN optimised = optimised controller setting within ASM. Linear eq. JCS = controller settings for high TN concentrations triggered by JCS. Right: Influence comparison of the different controller setting*

In order to manipulate the slope of the linear set-point equation, it is necessary to define the minimum and maximum DO set-points. This was achieved by modelling different controller settings for different TN concentrations. However, it is necessary to control

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the aeration in order to ensure that the permitted discharge limits are still met. These limits are as follows: COD = 75 mg L^{-1}, TSS = 30 mg L^{-1}, TN = 8 mg L^{-1} and TP = 1.5 mg L^{-1}. As the mWWTP has a low fraction of biologically available COD for denitrification due to the high fraction of iWW, it is important to avoid over-aeration. This was achieved by subsequently limiting the maximum DO concentration within the control concept to a specific threshold. When the total nitrogen concentration in the iWW stream was higher than that under normal conditions, the DO concentration in the aeration tanks of the mWWTP was increased faster in order to avoid a limitation of nitrification. Therefore, the JCS triggered a new slope for the aeration controller, when the TN concentration in the industrial influent of the mWWTP exceeded 20 mg L^{-1}. Figure 64 on the left shows the different DO set-points and the slope plotted against the ammonium concentration in the aeration tanks of the mWWTP. The minimum and maximum DO set-points for these straight lines were as follows: $DO_{min,actual}$ = 1 mg O_2 L^{-1}, $DO_{max,actual}$ = 4 mg O_2 L^{-1}; $DO_{min,optimised}$ = 1 mg O_2 L^{-1}, $DO_{max,optimised}$ = 3 mg O_2 L^{-1} and for the JCS: $DO_{min,JCS}$ = 0 mg O_2 L^{-1}, $DO_{max,JCS}$ = 5 mg O_2 L^{-1}. Figure 64 on the right illustrates the impact of the controller setting investigated with the active JCS on the TN effluent concentrations plotted against the TN inlet concentrations in the iWW. The curves displayed differ due to the different limitations for the maximum DO set-point in the aeration tanks. It can be observed that the curve for the actual controller setting already exceeded the permitted TN effluent concentration of 8 mg L^{-1} at an inlet concentration of 23 mg L^{-1} in the iWW, which corresponded to 60 mg L^{-1} in the mixed WW, while the curves for the optimised settings only exceeded this at 25 mg L^{-1} in the iWW (corresponding to 62 mg L^{-1} in mixed WW). For inlet concentrations of the iWW greater than 28 mg L^{-1} (65 mg L^{-1}), the optimised setting had no longer any advantage over the actual setting. However, if the maximum oxygen concentration was limited to 1.5 mg L^{-1}, the increase in the TN effluent concentration could be reduced. This can be explained by the fact that biologically available COD as not completely oxidized before denitrification began. Also, a post denitrification process with external carbon dosing can be an option for an optimised nitrogen removal. Consequently, the optimised setting ($DO_{min,optimised}$ = 1 mg O_2 L^{-1}, $DO_{max,optimised}$ = 3 mg O_2 L^{-1}), which includes a subsequent limitation of the DO concentration to 1.5 mg O_2 L^{-1}, is therefore recommended as set-points.

Joint control system performance and comparison with the baseline situation

The performance of the joint control system was evaluated after the first three months of operation in the real environment (Figure 65). Before the implementation of the JCS, the COD and TN loads in the influent were higher, while in the effluent, the COD and TN loads were lower and higher, respectively. While the COD concentrations in the effluent were nearly the same after the JCS was in operation, the TN concentration in the effluent decreased by a factor 1.5. After the start-up of the JCS, the COD/E and N/E ratios seemed to decrease from 0.56 kg COD $(kWh)^{-1}$ to 0.44 kg COD $(kWh)^{-1}$ and from 1.52 kg N $(kWh)^{-1}$ to 1.38 kg N $(kWh)^{-1}$, indicating the consumption of the same energy amount to eliminate a lower COD and N load with the JCS in operation. However, simultaneously the average flow rate increased by a factor 1.3 after the

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implementation of the JCS. Hence, the higher flow rate led to a dilution of the wastewater and required more energy for pumping and mixing. Nevertheless, after the JCS was in operation, the specific energy consumption of the mWWTP decreased from 0.4 kWh m^{-3} to 0.32 kWh m^{-3}. Therefore, to exclude the effect of the higher flow rate during the operation of the JCS, the COD/E and N/E ratios were normalized using the flow rate. Hence, the normalized ratios indicate the treatment of the actual COD and TN load, but in a smaller water volume normalized via relating it to the flow rate before the JCS's implementation. The comparison of those ratios showed that the normalized COD/E ratio was on a similar level as the COD/E ratio of the operation without JCS, while the normalized N/E ratio was slightly higher with a factor of 1.18. Hence, the plant operation with the JCS in operation seemed to have a positive effect on the TN concentration in the effluent as well as on the energy efficiency for N elimination.

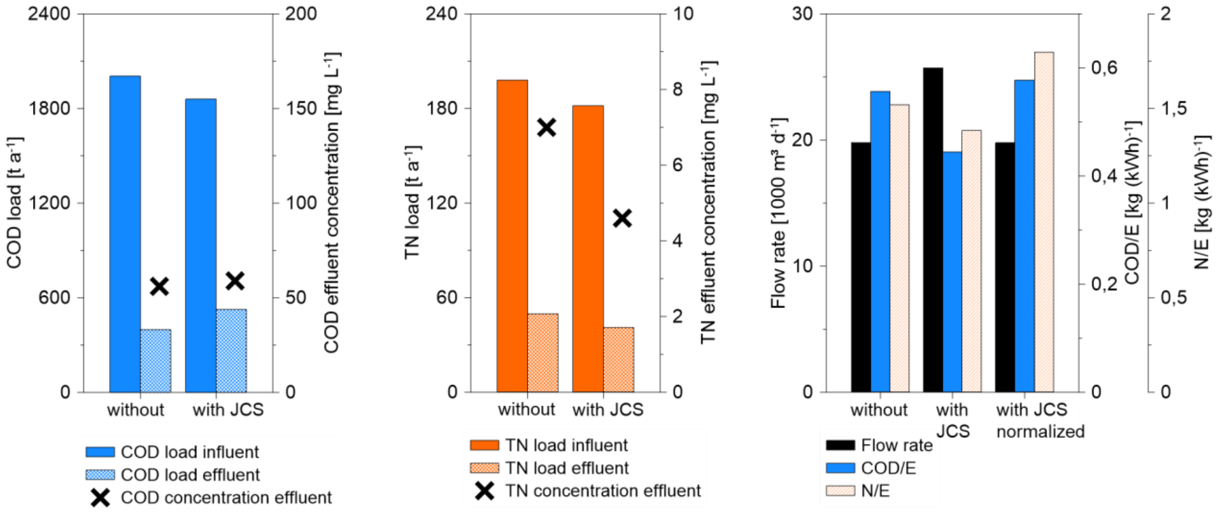

Figure 65 *Comparison of the COD and TN loads before and after the implementation of the joint control system as well as the corresponding COD/E and N/E-ratios. Average values from one year of operation were used for the results without JCS. For the results, when the JCS was in operation, average values of three months were used and extrapolated to one year. Due to different average flow rates, the COD/E and N/E-ratios were linearly normalised.*

Those are first results and need to be confirmed with data of a full year of operation. Shock loads of COD or TN were not observed in the testing time, also indicated by the lower COD and TN loads in the influent compared to the time period without JCS. The JCS was mainly designed to properly treat those events. The evidence therefore is still missing, but in a real environment the priority is to maintain "normal" operating conditions. Shock loads are undesired events and are avoided, if possible. Therefore, it was only possible to test the system under normal operating conditions until now. Nevertheless, the increase in the mWWTP's energy efficiency under normal operation conditions by a factor of 1.18 is in its expected range. Bertanza et al. (2021) observed also an increase in the energy efficiency of their plant after the optimisation of the aeration system. They saved 25% of the energy for aeration. Assuming, that 60% of the total energy consumption of a plant refers to the operation of the aeration system, this would correspond to 15%, what is roughly in the range of our observation.

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2.8.3. Conclusion

Lessons learned from modelling, technology operation and symbiotic relationship

For two adjacent WWTPs, an industrial and a municipal WWTP, a joint control system was developed. In order to do this, a relationship of trust between the parties involved is essential.

The joint control system aims at enhancing the nitrogen elimination process in the municipal wastewater treatment plant and at increasing its energy efficiency via a demand-driven aeration to avoid over-aeration. Therefore, an early warning system was developed using an empirical equation to predict the TN concentration coming from the iWWTP as early as possible. A stepwise warning was found to be useful 37 h, 70 min and 0 min before the iWW enters the mWWTP.

