nextGen
Circular Water Solutions

New approaches and best practices for closing the energy cycle in the water sector

Deliverable D1.4

AUTHORS : JUNGEUN KIM, JAN HOFMAN, ISTVAN KENYERES, ERZSEBET POOR-POCSI, ANNE KLEYBÖCKER, JANINA HEINZE, FABIAN KRAUS, ANA SOARES, ELEONORA PAISSONI, PETE VALE, MATTHEW PALMER, MARTIN BLOEMENDAL, STIJN BEERNINK, STEVEN ROS, NIELS HARTOG, JOS FRIJNS

DATE : 14/11/2022

Technical References

Project Acronym	NextGen
Project Title	Towards a next generation of water systems and services for the circular economy
Project Coordinator	KWR
Project Duration	53 months

Deliverable No.	D1.4 New approaches and best practices for closing the energy cycle in the water sector
Dissemination level [1]	PU
Work Package	WP1
Task	1.3
Lead beneficiary	UBATH
Contributing beneficiary(ies)	UBATH, AVA, KWB, STW, UCRAN, BIOPOL, CHEM, NYUA, EYDAP, CoA, KWR, PZH
Due date of deliverable	30/11/2022
Actual submission date	18/11/2022

[1] PU = Public
PP = Restricted to other programme participants (including the Commission Services)
RE = Restricted to a group specified by the consortium (including the Commission Services)
CO = Confidential, only for members of the consortium (including the Commission Services)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

Document history

V	Date	Beneficiary/Author	Action
1	04.10.2022	UBATH et al., Kim et al.	Send to internal reviewer
2	07.10.2022	KWR/Jos Frijns	Internal review
3	18.10.2022	UBATH et al., Kim et al.	Revision
4	27.10.2022	KWB/Christian Remy	Send to external reviewer
5	07.11.2022	UBATH et al., Kim et al.	Revision
6	14.11.2022	QA	Feedback of QA → revision and final check
7	18.11.2022	UBATH et al., Kim et al.	Final version, Submission

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

Executive Summary

As a potential solution to better use water-embedded resources, the transition to circular water systems and services requires technology-focused approaches that can enhance a positive reception by organizations in the public, business and government sectors. NextGen focuses on water, energy and nutrients/material cycles in the water and wastewater sector to make them economically and environmentally attractive.

This report addresses new approaches and best practices for closing the energy cycle in the water sector. Five NextGen case studies developed and demonstrated a wide range of innovative energy recovery technologies/approaches: Athens (EL), Filton Airfield (UK), Braunschweig (DE), Spernal (UK) and Westland (NL).

There are three energy recovery practice categories: (1) heat recovery from wastewater and local reuse – Athens and Filton Airfield, (2) biogas production from wastewater or sewage sludge – Braunschweig and Spernal and (3) heat storage and recovery - Westland. We explore the innovative energy recovery technologies and approaches demonstrated in selected demo case studies to provide unique selling points, technical and operational guidelines and lessons learned. Table 1 presents a summary of the NextGen key results for energy recovery practices with their respective case studies and specific technologies and approaches.

(1) Heat recovery from wastewater and local reuse

Athens (EL) demonstrated a small-scale combined heat exchanger and heat pump system to use available excess heat from treated wastewater produced from a sewer mining unit as an energy source. Wastewater thermal energy recovery was successful scaled down from MW to kW scale using clean treated wastewater and commercially available heat pump making decentralised energy recovery technically and commercially feasible which also can be simple to operate. As shown in Table 1, the small-scale heat recovery system demonstrated in the Athens site was set up in the 1-10 kW range. Thus, this resulted in acceptable system efficiencies with coefficient of performance (COP) values in the range of 4.0-5.12 in the heating mode and energy efficiency ratio (EER) values between 3 and 4.85 in the cooling mode. Although these values were lower than the typical values, 4.4-8.25 for COP heating mode and 6.5-6.9 for EER cooling mode, the system had less biofouling potential due to the fact that the system used the treated wastewater as the source of thermal energy. In addition, considering a full-scale decentralized system (250 m^3/d irrigation water) the net recoverable thermal energy (heat pump energy use deducted) can be as much as 230 MWh/year. More than 67% of this energy recovery can be credited and used for general heating and/or cooling purposes (the remaining 33% is used for composting/nutrient recovery boosting). However, more studies on long-term operation under various feed quality conditions are required to improve its transferability and scalability as a sustainable urban water-energy solution.

In addition, Filton Airfield (UK) conducted a feasibility study on low-grade heat recovery from wastewater using a simulation-based approach analysing the potential of energy savings based on wastewater flow and temperature profiles. Housing units generating a large amount of wastewater held significant potential for energy recovery. The results showed that if the

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

wastewater discharge is cooled by 3 °C for heat recovery, it is possible to recover up to 38,788 kWh/y (i.e., 7.85% of the total energy demand for the study area) for the residential area consisting of conventional houses, indicating that the total heat recovery potential is highly dependent on wastewater flow rates (Table 1). In the frame of the Filton Airfield development, a decentralized and compact heat recovery system (i.e., a combination of a heat pump and heat exchanger demonstrated in Athens) would be one of the favourable solutions to increase self-energy efficiency if considering treated wastewater as a heat recovery source.

Although it has been shown that the treated wastewater is a valuable source of clean energy with significant potential to improve the energy efficiency in Filton, it is required to conduct further investigation and development: (a) how heat loss and user behaviour affect the performance of the energy recovery potential, (b) the applicability of a heat storage system (e.g., aquifer thermal energy storage) and (c) the effect of a scale of development area (e.g., densified housing plan and completion of development).

(2) Biogas production from wastewater or sewage sludge

The goal of the Braunschweig (DE) case was to enhance biogas production via thermal pressure hydrolysis (TPH) at the municipal wastewater treatment plant (WWTP). Thermal pressure hydrolysis was performed as a pre-treatment of digestion, resulting in higher biodegradation during digestion. Correspondingly, the methane production rate increased on average by a factor of 1.2. Also, the dewaterability of the digestate increased by a factor of 1.1. This contributed to the additional use of biogas for steam production for the TPH and to generate more heat and energy via the combined heat and power (CHP) plant. Hence, the heat supply from external sources decreased from 106 to 17 kWh/year by 84% and the electricity production increased from 9,000 kWh/year to 9,800 kWh/year by 8%. More importantly, the dewatering efficiency of the digestate increased on average by 10% due to the higher biodegradation of the thermally hydrolysed sludge (Table 1). In this regard, it should be noted that only 42% of the organic load to the second digestion stage was pre-treated via the TPH. Such improvement resulted in the increased methane production rate by 20%. In addition, the increased temperature of one digester (from 38 °C to 55°C) was associated to the higher methane production rate, indicating that the technical feasibility of the TPH system has been successfully demonstrated during the NextGen project.

Furthermore, decentralized energy recovery from an anaerobic membrane reactor (AnMBR) combined with a methane degassing system was tested at the Spernal wastewater treatment plant (UK). The membrane degassing system demonstrated in Spernal can potentially recover methane from the AnMBR effluent to a dissolved methane concentration of 0.14 mg/L from an initial concentration of 20 mg/L (99% removal, designed values). The membranes are designed to operate at 2 Nm^3/h gas at 60 mbar. In addition, liquid ring vacuum pump technology was chosen to generate the vacuum. This system has several benefits, including the potential for energy neutrality, compact size with a low carbon footprint and low operation costs. The energy production on the Spernal demonstrator originates from the biogas produced in the anaerobic membrane bioreactor (AnMBR). On average the biogas yield recorded was 0.15 m^3 CH_4/kg COD removed, this includes the dissolved methane part of the biogas production. As presented in Table 1, two scenarios were considered: (a) generation

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

of electricity and heat via CHP and (b) upgrading of biogas for grid injection. Based on the scenarios, the theoretically recoverable energy was estimated for a capacity of 200 m^3/day (i.e., AnMBR effluent as a feed). Thus, it was expected to produce 44 kWh/day electricity and ~ 50kWh heat/d (assuming around 15% losses) for scenario (a) and 108 kWh/d of biogas for scenario (b). However, during the NextGen project, the methane degassing system has not been capable of recovering dissolved methane from AnMBR effluent that can be used as an energy source. This was mainly due to the influent wastewater quality, in particular sulphate. At present, the methane degassing system is given more attention by engineers/operators to reach higher TRL.

(3) Heat storage and recovery

A high-temperature aquifer thermal energy storage (HT-ATES) system was explored in the Westland region (NL) to store residual heat that can be used for the heat demand of horticulture companies. The results showed that there is sufficient residual heat available and that the aquifers are suitable for the application of ATES systems to store the heat. Residual heat in the Province of South Holland could contribute 100% of the heat demand of the horticulture companies in Westland. ATES systems can secure 10-15 PJ seasonal storage, which is sufficient for 10-15% of the annual total energy demand. The currently expected number of geothermal wells combined with HT-ATES can meet about 5% of the heating demand of the horticulture cluster Polanen. The performance of the HT-ATES system at Koppert Cress in the current situation shows that, although the heat recovery factor for the warm well is good (0.7-0.95, the expected value was 0.89 as shown in Table 1), the heat demand is not reached. The expected future addition of a geothermal heat source can provide in the required amount of extra heat. Large scale adoption of HT-ATES in the Westland could potentially save ~250 Mm^3 natural gas per year, which reduces the greenhouse gas (GHG) emissions with ~500 kt per year. The case study concluded that at the individual project/site level HT-ATES is technically, legally and financially feasible. The experiences of applying ATES at high temperatures illustrated the potential of HT-ATES by show-casing the increase in energy performance and CO_2 emission reductions of the greenhouse of the horticulture company Koppert Cress.

In conclusion, energy recovery technologies in NextGen were successfully demonstrated at different scales from city to regional levels. NextGen energy recovery technologies for the circular economy have proven the potential to improve energy infrastructure efficiency and reduce environmental damage and economic loss. Thus, they are promising starting points for exploring socio-technical aspects in other cities or regions.

Table 2 presents the main benefits and challenges of NextGen energy recovery technologies. The findings obtained during the NextGen project highlighted limitations to broader implementation as there were techno-economic challenges to expanding their applicability and scalability. Thus, there is a need to provide more practical ways to the transferability and scalability of the NextGen energy recovery technologies to apply at other sites. Future recommendations to maximise energy recovery linked to the water cycle are as follows:

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement N°776541

- ✓ More studies with direct attention to list techno-economic specifications should be performed to clearly highlight the advantage of energy recovery and reuse over conventional technologies in the future with the increasing cost of traditional energy sources.

- ✓ Further clarification on key features in relation to technical issues for long-term operations, monitoring and maintenance should be investigated and discussed between operators, developers, property owners and public and private organisations.

- ✓ In this context, further research should focus on generating economic, social and environmental benefits to support policy and regulatory frameworks and provide deeper insight into the reuse of heat recovered from wastewater or sewage sludge provides energy savings.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

Table 1 Overview about the NextGen technologies/approaches for energy recovery.

Case study	Sub task	Technology	Section	TRL	Purpose of the recovered energy	Inflow flow rate/capacity	Expected energy recovery values	Remark
Athens (GE)	1.3.4	Heat exchanger and heat pump	2.1	6 → 7	Boost Composting unit operation + office heating/cooling/showers	Inflow 25 m^3/day/ 1- 10 kW	Small-scale heat recovery system efficiency - COP heating: 4.0-5.12 - EER cooling: Min. 3-4.85	Small-scale prototype operation approx. 33% of the recovered energy is used to boost com composting the 67% can be credited for office heating/cooling/warm water
Filton Airfield (UK)	1.3.1		2.2	9	Domestic use-space and water heating	41 m^3/day	38,788 kWh/year recovered (theoretical)	Simulation-based study - 113 residential units - Theoretically estimated value by assuming the cooling temperature of 3 °C → 38,788 kwh/year recoverable energy (7.85% of the total energy demand of 463,300 kwh/year) can be credited.
Braunschweig (GE)	1.3.2	Thermal hydrolysis and two-stage digestion	3.1	9	Reuse within the WWTP: Digestion, CHP and buildings	Feed with dry matter 10-13% of wet weight	Increase in biogas production: 20%	Full-scale operation
Spernal (UK)	1.3.3	Decentralized energy recovery and usage from anaerobic MBR	3.2	7	Reuse within the WWTP or export of electricity or biomethane to grid.	200 m^3/day	Electricity & heat produced for the two scenarios: 1.CHP-electricity and heat: 44 kWh/day and ~ 50kWh heat/d (assuming around 15% losses) 2. Biogas upgrading: 108 kWh/d	Pilot scale operation Biomethane to grid would require additional upgrading technology to be deployed.
Westland (NL)	1.3.5	Aquifer thermal energy storage	4.1	4 → 6	Heating demand for horticulture	4200 MWh/y charged, and 3750 MWh/y discharged	Heat recovery factor: 0.89	Regional scale operation HT-ATES with 4 wells

*CHP – combined heat and power, COP – coefficient of performance, EER – energy efficiency rate, HT-ATES – High temperature aquifer thermal energy storage.

Table 2 Benefits and challenges of the NextGen technologies/approaches for energy recovery.

	Case study	Technology/ Approach	Benefits	Challenges
(1) Heat recovery from wastewater and local reuse	Athens (GE)	Heat exchanger and heat pump	- Small, decentralised system - Easy to operate - Competitive capital cost - Return on investment can be less than 1 year	- Relatively low coefficient of performance (COP) values (4.0-5.12) - Requirement of high treated water quality with very low suspended solid content
	Filton Airfield (UK)	Feasibility study of low-grade heat recovery and local reuse	- Provide practical insight on the applicability of local heat recovery and reuse	- Require more accurate data collection to simulate wastewater profiles, flow rates and temperature - Heat storage required to overcome temporal variations of heat availability and demand
(2) Biogas production from sewage sludge	Braunschweig (GE)	Thermal hydrolysis and two-stage digestion	- Higher biodegradation and enhanced biogas production - Better dewaterability of digest and reduction of disposal costs	- High maintenance technology - Risk of methane leakages - Performance efficiency is sensitive to temperature
	Spernal (UK)	Decentralised energy recovery from anaerobic membrane bioreactor	- Great potential for energy neutrality - Low carbon footprint - Compact system	- Use of energy for UF and degassing and cleaning chemicals - Complex to operate - High capital cost
(3) Heat storage and recovery	Westland (NL)	Aquifer thermal energy storage	- Energy saving potential and low greenhouse gas emissions - Optimal utilization of available heat, overcoming temporal discrepancy between demand and availability	- Require presence of suitable aquifers - Require extensive monitoring to increase efficiency and counteract possible imbalances and interference

Acronyms

AnMBR	Anaerobic Membrane Reactor
ATES	Aquifer Thermal Energy Storage
BNR	Biological nutrient removal
BOD	Biological oxygen demand
CAPEX	Capital expenditure
CE	Circular economy
CHP	Combined heat and power
CIP	Clean in place
COD	Chemical oxygen demand
COP	Coefficient of performance
DS	Dry solids
DSEAR	Dangerous Substances and Explosive Atmospheres
DTS	Distributed temperature sensing
EER	Energy efficiency rate
FOG	Fat, oil and grease
GHG	Greenhouse gas
HF	Hollow fibre
HRT	Hydraulic retention time
HT	High temperature
IEX	Ion exchange
KPI	Key performance indicator
LCA	Life cycle assessment
LT	Low temperature
MBR	Membrane bioreactor
MCU	Membrane contactor unit
N	Nitrogen
ORP	Oxidation reduction potential
P	Phosphorous
PE	Population equivalent
RCB	Rapid composting bioreactor
RO	Reverse osmosis
SD	Standard deviation
SRB	Sulphate reducing bacteria

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

SRT	Solids retention time
SWMM	Storm water management model
TPH	Thermal pressure hydrolysis
TMP	Transmembrane pressure
TN	Total nitrogen
TP	Total phosphorous
TS	Total Solids
TSS	Total Suspended Solids
UASB	Upflow anaerobic sludge blanket reactor
UF	Ultrafiltration
UV	Ultraviolet
UWWTD	Urban wastewater treatment directive
VFAs	Volatile fatty acids
VS	Volatile solids
VSS	Volatile suspended solids
WFD	Water framework directive
WP	Work package
WW	Wastewater
WWHR	Wastewater heat recovery
WWTP	Wastewater treatment plant

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

Disclaimer

The authors of this document have taken all possible measures for its content to be accurate, consistent and lawful. However, neither the project consortium as a whole nor individual partners that implicitly or explicitly participated in the creation and publication of this document hold any responsibility that might occur as a result of using its content. The content of this publication is the sole responsibility of the NextGen consortium and can in no way be taken to reflect the views of the European Union.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement N°776541

Table of Contents

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement N°776541

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement N°776541

List of Figures

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement N°776541

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

List of Tables

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

1. Introduction

The aim of the NextGen project is to develop and demonstrate innovative circular economy solutions and systems in the water sector. The exploitation of techniques and technologies will produce new approaches to enhance our ability to close a wide range of water-embedded resources - water, energy and material cycles as illustrated in Figure 1.

NextGen includes ten demonstration cases across Europe. Ten case studies developed and demonstrated a wide range of innovative circular economy technologies - Braunschweig (DE), Costa Brava (ES), Westland (NL), Altenrhein (CH), Spernal (UK), La Trappe (NL), Gotland (SE), Athens (EL), Filton Airfield (UK) and Timișoara (RO).

NextGen demonstrated the cycles of water, energy and nutrients/material. This report, deliverable D1.4, presents the results from the technological work package (WP1) focusing on the energy cycle in the water sector. Details on tasks related to the water and material cycles can be found in *D1.3 New approaches and best practices for closing the water cycle* (Plana Puig et al. 2022) and *D1.5 New approaches and best practices for closing materials cycle in the water sector* (Kleyböcker et al. 2022). Moreover, *D1.8 Greenfield implementation in Filton Airfield*, presents the results from a feasibility study at a district level to develop the area into a showcase in urban development for the UK. In addition, further detailed information on the results and approaches is available in *D1.7 Technology Evidence Base final version* and a non-official deliverable per case study via the Water Europe Marketplace at the case study section: https://mp.uwmh.eu/l/CaseStudy/. The environmental and economic assessments of the circular water technologies are presented in the WP2 deliverables D2.1 and D2.2.

This deliverable D1.4 offers a wide range of NextGen innovative technologies related to energy recovery demonstrated in four case studies and one feasibility study on the recovery of low-grade heat potential from domestic wastewater:

- Sub-Task 1.3.1 Local heat and energy recovery from wastewater (Filton Airfield)
- Sub-Task 1.3.2 Internal heat usage and heat management for two-stage digestion and sludge hydrolyses (Braunschweig)
- Sub-Task 1.3.3 Decentralized energy recovery and usage from anaerobic MBR (Spernal)
- Sub-Task 1.3.4 Flexible decentralized energy recovery for non-permanent settlements (Athens)
- Sub-Task 1.3.5 Aquifer Thermal Energy Storage (Westland)

The case-specific results of each technology and their approaches to energy management support the applicability of those technologies. D1.4 compares the baseline status of the case to the NextGen results obtained from all activities for recovering energy and heat intrinsically linked to the water and addresses lessons learned and best practice guideline for operating technologies including challenges and recommendations for future implementation. Table 3 describes an overview of energy recovery technologies and circular economy approaches

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

demonstrated in the NextGen demo cases. Detailed information about the baseline conditions of all case studies can be also found in *D1.1 Assessment of baseline conditions for all demo cases* (Kleyböcker et al. 2019).

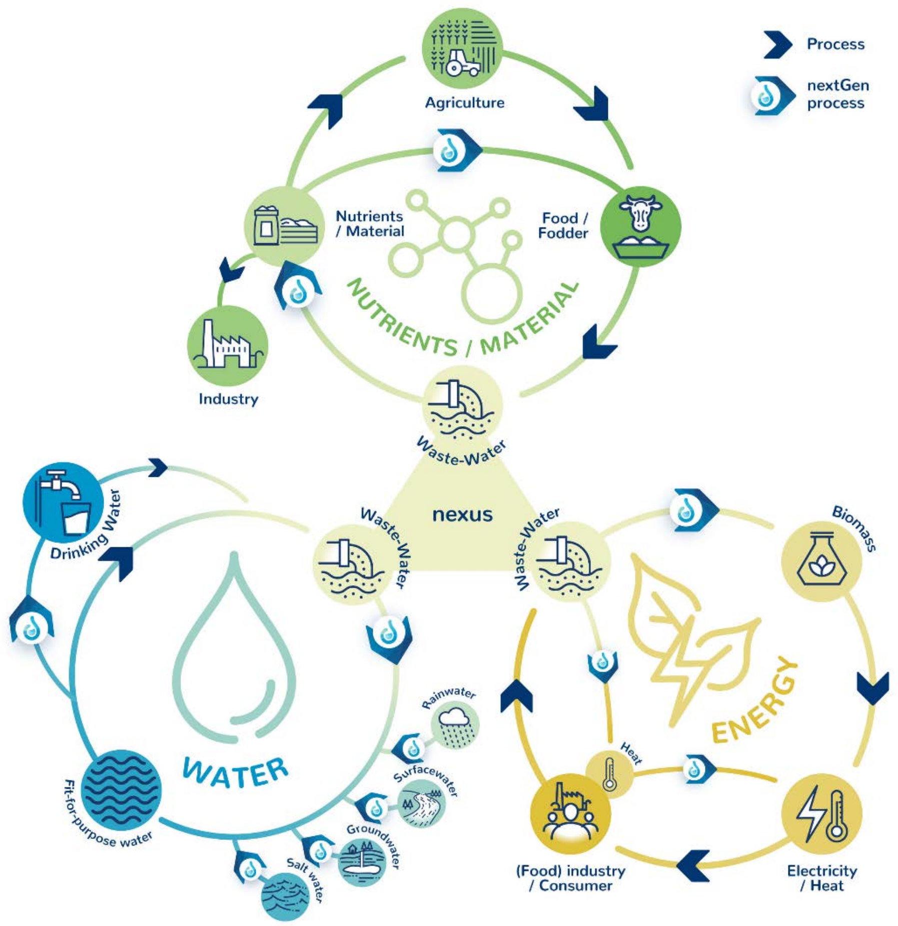


Figure 1 Infographic representing the cycles of water, energy and nutrients/material to be closed by the circular economy related technologies developed and demonstrated in NextGen.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

Table 3 Overview about the NextGen technologies/approaches for energy recovery.

Case study	Sub task	Technology	Section	TRL	Purpose of the recovered energy	Inflow flow rate/capacity	Expected energy recovery values	Remark
Athens (GE)	1.3.4	Heat exchanger and heat pump	2.1	4 → 6	Boost Composting unit operation + office heating/cooling/showers	Inflow 25 m^3/day/ 1- 10 kW	27,600 kWh/year System efficiency - COP heating: 4.0-5.12 - EER cooling: Min.3-4.85	Small-scale operation approx. 33% of the recovered energy is used to boost com composting the 67% can be credited for office heating/cooling/warm water
Filton Airfield (UK)	1.3.1		2.2	9	Domestic use-space and water heating	41 m^3/day	38,788 kWh/year recovered (theoretical)	Simulation-based study - 113 residential units - Theoretically estimated value by assuming the cooling temperature of 3 °C → 38,788 kwh/year recoverable energy (7.85% of the total energy demand of 463,300 kwh/year) can be credited.
Braunschweig (GE)	1.3.2	Thermal hydrolysis and two-stage digestion	3.1	9	Reuse within the WWTP: Digestion, CHP and buildings	Feed with dry matter 10-13% of wet weight	Increase in biogas production: 20%	Full-scale operation
Spernal (UK)	1.3.3	Decentralized energy recovery and usage from anaerobic MBR	3.2	7	Reuse within the WWTP or export of electricity or biomethane to grid.	200 m^3/day	Electricity & heat produced for the two scenarios: 1.CHP-electricity and heat: 44 kWh/day and ~ 50kWh heat/d (assuming around 15% losses) 2. Biogas upgrading: 108 kWh/d	Pilot scale operation Biomethane to grid would require additional upgrading technology to be deployed.
Westland (NL)	1.3.5	Aquifer thermal energy storage	4.1	4 → 6	Heating demand for horticulture	4200 MWh/y charged, and 3750 MWh/y discharged	Heat recovery factor: 0.89	Regional scale operation HT-ATES with 4 wells

*CHP – combined heat and power, COP – coefficient of performance, EER – energy efficiency rate, HT-ATES – High temperature aquifer thermal energy storage.