Using SIMBA# for modelling the mWWTP, the set-points for the joint control system were determined. The selected ASM3+BioP biokinetic model was adapted to the local conditions through a series of sensitivity analyses and calibration procedures. Especially the fractionation of the iWW turned out to be the bottleneck of the modelling part. In order to assess the goodness of model calibration and the model's predictive capability, different statistical tests (R^2, NSE and Λ) were conducted. The overall model efficiency was calculated to be 0.73 for the selected model outputs (COD, TSS, TN, NH_x-N, NO_x-N, TP and PO_4-P), indicating that the model accurately predicted 73% of the real-world conditions on site.

The calibrated model was used for scenario analysis in order to define the set-points for the novel JCS. By varying the TN concentrations within the iWW entering the mWWTP the plant behaviour was investigated and the DO-setpoints for the aeration controller and JCS were improved. To compare the actual and optimised settings, the plant-wide performance indices N/E and COD/E were computed. The optimised settings involving the JCS was related to an improved efficiency. The aeration energy decreased by 4%, while the energy efficiency for COD and nitrogen removal increased by 3% and 4%, respectively.

To test the JCS in the real environment, the early warning for the TN load coming from the iWWTP (70 min before the iWW enters the mWWTP) together with the TN signal of the BioTector in the influent of the mWWTP was tested in the first three months. The evaluation showed an almost 2-fold lower TN concentration in the effluent and a 1.18 higher energy efficiency to eliminate nitrogen in the mWWTP under normal process conditions. However, those results still need to be confirmed considering a longer time period, e.g. one year, and for treating nitrogen shock loads coming from the iWWTP. In addition, the empirical equation to generate an early warning already 37 h before the iWW enters the mWWTP will be integrated in the JCS in the next step.

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Best practices and recommendations for technology design and operation in the symbiotic frame

The joint control system is highly dependent on the quality of the sensors implemented in both WWTPs. The maintenance strategies were found to be sufficient, as good results were obtained for the correlation coefficients of higher than 0.5, even though 16 sensors and 23 sensors were used to predict the nitrogen concentration for the stepwise warnings. In general, a minimum of 4 sensors is needed to measure flow, ammonium, nitrite/nitrate and TSS. The BioTector sensor is quite expensive and might be replaced by the prediction of the TN load as long as the sensors deliver reliable data. The ammonium, nitrate and nitrite sensors in the iWW were maintained once a week and calibrated, when a drift occurred, while the ammonium sensors in the mWW were automatically calibrated every day and they were cleaned every 4 weeks or earlier, if a drift occurred. In addition, grab samples were taken and analysed in the laboratory to confirm the online measurements.

The step-wise warning of the joint control system provides safety by confirming measurements from different sensors. In addition, a first warning of 37 h before the iWW enters the mWWTP provides enough time to adjust the aeration strategy in the mWWTP. In the future, it is planned to slightly increase the total solids content within the 37 h in the aeration tanks in order to slightly increase the treatment capacity.

As DO set-points for the JCS in this particular combination of iWW and mWW, the modelling results revealed the best results for: $DO_{min,optimised}$ = 1 mg O_2 L^{-1}, $DO_{max,optimised}$ = 3 mg O_2 L^{-1}) with a subsequent limitation of the DO concentration to 1.5 mg L^{-1}.

Crucial factors for technology implementation and its optimal performance

- A minimum of 4 sensors (flow, ammonium, nitrate/nitrite and TSS) is needed for its implementation and the modelling of the system is recommended in order to determine the new aeration strategy.
- Trusting relationship and very good communication between both plant operators is essential
- Modelling provides valuable insights into optimisation potential of aeration system and is important for the DO-setpoint definition
- High reliability of real-time data through frequent maintenance and gradual alerts based on different measurements required
- COD/E and N/E are suitable indices to evaluate energy efficiency optimisation measures applied to WWTPs.

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3. Summary and conclusion of energy recovery concepts

3.1. Points of application, key performance indicators, energy saving potentials on CS level, benefits and challenges

In six of nine ULTIMATE case studies, energy-related technologies were conceptualised, developed and demonstrated. The technologies either recovered, stored and reused heat as in CS2, CS7 and CS8 or they produced and valorised biogas as in CS5 and CS6. In CS9, a joint control system enabled the increase in energy efficiency through a demand -driven aeration system. Figure 66 shows the points of application of the technologies.

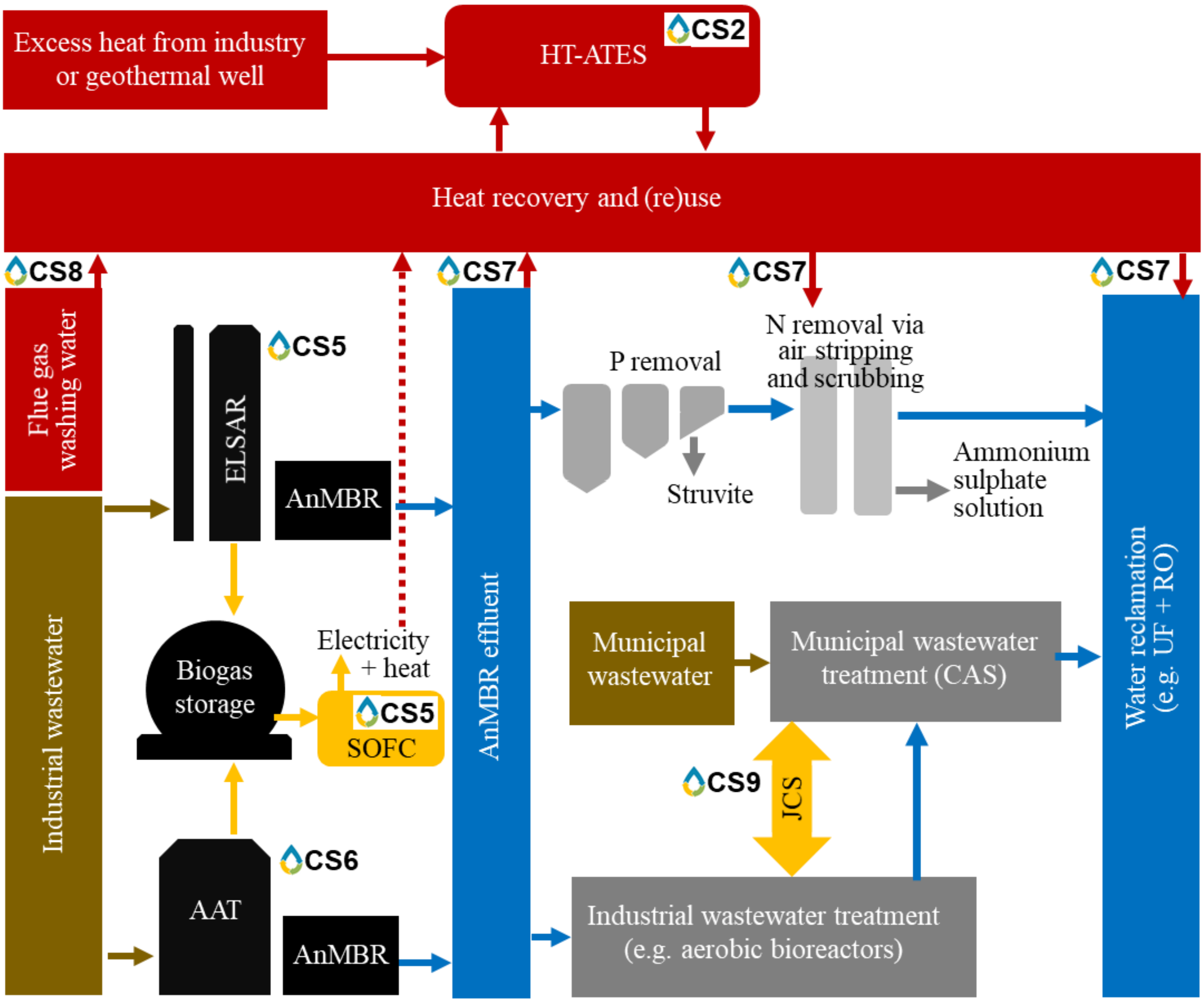

Figure 66 Points of application of the energy-related ULTIMATE technologies

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Heat management related technologies

For the HT-ATES, the point of application can be residual heat from industry or a geothermal well, as it was conceptualised in the feasibility study of CS2. The concept is feasible as long as excess heat and heat demand match each other, so that the excess heat can be stored in the HT-ATES in summer and be recovered and used in winter (Table 22). The study showed, that the concept for CS2 is technically and economically feasible. In CS8, the feasibility of applying the ORC using heat recovered from flue gas of a hazardous waste incineration plant was investigated. The study revealed that the availability of heat was too low to make this process economically viable. Also, the heat contained in used cooling water from hazardous waste incineration was not sufficient to be recovered and reused in an economical way. Alternatively, the application of a heat pump for steam generation was investigated using cooling water and the feasibility was neither economically nor technically viable. In contrast, CS7 showed that the heat contained in the effluent of an AnMBR can beneficially reused for further wastewater treatment processes such as the recovery of ammonia in an air stripping process or to reduce the dynamic viscosity by increasing the temperature of a RO feed stream to allow for a lower transmembrane pressure during RO filtration. For the ammonia stripping process however, more energy is needed to operate the process at 60 °C in order to reduce the pH to 9 and to save chemicals for pH adjustment.

Biogas related technologies

The AAT and the ELSAR each combined with AnMBRs are applied as anaerobic pre-treatments for industrial wastewaters containing high COD concentrations. Both systems allow for biodegradation of organic matter to produce biogas achieving COD removal rates between 40% and 96% (Table 22). The ELSAR achieved the highest COD removal rates corresponding to the highest methane yield. The reason therefore is very likely the bioelectrochemical system allowing for higher methane yields and degradation yields due to additional microbial and chemical processes induced by electroactive microorganisms. While the ELSAR was successfully tested with brewery wastewater, the AAT was applied to a mix of mWW with agro-industrial wastewater containing high COD loads and coming from e. g. olive oil mills, wineries and slaughterhouses. For biogas valorisation, a SOFC was tested producing electricity and heat as by-product. Table 22 provides more details regarding the reached TRLs, the capacities and the energy recovery rates of each system.

Joint control system to increase energy efficiency

The joint control system was implemented at two WWTPs, one industrial WWTP that pre-treats biotechnological WW, before it enters the mWWTP, where it is mixed with mWW. The first three months of operation revealed an increase in energy efficiency of 1.18 (Table 22). It should be noted, that in this time period no nitrogen shock loads occurred, for which the joint control system was actually designed. The energy efficiency increase still needs to be validated with a longer operational period and for the treatment of nitrogen shock loads coming from the iWWTP.

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Table 22 Summary of energy-related technologies with TRL increase in ULTIMATE, flowrates, KPIs and their feasibility

CS	Technology	TRL	Energy type produced or saved	Inflow flowrate/ capacity	Energy recovery rates (KPIs)	Feasibility and/or successful operation
2	HT-ATES	5→7	Heat for greenhouses	244-410 m³/h 15-25 MW	65-80% thermal energy recovery of HT-ATES	Technically and financially feasible
5	ELSAR	5→7	Biogas	500 m³/d 25 kg COD/m³/d	0.34 m³ CH_4/(kg COD) 90-96% COD removal	Successful full-scale operation
5	SOFC	7→9	Electricity	10 m³ biogas/d	1.3 kW electricity with electrical efficiency of 55%	Successful pilot operation
6	AAT	5→8	Biogas	100 m³/d 9-11 kg COD/m³/d 99.5 vol.-% mWW 0.5 vol.-% OMW	0.04-0.06 m³ CH_4/(kg COD) 40%-55% COD removal 18-47% polyphenol removal	Successful pilot operation
6	AAT+ AC/AnMBR	5→6	Biogas	2.4-18 L/d 1.5-11 kg COD/m³/d 99 vol.-% mWW 1 vol.-% OMW	0.29 m³ CH_4/(kg COD) 83-86% COD removal 52% polyphenol removal	Successful lab-scale test (pilot plant in Shafdan successfully constructed, but no operation possible due to war)
7	RO filtration	5→6	Heat reuse for RO filtration	0.1L/s inflow to RO	T increase: 20 °C → 30-40 °C flux increase by 11%	Successful lab-scale operation
7	Ammonia stripping	5→7	Heat reuse for ammonia stripping	0.5 m³ WW/h inflow to stripping unit	T increase: 20 °C → 60 °C enables lower pH conditions (11 → 9) in stripping process	Successful lab-scale operation, but additional energy required
8	ORC	2→4	Heat reuse for electricity production	Cooling water: 190-230 m³/h Flue gas: 60 000 Nm³/h	Energy recovery yields: Cooling water:5% Flue gas: 0.6%	Economically not feasible

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CS	Technology	TRL	Energy type produced or saved	Inflow flowrate/ capacity	Energy recovery rates (KPIs)	Feasibility and/or successful operation
8	Heat pump	2→4	Heat reuse for steam production	Cooling water: 190-230 m³/h	Energy recovery yields: 16, 32 and 49%	16%, 32%: neither economically 48%: nor technically feasible
9	Joint control system	5→8	Energy for aeration saved	Appr. 20.000 m³ WW treated in mWWTP	Increase in energy efficiency by 18%	3 months of operation → results need to be confirmed with a longer time in operation

For all technologies, that started at an TRL of 5 or 7, the demonstration at case study level was successful and increased their TRL to 7, 8 and 9. Only for the heat recovery technologies in case study 8, the TRLs were much lower at 2 increasing to 4 and the feasibility studies showed, that they were not suited for the application in waste incineration plants.

Table 23 shows the comparison of the expected energy savings at the beginning of ULTIMATE compared to the actual achieved energy savings at case study levels. The biogas production and valorisation technologies reached all their expected energy savings at case study level. However, the heat recovery technologies did not all reach the expected energy savings. Only the HT-ATES and the heat reuse for RO filtration could reach the targets. For the HT-ATES in particular, the size of the system has a major influence on the substitution potential of fossil energy. The larger heat supply system is and the smaller the HT-ATES system is, the lower the effect of fossil fuel substitution is. In CS2, the heat supply system for the greenhouse was quite large compared to the average size in the Netherlands.

Table 24 presents the benefits and challenges of the energy recovery technologies. For most of the technologies, there are more benefits than challenges. In addition, the challenges often refer to the demand of more research, as for the biogas related technologies. The successful lab and pilot demonstrations in ULTIMATE were important steps to evidence the high potential and feasibility of the technologies. The technologies are still not mature enough to be marketed directly, but they are very well suited for further investigations and more demonstration projects to accelerate their market-uptake. While the systems for heat recovery at a waste incineration plant were not suitable and won't be further investigated, the HT-ATES and the joint control system were very feasible and are considered to be ready for replication and market-uptake.

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Table 23 Comparison of expected energy savings at the beginning of ULTIMATE and the actual energy savings achieved at case study level

CS	Technology	Expected energy savings	Actual energy savings at case study level
2	HT-ATES	Substitution of fossil energy **15%**	Substitution of fossil energy: **5-6%** (very large system as in CS2) **20-30%** (average sized system)
5	ELSAR	**10%** reduction of energy demand	Reduced energy demand by 10%
5	SOFC	**30%** substitution of fossil energy	Compared to a CHP unit, the SOFC has a 50% higher electrical efficiency. Because heat is less needed than electricity, the target to use more recovered energy (30%) can be reached with the SOFC.
6	AAT	**20%** reduction of energy demand	The upscaled system is expected to achieve: >20% reduction in energy demand due to energy recovery
6	AAT/AnMBR		Expectation for an up-scaled system based on lab experiments 30-50% reduction in energy demand due to energy recovery
7	RO filtration	Maintaining **15%** reduction in fossil fuel as already reached, even with the implementation of the nutrient and water recovery units	**15%** is possible with an up-scaled system RO can be operated with a lower transmembrane pressure enabling a lower energy consumption (2-5% estimated)
7	Ammonia stripping	Maintaining **15%** reduction in fossil fuel as already reached, even with the implementation of the nutrient and water recovery units	**15%** is not possible Ammonia stripping process can be operated at a lower pH requiring lower dosage rates of NaOH for pH adjustment
8	ORC	Target for residual heat recovery yield**: 25%**	Only 0.6% and 5% can be reached
8	Heat pump	Target for residual heat recovery yield**: 25%**	32% and 49% can be reached, but economically and technically not feasible, respectively
9	Joint control system	Reduction in energy demand: **not defined**	Increase in energy efficiency: 1.18 → Energy demand decrease of **15%**

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Table 24 Benefits and challenges of the ULTIMATE energy recovery technologies