2. Heat recovery from wastewater and local reuse

2.1. Thermal energy recovery via heat exchanger and heat pump system in Athens (EL)

Authors: István Kenyeres (Biopolus), Erzsébet Poór-Pócsi (Biopolus)

2.1.1. Description of the demo site

Athens is a city of 4 million citizens; thus it suffers from urbanization issues such urban heat island effects, high cooling energy demands in the summer due to extreme heat events, and emerging water scarcity issues. The Athens demo application is located in an area called Athens Plant Nursery, which is part of the Goudi Park, an area in the process of redevelopment and regeneration to become one of the key Metropolitan parks of the capital. The area, which lies in the heart of Athens, is a mixed-use area, comprising of urban green and urban agriculture spaces as well as administration and residential uses. The regeneration is an effort to boost both the local economy and improve quality of life for the citizens of the Attica Region.

The Plant Nursery belongs to the Municipality of Athens and covers an area of approximately 39 ha, of which 16 ha are used in the production, development and maintenance of the plants, while the rest is used for general purposes such as administration building and offices of the Municipality of Athens. The Nursery supplies all urban parks and green spaces of Athens with plant material and uses potable water from Athens's Water Supply and Sewerage Company (EYDAP) for its irrigation. Furthermore, the nursery operates as a collection point for all pruning waste of all Athens urban green spaces, from where the waste is gradually transferred to the Athens landfill. At the same time, the Nursery uses fertilizers supplied by the local market. With regards to the energy needs, electrical power supply comes from the urban grid and heating is oil-based. In this respect, the city seeks alternative water sources to achieve environmental, social and financial benefits to address the water scarcity matters through autonomous and decentralized water systems.

2.1.2. Motivation of implementing circular economy solutions

The summers in Athens are hot and dry. Recent study(Founda et al., 2022) shows increasing tendency towards drier conditions, with increased variability of extreme rainfall events (periods of draught and flash flooding). Overall, Athens is becoming increasingly drier as precipitation is expected to decrease as longer dry spells and reduced rainfall intensity has been observed. With the longer, hotter, drier summers, green areas are more important than

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

ever to reduce the urban heat island effect. Lush green parks also create a positive environment for both the citizens and the local wildlife. Access to blue green urban spaces has positive effects on the mental and physical health of urban citizens. The green spaces also offer shelter for wildlife. However, green areas require both water and nutrients to remain healthy and vibrant. Athens currently lacks adequate nutrient rich soil, and the reduced rainfall and drier conditions mean more irrigation to keep green areas lush.

The Athens NextGen solution demonstrates how wastewater can be extracted locally from sewers to be treated and further processed. The system uses sewer mining, heat recovery, and rapid composting to create valuable sustainably sourced resources, which can be used to nurture Athens green spaces. The decentralised heat recovery unit can recover heat for use to boost the rapid composting unit, and it can be used for heating and cooling local buildings and/or greenhouses. The solution is in line with the Athens Resilient Strategy for a circular approach to water services by 2030.

2.1.3. Actions and case study objectives

The main objective of the Athens demo case is the demonstration of thermal energy recovered from urban wastewater via a heat exchanger and heat pump system to test commercially available heat pump system for small scale with a capacity of 10 kW. Table 4 summarises actions and objectives of the Athens case study.

Table 4 Actions and objectives of the case study in Athens.

Case Study number & Name	**#8 Athens, Greece**
Subtasks	Sub-Task 1.3.4
Technology baseline	Thermal energy is recovered from treated wastewater via heat exchanger & heat pump system
NextGen intervention in circular economy for water sector	Test and use commercially available heat pump equipment for small scale, readily available decentralized heat recovery for competitive integrated circular systems.
TRL	TRL 6 → 7
Capacity	10 kW
Quantifiable target	Thermal energy recovered and used to cover technology processes as well as thermal need of the nursery (*e.g.,* buildings, greenhouses)

2.1.4. Unique selling points

The NextGen solutions work to replace existing value chains (drinking water & fertilizer) with upcycled waste chains (green waste, wastewater, and sludge) to create a circular and sustainable solution for Athens green spaces.

Unique selling points for the implementation of the heat recovery unit are:

- ✓ Considerable amount of thermal energy can be recovered from wastewater both for general purposes (heating and cooling of spaces, warm water for showers) and also for

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

technology purpose, like boosting rapid composting during start-up and spring/autumn time.

- ✓ Using treated wastewater (high quality effluent from **membrane bioreactor,** MBR) reduces both corrosion and biofouling risks for energy recovery that is both simple and very cost competitive both in terms of investment and operational costs.
- ✓ The implemented solution can efficiently work even in small scale, which makes possible decentralized and integrated water, energy and nutrient recovery solutions viable and competitive.
- ✓ The implemented thermal energy recovery solution makes possible the use of commercially available mass-produced heat pump equipment, which can speed up the spread and acceptance of the technology.

As general benefits and selling points

- ✓ The citizens of Athens shall benefit from greener parks and spaces.
- ✓ Blue/green spaces have a positive effect on human health and wellbeing.
- ✓ These green areas have positive effects on climate change resiliency and help reduce urban island effects, making the Plant Nursery and similar green areas increasingly important in urban planning.
- ✓ Circular solutions that produce valuable resources from waste help promote a shift in people's mindsets regarding the need for a transition to circular economy.

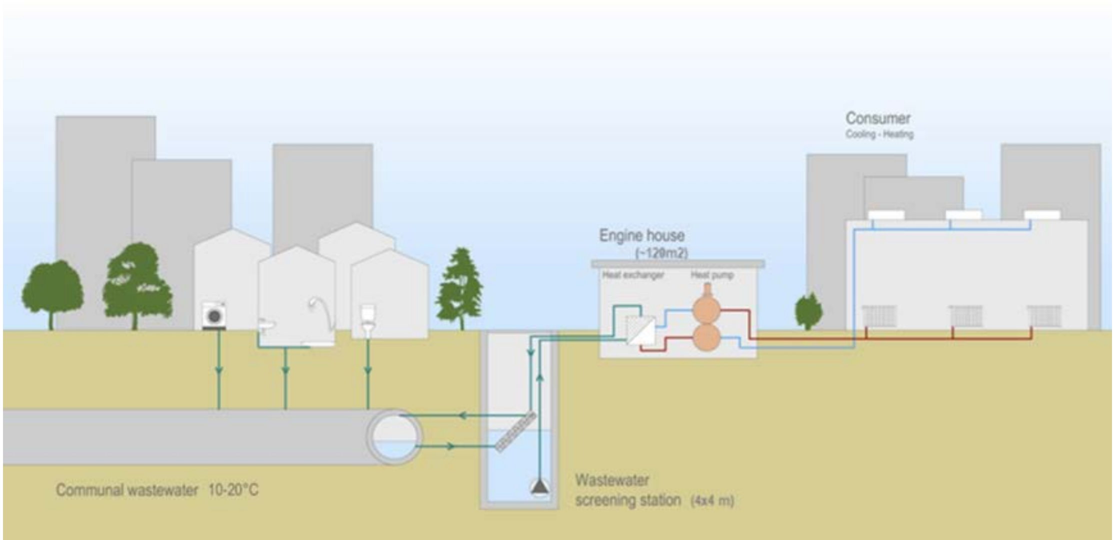
2.1.5. Principal and main characteristics of the technology

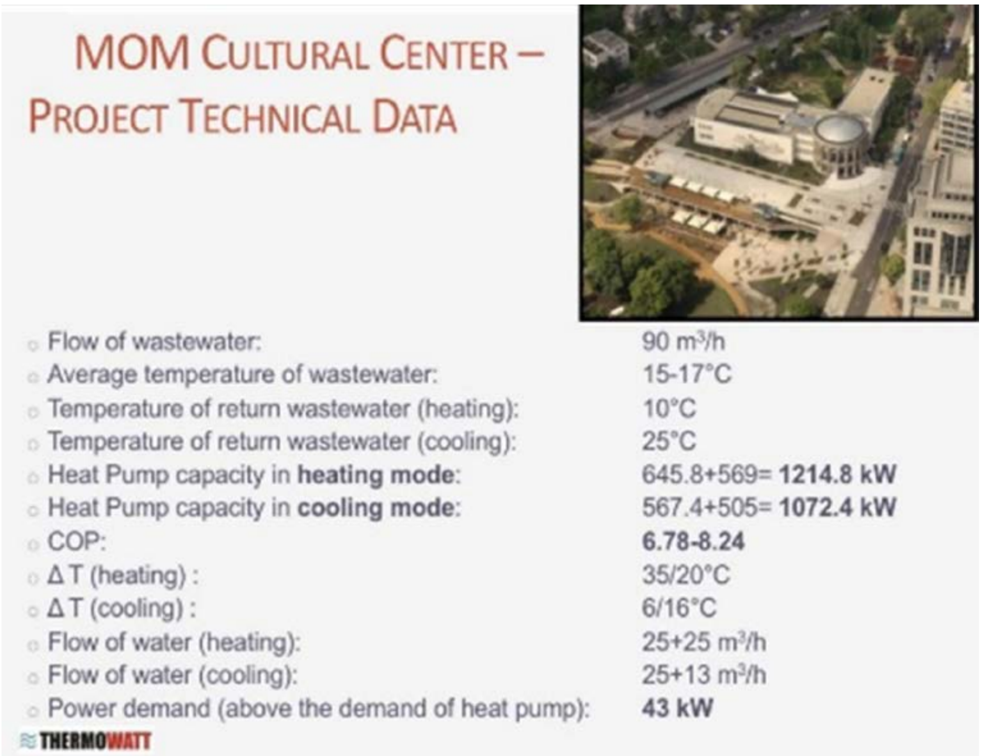
It is well known that municipal sewage contains considerable amount of thermal energy, which - unless it is properly recovered - is literally going down the drain. Typically, the wastewater from 10,000 people (200 L/day/ person wastewater production, with a 5°C temperature difference) carries a calculable estimated recoverable thermal energy of approximately 0.5 MW, which can be efficiently used either for heating or cooling.

Current state-of-the-art of thermal energy mining from sewers is typically performed using centralized facilities in the order of magnitude of 1 to 10 MW capacities, usually built at large diameter collection pipes running close to large institutional facilities (hospitals, shopping malls, office parks), where recovered energy can be the best utilized. Once example of a successful centralized sewer mining company is Thermowatt, and several references can be found on its website (https://thermowatt-global.com/references/). These units are usually built underground having a phase separation step to remove suspended solids before the raw sewage is fed to the heat exchanger/heat pump stage. After the thermal energy recovery step, the separated solids are mixed again with the filtered wastewater and fed back into the sewer line and finally treated in a centralized wastewater treatment plant (WWTP).

The following two examples (Figure 2 - process schemes, pictures, operational data, etc.) of thermal energy recovery units built and currently are in operation in Budapest can give a good description and illustration of the state-of-the-art technology.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541





This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

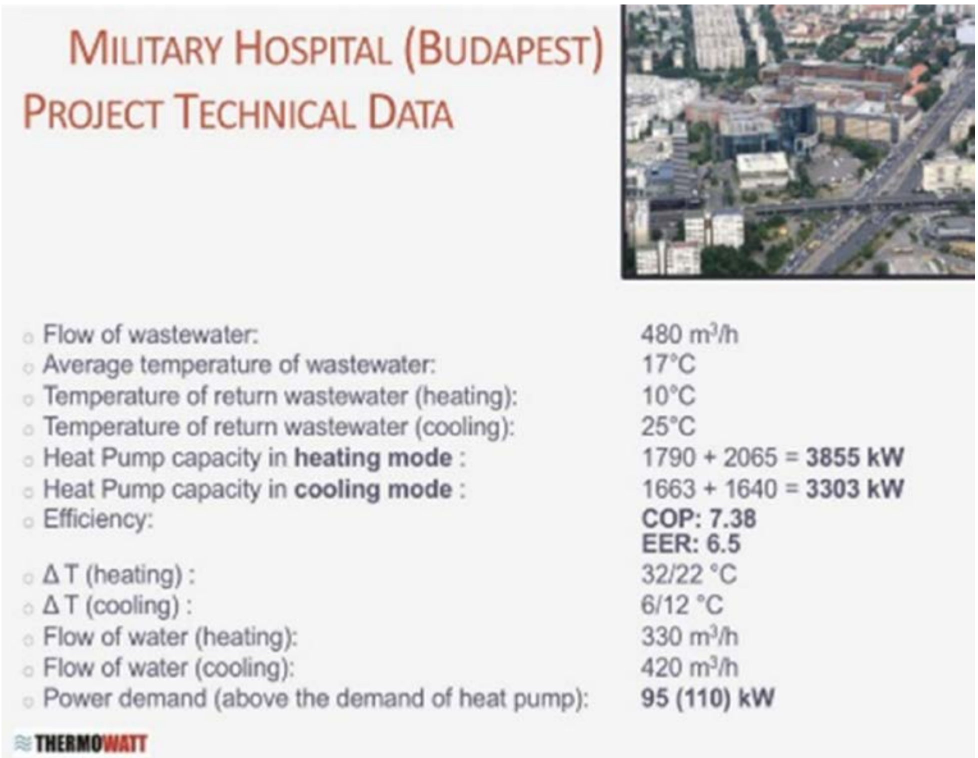


Figure 2 Large industrial scale energy recovery from wastewater at two locations in Budapest.

While the above solutions can provide very good energy efficiencies with coefficient of performance (COP) values typically in the range of 4.4 up to 8.24 in the heating mode and energy efficiency ratio (EER) values between 6.5 and 6.9 in the cooling mode, the technology has serious limitations in small scale distributed network applications (COP is the ratio of useful heating or cooling provided to the energy required. Higher COPs equate to higher efficiency, lower energy consumption, and lower operating costs. EER is the ratio of output cooling energy to input energy at a given operating point. The higher the EER rating, the more efficient the air conditioner.)

At the Athens demonstration site, an innovative down-sized adaptation of the known waste heat recovery technology from wastewater has been implemented using the following differentiating features:

- ✓ Energy recovery from the treated water, instead of the typically used screened and untreated sewage;
- ✓ Scaled down from centralized solutions to the 1 m^3/h flow and to the 4 to 8 kW regime, which can fit very well to small decentralized applications;
- ✓ Using commercially available water/water heat exchanger and heat pump equipment instead of highly specialized equipment developed for raw sewage;
- ✓ Flexible design which can be switched easily from community warm water/cooling use to boost composting reactor technology when needed in critical periods (ramping up and in colder seasons).
- ✓ The advantage of using treated effluent from an MBR membrane bioreactor is that no additional screening before the heat pump is required and the heat transfer surfaces do not need special cleaning and attention.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

Product Name	Product Image	Parameter	
Water Source Heat Pump		Model No.	MDS10D-SY
		Rated input power:	0.8KW
		Rated heating capacity:	3.2KW
		Rated cooling capacity:	2.4KW
		Rated voltage:	220V
		Rated frequency:	50HZ
		Rated current:	4A
		Rated outlet water temperature:	55℃
		Maximum outlet water temperature:	60℃
		Water source side water flow:	2000L/H
		Heat source side water flow:	1000L/H
		Pipe size of load side(mm):	DN25
		Pipe size of heat source side(mm):	DN25
		Noise:	≤40Db
		Evaporator:	Shell and tube heat exchanger
		Refrigerant	R417A/R407C/R410A optional
		Compressor:	Panasonic
		Condenser:	Double pipe heat exchanger
		Throttle units:	Thermal expansion valve
		Controlling system	Multi-mode control
		Level of security:	IP*4
		Electric shock protection grade	1 grade
		Product size:	660*560*770mm
		Packing size:	730*630*940mm

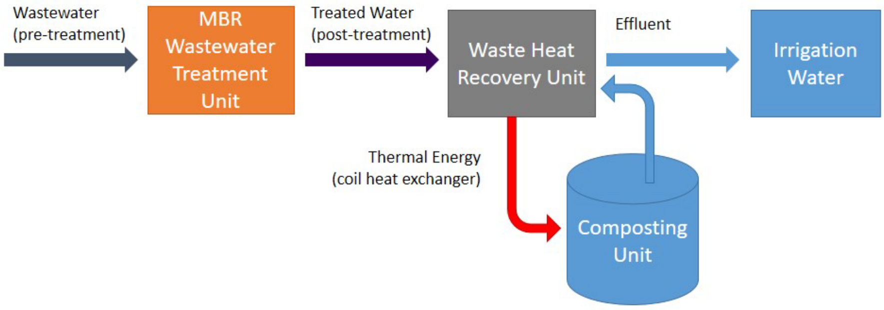
Note: Initial water temperature of load side: 15°C; Final water temperature of load side: 55°C.
Inlet water temperature of heat source side: 15°C; Outlet water temperature of heat source side: 10°C.

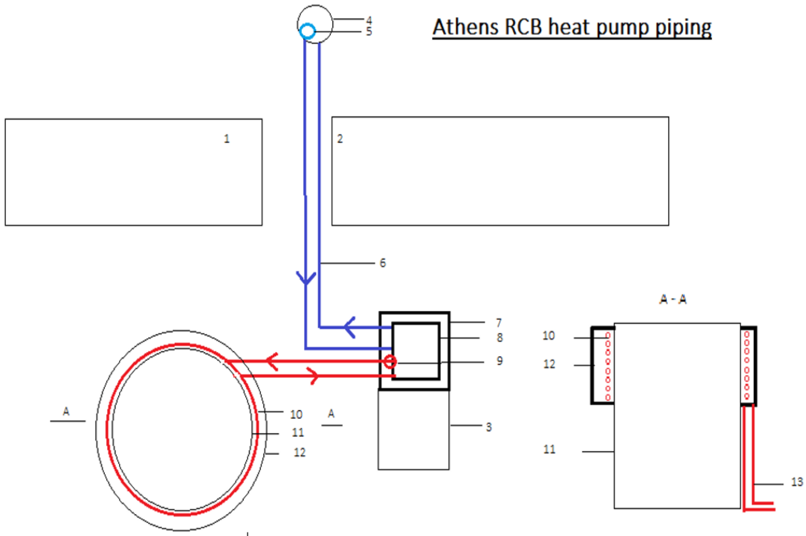
Figure 3 The energy recovery unit at the NextGen Athens pilot site.

The commercially available heat pump unit is rated as a 3.2 kW heater, which can recover this amount of thermal energy from max. 1,000 L/hour flow of low temperature treated wastewater using 0.8 kW of electricity input. The temperature difference on the thermal energy resource side is typically between 2 and 5 °C, the maximum temperature on the heated side is 60 °C, depending on the circumstances.

In the current set-up, the equipment (Figure 3) was intended to provide additional heat for the biological start-up of the composting reactor, until the exothermic biological reaction of the aerobic composting can sustain the required 60 to 70 °C temperatures to kill all the pathogens.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement N°776541





1 Container
2 MBR unit
3 Switch board shelter
4 Effluent tank
5 Cold water loop pump
6 Cold water loop
7 Heat pump shelter
8 Heat pump
9 Hot water loop pump
10 RCB coil heat exchanger
11 RCB tank
12 Heat exchanger thermal insulation
13 Hot water loop

Figure 4 Overall scheme of heat recovery system in Athens.

2.1.6. Requirements for the implementation of the technology and operating conditions

With the traditional technologies the efficiency of heat recovery in a sewer relies on different parameters such as the flow rate and temperature in the sewer, the temperature difference of the wastewater upstream and downstream of the heat exchanger, the material of the pipe and of the heat exchanger, the viscosity of the wastewater, the velocity of the fluids in the heat exchanger, the heat transfer resistance caused by biofilm formation, the heat exchange coefficient and the heat transfer surface. Thus, for an economically rewarding heat recovery from wastewater in sewers, the following requirements should be met. For large, centralised facilities, the diameter of the sewer and the flow rate in the sewer should be at least 800 mm

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

and 15 L/s, respectively. However, in Bologna for example flow rates between 200 and 400 L/s were considered for such a system (Cipolla and Maglionico 2014) and in Brno (Czech Republic) the flow rates ranged between 130 L/s and 470 L/s (Cecconet et al. 2019).

In order to have an as high heat potential as possible, the heat exchanger in the sewer should be as close to the heat source as possible. Therefore, Brunck et al. 2013 suggest a maximum distance of 300 m to the heat source. The heat recovery is technically possible from wastewater with a minimum temperature of 10 °C. and the recommended delta T should be at least 5 °C, the higher the better. Thus, before planning such a traditional heat recovery unit, it should be carefully investigated which temperature will result in the effluent at the corresponding wastewater treatment plant.

In the Athens project, the design philosophy has been changed from the traditional one in a way, that the thermal energy is recovered from the wastewater stream AFTER it has undergone MBR treatment (water temperature may increase during MBR due to biological activity) and UV disinfection (negligible effects on water temperature). Heat recovery from treated wastewater has several benefits overheat recovery systems applied directly to the sewer line.

- ✓ Traditionally, heat recovery from sewers requires more complex equipment and machinery to prevent clogging and biofouling. Therefore, a larger system is installed in order to make the investment worthwhile. These larger systems can recover at least 1 MW (10,000 PE Wastewater) thermal energy to be used to heat/ cool businesses and homes. Smaller and cheaper local heat recovery systems can be installed to recover heat from locally treated wastewater (via small, decentralised wastewater treatment facilities), to be used locally to boost technological systems such as the rapid composting unit.
- ✓ Heat recovery from treated wastewater is cheaper to build and easier to operate.
- ✓ Heat recovered from treated wastewater results in significantly less biofouling.
- ✓ And finally, a significant advantage is that if the thermal energy is recovered after the wastewater treatment is complete, then it does not affect the biological processes of wastewater treatment by reducing the temperature of the untreated water. If heat is removed after wastewater treatment, it can be particularly beneficial when the water is used for irrigation, that is lowering the thermal stress of the irrigated plants.

2.1.7. Results obtained

The heat pump equipment for the heat recovery unit was selected to be able to provide both general purpose heating and cooling needs, in addition to providing heat for technology boosting. However, the heat recovery unit within the pilot setup was piped to only service as a boosting mechanism for the pilot scale rapid composting bioreactor (RCB), as the below flowchart illustrates in Figure 5.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

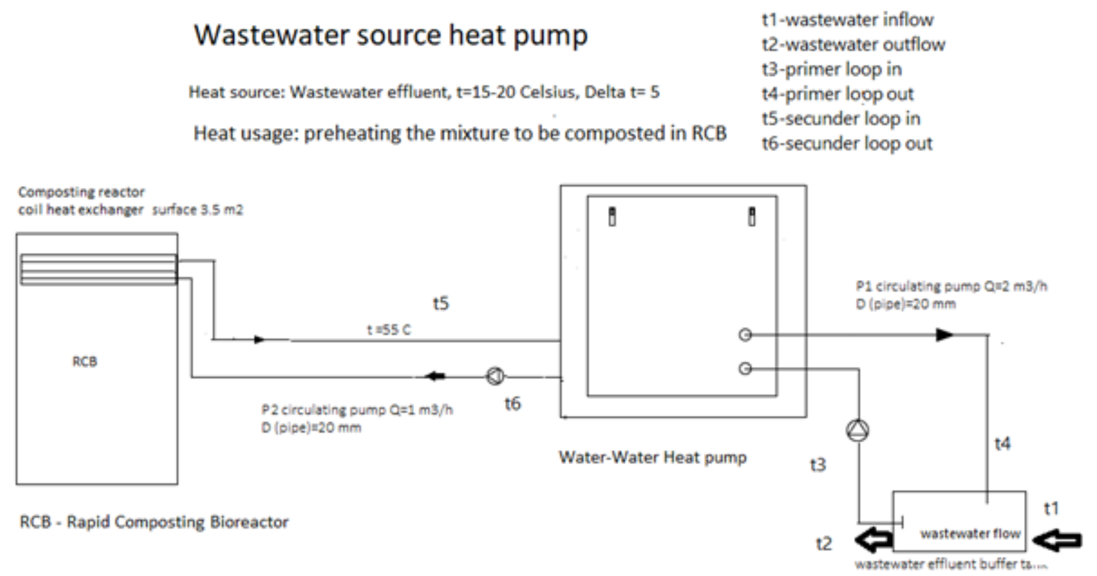


Figure 5 Flowchart of rapid composting bioreactor and wastewater source heat pump.

The RCB pilot went through a long series of testing and modifications of mixing arms and drives and compost raw material preparatory tests and modifications (discussed in more details in the Rapid Composting Unit Demo Report), and therefore the Heat Recovery Unit could not be fully tested for technology purposes, however, a couple of measurements have been done to check the heat pump base capabilities.

As shown in Table 5 and Figure 6, during these test runs on the energy source side, the treated water temperature (T3) from the MBR sewer mining and wastewater treatment unit was consistently around 24 °C, while the temperature of the heated forward stream (T6) was typically between 52 and 55 °C. See Figure 6.

The temperature difference in the primary loop typically was between 2 and 2.5 °C at a circulation rate of 2 m^3/h, resulting in extracted energy estimated between 4.75 kW and 5.25 kW. We could not measure the heat actually delivered; however, it can be estimated to be around 4.0 kW, based on equipment specifications. Looking at the initial pilot results and the specifications, we estimate a maximum COP of 4 and an EER of 3.

Table 5 Temperature measurements.

		7/25/2022	7/26/2022	7/27/2022	7/28/2022	7/29/2022
T, return water from the heat pump	T4	24	24	23.9	24	24.1
T, irrigation tank	T2	25.9	26.2	26.4	26	26.1
T, after UV	T1	25.4	25.7	25.6	25.5	25.6
T, heat pump	T6	53	54	53	52	52
T, buffer tank	T3	26	26.5	26.4	26.5	26.6

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

Figure 6 Picture of the system.

Tests resulted in critically reconsidering the flow scheme to one that provides simple switching options between the different uses. The following revised scheme illustrates this new intelligent approach to maximize thermal energy usage in a small, decentralized environment (Figure 7).

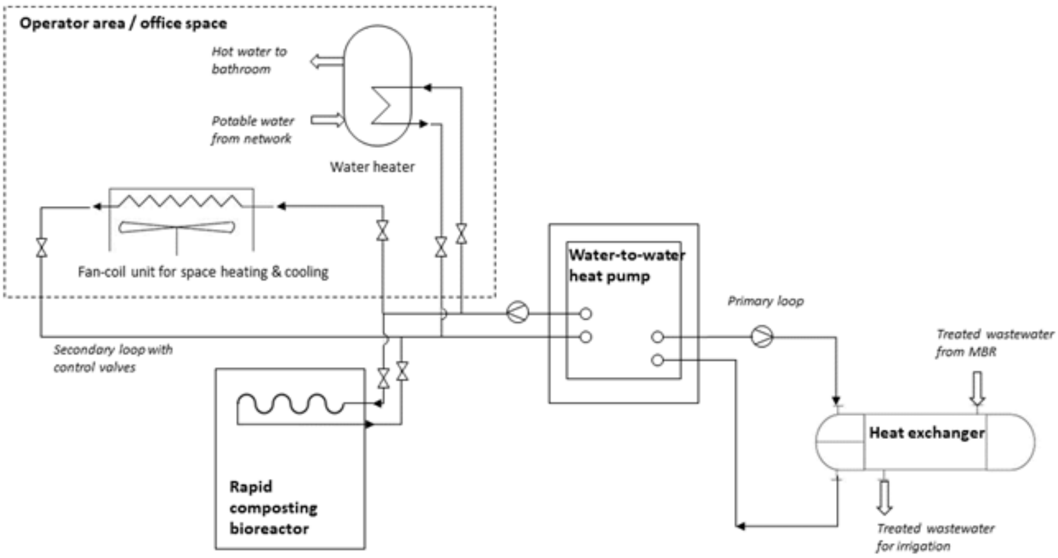


Figure 7 Revised scheme of heat recovery system.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

2.1.8. Comparison of baseline situation and NextGen KPIs

Traditional centralized sewage heat recovery shows good efficiencies in heating and cooling modes (COP and EER); however, they require industrial pre-treatment screening, and often result in corrosion and biofouling. This system operates in the MW range.

The decentralized, commercially available small-scale heat recovery unit used in the pilot produces lower but still acceptable COP and EER, however it does not result in corrosion or biofouling. This set-up is operated in the 1-10 kW range.

A full-scale decentralized commercially available unit will have a higher efficiency close to the traditional centralized large-scale units, however it will have the advantages of being decentralized, easy to operate, and it will have a competitive CAPEX.

Table 6 KPIs of Athens case study (CAPEX shows specific investment costs per kW recovered thermal energy).

System	Source of thermal energy	Capacity range	COPheating mode	EER Cooling mode	CAPEX €/kW	Technology specifics	Biofouling risks
Traditional centralized sewage heat recovery	Raw sewage	1,000 to 10,000 kW	4.4 to 8.25	6.5 to 6.9	1,000 to 1,200	Needs efficient screening + special corrosion resistant surfaces	Significant, needs frequent checking and cleaning
New sewage heat recovery – Small	Treated wastewater after MBR	1 to 10 kW	4.0 to 5.12	Min. 3.0 to 4.85	625	No need for screening, commercially available water/water heat pumps can be used	minimal (expected)
New sewage heat recovery – Decentralized large Scale	Treated wastewater from adequate treatment	10 to 100 kW	4.4 to 8.25	4.5 to 6	450 to 500	No need for screening, commercially available water/water heat pumps can be used	minimal (expected)

Note: Pilot trials did not show definitive results. COP and EER are estimates based on pilot results and specifications. The decentralized large-scale models work at a higher efficiency, for example a 50 kW commercially available unit has the following COP and EER values of 5.12 and 4.85. *See https://www.flexpro-industry.com/e-commerce/en/water-source-pump-industry/198-capwater-reversible-50kw-geothermal.html*

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

2.1.9. Lessons learned

The following lessons are assumptions based on initial pilot results. For conclusive lessons and results, long-term operation is necessary of the unit.

Required competence	LOW  HIGH
▪ Which knowledge is required to operate the plant? trained labour (system works similar to a residential air conditioner) ▪ What kind of training is necessary? short training lasting approximately 2 hours	
Maintenance	LOW  HIGH
▪ Frequency of plant maintenance per month or per year: Annual maintenance inspection. ▪ Duration of a normal maintenance procedure: Approximately 1 day ▪ Duration of active process control per day (manual process control, unforeseen events): Not applicable. ▪ Are external experts required to conduct the maintenance procedure? Yes. An HVAC (heating, ventilation, air conditioning) expert is needed.	
Technological risks	LOW  HIGH
▪ Reasons for downtimes or technical risks: Power outage, Fouling, Calcification ▪ Frequency of plant downtimes per year: Once every two years for bi-annual cleaning. ▪ Duration of plant downtimes. 1 day for the bi-annual cleaning ▪ Are external experts required to restart the plant? No. ▪ Which measures can avoid such downtimes? Monitoring and proper maintenance.	

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

2.1.10. Best practice guideline for operating the technology

- What is important to consider during the construction of the plant?

  - During installation of the Heat Recovery unit, particular care should be taken that the circulation loops ensure constant fluid flow. Valves should be included so that air can be removed from the system. The equipment should be installed so that it is protected from vandalism and theft. Otherwise, installation of the system is straightforward.

- What is crucial for the start-up of the plant?

  - A professional HVAC (Heating, ventilation, air conditioning) expert should be available for start-up of the system.

- Which parameters are crucial for the optimization of the production process?

  - A minimum of ΔT = 2 °C is needed in the primary loop of the Heat recovery system. This can be ensured by a proper sizing of the heat exchanger and the respective circulation loops.

- Which ranges for the crucial parameters delivered the best removal and production results?

  - The COP and the EER of the system are increased as ΔT is increased in the primary loop.

2.1.11. Literature references

Cecconet, D. et al., Energy recovery from wastewater: a study on heating and cooling of a multipurpose building with sewage-reclaimed heat energy. Sustainability, 2019. 12(1): p. 116.

Cipolla, S.S. et al., Heat recovery from urban wastewater: analysis of the variability of flow rate and temperature in the sewer of Bologna, Italy. Energy procedia, 2014. 45: p. 288-297.

Founda, D. et al., The extreme heat wave of summer 2021 in Athens (Greece): cumulative heat and exposure to heat stress. Sustainability, 2022. 14(13): p. 7766.

Neugebauer, G. et al., Mapping thermal energy resource potentials from wastewater treatment plants. Sustainability, 2015. 7(10): p. 12988-13010.

Seybold, C. et al., In-house wastewater heat recovery. REHVA Journal, 2013: p. 18-21. *https://www.flexpro-industry.com/e-commerce/en/water-source-pump-industry/198-capwater-reversible-50kw-geothermal.html*

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

2.2. Feasibility study of low-grade heat recovery potential in Filton Airfield (UK)

Authors: JungEun Kim, Jan Hofman (UBATH)

2.2.1. Description of the demo site

The Filton Airfield site was purchased in 2015 by and slated for development by YTL Development UK Ltd, a subsidiary of the multinational YTL Corporation. The £800 million scheme, a new suburb to be named Brabazon, will comprise more than 2,675 new homes and 62 acres of commercial space, as well as new schools, recreation spaces and health facilities (Figure 8). As the parent company of Wessex Water, YTL is set to place significant focus on the development's water management capability and is working with the University of Bath's Water Innovation and Research Centre (WIRC) to investigate and implement the waste-minimising circular economy practices it will need to appeal to planners and future residents. The large size of the development presents a unique opportunity to fully demonstrate and test these practices.

A masterplan for the site development is available, but further development and exploration of ideas for sustainable development are required. Within NextGen, energy management as part of this masterplan will be further developed and the viability for implementation will be further explored. However, before that, an attempt to build approaches for easy assessment of heat availability in Filton Airfield is required. Domestic wastewater contains a relatively high amount of thermal energy, originating from hot water use at homes. Sewage will have an elevated temperature (20-30 °C). The Filton Airfield Development has a size (2675 homes, 24 ha commercial space) that offer opportunities for heat recovery from sewer systems. Because the heat is low grade heat, it cannot be transported over long distances. The Filton area is ideal for local heat recovery, as several potential end-users for the heat are available (schools, nurseries, community facilities). The task will demonstrate the feasibility of heat recovery by modelling the heat balance (input, loss, use) of the Filton sewer system.

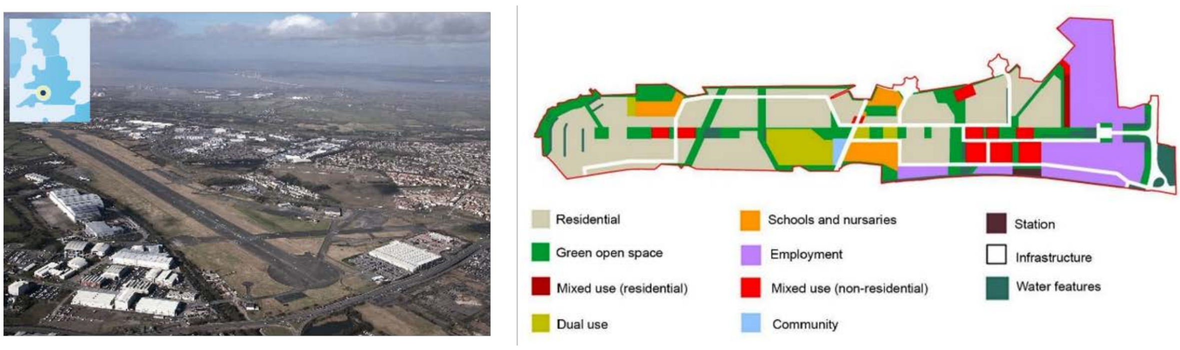


Figure 8 Location of Filton Airfield and Filton Airfield master plan.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

2.2.2. Motivation of implementing circular economy solutions

In the UK 1.21 billion litres of domestic wastewater are discharged into sewers every day under dry flow conditions with an average temperature of 17.5 °C (Ali et al., 2019). Due to the high heat capacity of water, if 3 °C of cooling could be used for wastewater heat recovery (WWHR) it would be possible to generate 1.5 TWh of heat energy annually which would be 1.2% of total UK renewable energy generation in 2019 (ONS, 2021).

Due to the low grade of heat collected through WWHR, transforming it into electricity is not a viable option and it is instead used for heating. When collected outside of the home this energy is instead better used in a heat network/district heating which directly delivers hot water to a heat exchanger inside domestic buildings through a network of pipes (DBEIS, 2018). Due to the large percentage of domestic energy consumption which is used for heating the UK government does not believe that it will be able to meet its 2050 decarbonization target unless at least 18% of UK heat is distributed by heat networks from sources such as WWHR (DBEIS, 2018). To this end the UK government is providing £320m of investments and other incentives to support heat networks, making identifying locations at which WWHR may be implemented a priority.

As wastewater contains low-grade energy, it cannot be transported over long distances but could be re-used in the local area, for instance for heating a house, a swimming pool or a shopping centre. In this context, the Filton development scheme, comprising mixed-use development will be well-placed and deliver sufficient energy to be used for space or water heating in residential and commercial buildings. Therefore, in the Filton Airfield case, a feasibility study of wastewater heat recovery potential was carried out and assessed its reuse for space heating and water heating via theoretical quantitative analysis (energy consumption reduction). This study offers insights into the transferability of wastewater recovery and its local reuse in Filton Airfield.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement N°776541

2.2.3. Actions and case study objectives

The main objective of the Filton Airfield demo case is a feasibility study of low-grade heat recovery from wastewater and local reuse. Table 7 summarises actions and objectives of the Filton Airfield case study.

Table 7 Actions and objectives of the case study in Filton Airfield.

Case Study number & Name	**# 9, Filton Airfield, A former airfield in South Gloucestershire, north of Bristol**
Subtasks	Sub-Task 1.3.1 Local heat recovery from wastewater
Technology baseline	- A former airfield in South Gloucestershire, north of Bristol, UK YTL Developments will develop this former airfield into an attractive and sustainable area
NextGen intervention in circular economy for water sector	- Decentralized solutions for increased circularity in new housing districts - The water, materials and energy circular solutions will be included in a masterplan for the site development
TRL	TRL 9
Capacity	113 houses
Quantifiable target	Domestic heating (space or water heating): energy savings

2.2.4. Unique selling points

While the technology required for recovering heat from sewers is well understood there are still many practical considerations including maintenance and economic viability which remain unclear, and it has not yet been implemented in the UK. This feasibility study will assist in evaluating the viability of in-sewer wastewater heat recovery in residential areas and demonstrate how to quantify the flow and temperature patterns of wastewater within the sewer network to estimate the energy available for recovery as a preliminary study. Therefore, this will support the assessment of the heat recovery reliability from a real large sewer network over different weather conditions within a year.

2.2.5. Methodology - Simulation approach

Study site - Filton Airfield eastern infrastructure

The Brabazon Development is a mixed-use development located at the Filton Airfield site. The intention is to integrate a sustainable residential neighbourhood with education and commercial opportunities while promoting the historical significance of the Filton Airfield (YTL Developments, 2019). The construction of the development is expected to last for over 10 years, leading to the final phase of homes and office spaces after 2030. However, the first phase of the development includes 278 housing units. We focussed on this first phase of the development with the intention that the results and findings from the research providing a useful business case for YTL Developments in the future phases of the development. Figure 9 shows simple plan for the Brabazon Development, with the location of the first phase indicated and named 'Hangar District'. The site chosen for analysis was the first phase of the

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

Brabazon development near Bristol in Southwest England. The developers are interested in supporting sustainable living, including reductions in carbon footprint which makes the development worthy of consideration, and the new sewer network would make installation of WWHR systems less problematic than with older sites. Figure 9 shows a map of the first phase of development housing with its sewer network super imposed, which includes 113 houses and a tower block containing 33 apartments. Figure 10 therefor gives an overview of the modelling approach used during this project. Data from the UK time use survey, UK household occupancy statistics, and survey of UK appliance penetration were required to generate water and wastewater discharge profiles for households in simulation. Details are described as follows.

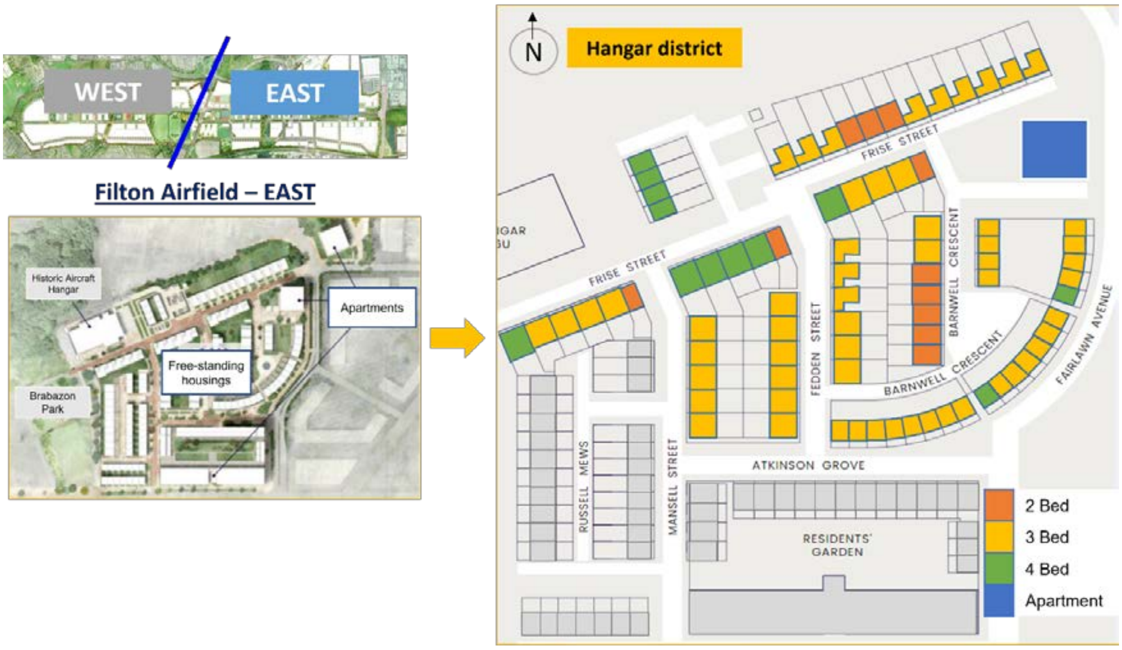


Figure 9 Filton Airfield eastern infrastructure development: "The Hangar District".

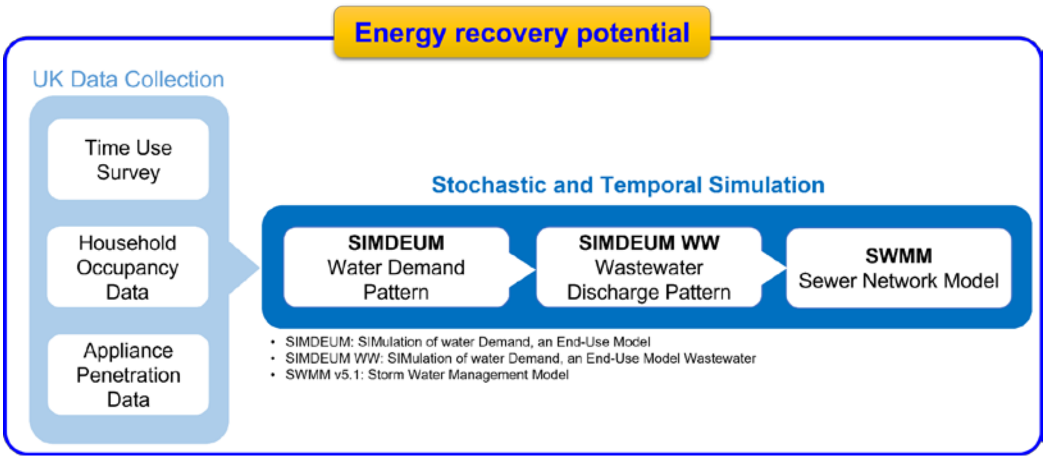


Figure 10 Overview of simulations used to calculate energy recovery potential.

Household water demand and discharge profiles – SIMDEUM and SIMDEUM WW

"Simulation of Water Demand, End-Use Model" (SIMDEUM) is a stochastic model of water use and discharge patterns (Blokker et al., 2017) at the household level. For a given building it generates a random number of occupants based on demographic data and determines

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

whether they are awake and present in the building based on the diurnal patterns for the occupant's demographic cohort. Each building is assigned a number of water appliances based on an associated percentage for that building type, and if an occupant is both present and awake there is a chance that they might use an appliance based on the average frequency of use for that demographic. Additionally, SIMDEUM distinguishes between different uses for the same appliance so that bathroom taps may be used either to wash hands or to shave, producing different discharge volumes and temperatures accordingly. For the purposes of assessing the viability of WWHR, stochastic modelling of discharge has an advantage over continuous models in that it may highlight where irregularities in wastewater flowrate may undermine performance of recovery equipment. For example, if there was only one house with a single occupant discharging into a system, whatever the average flowrate might be across a 24-hour period the modal flowrate would presumably be 0 LPM.

Household wastewater discharge patterns and quality loading were generated using SIMDEUM WW®. The SIMDEUM WW can convert water demand patterns obtained from the SIMEUM® into wastewater discharges, including flow and temperature (Bailey et al., 2019; Bailey et al., 2020b). Through a review of relevant literature, appropriate input values for temperature used in this study are presented in Table 8.

Table 8 Appliance-specific pollutant concentrations for improved SIMDEUMWW® (Bailey et al., 2020a; Bailey et al., 2020b).