CS	Techno-logy	Benefits	Challenges
2	HT-ATES	• Residual heat can be stored and reused when needed • Reduction of energy cost • Low CO_2 emissions • Little space needed due to system in subsurface • High storage capacity • Heating and cooling depending on season	• Exploration of subsurface is expensive • High investment costs • Possible impact on groundwater quality • Feasible only for large capacity storage (> 200 000 m³) • Specific subsurface conditions required
5	ELSAR	• Higher energetic performance than that of a conventional high-rate anaerobic reactor (HRAR), thanks to higher H_2 content in biogas, which confers higher heat power of produced biogas • Higher robustness than HRAR under stress conditions. • High energetic efficiency and minimum sludge production, compared to aerobic wastewater treatments.	• More research needed to understand the processes of bioelectrochemical stimulation in detail to allow for accurate design and upscaling
5	ELSAR + AnMBR	• Combines optimal energetic performance with high treated water quality (tertiary grade) • Membranes help to retain the anaerobic biomass, optimising the biomass retention	• Further research on membrane fouling needed allowing OPEX minimisation and permeability optimisation. • For AnMBR inclusion: to be determined if extra CAPEX+OPEX delivers an economical advantage
5	SOFC	• Higher electrical efficiency compared to that of a conventional CHP • Simplicity in replacements • Probable lower OPEX than that for a CHP; modular technology • Simple and known biogas pre-treatment • Possibility to combine with Power-to-Gas / H_2 projects by means of SOFC.	• Lower heat efficiency than CHP. • FC market in the wastewater sector is still immature, still in the very early-adopter stage. SOFC references are rare and suppliers not always available. • Current EU policy, which promotes biomethane projects, does not contribute to FC implementation. • Currently higher CAPEX costs than CHP.

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CS	Techno-logy	Benefits	Challenges
6	AAT	• Protecting the WWTP, shaving the peaks of sudden discharge of high COD, and • increase the production of biogas leading to • saving in energy demand and • reduction of the sludge production	• Maximum OLR of OMW (OLR=3-4 kg COD/(m³*d)), that can be mixed with domestic WW (OLR=11 kg COD/(m³*d)) • Temperature of water above 18 C required → lower temperature is highly challenging.
6	AAT/AC/ AnMBR	• Same benefits as for AAT • Effluent quality is equivalent to secondary effluent in terms of organic matter.	• Cost-effectiveness of the membrane system should be assessed before implementation
7	RO filtration	• Increased temperature of the water through residual heat utilisation is shown to improve filterability and • hence reduce the pressure requirement (reduction in energy demand) or • the flux at a set pressure (reduction CAPEX)	• The increased temperature of the feed water may lead to increase salt passage and • hence a poorer effluent quality.
7	Ammonia stripping	• Increased temperature of the water through residual heat utilisation will improve the performance of the ammonia stripping system and/or • reduce the chemical usage for pH adjustment.	• The residual heat present in the effluent is not sufficient to make a significant impact and • additional heat from, for example, biogas (conversion in steam boiler or through CHP engine) will then be required
8	ORC	• Power generation, which could be used on-site	• The temperature of the hot sources is too low to reach the targeted electricity production yields
8	Heat pump	• Low pressure steam production	• To achieve the recovery rate target, a significant amount of steam must be produced and consumed. • As self-consumption isn't sufficient, it is necessary to find other consumers nearby. • The investments and operating costs required to produce this steam were not economically viable for CS8.

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CS	Techno-logy	Benefits	Challenges
9	Joint control system	• Increases energy efficiency of aeration in CAS of subsequent WWTP	• High dependency on real time data from sensors • Frequent maintenance of sensors required to produce reliable data

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3.2. Recommendations for best practice for the implementation and application of the technologies under different process conditions

Heat management related technologies

For the replication of the heat recovery, storage and reuse related ULTIMATE technologies, the requirements/recommendations are:

- Identify potential external customers for the energy produced by the recovery and storage system
- A suitable heat source to match (part of) the demand and that provides the right conditions for storage or recovery for reuse has to be found
- Sufficiently high supply heat quantities to make the storage and recovery cost effective
- Minimise distances between systems to avoid heat losses and maximise the benefit of increased temperature in each of the systems.
- Pipe and system insulation is critical to also avoid losses in colder climates.
- Evaluate the carbon impact of the solution implemented to ensure its overall environmental efficiency.
- Suitable hydrogeological conditions for storage of thermal energy with a sufficiently high recovery factor for economic operation
- Obtaining the permits for drilling to establish the HT-ATES can take a long time and should be started as early as possible

Heat recovery and direct reuse without heat storage is legally easy to implement. Only for the implementation of an ATES, a legal framework for licensing is still missing and should be developed and implemented. A legal framework would allow the responsible authorities to consider HT-ATES permit applications in a consistent manner. For the initiator of an HT-ATES system, the framework provides clarity about the boundary conditions obtaining a license. Currently, the permit procedure for an HT-ATES requires usually several years. We strongly suggest accelerating this procedure and to promote the demonstration of full-scale pilot systems in order to develop suitable policies and to show in practice that HT-ATES is a renewable, clean and safe technique. A further barrier for the replication of HT-ATES are the very expensive and time-consuming exploration methods such as test drillings to assess whether a subsurface is suitable for an HT-ATES. The use of a deepening drilling in combination with a geothermal drilling for subsurface exploration was very suitable to determine the suitability of the hydrological conditions for an HT-ATES. More research and demonstration projects are recommended to establish inexpensive, reliable and innovative technologies and their combinations in order to avoid uncertainties during planning of an HT-ATES and to accelerate the planning process.

Target sectors are heat producers such as geothermal plants, waste incineration plants, refineries and steel and concrete producing industries, which are spatially close

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to a potential end-user such as greenhouses, district heating, process industry needing low grade heat. The symbioses can be formed in different ways, depending on the stakeholders involved.

1) Setting up a cooperative with the specific task of providing the service, with cooperative members being the end-users of the heat (e.g. greenhouses), with as further possible members other parties, such as the heat supplier and/or a service provider
2) Setting up a separate company that is responsible for managing the HT-ATES and all associated activities,
3) Delegating the work to an existing service provider, e.g. the company in charge of district heating network in this case study.

Biogas production and valorisation related technologies

Even though different anaerobic treatment technologies were investigated such as the ELSAR, AAT and their combinations with a membrane such as the ELSAR/AnMBR and ATT/AC/AnMBR, the requirements for their operation and recommendations are similar:

- Equalised, between pH 6 and 8, warm, low-sulphate, biodegradable wastewater is essential for anaerobic processes.
- The collection and adequate storage of substrates with high organic content such as the OMW (proper and accessible storage tank) is essential.
- OMW contains inhibitory compounds such as polyphenols. Their accumulation can inhibit anaerobic microbial activity. A higher OLR of OMW than 3-4 kg COD/(m^3*d) additionally to mWW is a limiting factor for the biogas production performance. Gonzalez Camejo et al. (2024, D1.5) suggest, how to recover polyphenols from OMW to avoid microbial inhibition.
- Low temperatures (< 18 °C) during a long period as in wintertime can negatively affect the biogas production performance.
- When combining an anaerobic treatment (ELSAR or AAT) with a membrane (AnMBR), their separation is essential to ensure adequate performance and protection of the membrane unit from the anaerobic biomass and solids, because high TSS loads can significantly damage membranes.
- The higher the content in biodegradable COD, the higher the benefits vs. traditional aerated alternatives, in terms of OPEX and biogas profits. Hereby, it is important to pay attention to inhibitory substances and to investigate to what is the limiting concentration of them.
- The higher the prices of electricity, gas (or heat) or sludge treatment, the more attractive the anaerobic processes
- The acceptance of the technology by the stakeholders (e.g. Ministry of Environmental Protection and the Water Authority) is the main and crucial factor for its implementation.

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For biogas valorisation using a SOFC, the following aspects should be considered prior to its replication:

- A techno-economic market study for 60-250 kW FC is required to understand better the potential of SOFC solution.
- SOFCs are, like CHPs, solutions intended to produce electricity and heat from biogas. Public support to grid injection of biogas (in form of biomethane) can negatively influence the promotion of SOFC or CHP systems.
- Nevertheless, it is important to remark that injection of biogas is usually linked to landfills or to agri-food waste, and seldom to WWTP, where the biogas production potential is lower. Moreover, energetic self-sufficiency of large WWTPs is one of the mandatory requirements stated in the new draft WW EU directive. In such a context, self-consumption of biogas is a coherent and interesting strategy for WWTP operators. Therefore, SOFCs represent an opportunity for efficient energy obtention, energy that can be used in the WWTP processes, either in form of heat or in form of electricity.

To replicate biogas production and valorisation technologies in Europe, stable prices for upgraded biogas and electricity are needed at least for a period of five years to amortise the plant. Another five years would be beneficial, after an adaption on the energy market, to provide incentives to the investors. To bridge a potential gap between the guaranteed price and the actual market price, subsidies might be needed. A minimum quota for upgraded biomethane in the gas grid can further support the willingness of investors to implement biogas production technologies and upgrading units. A simplification of administrative formalities and financial support related to the gas grid connection can highly accelerate the implementation of biomethane producing technologies.