Appliance	Temperature (°C)
Bath	36
Shower	35
Bathroom tap (BrTap)	40
Kitchen tap (Ktap)	40
Dishwasher (Dw)	35
Washing machine (Wm)	35, 35, 35, 45
Toilet (Wc)	20

UK time use survey - diurnal patterns

Shown below in Figure 11 is the diurnal patterns for the relevant demographic groups recognized by the UK Time Use Survey data. A working adult in SIMDEUM is defined as an adult who works more than 20 hours a week. This information was used to simulate average weekday and weekend diurnal patterns in the UK within SIMDEUM. This study, however, used default data within SIMDEUM due to the limitations of other input variables, including statistics on male or female, age, and hours worked, as well as the individual's water usage habits (average number of toilet uses, average shower time, etc.). The dashed red line indicates the method for calculating the standard deviation around the time of getting up and sleep. Values obtained from this figure were summarized in and used for SIMDEUM simulation.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

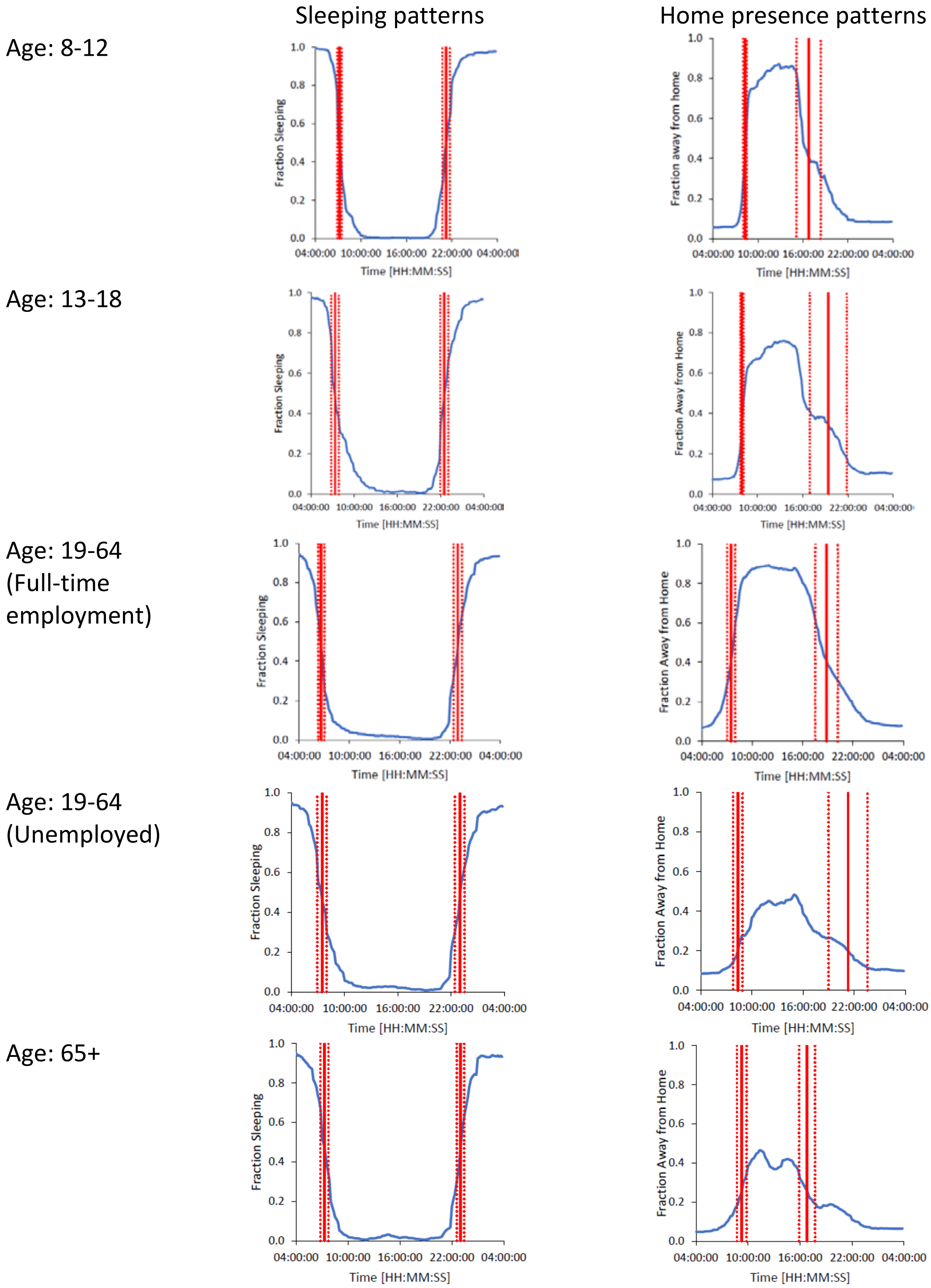


Figure 11 Diurnal patterns. The dashed red line indicates the method for calculating the standard deviation around the time of getting up and sleep. Values obtained from this figure were summarized in Table 9 and used for SIMDEUM simulation.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

Table 9 Summarized time budget data for the UK used for the SIMDEUM® simulation (Gershuny, 2017).

		Time of getting up		Time of leaving the house		Duration of no presence at home		Duration of sleeping	
		Avg.	SD	Avg.	SD	Avg.	SD	Avg.	SD
Child, 8-12	Week	7:11	0:30	8:20	0:40	8:00	1:00	9:56	0:30
	Weekend	7:57	1:00	9:35	1:00	8:50	1:30	10:24	1:30
Teen, 13-18	Week	7:17	0:50	8:02	0:45	8:38	1:30	8:46	0:50
	Weekend	9:10	0:50	10:35	0:45	9:17	1:30	10:12	1:00
Working adult, 19-64	Week	6:31	0:30	7:44	0:30	9:32	1:15	7:34	0:30
	Weekend	6:58	1:15	8:01	1:00	10:54	2:00	7:50	1:00
Home adult, 19-64	Week	7:22	0:30	8:45	1:30	9:46	1:30	8:20	0:50
	Weekend	7:59	0:50	9:52	1:30	8:48	2:00	8:51	1:00
Senior, 65+	Week	7:15	0:45	9:17	1:00	7:32	1:30	8:15	1:00
	Weekend	7:35	1:10	9:35	1:00	7:48	2:30	8:32	1:20
Total	Week	6:59	1:00	8:09	0:50	9:48	1:10	8:07	0:50
	Weekend	7:55	1:30	9:31	1:30	9:29	2:00	8:57	1:30

*Avg.: Average, SD: Standard Deviation

UK household occupancy statistics

First, a calibration within SIMDEUM was conducted using the UK's official household occupancy statistics (Statistics, 2020) and the UK time use survey (Gershuny, 2017) by replacing the default Dutch data. Using the UK household occupancy statistics, the proportion of each household's occupancy (one, two, or family) for each house type was identified and thus used as input data within the SIMDEUM model (Figure 12). Table 10 shows the average household occupancy for house with different types of bedrooms.

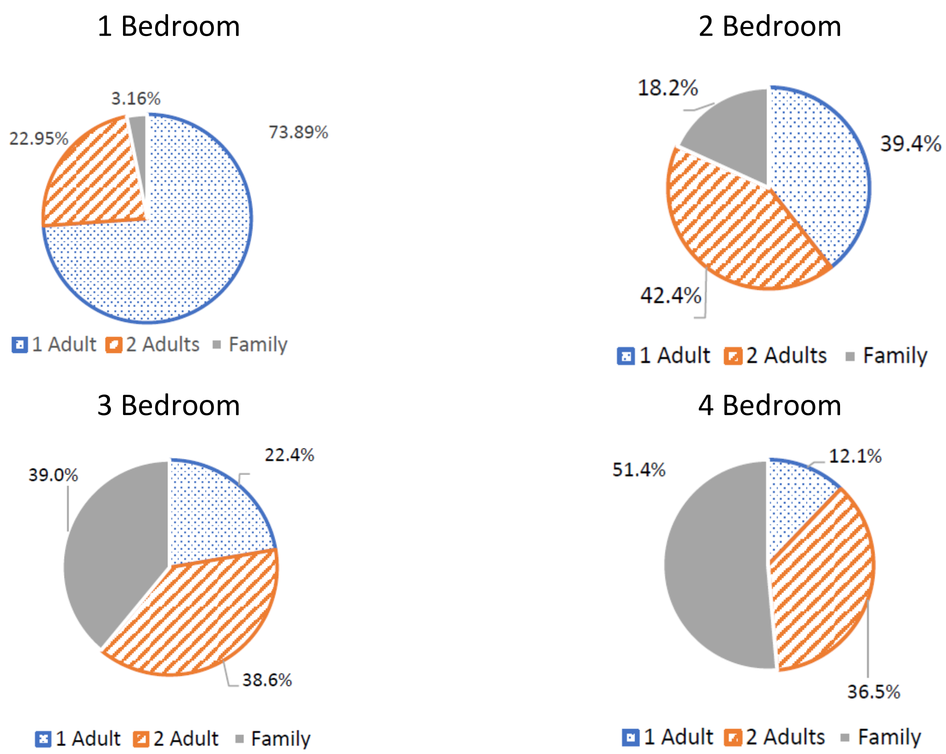


Figure 12 Proportion of SIMDEUM household types for all housing, social housing and private housing.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

Table 10 Average household occupancy for house with given number of bedrooms ± standard deviation.

	1 Bedroom	2 Bedrooms	3 Bedrooms	4 Bedrooms
Average household occupancy	1.31 ± 0.59	1.86 ± 0.90	2.45 ± 1.20	2.88 ± 1.30

Sewer network modelling

Storm Water Management Model (SWMM) is the sewer modelling software developed by the US Environmental Protection Agency (Huber, 1997). The SWMM can simulate urban runoff and sewer system hydraulics and quality for short- or long- term period and so this model has been widely applied for urban planning, analysis and design associated to sewer network systems in urban areas (Gironás et al., 2010).

Figure 13 shows the description of a sewer network of the study area, Brabazon community (Figure 9). Detail information on the network system of the study area was adapted from YTL development master plan, including length between inflow nodes, length between junction nodes, depth of manholes, and pipe diameter. Simulation results of wastewater discharge flow and quality obtained from the SIMDEUM WW® were used as input data for the SWMM simulations and thus producing results of wastewater flow and temperature. All simulations were conducted over a 5-day period (Monday to Friday). By reading the map of the sewer network it was established that the path of flow through the sewer network to the network outfall was no more than 250 m for any node, and the maximum direct distance between the outfall and a network node was 168 m. This satisfies the proximity requirements for WWHR suggested by (Ali et al., 2019), making the site suitable for assessment. As the viability of WWHR systems is usually defined in terms of dry weather flow conditions, all that was required at this stage was to link each inflow node to a flow and temperature time series produced by SIMDEUM WW for the associated housing type.

Figure 13 Map of the development with overlaid sewer network adapted from YTL Developments (113 housing units).

For the purposes of a modelling a closed gravity sewer the network consists of inflow nodes, junction nodes, outfalls, and channels. At inflow nodes wastewater is added to the network as described by a time series. At junction nodes flows are combined and are proceed onwards

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

as a perfectly mixed plug. The outfall is simply the last node in the network where wastewater is removed. Channels carry wastewater along their length between nodes according to the Manning Equation 1 given below

$$F = \frac{1.49}{n_M} AR^{2/3} S^{1/2}$$ *Equation 1*

where F is the flow rate ($m^3 s^{-1}$), n_M is the Manning roughness coefficient for the channel material (-), A is the cross-sectional area of flow through the channel (m^2), R is the hydraulic radius of channel (m), S is the slope of the channel (-) and 1.49 is a unit conversion factor. Hydraulic radius is described by Equation 2 below

$$R = A/P_w$$ *Equation 2*

where P_w is the wetted perimeter of the conduit (m).

SWMM does not track dispersion, treating the network as a series of plug flows. This results in higher peak flowrates with periods of no flow that would not be encountered in actual sewers.

While SWMM does account for atmospheric temperature when determining inflows due to snow melt or losses due to evaporation, it does not natively track the temperature of wastewater itself. However, as SWMM does track pollutant concentrations in wastewater a simple model of wastewater temperature could be created by treating it as a material pollutant in an otherwise homogenous flow. SWMM ignores diffusion of pollutants, instead treating them as a slug.

In a simple case of two flows (F_1, F_2) with different temperatures (T_1, T_2) mixing at a junction node (as illustrated right in Figure 14), the temperature of wastewater leaving that junction node (T_3) would be described by Equation 3 below

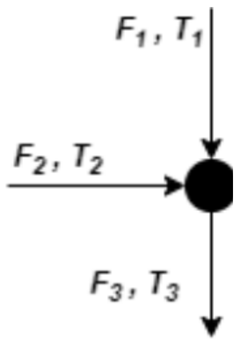


Figure 14 Example of mixing flow at junction.

$$T_3 = \frac{T_1 F_1 + T_2 F_2}{F_1 + F_2}$$ *Equation 3*

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

In general, this takes the form shown below in Equation 4 for a confluence of *n* pipes.

$$T_{mix} = \frac{T_1F_1 + T_2F_2 + \cdots + T_nF_n}{\sum F_n} \quad \text{Equation 4}$$

where T_{mix} is the temperature of the resultant flow.

Pollutants can be removed from any node in the network using a treatment function which takes the form of an equation describing either the outlet concentration or removal fraction from that node. Depth of wastewater, flowrate, surface area, simulation time step, and hydraulic residence time at the node are all valid variables for removal expressions.

Heat recovery potential calculation

The potentially recoverable power (Q_{PR}) at a given time interval was estimated from the product of the wastewater flowrate (F_w), specific heat capacity and density of wastewater (c and ρ_{ww}), and the change in water temperature taking place due to the heat exchanger (ΔT_{HX}) as shown below in Equation 5.

$$Q_{PR} = F_W \cdot c_p \cdot \Delta T_{HX} \cdot \rho_{WW} \quad \text{Equation 5}$$

The specific heat capacity was taken as 4.18 $kJ \cdot kg^{-1} \cdot K^{-1}$ and the density of wastewater was assumed to be 1000 kg m^{-3} based on Funamizu et al. (2001), and the change in wastewater temperature due to heat exchange was the elevated temperature above 15.2°C capped to a maximum value of either 0.5°C to ensure no impact on downstream WWTPs, 2°C following the specifications given by Huber (2021), or 3°C as an optimistic best case scenario with current technology given by Ali et al. (2019). 15.2°C was chosen as the reference point as this was the value given by the Trust (2013) for the average main's water temperature in the UK and it is assumed that heat transfer from wastewater would be poor beneath this temperature. In addition, there are concerns that in-sewer heat recovery could have a negative impact on downstream processes, the wastewater treatment plant. As the biological process responsible for much of wastewater treatment, the temperature loss due to heat recovery and transport within sewer pipes negatively impacts the biological treatment efficiency (Ali et al., 2019).

2.2.6. Results obtained

Discharge patterns

Figure 15 shows the flowrate at the network outfall. An average of 16,000 L was discharged into the network each day. Commercially available systems require high dry weather flowrates to be economically viable by the admission of their manufacturers, with minimum flow requirements ranging from 600 – 1,500 LPM (Ostapczuk et al., 2013). However, the flowrate failed to meet the recommended values. Figure 16 further shows the temperature of the wastewater in excess of 15.2 °C, temperature met target 55.6% of the time as it was chosen as the reference point for the average main's water temperature in the UK (Trust,

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

2013). The flow rates clearly showed periodic fluctuations. The minimum discharge appears after midnight while the maximum discharge occurs during the morning (Figure 15). The warm discharge starts to increase little before 6:00 am, reaching to maximum from 10:00 to noon (Figure 16). After midday, warm discharges drop, and no discharge occurs until late afternoon. This corresponds to the consumer's behaviour.

Stochastic flow and average wastewater temperatures could be quickly calculated at any node in the sewer network allowing for the comparison of multiple locations. These results allow a better approximation of continuous flow when the simulation output is averaged over multiple days and as the number of houses considered increases. By treating temperature as a material pollutant subject to exponential decay it is possible to model wastewater temperatures as being higher closer to their source, aiding comparison of different locations.

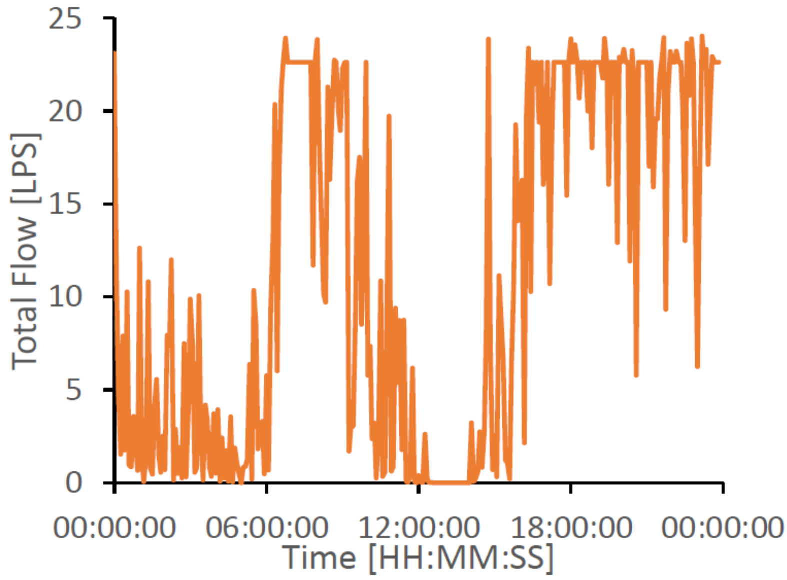


Figure 15 Total flowrate at the network outflow.

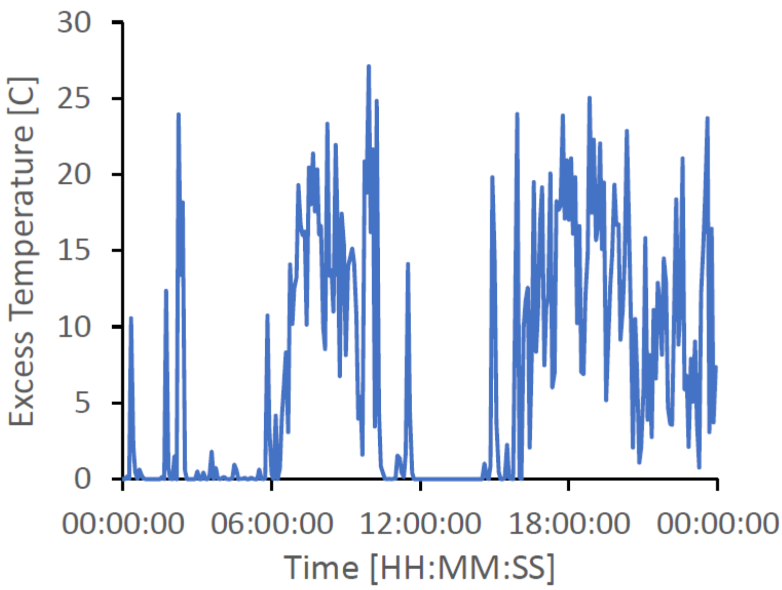
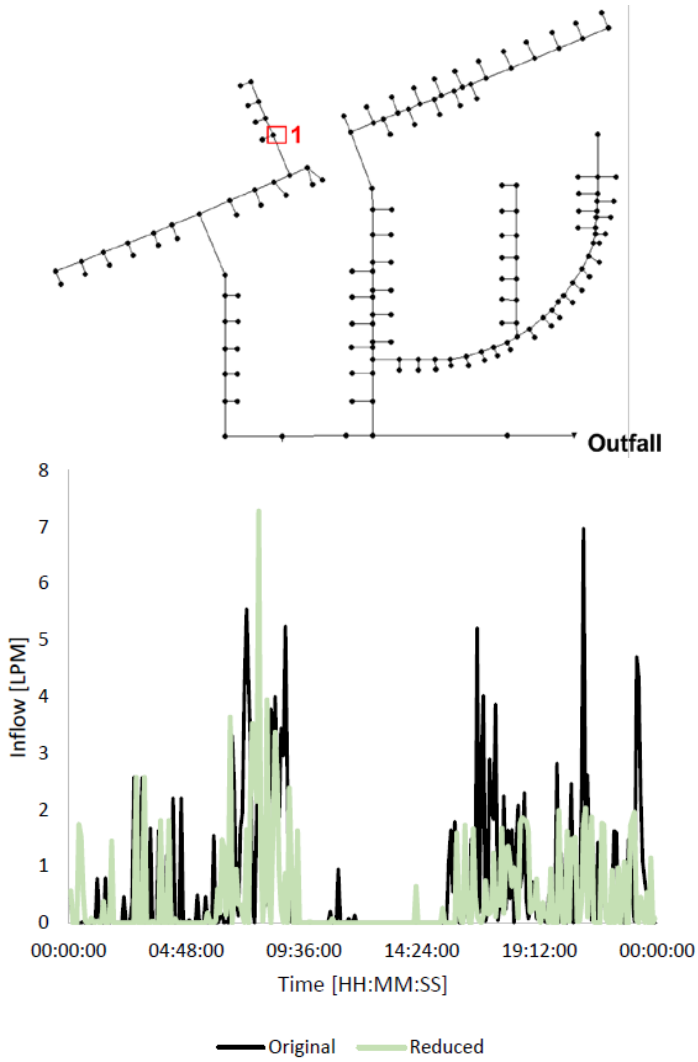


Figure 16 Temperature in excess of the average water mains temperature of 15.2℃ at the network outflow.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

As many more appliances were added to households than were found present in any of the demo files packaged with the SIMDEUM software it was decided to investigate the impact of device frequency. This was done by creating new simulation data files, dividing the original appliance frequency of toilets, bathroom taps, and showers by the number of those appliances present in the house (i.e., 4, 4, and 3 respectively), and measuring the impact on flowrates and temperatures around node 1. on Figure 17. For bathroom taps the frequency of shaving was restored to “average” for each tap as otherwise the frequency of shaving would have been adjusted down by too much. This modification allowed for multiple showers to be in use at a single time, which could result in higher overall usage as each device has an independent minimum time between two uses (offset) but not to the same degree as multiple copies of an appliance would – importantly for the hydraulic model in general it allowed for higher peak discharge. Files for discharge patterns were selected to ensure that the same number of occupants (11) were present in both the original and reduced frequency scenario.

Figure 17 shows inflow at node 1. over a 24-hour period averaged over five days at the original appliance frequency and the reduced device frequency discussed earlier. Total inflow was found as shown in Table 11 below. As expected, the total inflow decreased with less use of devices, from 960 L to 638 L (33.5% reduction).



This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement N°776541

Figure 17 Inflow at node 1. averaged over five days with original and reduced appliance frequencies.

Table 11 Total inflow through Node 1. Over one day with original and reduced appliance frequencies.

Appliance Frequency	Total Inflow [L]	Total Inflow Per Person [L]
Conventional	960	87
Ecohouse (reduced frequency)	638	58

Recoverable heat potential

Figure 18 shows the maximum potential power recovery at the network outfall averaged over five days, under three assumptions of maximum cooling: 0.5, 2 and 3 °C. In Figure 19, the water heating energy demand data obtained from the household electricity survey conducted by Zimmermann et al. (2012) was compared with the recoverable heat potential with maximum cooling of 3 °C as demonstrated in the previous study conducted in the UK (Farman Ali et al., 2021). Overall, the main peak of the energy demand for water heating was the morning and evening for weekdays. However, there is an opportunity to recover more heat from wastewater. If 5°C of cooling could be used for WWHR it would be possible to recover more heat from wastewater, which can contribute to the total UK renewable energy generation. However, this study assumed that daily discharge is cooled by maximum 3 °C for heat recovery because heat losses during transport should be considered.

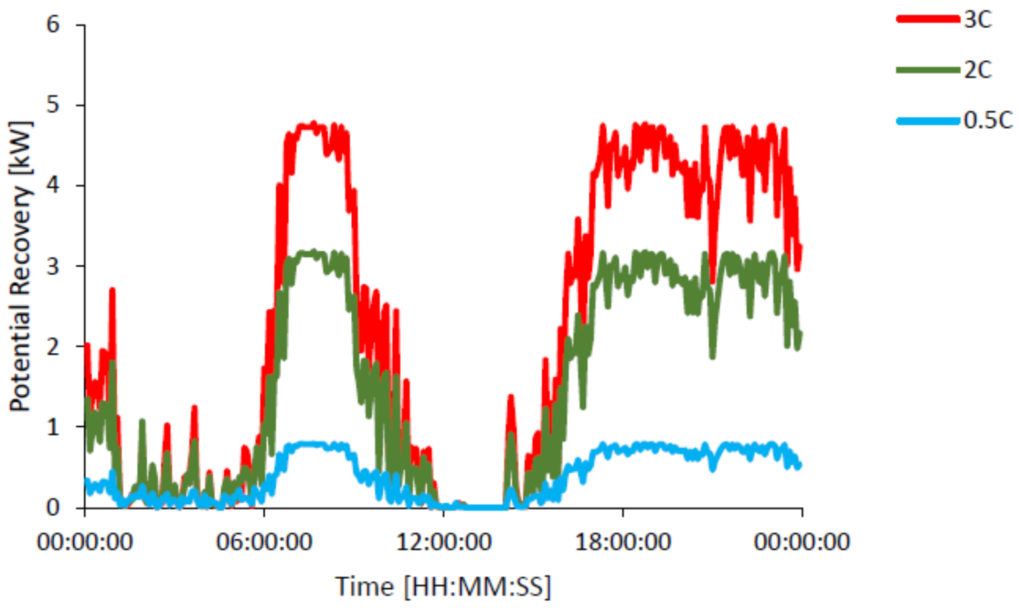


Figure 18 Potential recovered power at network outfall averaged over five days under three different assumptions of maximum useful cooling, 0.5, 2 and 3 °C.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

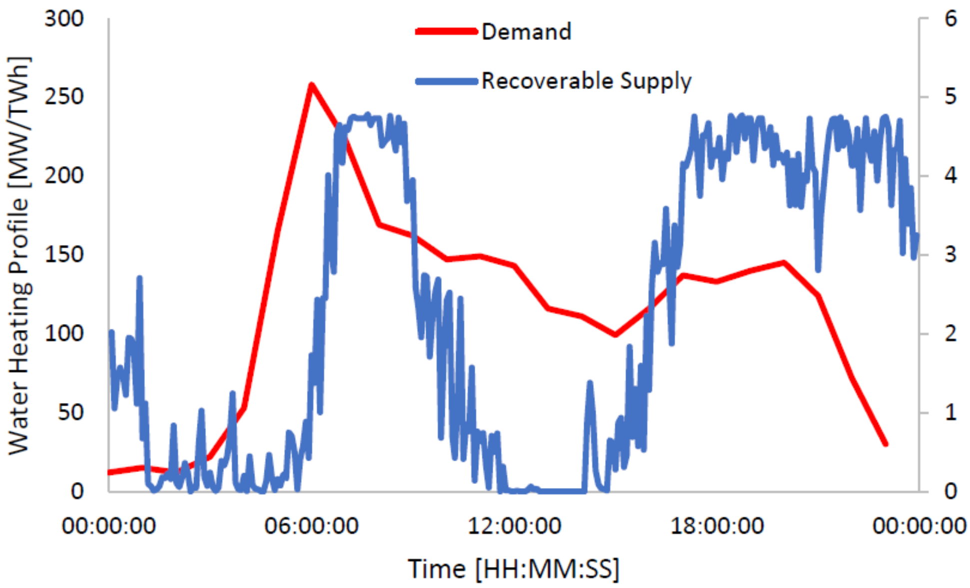


Figure 19 Potential recovered power at network outfall against water heating demand obtained from (Zimmermann et al., 2012).

Discussion

The simulation produced satisfactory diurnal patterns that mirror results seen in sewers elsewhere: an initial peak following the morning followed by a lull due to people leaving their homes, followed by a more extended period of high flow in the evening. This can be seen in Figure 19 where heating demand precedes available power, although there is a base load not accounted for in this curve. Assuming an average occupancy of 2.4 for the 113 housing units modelled the total flow per person was approximately 60 L/day. When examining the node 1 (Figure 17). With a known number of upstream occupants, the average daily discharge was found to be 87 L/pp/day, which is 58% of the 150 L/pp/day UK average (Aquaterra, 2008). This result was obtained by the simulation conducted using SIMDEUM for the 113 housing units as mentioned earlier. It has to be noted here that for the simulation, we have assumed to have less frequency of using the same appliances (i.e., less than the average frequency of use). Thus, the result shows much less water demand than the UK average. Reducing the appliance frequency of housing in proportion to the additional appliances led to an average 33.5% reduction in discharge to sewers, which suggests that the SIMDEUM model handles additional appliances well if they are of the same type. In the further development stage of building new residences in Filton Airfield, the approach used in the current study can be applied to the more significant number of housing units to simulate water demand and discharge profiles.

Minimum flowrate for in-sewer WWHR systems not reached with maximum flowrates in the region of 24 LPM compared to the minimum of 600 LPM recommended by manufacturers (Ostapczuk et al., 2013), suggesting that any heat recovery station should be located further downstream. This is not surprising as Frank Oesterholt (2014) found that WWHR was not well suited for small housing projects of 50 homes and the first stage of the Brabazon development is not much larger. However, Hrabová et al. (2019) noted that in-sewer WWHR systems may be viable even on scales as small as 10 kW, which is only twice what was obtained at the network outfall under the assumption of 3°C during peak times. If 5°C of cooling is used for WWHR it would be possible to recover more heat from wastewater. In this study, a 10 kW

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

WWHR system may be viable with adequate storage for heat recovered during peak times. Furthermore, as the heat recovery station can be sited within 500 m of the network outfall tested, this provides the possibility of including the region as part of a wider district heating system. In this context, the decentralised heat recovery unit demonstrated in Athens (Section 2.1) can be applied for heat recovery in Filton Airfield. For example, when treated wastewater after membrane bioreactor as a source of thermal energy, the system capacity ranged from 1 to 10 kW. In addition, the coefficient of performance of the heat recovery system for heating mode was between 4.0 and 5.83. For this application, it has been shown that the system has minimal biofouling risks. Therefore, the implemented heat recovery solution in Athens can effectively work in Filton Airfield, which can promote the spread and acceptance of thermal energy recovery solutions. Such thermal energy recovery solution can make possible the use of commercially available heat recovery system, which can accelerate the acceptance of the technology. However, there are challenges we need to consider prior to the installation of the heat recovery system. For example, Athens used treated wastewater as a heat recovery source, and the system showed good performance with minimal biofouling risks. This indicates that heat recovered from the treated wastewater is more beneficial. In addition, the most suitable location for the heat recovery system should be investigated. Since we are recovering low-grade heat from wastewater the distance is the key factor for the Filton case. There are three locations that we can consider, including component level (direct recovery from wastewater), Building level (collection tank) and sewer network level (installation of a heat exchanger in the sewer network and installation of an external heat exchanger with upstream filtration). As such, an appropriate treatment process for influent wastewater and the location of the heat recovery system should be investigated and determined as it has direct impacts on heat source properties, system maintenance and overall recovery efficiency.

2.2.7. Comparison of baseline situation and NextGen KPIs

In Filton Airfield, the NextGen technology for energy recovery comprises a heat recovery system. In terms of energy recovery, the relevant KPIs are wastewater temperature and flowrate and thus demonstrating heat recovery potential. Domestic energy consumption can be distributed by five activities, including space heating, water heating, cooking, lighting and appliances and their respective contribution to the total domestic energy consumption is shown in Table 12. Based on the household energy contribution in Table 12, Table 13 and Table 14 present the baseline situation which refers to the energy consumption and energy bill of the Filton site estimated using the historical energy consumption and bill of Bristol, Southwest, UK (2005-2020). While heat recovery potential with implemented NextGen system (i.e., low-grade heat recovery from wastewater) is shown in Table 15.

There are two scenarios for demonstrating heat recovery potential and its reuse: (1) residential area consisting of conventional houses and (2) residential area consisting of ecohouse. Our study area is the first phase of the Hanger District construction, 113 housing units. The change in water temperature occurring due to heat exchanger - 0.5, 2 and 3 °C - were considered as addressed in previous Section 2.2.6. In addition, the temperature of the wastewater less than 15.2 °C was ruled out.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

Table 14 shows that the total energy demand for the study area was estimated to be 463,300 kWh/y and followed by 293,800 kWh/y for space heating and 101,700 kWh/y for water heating. Theoretically, if above daily discharge is cooled by 0.5, 2 and 3 degrees for heat recovery, for baseline (conventional house) it is possible to recover 6,465, 25,859 and 38,788 kWh/y and for ecohouse 2,915, 11,659, 17,488 kWh/y (Table 15). Although there is a concern in relation to temperature drop below the legal limit (WWTP inlet < 15.2 °C (Ali et al., 2019)) after more is extracted, it was assumed that the presence of a densely populated area downstream can keep temperature above the legal limit.

The results obtained from this study show that residential area with conventional houses could recover more energy due to higher wastewater discharges. For example, the total heat recovery potential is shown to be 7.85**%** and 3.54**%** for baseline and ecohouse, respectively. More specifically, for space heating, the energy recovered from wastewater can contribute 13.2% and 5.95% for baseline and ecohouse, respectively. In addition, for water heating, the energy recovered from wastewater can contribute 38.14% and 17.2% for baseline and ecohouse, respectively.

This indicates that the impact of wastewater flow rates is significant to recover thermal energy from wastewater. As shown in Figure 18, potential recovered heat at network outfall exhibits diurnal pattern like wastewater and temperature. When wastewater discharge flow is maximum so is the temperature and hence heat recovery potential, occurring in two peaks (early morning and late afternoon and evening). This periodic changes in recovered heat suggests that thermal energy storage should be considered at plan and design stage so that energy can be recovered and stored when it is available and collected for reuse from the storage when there is demand. As demonstrated in the Westland case, the aquifer thermal energy storage system can credit 10-15% of the annual total energy demand. This result indicates that if this heat storage system is applied to the Filton case, we can benefit from using stored heat and thus be economically and environmentally viable. However, it needs to be investigated further for applying this site-specific technology in Filton.

Table 12 Contribution of each activity consuming energy in a household unit to the total energy consumption (averaged from 1970 to 2020 in the UK using dataset obtained from Parker (2021)).

Energy use	% household energy contribution
Space heating	**62.1%**
Water heating	**22.0%**
Cooking	3.9%
Lighting	3.1%
Appliances	8.9%

Table 13 Baseline KPIs - Historical average energy consumption in Bristol, Southwest, UK (2005-2020) (BEIS, 2021).

	Mean (kWh/year/unit)		
Bedroom type	**Total**	**Space heating (62.1%)**	**Water heating (22.0%)**
1	3,100	2,000	700
2	3,700	2,300	900
3	4,200	2,700	1,000
4	5,300	3,300	1,200
Average	4,100	2,600	900

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

Table 14 NextGen KPIs - Estimated energy consumption and energy bill in Filton using historical energy consumption in Bristol, Southwest, UK (2005-2020) (BEIS, 2021).

Demand	Energy consumption (kWh/year)			Bill (£/year)		
	Total	Space heating	Water heating	Total	Space heating	Water heating
Total	463,300	293,800	101,700	83,950	53,237	18,428

*Southwest – 18.12 pence per kWh

Table 15 Estimation of theoretical heat recovery potential and energy savings under different NextGen scenarios.

		Units	Value
Scenario 1 – Conventional house			
Heat recovery potential		kWh/year @ 0.5 °C	6,465
		kWh/year @ 2 °C	25,859
		kWh/year @ 3 °C	38,788
Energy saving potential	Total saving	% @ 0.5 °C	**1.31**
		% @ 2 °C	**5.23**
		% @ 3 °C	**7.85**
	Space heating	% @ 0.5 °C	**2.20**
		% @ 2 °C	**8.80**
		% @ 3 °C	**13.20**
	Water heating	% @ 0.5 °C	**6.36**
		% @ 2 °C	**25.43**
		% @ 3 °C	**38.14**
Scenario 2 – Ecohouse			
Heat recovery potential		kWh/year @ 0.5 °C	2,915
		kWh/year @ 2 °C	11,659
		kWh/year @ 3 °C	17,488
Energy saving potential	Total saving	% @ 0.5 °C	**0.59**
		% @ 2 °C	**2.36**
		% @ 3 °C	**3.54**
	Space heating	% @ 0.5 °C	**0.99**
		% @ 2 °C	**3.97**
		% @ 3 °C	**5.95**
	Water heating	% @ 0.5 °C	**2.87**
		% @ 2 °C	**11.46**
		% @ 3 °C	**17.20**

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

2.2.8. Lessons learned

Required competence	LOW		HIGH

- Understanding wastewater heat recovery for various purposes, depending on the magnitude of heat available and locations
- Understanding heat recovery techniques (e.g., heat exchanger and heat pump) and analysing varieties of wastewater temperature and flow rate complying with future needs
- Understanding consumer demands and perceptions

Maintenance	LOW		HIGH

- Cleaning of heat exchanger – as needed
  - Online cleaning: maintain acceptable performance efficiency without interruption of operation but require extra operational cost
  - Offline cleaning: mechanical and chemical cleaning of the inside surfaces
- Replace or clean filters every month or as required
- Heat pump maintenance with a professional at least once a year

Technological risks	LOW		HIGH

- Maintain a balance between heat demand and supply (e.g., seasonal effect on heat recovery potential)
- Accumulation of unwanted deposits on the surface of heat exchanger causes additional maintenance cost
- Corrosion can happen due to electrochemical mechanism that is the deterioration of general metal and alloys, and this will increase maintenance cost
- Dirty filters, coils, and fans reduce cause the heat transfer performance of heat exchanger to decline with time

2.2.9. Best practice guideline for operating the technology

- Determine a configuration of wastewater heat recovery (WWHR) system
  - Single use of a heat exchanger or a combination of a heat pump and heat exchanger
  - Analyse heat exchanger types and their performances
    - Double-pipe parallel flow
    - Double-pipe counterflow
    - Shell-and-tube
    - Plate-and-frame

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

- Determine energy recovery locations (Nagpal et al., 2021)
    - Component level – heat is recovered from wastewater directly after it is discharged from specific activities (e.g., showering, cooking, food processing, etc.). The most common heat source at this level is shower water.
    - Building level – heat is recovered from the collective wastewater discharge from a single building and stored in a collective system. The characteristics of wastewater discharged depend on building type (e.g., residential or commercial). Wastewater is commonly collected in a tank, and heat is recovered using a heat exchanger or heat pump.
    - Sewer network level – there are two possible options (a) installation of a heat exchanger in sewer network and (b) installation of external heat exchanger with upstream filtration (Ali et al., 2019).
    - Wastewater treatment plant level – there are three possible options (a) from raw wastewater, (b) from partially treated water within the plant, and (c) from effluent discharge after treatment. The most favourable option is heat recovery from the effluent discharge. This is because relatively low variation in water temperature and cleaned effluent (i.e., low fouling deposition) will improve heat recovery system efficiency. However, a major concern of this recovery option is that the heat supply must be transported over long distances, thus leading to high heat losses. Thus, on-site consumption can be preferred in such cases to heat facilities in the WWTP precinct.
- Analyse wastewater profiles: temperature and flow rate
    - Component level and building level: higher temperature and relatively low amount of wastewater with higher fluctuations
    - Sewer pipe level and WWTP level: relatively low temperature due to heat losses and higher flow rates and more stable throughout the year
- Future work to improve accuracy of the simulation
    - Data collection and management: Much of the data used in this study will soon be able to be updated due to the 2021 census. Specifically, washing machine penetration and household occupancy can be updated shortly. Diurnal patterns for weekends can be found using the same dataset as was used to find weekday patterns and should be used to give a more accurate picture of flow patterns. It was found that there are still some discrepancies between the demographic groups used within the SIMDEUM and those in the data collected by ONS which might be useful to resolve, but these are a minor concern relating to the definition of children aged 17-21.
    - Updating the frequency of appliance usage is a high priority as demonstrated by the four-household test case, but more research will be required to find how additional appliances change the frequency of use in real cases. As Blokker et al. (2017) advises, it would be wise to update other demand to

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement N°776541

match the British context as the system was calibrated around Dutch water usage. Currently there is an issue with how SIMDEUM handles washing machine cycles that start near the end of a simulated timespan, causing the simulation to fail. The likelihood of encountering this error increases with the number of days and houses simulated, which limits the tool's ease of use. SIMDEUM does not generate single parent households or households made of more than two adults with no children. SIMDEUM cannot switch between weekday and weekend demand patterns. Although it is possible to combine the output created by two different demand patterns there will be slight inconsistencies due to the randomly generated household composition so that a house that is simulated as having four occupants during the week would only have one at a weekend or vice versa.

2.2.10. Literature references

Ali, S., Gillich, A. 2019. Determining the UK's potential for heat recovery from wastewater using steady state and dynamic modelling-preliminary results. *2nd Global Conference on Energy and Sustainable Development, GCESD2018*. WEENTECH.

Aquaterra. 2008. International comparisons of domestic per capita consumption Environment Agency.

Bailey, O., Arnot, T., Blokker, E., et al. 2020a. Predicting impacts of water conservation with a stochastic sewer model. *Water Science and Technology*, **80**.

Bailey, O., Arnot, T., Blokker, E., et al. 2019. Developing a stochastic sewer model to support sewer design under water conservation measures. *Journal of Hydrology*, **573**, 908-917.

Bailey, O., Zlatanovic, L., van der Hoek, J.P., et al. 2020b. A Stochastic Model to Predict Flow, Nutrient and Temperature Changes in a Sewer under Water Conservation Scenarios. *Water*, **12**(4), 1187.

Beernink, S., Hartog, N., Bloemendal, M., et al. 2019. ATES systems performance in practice: analysis of operational data from ATES systems in the province of Utrecht, The Netherlands. in: *European Geothermal Congress*. The Hague, Netherlands.

BEIS. 2021. National Energy Efficiency Data-Framework (NEED), Department for Business, Energy and Industrial Strategy (BEIS) London.

Bloemendal, M., Beernink, S., Bel, N., et al. 2020. Transitie open bodemenergiesysteem Koppert-Cress naar verhoogde opslagtemperatuur. Evaluatie van energiebesparingen en grondwatereffecten. KWR Water Research Institute.

Bloemendal, M., Beernink, S., Hartog, N., et al. 2019. Transforming ATES to HT-ATES. Insights from dutch pilot project. in: *European Geothermal Congress EGC*. Den Haag, pp. 6.

Bloemendal, M., Hartog, N. 2018. Analysis of the impact of storage conditions on the thermal recovery efficiency of low-temperature ATES systems. *Geothermics*, **17**, 306-319.

Blokker, M., Agudelo-Vera, C., Moerman, A., et al. 2017. Review of applications for SIMDEUM, a stochastic drinking water demand model with a small temporal and spatial scale. *Drinking Water Engineering and Science*, **10**(1), 1-12.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

DBEIS. 2018. What is a heat network?, (Ed.) E.I.S. Department for Business, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/696273/HNIP_What_is_a_heat_network.pdf.

Drijver, B., Aarssen, B., De Zwart, B. 2012. High-temperature aquifer thermal energy storage (HT-ATES): sustainable and multi-usable. in: *Innostock 2012*, IF Technology.

Farman Ali, S., Gillich, A. 2021. Opportunities to decarbonize heat in the UK using Urban Wastewater Heat Recovery. *Building Services Engineering Research and Technology*, **42**(6), 715-732.

Frank Oesterholt, J.H. 2014. Feasibility of Small Scale Heat Recovery from Sewers. KWR.

Funamizu, N., Iida, M., Sakakura, Y., et al. 2001. Reuse of heat energy in wastewater: implementation examples in Japan. *Water Science and Technology*, **43**(10), 277-285.

Gershuny, J., Sullivan, O. 2017. United Kingdom Time Use Survey, 2014-2015, http://doi.org/10.5255/UKDA-SN-8128-1, [data collection]. UK Data Service. SN: 8128.

Gironás, J., Roesner, L.A., Rossman, L.A., et al. 2010. A new applications manual for the Storm Water Management Model(SWMM). *Environmental Modelling & Software*, **25**(6), 813-814.

Haehnlein, S., Bayer, P., Blum, P. 2010. International legal status of the use of shallow geothermal energy. *Renewable and Sustainable Energy Reviews*, **14**(9), 2611-2625.

Hartog, N., Bloemendal, M., Slingerland, E., et al. 2017. Duurzame warmte gaat ondergronds. *VV+*, **sept-okt 17**.

Holstenkamp, L., Meisel, M., Neidig, P., et al. 2017. Interdisciplinary review of medium-deep Aquifer Thermal Energy Storage in North Germany. in: *11th International Renewable Energy Storage Conference, IRES*. Dusseldorf, Germany.

Hrabová, K., Hrdlička, T., Tlašek, M. 2019. Use of Heat from Wastewater. *IOP Conference Series: Earth and Environmental Science*. IOP Publishing. pp. 012095.

Huber, W.C. 1997. *EPA Storm Water Management Model (SWMM), Versions 4.31 and 4.4*. Department of Civil, Construction, and Environmental Engineering, Oregon ….

Nagpal, H., Spriet, J., Murali, M.K., et al. 2021. Heat recovery from wastewater—A review of available resource. *Water*, **13**(9), 1274.

ONS, O.f.N.S. 2021. Energy consumption in the UK 2021.

Ostapczuk, R., Railsback, D. 2013. Assessment of sewage heat recovery technology and applicability to the Milwaukee Metropolitan Sewerage District. *Milwaukee, août*.

Parker, S. 2021. Final Energy Consumption by sector and fuel 1970-2020, (Ed.) N. Statistics, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1021836/Energy_Consumption_in_the_UK_2021.pdf.

Schout, G., Drijver, B., Gutierrez-Neri, M., et al. 2013. Analysis of recovery efficiency in high-temperature aquifer thermal energy storage: a Rayleigh-based method. *Hydrogeology Journal*, **22**(1), 281-291.

Statistics, O.f.N. 2020. 2011 Census: Aggregate Data, http://doi.org/10.5257/census/aggregate-2011-2, UK Data Service.

TNO. 2017. REGIS II. Utrecht.

Trust, E.S. 2013. At Home with Water - Energy Saving Trust.

van Lopik, J.H., Hartog, N., Zaadnoordijk, W.J. 2016. The use of salinity contrast for density difference compensation to improve the thermal recovery efficiency in high-temperature aquifer thermal energy storage systems. *Hydrogeology Journal*, **24**(5), 1255-1271.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

Willemsen, N. 2016. Rapportage bodemenergiesystemen in Nederland. RVO / IF technology.
Zimmermann, J.-P., Evans, M., Griggs, J., et al. 2012. Household Electricity Survey: A study of domestic electrical product usage. *Intertek Testing & Certification Ltd*, 213-214.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

3. Biogas production from wastewater or sewage sludge

3.1. Enhancing biogas production via thermal pressure hydrolysis in Braunschweig (DE)

Authors: Anne Kleyböcker (KWB), Janina Heinze (AVB), Fabian Kraus (KWB)

3.1.1. Description of the demo site

The wastewater treatment plant Steinhof, near Braunschweig, has a long tradition of water and nutrient reuse. Already at the end of the 19th century, fields were irrigated with sewage. From 1954 on, the wastewater was mechanically clarified and reused for irrigation. Finally, in 1979, the wastewater treatment plant (WWTP) was built and comprised a conventional activated sludge treatment system and a digestion stage. Until 2016, in summer, the digestate was directly reused in agriculture, while in winter, the digestate was dewatered and stored until the summer season. However, due to the new legislation in Germany, since 2017 only 60% of the digestate can be applied on the fields. The reasons are restricted periods for fertilising with digested sewage sludge and the limitation of the nitrogen load to the agricultural fields. Thus, the other 40% of the digestate were dewatered and incinerated.

In 2019, a new circular economy concept was implemented. Here, energy recovery technologies are combined with nutrient recovery technologies. Therefore, the sludge management concept was adapted to increase the nutrient recovery rate and simultaneously, as a synergetic effect, the biogas recovery rate increased. Hence, circular economy solution comprises a thermal hydrolysis process between two digestion stages and a full-scale nutrient recovery plant consisting of a struvite production unit to recover phosphorus and an ammonium sulphate solution production unit to recover nitrogen.

The secondary fertilisers will be reused by the local farmers and the produced energy in the form of biogas and heat is reused by the plant itself.

3.1.2. Motivation of implementing circular economy solutions

The original WWTP was designed for 275,000 population equivalents. However, the actual load refers to 380,000 population equivalents. In order to guarantee a clean effluent of the WWTP complying with legal thresholds, a circular economy approach was implemented not only to remove nutrients from the wastewater, but also to recover them in combination with an enhanced energy recovery system. In detail, phosphorus and nitrogen are recovered via

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement N°776541

the production of struvite and ammonium sulphate and the biogas production rate is enhanced due to a thermal pressure hydrolysis (TPH) of excess sludge.