Target sectors are agro-food and beverage industries having wastewaters containing high loads of organic matter. Even sectors with challenging wastewater such as OMW containing inhibitory substances are suitable due to the very robust anaerobic treatment technologies. The ELSAR and also the AAT showed their capability of treating such wastewaters having high loads of organic matter, fluctuations in the OLR and/or containing inhibitory substances.

The symbiosis can be formed differently, depending on the stakeholders involved:

1) Setting up a partnership between the industry and an existing service provider such as a utility for wastewater treatment and/or a service provider to produce and supply energy
2) Setting up a separate company that is responsible for managing the biogas plant and all associated activities

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Joint control system to increase energy efficiency

For the replication of a joint control system at two connected wastewater treatment plants, the following requirements and recommendations should be considered:

- Trusting relationship and very good communication between both plant operators is essential
- Modelling provides valuable insights into optimisation potential of aeration system
- High reliability of real-time data through frequent maintenance and gradual alerts based on different measurements required
- COD/E and N/E are suitable indices to evaluate energy efficiency optimisation measures applied to WWTPs

The target sector is wastewater treatment and the symbiosis can be formed by the parties operating the WWTPs. A third party to operate the joint control system won't be necessary, because the knowledge, how to operate is already available among the WWTP operators.

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Annex

Supplementary results to

2.7 Feasibility study for heat recovery from flue gas washing water at the Chemical Platform Roussillon (FR)

Section 2.7.2 presents the business results of the **Heat recovery** study, obtained by SUEZ RR, as part of the French case study CS8. This section completes section 2.7.2 by presenting the technical results, obtained by 3S, concerning the configuration and integration of the ULTIMATE IT application, deployed as part of CS8. The design and functional specifications for the ULTIMATE application are presented in the subsection "*Design, IT development, configuration and test of a monitoring and control application (ULTIMATE IT application)*"

Connection to the ULTIMATE IT application

As already shown in the section 2.7.2, the ULTIMATE IT application is operational and can be accessed online for users for whom accounts have been created in advance (Figure 59). User accounts have been created for:

- **3S** to configure the ULTIMATE application and monitor its operation
- **SUEZ RR** to use the ULTIMATE application within the framework of the project and to identify anomalies, which were then communicated to 3S for correction

Figure 67 illustrates the data tree (measurements and calculated business indicators) of the ULTIMATE application. This data tree is common for the two CS8 studies: **Heat recovery** (see section 2.7 of this deliverable D1.4) and **Sulphur recovery** (see section 2.7 of deliverable D1.5).

Frame 1 is the list of all the parameters configured in the ULTIMATE IT application for the two studies Heat recovery and Sulphur recovery of CS8: the collected measurements (see icons) and the business indicators (see icons). These parameters are organised by type ("Bilan Matière" = Material Balance, Concentration, "Débit" = Flow, etc.).
Frame 2 is the list of all "Pressure" type parameters. The 4th column ("Type de source" = Source type) indicates whether each parameter is a collected measurement ("Acquisition") or a business indicator ("Computation").

Business indicators

This section illustrates some results obtained for the configuration of business indicators. All the business indicators for the **Heat recovery** study have been created and configured in the ULTIMATE application, in accordance with SUEZ RR requirements (see details in subsection "*b. Create and configure business indicators*").
Figure 68 shows the configuration of the business indicator "Chaleur récupérée sur

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E5525” (in English, “Heat recovered from E5525”), displayed in the widget in Figure 76.

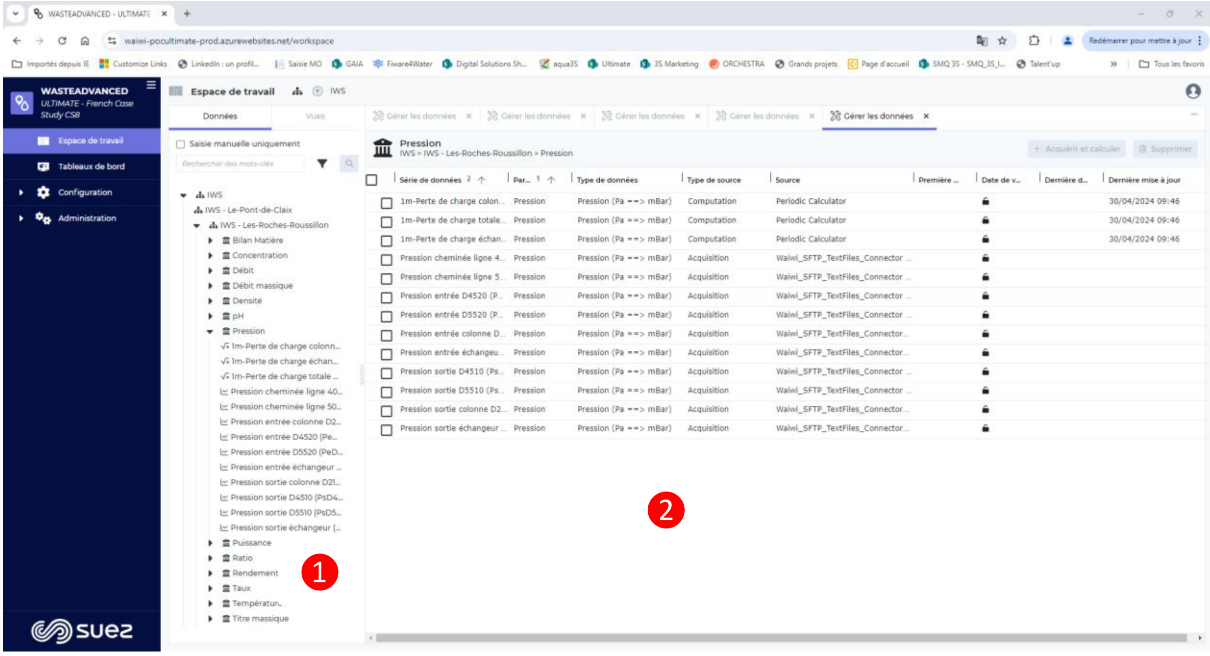

Figure 67 Data tree (measurements and calculated business indicators) of the ULTIMATE IT application

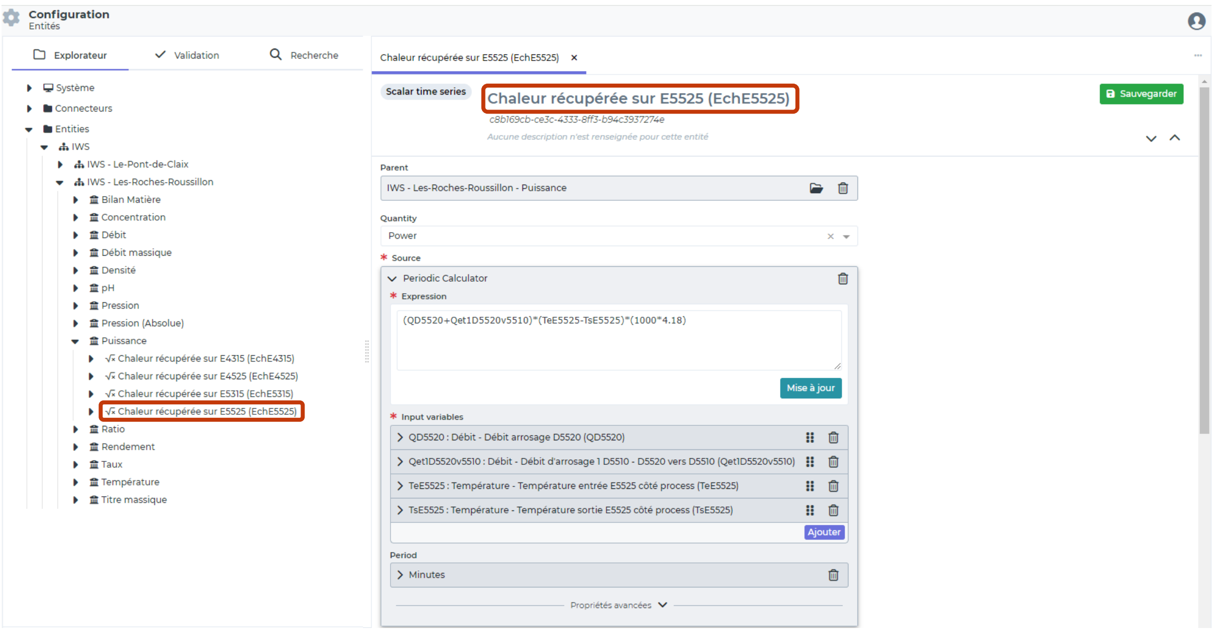

Figure 68 Configuration of the business indicator “Heat recovered from E5525”, displayed in the widget in Figure 76

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Figure 69 shows the display of the business indicator “Heat recovered from E5525”.