The benefits of the thermal pressure hydrolysis are:

- ✓ Subsequent anaerobic digestion: increase in methane yield up to 25% due to TPH

The TPH breaks down complex organic carbon compounds such as microbial cells into soluble compounds. In a subsequent anaerobic digester, microorganisms degrade those soluble compounds resulting in an increase in the methane yield of about 15% – 25% compared to anaerobic digestion without TPH (DWA 2014).

- ✓ Reduction of the sludge disposal volume and correspondingly their disposal costs

Due to the higher degradation rate in a subsequent anaerobic digester to the TPH, the volume of the digestate decreases correspondingly. Furthermore, according to Neyens and Baeyens (2003), the dewaterability is enhanced after TPH. Hence, the volume of the dewatered sludge can be reduced reaching a dry matter content of up to 30% and more due to the better dewaterability and the higher degradation rate during anaerobic digestion (Metcalf et al. 2013, Neyens and Baeyens 2003). Thus, the disposal costs for the dewatered sludge decrease, too. Phothilangka et al. (2008) saved 25% of their disposal costs with TPH implementation.

- ✓ TPH enables the operation of the downstream digestion at higher dry solids (DS) contents and with higher organic loading rates

TPH leads to a lower viscosity (Higgins et al. 2017) enabling the operation of the downstream digestion process at higher DS contents still achieving favourable mixing conditions. Furthermore, the enhanced biodegradability leads to higher digestion rates and thus, to a higher capacity of the existing digester volume. Hence, the system can be operated with lower hydraulic retention times allowing for the operation at higher organic loading rates (Pilli et al. 2015).

- ✓ Release of ammonium and phosphate for a subsequent nutrient recovery

The disintegration process in the TPH enhances the performance of the anaerobic digestion process also resulting in a higher ammonium and phosphate release into the liquid phase. Toutian et al. (2020) observed an increase in the solubilisation degree of undissolved phosphorus between 22 and 43% at temperatures between 130 and 170 °C. In this temperature range however, no solubilisation of nitrogen was observed. Wilson and Novak (2009) showed an increase in ammonium concentration at temperatures between 170° and 220 °C by a factor of two and higher. Due to the accumulation of ammonium and phosphate, the resulting liquor is very suitable for a subsequent nutrient recovery such as ammonium stripping or struvite production.

- ✓ Sterilized sludge after high temperature TPH

Due to high temperatures between 130 °C and 180 °C and the rapid decompression from 6 bar to 0.2 bar, microbial cell walls are destroyed (Pilli et al. 2015) and thus, pathogenic organisms, too.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

3.1.3. Actions and case study objectives

The main objective of the Braunschweig demo case is to demonstrate a two-stage digestion system with a thermal pressure hydrolysis between the stages and evaluate the reuse of excess heat from TPH and more available heat from combined heat and power (CHP) due to increased methane production. Table 16 summarises actions and objectives of the Braunschweig case study.

Table 16 Actions and objectives of the case study in Braunschweig.

Case Study number & Name	**#1 Braunschweig, Location: WWTP Steinhoff**
Subtasks	Sub-Task 1.3.2 Internal heat usage and heat management for two stage digestion system & thermal pressure hydrolysis (TPH)
Technology baseline	Three one-stage digesters; heat reuse from CHPs for tempering the digesters and surrounding buildings
NextGen intervention in circular economy for water sector	Two-stage digestion system with thermal pressure hydrolysis of digested excess sludge between the stages: higher heat demand due to TPH, reuse of excess heat from TPH and more available heat from CHPs due to increased methane production
TRL	Digestion system with TPH: TRL 8 → 9
Capacity	On average up to 250 m^3/h methane production; with TPH increase on average to 300 m^3/h (max. 330 m^3/h)
Quantifiable target	Enhanced biogas production due to TPH: Increase in methane production on average by factor of 1.2

3.1.4. Unique selling points

Unique selling points for the implementation of a thermal pressure hydrolysis unit are:

- ✓ Release of soluble organic matter leading to higher degradation during anaerobic digestion → enhancing biogas production and decreasing the organic matter content in the digestate
- ✓ Better dewaterability of digestate → reduction of disposal costs
- ✓ Release of phosphate and ammonium from disintegrated organic compounds, which is a unique selling point, if the technology is combined with a phosphorus and nitrogen recovery system from liquor

3.1.5. Principal and main characteristics of the technology

The TPH process is used as a pre-treatment for anaerobic digestion usually at wastewater treatment plants with a capacity for 100,000 population equivalents and greater. Originally, TPH was used to enhance the dewaterability of sludge (Zhen et al. 2017). However, in addition it was shown, that TPH improves the solubilisation of the sludge, reduces its viscosity

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

(Bougrier et al. 2006, Higgins et al. 2017, Liu et al. 2019) and increases its biogas yield (Neyens and Baeyens 2003).

Usually, excess sludge or mixed sludge consisting of primary and excess sludge are pre-treated via TPH and disintegrated at temperatures between 60 °C and 180 °C (Zhou et al. 2021). The TPH breaks down complex organic compounds and cell structures into more soluble compounds and thus, increases the substrate availability for anaerobic biodegradation. In order to save energy and CAPEX, the feed sludge to the TPH is dewatered to 12-20% DS.

As an example, the high temperature thermal hydrolysis process is described in detail here (Figure 20 and Figure 21). Typical high temperatures are between 140 °C and 180 °C. In addition, the TPH is operated at high pressure conditions usually ranging between 5 and 8 bar. For the sludge disintegration, first the sludge is tempered to 85 °C in a preheater for example by using excess heat from the hydrolysate. Then, the sludge passes through three tanks: (1) the pressuriser, (2) the reactor and the (3) economiser. In the pressuriser, the sludge is further heated to 105 °C by steam injection and the pressure is increased between 5 and 8 bar. In the reactor, the high pressure is maintained, while the temperature is further increased to around 140 °C or more with more steam. In the economiser, the pressure is decreased via a rapid decompression to 0.2 bar, forcing the sludge through a small orifice. Due to high mechanical shear forces with this “flash”, the microbial cell walls are destroyed and thus, soluble organic compounds are released.

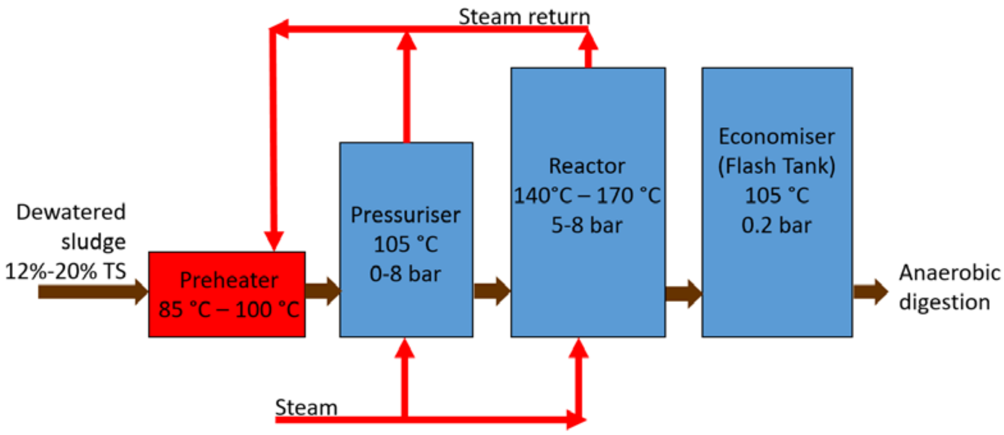


Figure 20 Flow scheme of the thermal pressure hydrolysis unit (Haarslev process).

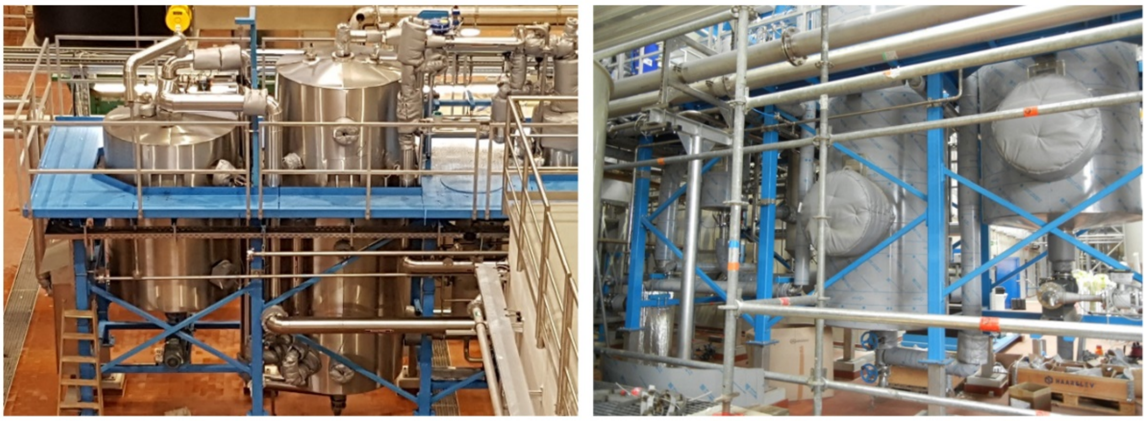


Figure 21 Pictures of the thermal pressure hydrolysis units (Haarslev process).

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement N°776541

3.1.6. Requirements for the implementation of the technology and operating conditions

Prior to the treatment as a specific feature in Braunschweig, the excess sludge is digested in order to reduce its organic matter content and then, it is thickened usually to a dry solids content of up to 18% (Table 17 and Figure 22). In order to disintegrate organic compounds such as microbial cells, the sludge must be heated to a range between 60 °C and 180 °C. At temperatures until up to 100 °C, the process is operated at normal pressure conditions. At high temperatures between >100 °C and 180 °C, the TPH is maintained at high pressure conditions between 2 and 10 bar. In detail, for the typical temperature range between 140 °C and 180 °C, the pressure is usually operated between 5 and 10 bars (DWA 2014). The hydraulic retention time (HRT) usually ranges between 15 and 60 min.

Table 17 Requirements and operating conditions for the thermal pressure hydrolysis.

Parameter	Units	Min	Max	Reference
DS sludge feed	%	**12**	**18**	DWA 2014, Heinze, J. (2022)
Temperature	°C	**60**	**180**	Zhou et al. 2021, DWA 2014; Neyens and Baeyens 2003
High pressure conditions (T > 100°C)	bar	**2**	**10**	Zhou et al. 2021, Pilli et al. 2015, DWA 2014
Hydraulic retention time	min	**15**	**60**	Zhou et al. 2021

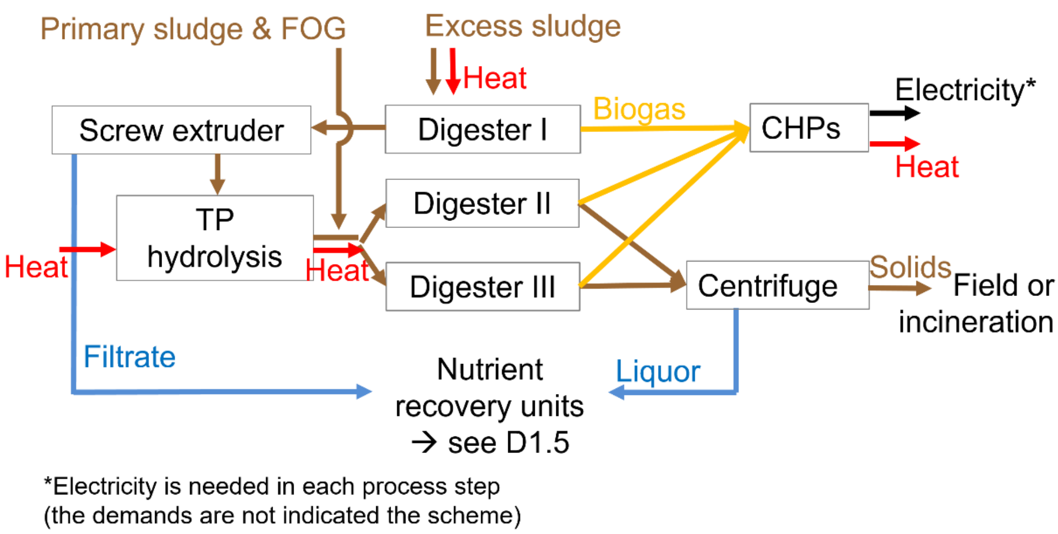


Figure 22 Flow scheme of the specific approach in Braunschweig: digestion of excess sludge followed by lysis of excess sludge (TPH) and again digestion (DLD) of the hydrolysed sludge together with the primary sludge and fat, oil and grease (FOG).

3.1.7. Results obtained

To evaluate the effect of the thermal pressure hydrolysis on the enhancement of the biogas production process, the methane production rate was considered as crucial parameter, because the methane content is crucial for the energy production via the combined heat and power plant.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

End of 2019, the thermal pressure hydrolysis (TPH) was implemented and put into operation. Beginning of 2019, when the two-stage digestion process had already been established, the methane production rate usually ranged between 230 m^3/h and 280 m^3/h as shown in Figure 20 for the first 280 days. Due to the effect of the TPH and hence, the better biodegradation of the hydrolysed sludge, the methane production rate increased from a minimum around 200 m^3/h to even 400 m^3/h at maximum. When the TPH was switched off, the methane production rate decreased to its old ranges. As soon as the TPH was put into operation again, the methane production rate increased again and remained on a higher level between 270 and 330 m^3/h. On average, the methane production rate increased by a factor of 1.2 due to the effect of the TPH.

A second benefit of the TPH is the better dewaterability of the digestate. Figure 23 shows the total solids content of the digestate before the implementation of the TPH and after. Without the effect of the TPH and the old adjustment of the old polymer, the total solids content ranged between 21% and 23%. Due to the effect of the TPH and after the adjustment of the polymer type and dosage from 22 g polymers/(kg DM) to 18 g polymers/(kg DM) due to the new characteristics of the hydrolysed digestate, the total solids content increased to a range between 24% and 26% in the final dewatering step. However, it should be noted, that also for the first dewatering step prior to the TPH, polymers are also needed, so that its total demand increased compared to the situation without TPH. On average the total solid content increased by a factor of 1.1. The better biodegradability and dewaterability led to a lower volume flowrate of dewatered digestate and hence, decreased its disposal costs.

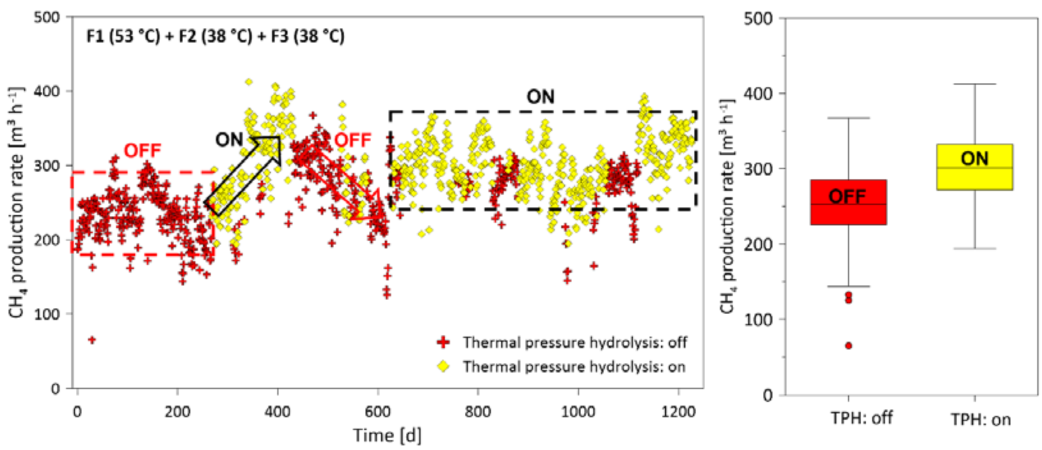


Figure 23 Methane production rate of the two-stage digestion system with (ON) and without (OFF) the effect of the thermal pressure hydrolysis.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

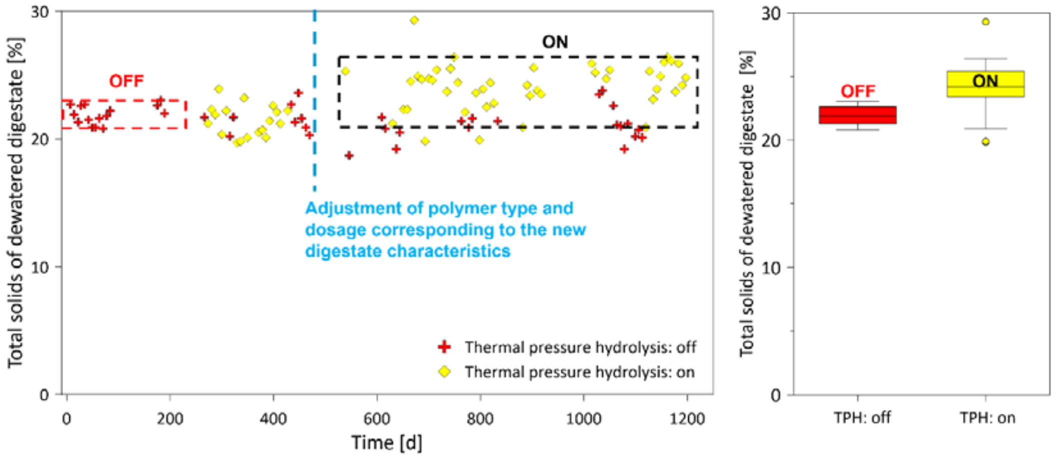


Figure 24 Total solids content of the dewatered digestate with (ON) and without (OFF) the effect of the thermal pressure hydrolysis.

The increased methane rate allows the combined heat and power plant (CHP) to produce more heat and electricity compared to the situation before NextGen. The increased heat production by the CHP and the heat demand of the thermal pressure hydrolysis and digesters are influencing the heat balance. To show the changes between heat demand and supply for different operation modes regarding heat supply of the thermal pressure hydrolysis three scenarios had been investigated:

a) A **Baseline** scenario before implementation of the NextGen scheme
b) The realised **NextGen I.** scenario with the thermal pressure hydrolysis using steam from a **steam generator using biogas**
c) A hypothetic **NextGen II.** Scenario with the thermal pressure hydrolysis using steam generated by **utilisation of HT** (high temperature heat) **from the CHP**

The CHP has a thermal efficiency of around 38%, whereby about 45% of the heat generated by the CHP is low temperature heat (LT) below 100 °C and 55% of the heat generated by the CHP is high temperature heat (HT) above 100 °C. LT heat can be used for various purposes e.g. heating the digester and associated buildings or pre-heating the return load for ammonium recovery, however the generation of steam for a thermal pressure hydrolysis is not possible with LT heat. This is only possible with HT heat, whereby of course HT heat can also be used for LT heating purposes.

A further limitation in terms of heat valorisation is the seasonal fluctuating heat demand, which is higher in the winter season and lower in the summer season.

a) Baseline before NexGen

Assuming a constant operation of the CHP in the baseline scenario, a constant amount of heat was produced over the whole year, resulting in a heat surplus in summer and a heat deficit in winter (= 106 MWh/year), which needs to be covered by gases from external sources (e.g., natural gas). This is illustrated in Figure 24. The heat surplus in summer (e.g., 1,800 MWh/year) was lost.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

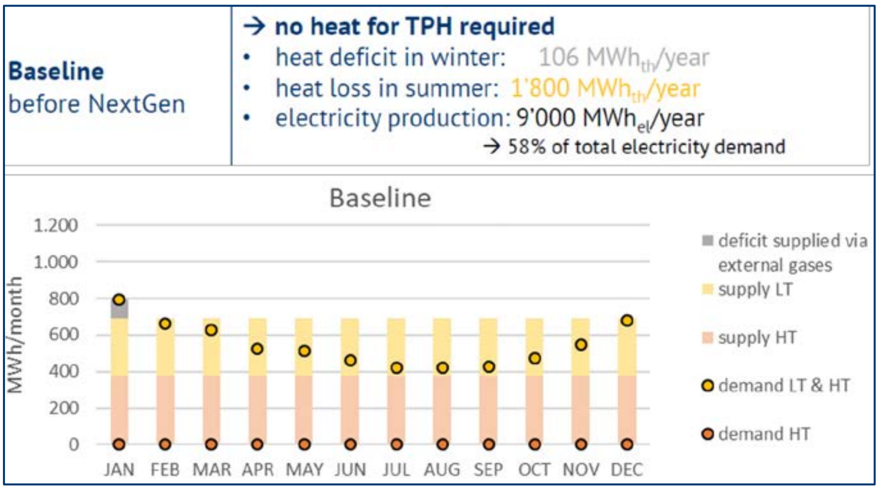


Figure 25 Monthly heat management and annual electricity generation for the Baseline scenario.

b) NextGen I. Steam generator uses biogas

The NextGen technologies (NextGen I.) have a strong impact on the heat management of the WWTP. The implementation of the thermal pressure hydrolysis using steam created a constant demand of HT heat, whereby the demand of LT heat decreased moderately (additional heat demand of nutrient recovery and reduced heat demand of digesters due to mixing the heated hydrolysed excess sludge with cold primary sludge). In total, the heat demand total system (TPH, digestion & ammonia stripping unit) increased by about 25%, however also the heat supply from the CHP increased by 8% on average due to the higher methane production rate as a result of the hydrolysis treatment, however 60% of the additional biogas is needed for steam generation. The HT heat for the steam production is realised via a steam evaporator using biogas. The consequential heat balance is shown in Figure 25. Compared to the baseline, the demand of natural gas is reduced by 85%. The heat loss in summer is increased towards 2,800 MWh/year, hence the increased excess heat produced by the CHP cannot be utilised in summer.

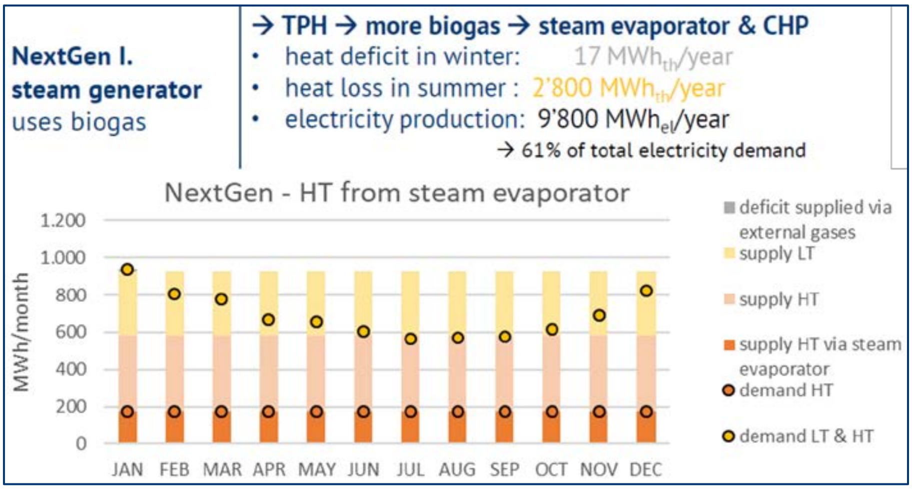


Figure 26 Monthly heat management and annual electricity generation for the NextGen I. scenario.

c) NextGen II. – Steam generated from HT heat from the CHP

An alternative for this scenario would be to use the present HT heat from the CHP for steam generation (scenario NextGen II.). However, this process requires in addition very expensive

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

heat exchangers and was due to high capital costs at the WWTP. This scenario is shown in Figure 26. There is an increasing demand heat from external sources in winter of 118 MWh/year, however the electricity production is increased since all biogas is utilised in the CHP. Thereby the own production might cover up 67 % of the total electricity demand of the WWTP compared to 61 % in the scenario NextGen I.

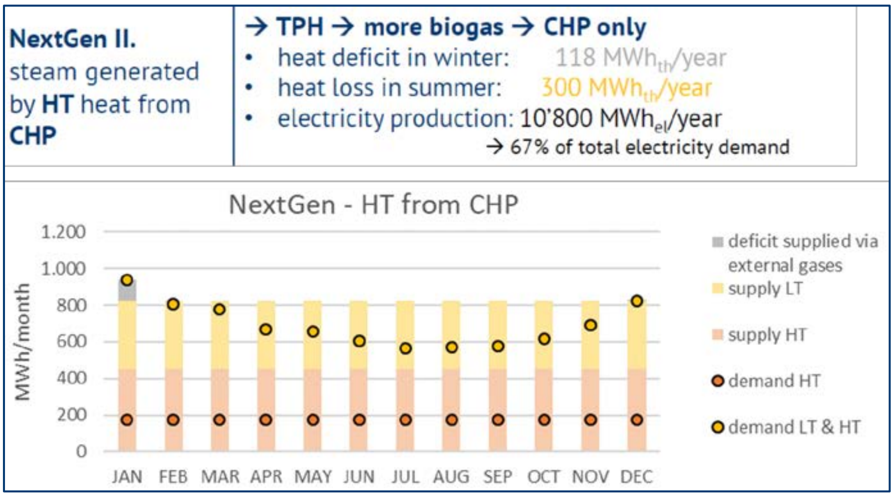


Figure 27 Monthly heat management and annual electricity generation for the NextGen II. scenario

Conclusion:
The NextGen I. scenario was the most economic one due to high CAPEX costs of the scenario NextGen II. The fact that the WWTP uses green gases (landfill and biogas from an agricultural biogas plant) for stream production reduces the carbon footprint of the NetGen scenario compared to the usage of natural gas. The analysis shows a clear preference for the Scenario NextGen II due to a higher electricity production and an overall heat balance targeted on demand, although a higher amount of natural gas must be supplied in winter. Also, the CO_2-footprint of Scenario NextGen II reveals higher benefits (see D2.1 of the NextGen project in the corresponding life cycle analysis (LCA)). However, due to high site-specific investment costs, this option had not been realised yet in Braunschweig.

3.1.8. Comparison of the baseline situation and the NextGen KPIs

Before the implementation of NextGen (baseline situation), the primary and excess sludge as well as fat, oil and grease (FOG) were digested in three one-stage digesters. The system did not involve a thermal pressure hydrolysis. The digesters were operated in parallel at a temperature of 38 °C. With the implementation of the thermal pressure hydrolysis, the one stage digesters were connected to a two-stage digestion system and one reactor was operated at an elevated temperature of 55 °C (Table 18 and Table 19). As already shown in chapter 3.1, the biogas production rate increased because of the thermal pressure hydrolysis. Correspondingly, the methane production rate increased on average by a factor of 1.2. Also, the dewaterability of the digestate increased by a factor of 1.1.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

Table 18 Biogas production rates with non-hydrolysed sludge (TPH=OFF).

TPH=OFF; two stage digestion						
		Units	**Mean**	**Standard deviation**	**Frequency or number of measurements**	**Comments**
Dry matter content of digestate after dewatering		%	22	1	Once a week	2019-2022 TPH: OFF
Digester 1 (1st Stage)	Operating temperature	°C	38			
	Digester volume	m^3	4.450			
	Methane production rate	Nm^3/h	119	56	Continuous flow measurement	2019-2022
	Methane content	%	61	1		
Digester 2 (2nd Stage)	Operating temperature	°C	55			
	Digester volume	m^3	2.100			
	Gas production rate	Nm^3/h	132	40	Continuous flow measurement	2019-2022
	Methane content	%	60	1.6		
Digester 3 (2nd Stage)	Operating temperature	°C	38			
	Digester volume	m^3	4.450			
	Gas production rate	Nm^3/h	165	69	Continuous flow measurement	2019-2022
	Methane content	%	61	1.4		

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

Table 19 Biogas production rates with hydrolysed sludge (TPH:ON).

WITH IMPLEMENTED NEXTGEN SYSTEM						
		Units	**Mean**	**Standard deviation**	**Frequency or number of measurements**	**Comments**
Dry matter content of digestate after dewatering		%	24	2	Once a week	2019-2022 TPH: ON
Digester 1 (1st Stage)	Operating temperature	°C	38			
	Digester volume	m^3	4.450			
	Gas production rate	Nm^3/h	162	35	Continuous flow measurement	2019-2022 TPH: ON
	Methane content	%	61	0.7		
Digester 2 (2nd Stage)	Operating temperature	°C	55			
	Digester volume	m^3	2.100			
	Gas production rate	Nm^3/h	127	40	Continuous flow measurement	2019-2022 TPH: ON
	Methane content	%	61	1.3		
Digester 3 (2nd Stage)	Operating temperature	°C	38			
	Digester volume	m^3	4.450			
	Gas production rate	Nm^3/h	206	60	Continuous flow measurement	2019-2022 TPH: ON
	Methane content	%	61	1.4		

The additional biogas is used for steam production for the thermal pressure hydrolysis and to produce more heat and energy via the CHP. Hence, the heat supply from external sources decreased from 106 to 17 kWh/year by 84% and the electricity production increased from 9,000 kWh/year to 9,800 kWh/year by 8%. As already explained in chapter 3.1, a future scenario, in which the total biogas is used in the CHP to produce HT heat and electricity could further reduce the heat loss in summer and increase the electricity production by additional 12%, if the HT heat would be reused for the steam production process.

The increase of 20% in the methane production rate was caused by an improved solubilisation of the sludge that increased the availability of substrate for anaerobic biodegradation due to the effect of the thermal pressure hydrolysis. Hereby, it should be noted, that only 42% of the organic load to the second digestion stage was pre-treated via the thermal pressure hydrolysis. Usually only excess sludge is pre-treated, because primary sludge already has a very good biodegradation and dewaterability. This means that the methane production rate referring only to the hydrolysed substrate increased on average more than 20%.

An increase in the biogas production rate due to the thermal hydrolysis process was also observed by Neyens and Baeyens (2003) and Razavi et al. (2021). Razavi et al. (2021) even showed an increase of 40% in their methane yield. The German network of experts for water, wastewater and waste (DWA) indicates in its guidelines that typical increasing rates in biogas production due to a thermal treatment of a side stream, for which a part of the digested sludge was dewatered, hydrolysed and fed back to the digester, can be between 15 and 25%

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

(DWA 2014) what is in the range of the observed enhancement of the biogas production process in Braunschweig, where also only a side stream (only digested excess sludge without primary sludge) via TPH was treated.

The better dewaterability of the digestate due to the thermal pressure treatment was also shown by Zhen et al. 2017. Neyens and Baeyens (2003) and Metcalf et al. 2013 even reached dry solids contents between 30% and 52%. It should ge noted, that 52% are very high and typical values are rather expected around 30%. In Braunschweig the dry solids content of the digestate increased only from 22% to 24% on average. However, in this case, only 15% of the influent volume flowrate to the second digestion stage was pre-treated via the thermal pressure hydrolysis and hence, 85% was not affected by the treatment, but contributed to the dry solid content. Thus, to achieve a better dewaterability of 10% of the mixed digestate, the hydrolysed fraction must have had a higher dry solid content. Nevertheless, the observations of Neyens and Baeyens (2003) and Metcalf et al. (2013) suggest, that even a higher dewaterability might be obtained in Braunschweig with further optimisation of the polymer type and dosing.

3.1.9. Lessons learned

<table>
<tr><td>Required competence</td><td>LOW  HIGH</td></tr>
<tr><td colspan="2">An intensive training is needed to provide a knowledge that is far beyond the “standard” wastewater treatment knowledge such as:
• Thermal hydrolysis process
• Operation and maintenance of a high pressure and high temperature (145 - 165 °C) system
• Explosion proof systems/environments
• Steam production
Due to the innovative technology, open minded and solution-oriented personnel is beneficial to operate such a technology. A daily manual process control and maintenance is conducted during at least 2h/d.</td></tr>
<tr><td>Maintenance</td><td>LOW  HIGH</td></tr>
<tr><td colspan="2">The thermal pressure hydrolysis unit is a high-maintenance product. Under normal conditions the effort for maintenance and manual process control is 2 h/d. Due to unforeseen events such as broken elements or unexpected gas leakages, the effort increases above 2 h/d.
Twice a year extensive maintenance work is required lasting around one week. In this case, the following steps are required:
• Intensive investigation regarding wearing of plant components
• Functional tests
• Cleaning of plant components</td></tr>
</table>

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement N°776541

<table>
<tr><td colspan="2">For this work, usually external experts support the extensive maintenance work. During the first three years of operation, the plant usually had two downtimes per month.</td></tr>
<tr><td>Technological risks</td><td>LOW  HIGH</td></tr>
<tr><td colspan="2">
Leakages of gas, steam or hot sludge can occur; in the case of methane emissions → explosion proof design of the unit is required. Only with an explosion proof design the technological risk is considered as relatively low.
Depending on the temperature non-biodegradable soluble (refractory) COD can form (~10 mg/L) → not critical for Braunschweig (COD$_{eff}$= 35 mg/L $<$ 50 mg/L) due to the temperature of 145 °C in the TPH that strongly reduces the formation of refractory COD
Due to the better biodegradability in the subsequent digestion, ammonium and phosphate concentrations increase. In combination with a nutrient recovery unit however, this is a benefit. Otherwise, the return loads of nitrogen and phosphorus to the WWTP increase.
Due to the innovative technology, it is important that the supplier of the technology is available for a longer time period after the installation and commissioning of the system in order to optimize the plant
</td></tr>
</table>

3.1.10. Best practice guideline to design and operate the technology

Important aspects to consider during the design and construction of the plant:

- Reuse of excess heat for steam generation increases energy efficiency of the whole system
- Enabling the recirculation of exhaust gas and/or exhaust steam
- Required operating conditions for pressure, temperature and hydraulic retention time must be easily to be controlled, so that they can be adjusted if needed
- Suitable materials must be used for the system (corrosion resistant, explosion proof, etc.)
- Explosion proof environment and system due to methane content and possible leakages
- Compliance with the country specific requirements for health and safety

Tested parameters for the optimisation of the TPH process:

Pressure, temperature and hydraulic retention time (HRT) as shown in (Table 19) were observed to decrease the formaton of non-biodegradable dissolved organic mater (refractory COD) and hence, delivered good results for 145 °C at 4 bars with an HRT of 90 min. In general, higher temperatures with a shorter HRT such as 165 °C at 6 bars and a HRT of 30 min are also possible. However, the higher the temperature, the lower the formation of refractory COD was (data not shown).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

Table 20 Crucial operating parameters for the thermal pressure hydrolysis: ranges for the best results regarding the release of dissolved organic matter.

Parameter	Units	Min	Max
TS feed	%	**10**	**13**
Pressuriser			
• **Temperature**	°C	**105**	
• **Pressure**	bar	**0 → 8**	
• **HRT**	min	**5**	
Reactor			
• **Temperature**	°C	**145**	
• **Pressure**	bar	**4**	
• **HRT**	min	**90**	
Economiser			
• **Temperature**	°C	**105**	
• **Pressure**	bar	**0.2**	
• **HRT**	min	**10-15**	

3.1.11. Literature references

AbwV (2022). Verordnung über Anforderungen an das Einleiten von Abwasser in Gewässer (Abwasserverordnung – AbwV vom 17. Juni 2004 BGBl. I S.1108, 2625 und vom 20. Januar 2022 BGBl. I S. 87). Bundesministerium der Justiz und Bundesamt für Justiz. http://www.gesetze-im-internet.de/abwv/AbwV.pdf

Barber, W. (2016). Thermal hydrolysis for sewage treatment: a critical review. Water Research, 104, 53–71. https://doi.org/10.1016/j.watres.2016.07.069

Böhler, M., Büttner, S., Liebi, C., Siegrist, H. (2012). Ammoniakstrippung mittels Luft zur Behandlung von Faulwasser und Urin auf der auf der Kläranlage Kloten/Opfikon. Aqua & Gas, 1, 1-7. https://doi.org/10.2166/wst.2009.045

Bougrier, C., Albasi, C., Delgenès, J., Carrère, H. (2006). Effect of ultrasonic, thermal and ozone pre-treatments on waste activated sludge solubilisation and anaerobic biodegradability. Chemical Engineering and Processing: Process Intensification, 45, 8, 711–718. https://doi.org/10.1016/j.cep.2006.02.005

Cornel, P., Schaum, C. (2009). Phosphorus recovery from wastewater: needs, techniques and costs. Water Science and Technology, 59, 1069–1076. https://doi.org/10.2166/wst.2009.045

Desmidt, E., Ghyselbrecht, K., Zhang, Y., Pinoy, van der Bruggen, B., Verstraete, W., Rabaey, K., Meesschaert, B. (2015). Global phosphorus scarcity and full-scale P-recovery techniques, Critical Reviews in Environmental Science and Technology, 45, 336-384. https://doi.org/10.1080/10643389.2013.866531

DüMV (2012). Verordnung über das Inverkehrbringen von Düngemitteln, Bodenhilfsstoffen, Kultursubstraten und Pflanzenhilfsmitteln (Düngemittelver-ordnung – DüMV vom 5. Dezember 2012, BGBl. I S. 2482), Bundesministerium der Justiz und Bundesamt für Justiz. https://www.gesetze-im-internet.de/d_mv_2012/D%C3%BCMV.pdf

DWA 2014. Merkblatt DWA-M 302 Klärschlammdesintegration, DWA Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e.V., Hennef, 82 S., ISBN 978-3-88721-227-8

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

González, C., Fernández, B., Molina, F., Camargo-Valero, M., Peláez, C. (2021). The determination of fertiliser quality of the formed struvite from a WWTP. Water Science and Technology. 83, 12, 3041-3053. https://doi.org/10.2166/wst.2021.162

Heidel, B., Rogge, T., Scheffknecht, G. (2014). Controlled re-emission of mercury in waste water treatment. Energy Procedia 61, 2307-2310. https://doi.org/10.1016/j.egypro.2014.11.1190

Heinze, J. (2022). Own data (personal communication), Abwasserverband Braunschweig.

Higgins, M., Beightol, S., Mandahar, U., Suzuki, R., Xiao, S., Lu, H., Le, T., Mah, J., Pathak, B., DeClippeleir, H., Novak, J., Al-Omari, A., Murthy, S. (2017). Pretreatment of a primary and secondary sludge blend at different thermal hydrolysis temperatures: impacts on anaerobic digestion, dewatering and filtrate characteristics. Water Research, 122, 557–569.
https://doi.org/10.1016/j.watres.2017.06.016

Kleyböcker, A., Kraus, F., Moermann, W., Pudova, N., Holba, M., Dünnebeil, A. (2020). Efficient carbon, nitrogen and phosphorus cycling in the European agri-food system and related up- und down-stream processes to mitigate emissions, Circular Agronomics, Deliverable 3.1, Grant Agreement Number 773649. https://www.circularagronomics.eu/wp-content/uploads/CA-D3.1-E-0820-Classification-streams.pdf

Kratz, S., Vogel, C., Adam, C. (2019). Agronomic performance of P recycling fertilizers and methods to predict it: a review, Nutrient Cycling in Agroecosystems, 115, 1-39. DOI: https://doi.org/10.1007/s10705-019-10010-7

Kuhn, E., Rensch, D., Haueter, R., Kopp, J. (2013). Stand der Technik für die (mechanische) Entwässerung von Klärschlamm, Ermittlung und Beschreibung, AWEL Amt für Abfall, Wasser, Energie und Luft, Abteilungen Abfallwirtschaft und Betriebe sowie Gewässerschutz, Baudirektion Kanton Zürich, Schweiz, 16 S.
http://docplayer.org/53056282-Stand-der-technik-fuer-die-mechanische-entwaesserung-von-klaerschlamm.html (accessed on 2020-12-14)

Liu, X., Xu, Q., Wang, D., Yang, Q., Wu, Y., Li, Y., Fu, Q., Yang, F., Liu, Y., Ni, B.J., Wang, Q., Li, X., 2019. Thermal-alkaline pretreatment of polyacrylamide flocculated waste activated sludge: process optimization and effects on anaerobic digestion and polyacrylamide degradation. Bioresource Technology, 281, 158–167.
http://hdl.handle.net/10453/131838

Metcalf & Eddy, Inc., Tchobanoglous, G., Stensel, H., Tsuchihashi, R. Burton, F. (2013). Wastewater Engineering: Treatment and Resource Recovery, Fifth Edition, McGraw-Hill Education, New York, 2018 p. ISBN 978-0-07-340118-8

Muy, M., Phukana, R., Brader, G., Samad, A., Moretti, M., Haiden, B., Pluchonc, S., Roeste, K., Vlaeminck, S., Spiller, M. (2021). A systematic comparison of commercially produced struvite: Quantities, qualities and soil-maize phosphorus availability. Science of the total Environment, 56, 143726, 1-12.
https://doi.org/10.1016/j.scitotenv.2020.143726

NuReSys 2020: http://www.nuresys.be/references.html (accessed on 2020-12-14)

Neyens, E., Baeyens, J. (2003). A review of thermal sludge pre-treatment processes to improve dewaterability. Journal of Hazardous Materials B98, 51-67. https://doi.org/10.1016/S0304-3894(02)00320-5

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

Park, N., Chang, H., Jang, Y., Lim, H., Jung, J., Kim, W. (2020). Critical conditions of struvite growth and recovery using MgO in pilot scale crystallization plant. Water, Science and Technology, 81, 12, 2511-2521. https://doi.org/10.2166/wst.2020.306

Phothilangka, P., Schoen, M., Wett, B. (2008). Benefits and drawbacks of thermal pre-hydrolysis for operational performance of wastewater treatment plants. Water Science and Technology, 58, 8, 1547-1553. https://doi.org/10.2166/wst.2008.500

Pilli, S., Yan, S., Tyagi, R., Surampalli, R. (2015). Thermal pretreatment of sewage sludge to enhance anaerobic digestion: a review. Critical Reviews in Environmental Science and Technology, 45, 6, 669-702. https://doi.org/10.1080/10643389.2013.876527

Rahman, M., Salleh, M., Rashid, U., Ahsan, A., Hossain, M., Ra, C. (2014). Production of slow release crystal fertilizer fromwastewaters through struvite crystallization – A review. Arabian Journal of Chemistry, 7, 139-155. http://dx.doi.org/10.1016/j.arabjc.2013.10.007

Razavi, A., Kaker, F., Koupaie, E., Hafez, H., Elbeshbishy, E. (2021). Biomethane production improvement by hydrothermal pretreatment of thickened waste activated sludge, Water, Science and Technology, 83, 2, 487-500 https://doi.org/10.2166/wst.2020.598

Sengupta, S., Nawaz, T., Beaudry, J. (2015). Nitrogen and Phosphorus recovery from wastewater. Curr Pollution Rep, 1, 155-166. https://doi.org/10.1007/s40726-015-0013-1

Shaddel, S., Ucar, S., Andreassen, J., Østerhus, S. (2019). Engineering of struvite crystals by regulating supersaturation – Correlation with phosphorus recovery, crystal morphology and process efficiency. Journal of Environmental Chemical Engineering, 7, 102918. https://doi.org/10.1016/j.jece.2019.102918

Szymańska, M., Sosulski, T., Szara, E., Wąs, A., Sulewski, P., van Pruissen, G., Cornelissen, R. (2019). Ammonium sulphate from a bio-refinery system as a fertilizer - agronomic and economic effectiveness on the farm scale. Energies, 12, 4721, 1-15. https://doi.org/10.3390/en12244721

Toutian, V., Barjenbruch, M., Unger, T., Loderer, C., Remy, C. (2020). Effect of temperature on biogas yield increase and formation of refractory COD during thermal hydrolysis of waste activated sludge. Water Research, 171, 115383.

Watson, C., Clemens, J., Wichern, F. (2019). Plant availability of magnesium and phosphorus from struvite with concurrent nitrification inhibitor application. Soil Use and Management, 35, 4, 675-682. https://doi.org/10.1111/sum.12527

Wilson, C., Novak, J. (2009). Hydrolysis of macromolecular components of primary and secondary wastewater sludge by thermal hydrolytic pretreatment. Water Research, 43, 18, 4489-4498.

Zhen, G., Lu, X., Kato, H., Zhao, Y., Li, Y. (2017). Overview of pretreatment strategies for enhancing sewage sludge disintegration and subsequent anaerobic digestion: current advances, full-scale application and future perspectives. Renewable and Sustainable Energy Reviews 69, 559–577. https://doi.org/10.1016/j.rser.2016.11.187

Zhou, P., Meshref, M., Dhar, B. (2021). Optimization of thermal hydrolysis process for enhancing anaerobic digestion in a wastewater treatment plant with existing primary sludge fermentation. Bioresource Technology 321, 124498. https://doi.org/10.1016/j.biortech.2020.124498

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

3.2. Decentralized energy recovery from anaerobic membrane bioreactor in Spernal (UK)

Authors: Ana Soares (UCRAN), Eleonora Paissoni (UCRAN), Pete Vale (STW), Matthew Palmer (STW)

3.2.1. Description of the demo site

Spernal wastewater treatment plant (WWTP) is a medium sized plant serving the towns of Redditch and Studley located approximately 24 km south of Birmingham (UK) (Figure 27). The site has a dry weather flow of 1,150 m^3/h (or 27,6000 m^3/day) serving 92,000 population equivalent (PE). Spernal WWTP includes a preliminary treatment, primary treatment, an activated sludge plant, secondary clarifiers, and sand filters. The treated effluent is discharged to the River Arrow, which is designated as a sensitive area under the Urban Wastewater Treatment Directive (UWWTD) and has an overall water body status of moderate under the Water Framework Directive (WFD). The sludge produced on site, and other local rural works, is further treated in anaerobic digesters and dewatered before being recycled to local farmland and industries. The biogas produced by digesters is burnt in combined heat and power (CHP) engines to produce heat and electricity.

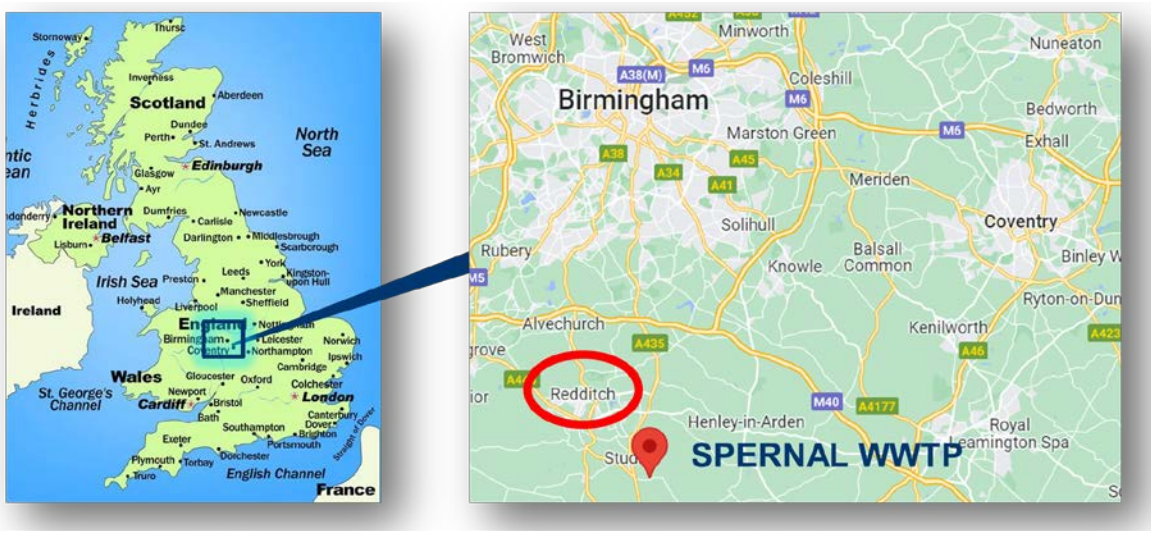


Figure 28 Location of the Spernal wastewater treatment plant (WWTP) within the United Kingdom (left) and local map (right).