Figure 69 Display of the business indicator “Heat recovered from E5525”

Figure 70 shows the configuration of the input “Température entrée E5525 côté process” (in English, ”Input temperature E5525 on process side”), the 3rd of the 4 inputs required to calculate the business indicator “Heat recovered from E5525” in Figure 68.

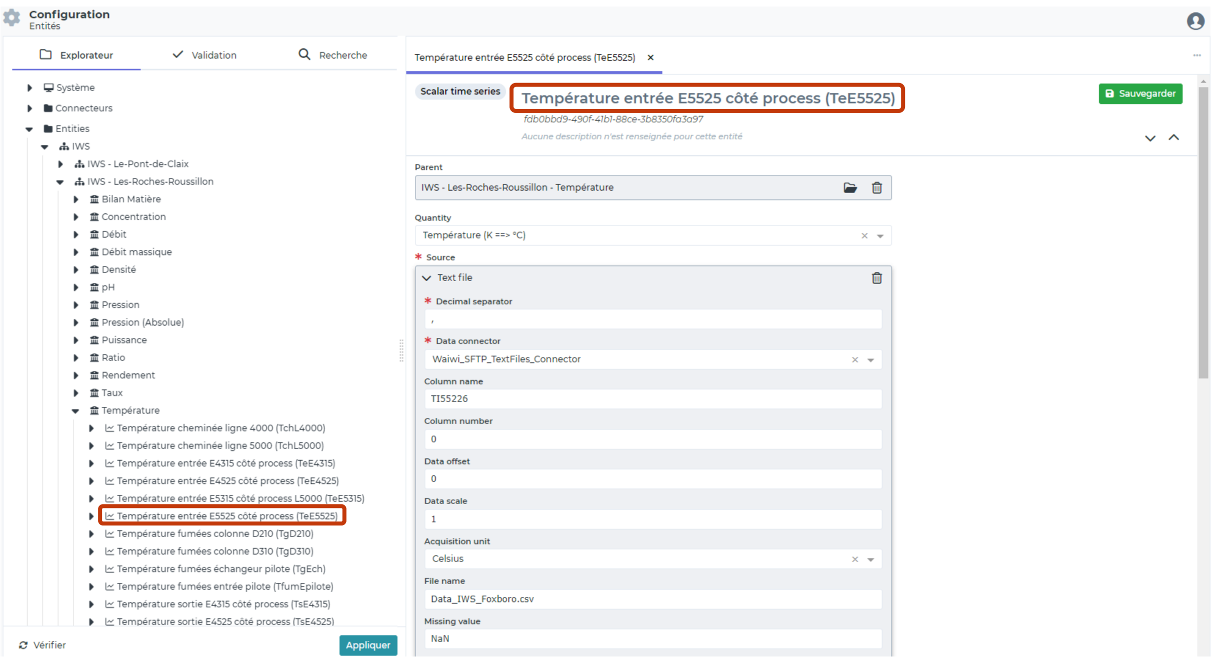

Figure 70 Configuration of the input “Input temperature E5525 on process side”, the 3rd of the 4 inputs required to calculate the business indicator “Heat recovered from E5525” shown in Figure 68

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Figure 71 shows the display of the input "Input temperature E5525 on process side", the 3rd of the 4 inputs required to calculate the business indicator "Heat recovered from E5525".

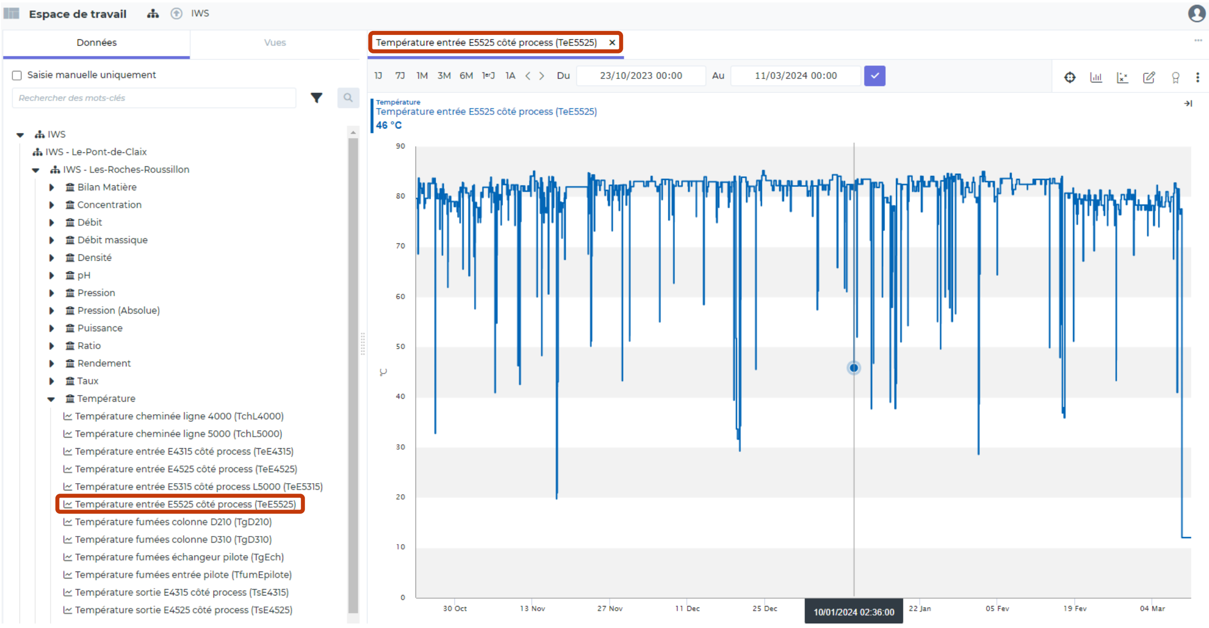

Figure 71: Display of the input "Input temperature E5525 on process side", the 3rd of the 4 inputs required to calculate the business indicator "Heat recovered from E5525"

Figure 72 shows the configuration of the business indicator "Chaleur récupérée sur E5315" (in English, "Heat recovered from E5315"), displayed in the widget in Figure 78.

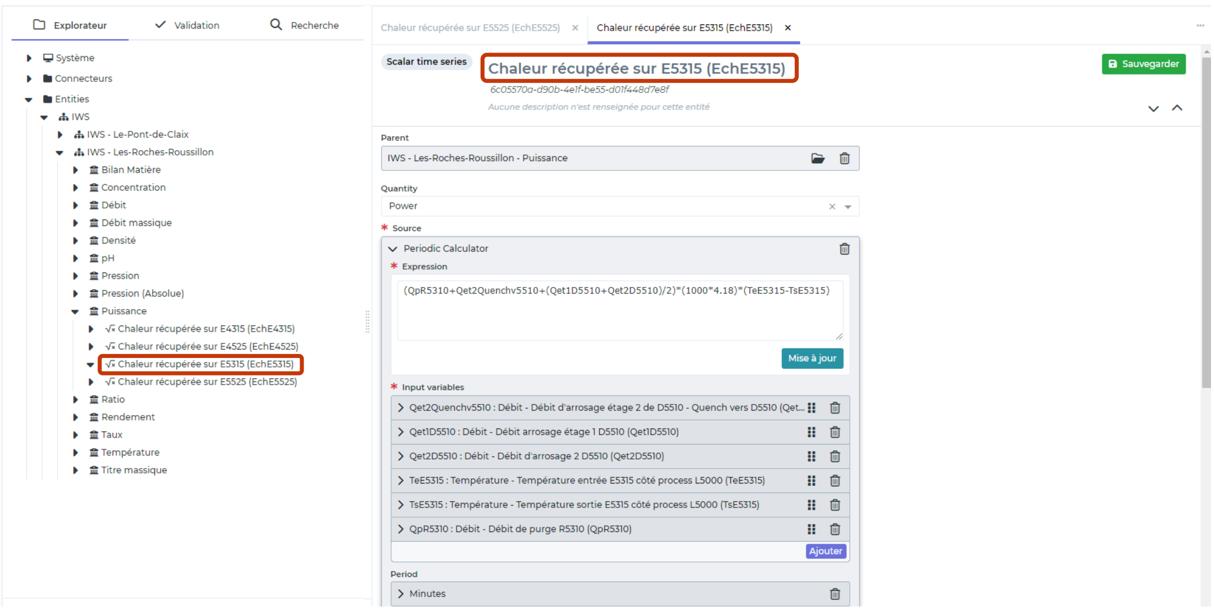

Figure 72 Configuration of the business indicator "Heat recovered from E5315", displayed in the widget in Figure 78

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Figure 73 shows the display of the business indicator “Heat recovered from E5315”.

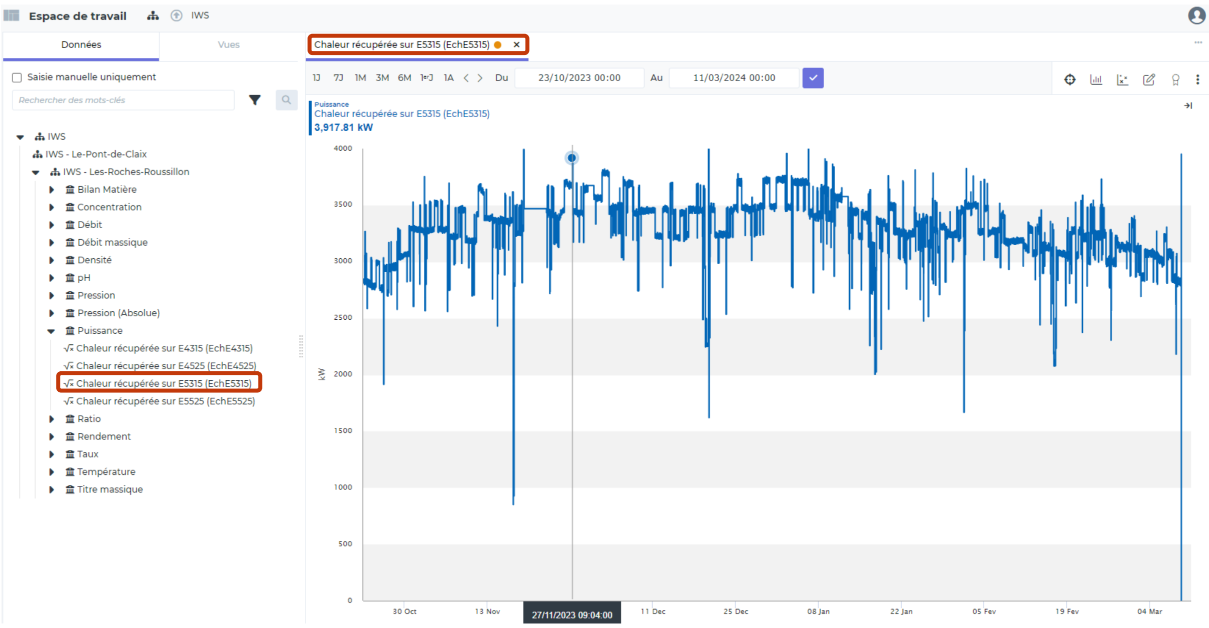

Figure 73 Display of the business indicator “Heat recovered from E5315”

Figure 74 shows the configuration of the input “Température entrée E5315 côté process” (in English,” Input temperature E5315 on process side”), the 4th of the 6 inputs required to calculate the business indicator “Heat recovered from E5315” in Figure 72.

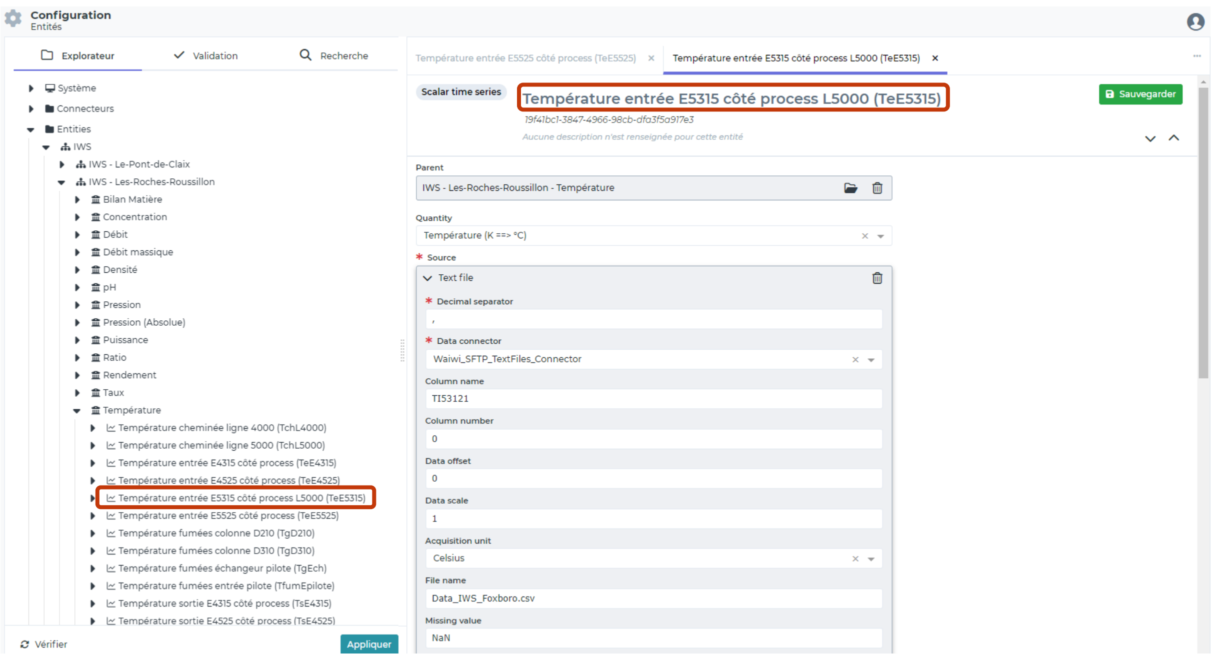

Figure 74 Configuration of the input “Input temperature E5315 on process side”, the 4th of the 6 inputs required to calculate the business indicator “Heat recovered from E5315” shown in Figure 72

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Figure 75 shows the display of the input “Input temperature E5315 on process side”, the 4th of the 6 inputs required to calculate the business indicator “Heat recovered from E5315”.

Figure 75 Display of the input “Input temperature E5315 on process side”, the 4th of the 6 inputs required to calculate the business indicator “Heat recovered from E5315”

Widgets

This section illustrates two of the four widgets configured in the ULTIMATE IT application, for the “CS8 **Heat recovery** study”. All the widgets for the heat recovery study have been created and configured in the ULTIMATE application, in accordance with SUEZ RR requirements (see details in subsection “*c. Create and configure widgets*”).

Figure 76 shows the widget entitled “Energie dispo sur colonne basique L5000” (in English, “Energy available on L5000 basic column”).
Figure 77 shows the parameter “Débit eau de refroidissement sur E5525” (in English, “Cooling water flow rate on E5525”), one of the 4 parameters displayed in the widget in Figure 76.
Figure 78 shows the configuration of the widget entitled “Energie disponible sur le quench L5000” (in English, “Energy available on the L5000 quench”).
Figure 79 shows the parameter “Débit eau de refroidissement sur E5315” (in English, “Cooling water flow rate on E5315”), one of the 4 parameters displayed in the widget in Figure 78.

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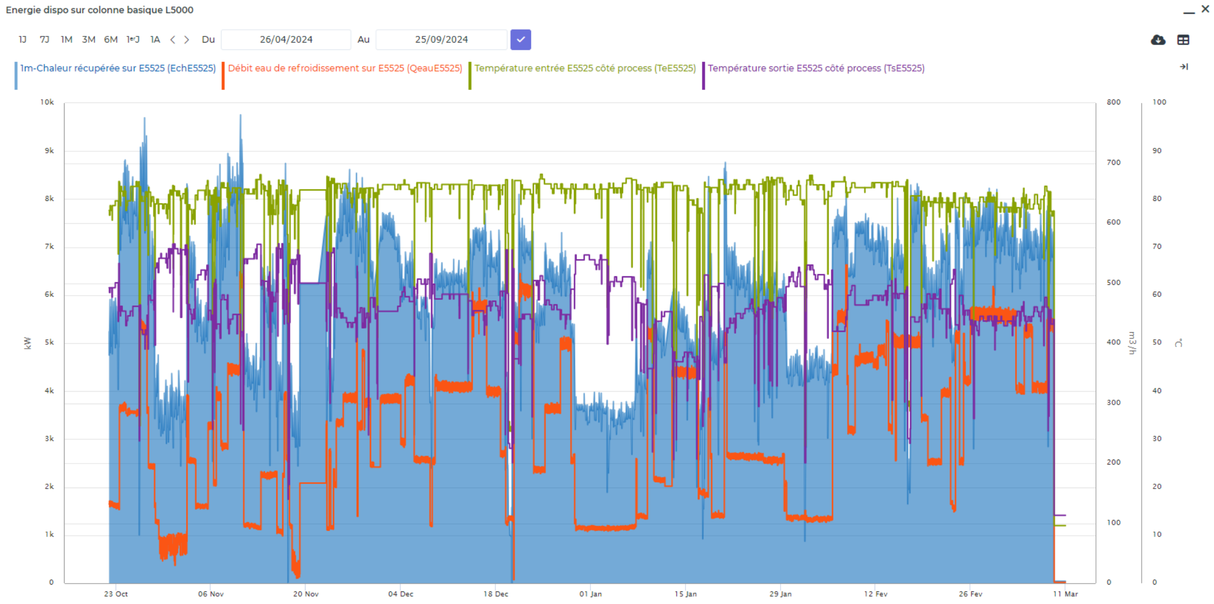

Figure 76 Widget “Energy available on L5000 basic column”

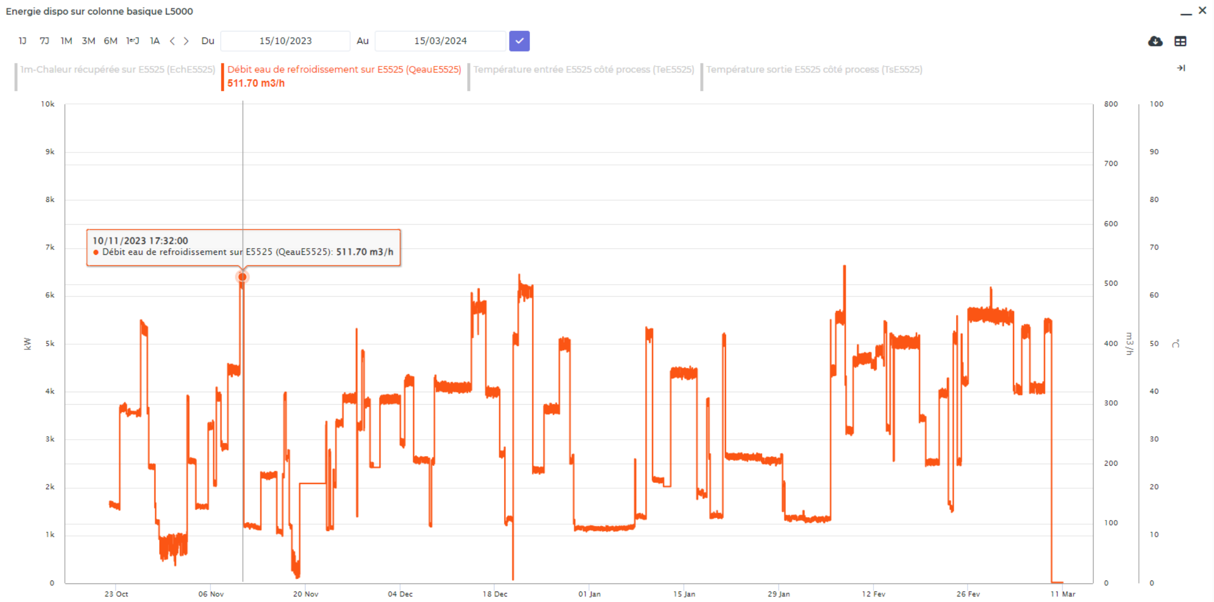

Figure 77 Parameter “Cooling water flow rate on E5525, one of the three parameters displayed in the widget in Figure 76

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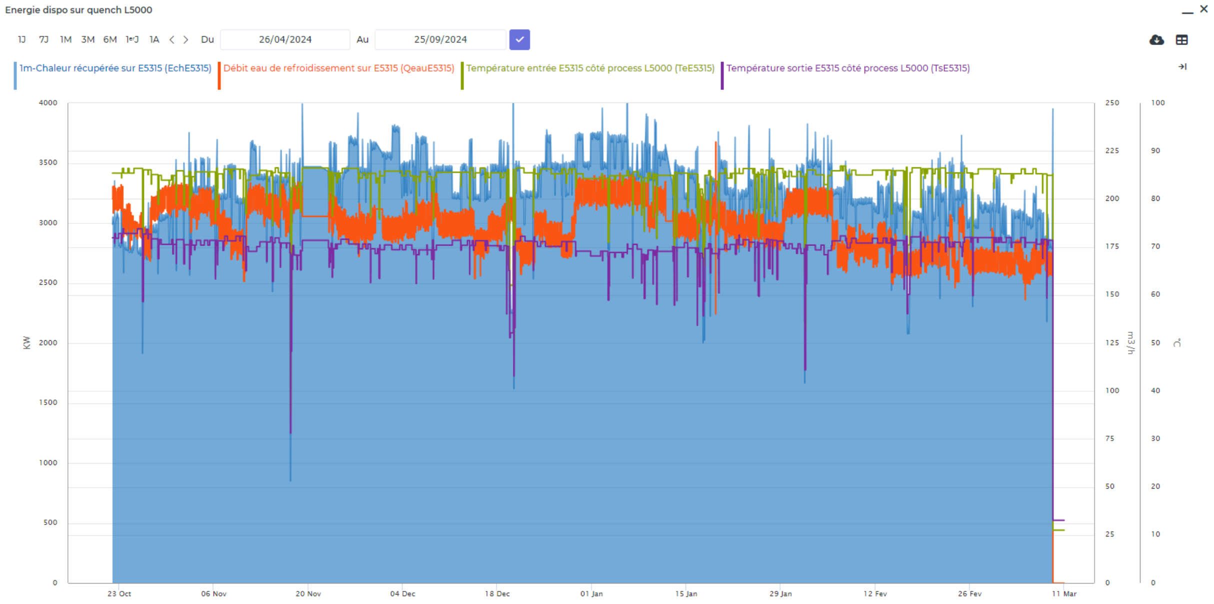

Figure 78 Widget "Energy available on the L5000 quench"

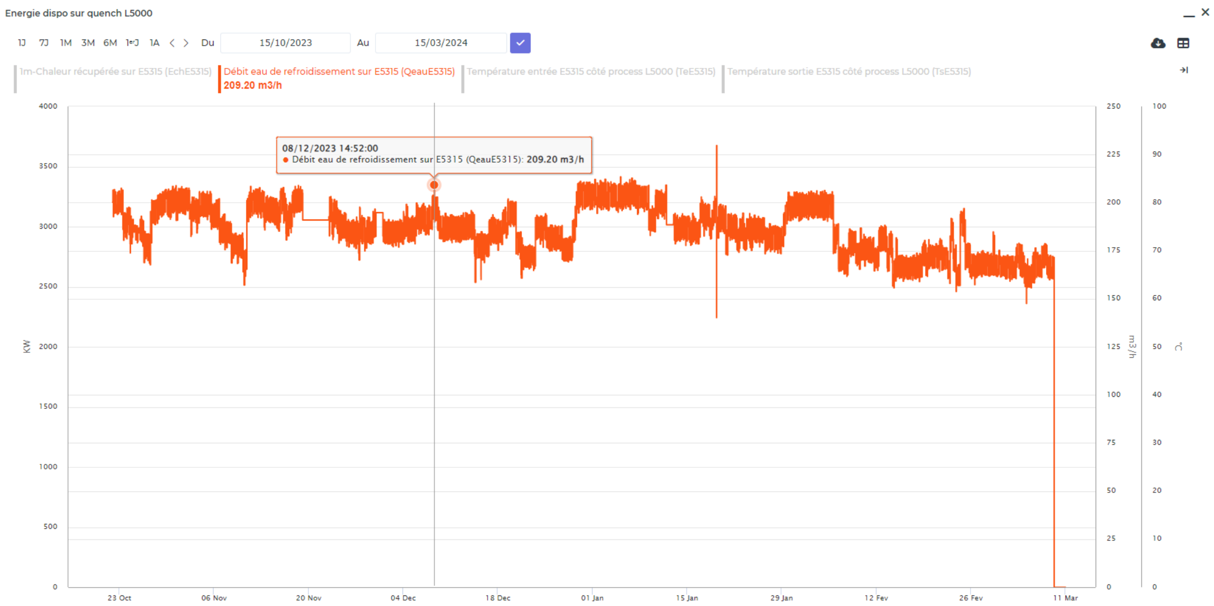

Figure 79 Parameter "Cooling water flow rate on E5315", one of the three parameters displayed in the widget in Figure 78

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