Spernal serves as Severn Trent Water's "Urban Strategy Demonstration Site" where emerging technologies compatible with low energy demand, low greenhouse gas emissions and a circular economy approach are being evaluated (Figure 28). The "Urban Strategy Demonstration Site" contains all the infrastructure; power, wastewater feed, drainage, telemetry and biogas handling equipment necessary for the NEXT-GEN trials, together with office and laboratory facilities. Among the technologies tested is a multi-stream demonstration scale anaerobic wastewater treatment plant for carbon management and ion exchange processes for nutrient management (Figure 29). The demonstration plant

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

incorporates an anaerobic membrane bioreactor (AnMBR) complete with a membrane degassing unit to recover dissolved methane. AnMBR combines several benefits such as: no aeration energy for removal of COD/BOD, low sludge production and associated treatment efforts, biogas production (production of electricity/heat), pathogen and solids free effluent which can be re-used in several applications (e.g., farming and industrial use). The ion exchange (IEX) process enables targeted ammonia (N) and phosphorus (P) removal and recovery to produce a high-quality effluent whilst recovering calcium phosphate salts and ammonia sulphate solutions.

Figure 29. Areal picture showing the Urban Strategy Demonstration Site at Spernal WWTP and the location where the NextGen demonstrator was built.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

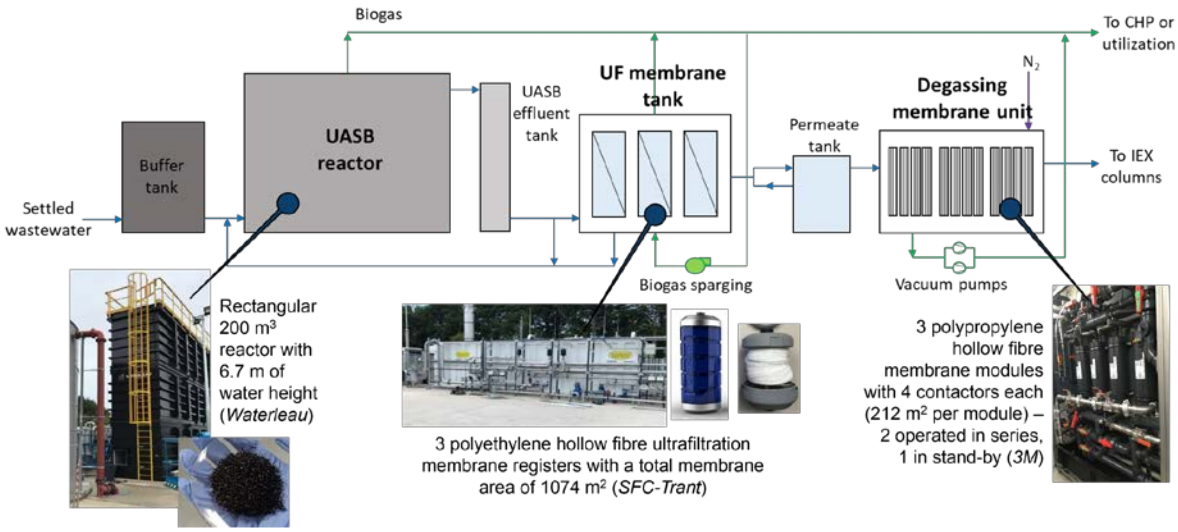


Figure 30 Areal picture showing the NEXT-GEN demonstrator including the anaerobic membrane reactor and degassing unit (top) and the schematic representation of the process (bottom).

The data gathered at the Spernal WWTP innovative technology flowsheet aims to demonstrate and showcase the viability of this transformative approach to wastewater treatment in cold- climate northern European countries, enabling a future of energy recovery combined with effective recovery of nutrients. The project confirms the optimal design and operating parameters to deliver a comprehensive energy balance and cost benefit assessment.

3.2.2. Motivation of implementing circular economy solutions

The water sector is a relatively large user of energy and a significant emitter of fugitive greenhouse gases (nitrous oxide and methane) it is therefore incumbent on water utilities to address the challenge of climate change by striving to reduce its carbon footprint. Transitioning to a more circular way of operating; reducing the amount of energy and chemicals required in treating water and recovering and reusing the energy, materials and water that is plentiful in wastewater will become a central strategy of water utilities.

The AnMBR/ion exchange flowsheet, once proven, can deliver an energy neutral wastewater treatment process, reduce process emissions by removing the main contributor to nitrous oxide emissions – biological nitrification and denitrification and facilitate resource recovery through producing a solids free disinfected effluent ideal for nutrient (N and P) recovery and/or the recovery of water and nutrients through fertigation.

3.2.3. Actions and case study objectives

The main objective of the Spernal demo case is the demonstration of an anaerobic membrane bioreactor (AnMBR) coupled with a membrane degassing unit to recover dissolved methane and thus increase biogas recovery and energy production through two scenarios as presented in Table 20.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement N°776541

Table 21 Actions and objectives of the case study in Spernal.

Case Study number & Name	**# 5 Spernal, Location: Spernal WWTP**
Subtasks	Sub-Task 1.3.3 Decentralized energy recovery and usage from anaerobic MBR (Spernal)
Technology baseline	Spernal wastewater treatment plant serves as Severn Trent Water's "Urban Strategy Demonstration Site"
NextGen intervention in circular economy for water sector	Biogas recovery and energy production throughout two scenarios: (1) CHP – electricity & heat (assuming an CHP engine efficiency of 40%) (2) Biogas upgrading and injection to the natural gas network
TRL	TRL 7→ 8
Capacity	Expected methane yields based on pilot scale work at Cranfield University: - At 20°C - 0.28 L CH_4 /g COD removed - At 7°C - 0.19 L CH_4 / g COD removed Assuming 90% removal of COD (from pilot trials): - Maximum production: 33 m^3 CH_4/day - Average: 11 m^3 CH_4/d
Quantifiable target	Electricity & heat produced for the two scenarios: 1) 44 kWh/day and ~ 50kWh heat/d (assuming around 15% losses) 2) 108 kWh/day

3.2.4. Unique selling points

Anaerobic membrane reactor combined with methane degassing system from effluent:

- ✓ No aeration energy required for removal of chemical and biological oxygen demand
- ✓ Low sludge production and associated treatment efforts
- ✓ Chemical free process to remove methane from liquids
- ✓ Up to 99% methane recovered from the dissolved fraction
- ✓ 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 footprint – low operation costs.

3.2.5. Principal and main characteristics of the technology

Anaerobic membrane bioreactor (AnMBR)

Anaerobic membrane bioreactor (AnMBR) combines an upflow anaerobic sludge blanket reactor (UASB) with physical separation membranes, ultrafiltration (UF) for solid-liquid separation and membrane contactor for gas-liquid separation. As shown in Figure 30, the UF membrane system is integrated with the UASB through the recirculation line side-stream configuration and both technologies should be evaluated together. The combined technologies result in solids, organic contaminant removal from wastewater and biogas production for energy recovery. The AnMBR treats typically 200 m^3/d (max 500 m^3/d) of settled wastewater. In the UASB reactor (Waterleau), inoculated with mesophilic industrial granular sludge, the recirculation (with the UASB effluent and/or from the UF membrane tank)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

is used to sustain an up-flow velocity of 0.8 m/h and a hydraulic retention time (HRT) of 8-10h. The three-polyethylene hollow fibre ultra-filtration membrane reactor (C-MEM from SFC-Trant) has a total membrane area of 1074 m^2 and are sparged with the biogas produced in the UASB reactor. The HRT in the UF is 1.3h and the flux is 10 LMH.

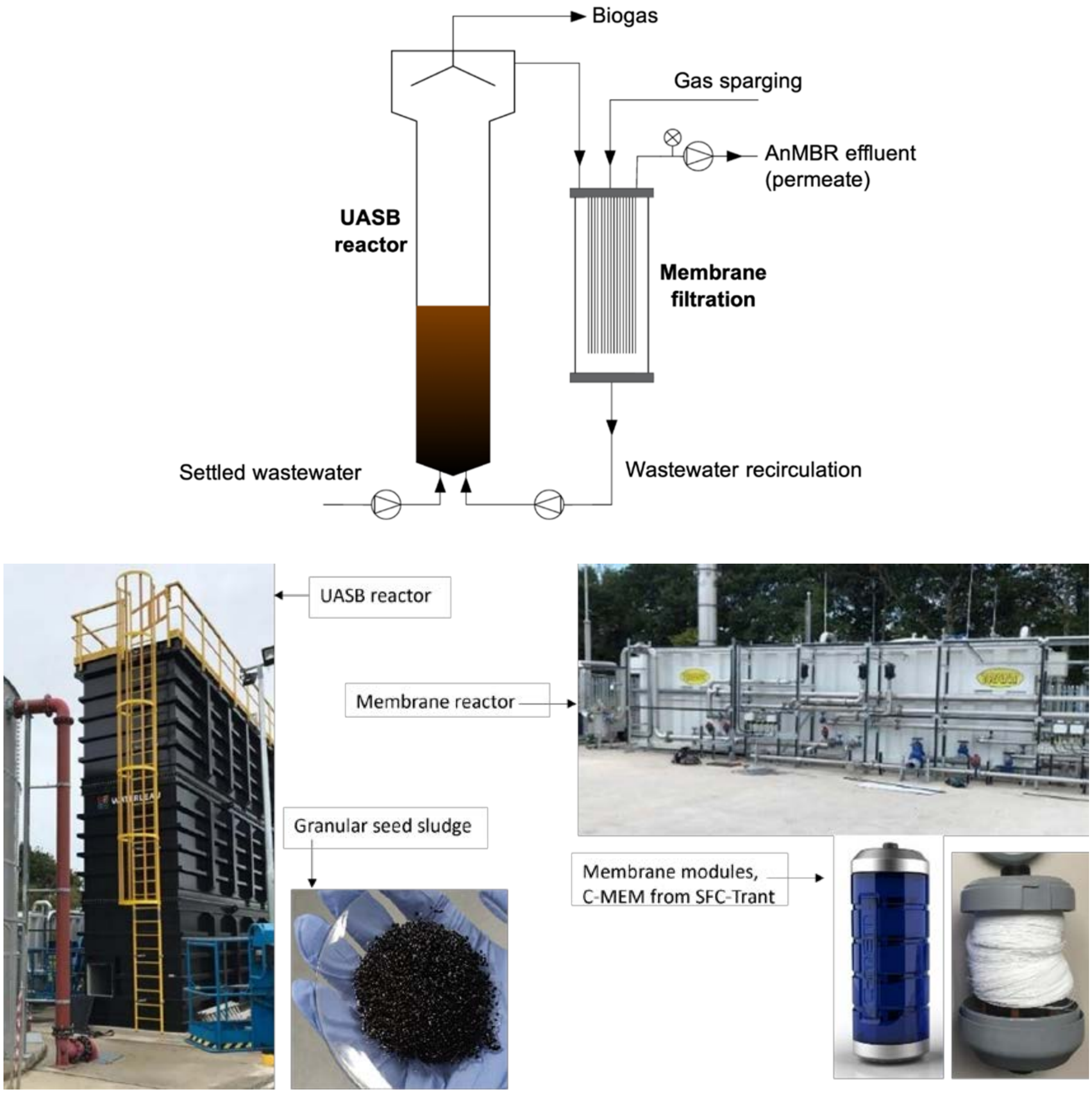


Figure 31 Schematic representation of the process of the AnMBR (top) and pictures of the technologies at Spernal WWTP (bottom).

Membrane contactor for methane degassing

The membrane contactor unit (MCU) has become reliable and efficient for recovering dissolved gases such as methane (CH_4) from AnMBR effluents. This methane can be used as an energy source. MCU employs a microporous hollow fibre membrane, which is the most used configuration for MCU due to its high gas-liquid separation efficiency and very high surface area as compared to flat sheet membranes. In the process, water passes through the outside (shell side) of the hollow fibres while a sweep gas (or vacuum) is applied to the inside (lumen side) of the fibres. Because the membrane is hydrophobic it allows direct contact between gas and water without dispersion. Applying a higher pressure to the water stream relative to the gas stream creates the driving force for dissolved gas in the water to pass through the membrane pores. The gas is then carried away by a vacuum pump and/or sweep

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

gas and combined into biogas to generate electrical and thermal energy. The degassing unit, composed of 3 modules of 3M Liqui-Cel hollow fibre membrane contactors, was operated applying vacuum and occasionally sweep gas (nitrogen) to the lumen side of the fibres.

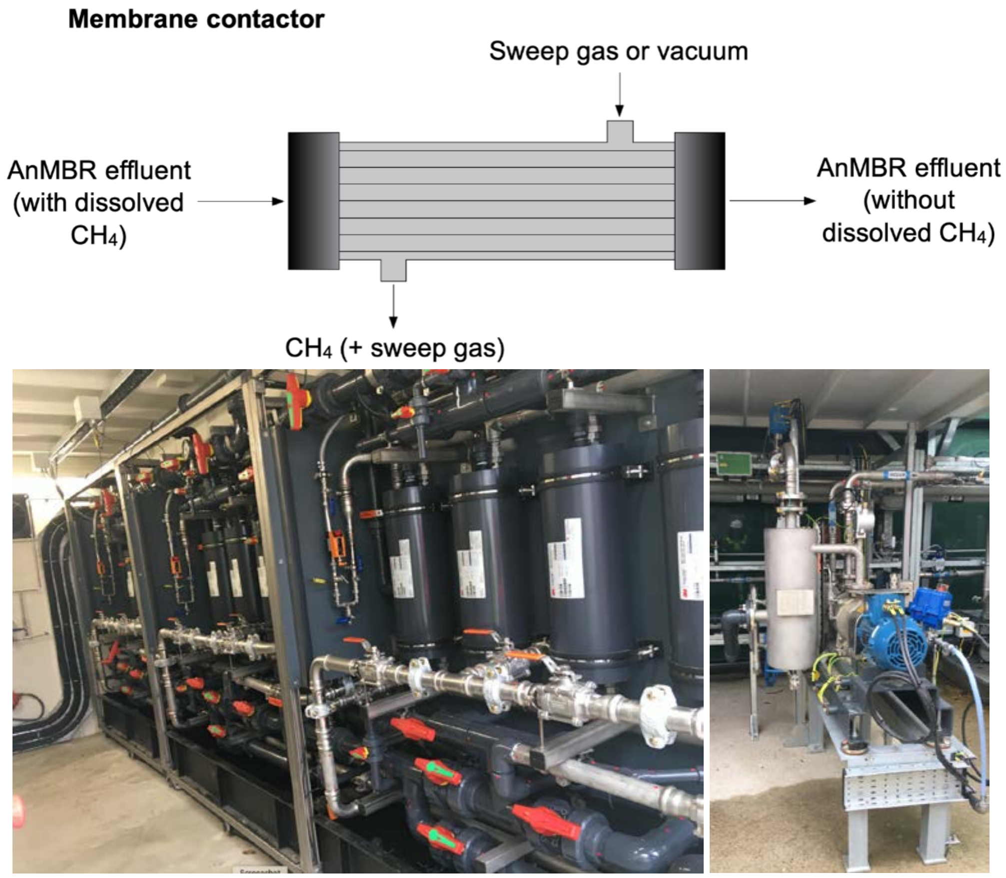


Figure 32 Schematic representation of the membrane contactor for methane degassing (top) and pictures of the technology at Spernal WWTP (bottom).

3.2.6. Requirements for the implementation of the technology and operating conditions

Anaerobic membrane bioreactor (AnMBR)

There are several parameters that affect biogas production from anaerobic membrane bioreactors (AnMBRs), including hydraulic retention time (HRT), solids retention time (SRT), temperature, pH, organic loading rate (OLR). The feasibility of anaerobic wastewater treatment in the UK has been demonstrated through pilot-scale trials that have taken place at Cranfield University since 2003. The work completed to date has showed that treating municipal low strength wastewater (COD<400 mg/L) at real temperatures (6-22°C, with an average of 14°C) is feasible and it has potential to replace traditional energy consuming aerobic wastewater treatment processes. Hydrolysis is the limiting step, also emphasising the need to provide long sludge retention times to ensure stable biogas production and solids can be maintained in the reactor by using a membrane filtration after the UASB. This combined system has been thoroughly investigated at pilot-scale. The operational envelope includes fluxes of 8-13 LMH and HRT 4-12h (Table 21). Membrane fouling is of physical nature and can

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement N°776541

be controlled by intermittent gas sparing practices using biogas, whilst still maintaining the process energy efficiency. The membrane operation can be turned up-down enabling design at average flow rather than full-flow to treatment. COD removals of 60-70% can be regularly achieved. Removals of 90-95% can be achieved when coupling the UASB with a membrane, producing effluents with 0 mg TSS/L; <20 mg COD/L and <10 mg BOD/L. Methane composition in the biogas is high (80%) facilitating its upgrading or other uses. On the other side, nutrients removal in the anaerobic reactor is negligible (5-10% phosphate removal and ammonia increase by 5-15% due to solids hydrolysis). Post-treatment for nutrients removal/recovery is necessary.

Table 22 Required operating conditions of the AnMBR.

Parameter	Units	Min	Max	Reference
Anaerobic bioreactor				
pH	-	6	8.2	Paissoni et al. 2022
Temperature	°C	4	25	
Flow rate	m^3/d			
Hydraulic retention time (HRT)	day	3	15	
Sludge retention time (SRT)	day	10	150	
Membrane contactor				
pH	-	6	8.2	Paissoni et al. 2022
Temperature	°C	4	25	
Flow rate	m^3/d			
Water Flux	$L/m^2/h$	5	50	
Specific gas demand per membrane area	$m^3/m^2 \cdot h$	1	10	

Other practical requirements for implementation of the technology:

- Old asset that is expired, such an ASP or trickling filters and WWTP needs rebuild
- Green field site (very rare)
- WWTP needing a significant upgrade
- Refurbish and upgrade a rural works (just the UASB)
- WWTP that requires the production of water for re-use (e.g., fertigation)
- Available fresh settled wastewater, ideally with low sulphates concentration.

Membrane contactor for methane degassing

The membrane degas system is implemented downstream of the AnMBR, treating a solids free effluent with dissolved methane (Table 22).

Table 23 Required operating conditions of the degassing system.

Parameter	Units	Min	Max	Reference
Influent dissolved methane	mg/L	1	20	Paissoni et al. 2022
Temperature	°C	4	30	
pH	-	6	9	
Pressure	mbar	2	60	
Gas extraction driver		Liquid ring vacuum pump technology and/or nitrogen gas		

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

Other practical requirements for implementation of the technology:

- Suitable for large works (size to be clarified) where an AnMBR has been implemented to avoid GHG emissions from uncontrolled release of dissolved methane.

3.2.7. Results obtained

Anaerobic membrane bioreactor (AnMBR)

The AnMBR was first fed from Sep-Nov 2021. After 4 weeks of operation (from start-up period), the system has been achieving >95% TSS removal, mostly due to the UF membrane (Figure 32). The SO_4 removal was >80%, indicating an active community of sulphate-reducing bacteria in the UASB reactor and no biogas production was observed after 1 month of operation. Overall, the AnMBR performance was not as expected. After thorough investigative work, the main reason for the limited performance and no biogas production was a septic influent to the AnMBR. This happened because the influent was first stored in a buffer tank with large capacity and very long hydraulic retention time (HRT), that made the tank act as an uncontrolled anaerobic reactor. Under these conditions the sulphate (over 100 mg/L, Figure 32) and COD were converted to H_2S, decreasing the oxidation reduction potential (ORP) of the wastewater to values of -100 to -200 mV and the wastewater became septic. Under such circumstances, specifically the very low ORP and high sulphates, the microbial community in the UASB was gradually shifted from anaerobic digestion to sulphate reducing bacteria. To solve the problem modifications were made to the buffer tank to reduce the HRT and new guidelines were issued to clean the buffer tank regularly.

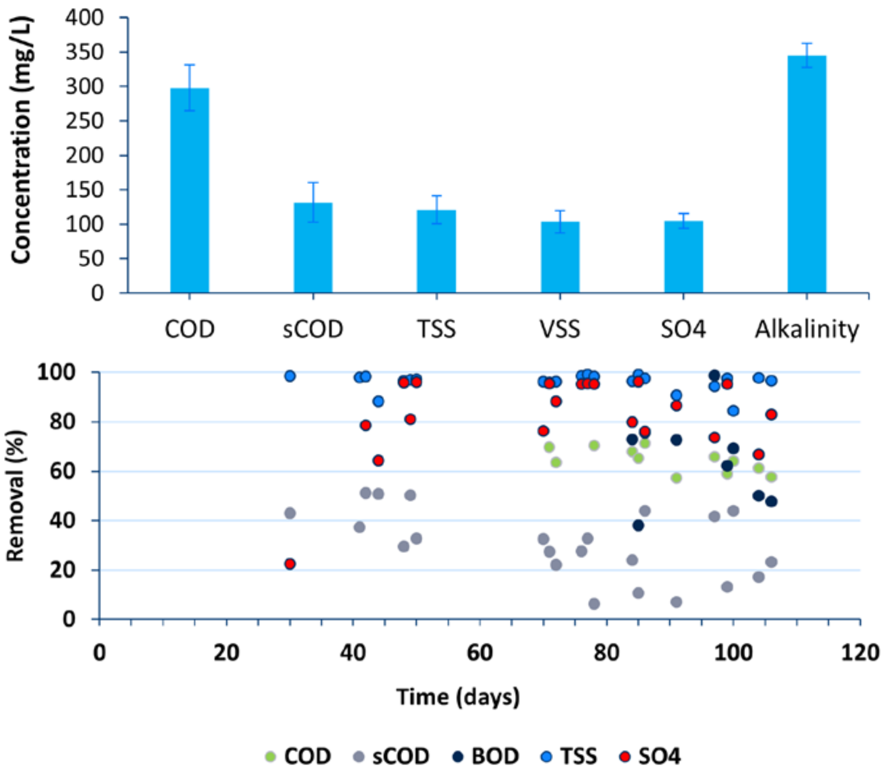


Figure 33 Influent characterisation to the AnMBR between Sep-Nov 2022 (top) and percent removals of various wastewater pollutants (bottom).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

From 22/11/2021 to 31/05/2022 the demonstration plant faced several issues that took some time to diagnose and fixe. The first one was a blockage in the UASB influent pump, that prevented the system to be fed. The problem was related with rag accumulation, and it was fixed by cleaning some internal components in the reactor. The second major issue was a compressor fail, also required for the UASB operation, as the valves were actuated by compressed air. Due to supply chain issues the spare to the compressor were not readily available leading to a long period of system shut-down. The AnMBR was finally put back in operation on the 31/05/2022. Issues with the UF cleaning and overpressure were also recorded and these have not been fully solved.

The AnMBR was re-seeded on the 8 Jun 2022 to guarantee that fresh active biomass in the reactor and also to ensure that methanogenic activity could be re-established, after the issues with septicity and long period without any fed or recirculation.

The AnMBR was started again on the 13/06/2022 after re-seeding with granular sludge supplied by Waterleau from an industrial wastewater treatment plant.

From the 13/06/2022 to the 12/07/2022, the temperature of the influent wastewater was in average 17.7±0.6°C. The characterisation of the influent settled wastewater (Table 23) shows low concentrations of COD (171 mg/L) and sCOD (91 mg/L), a BOD/COD ratio of 0.26 and a COD/SO_4 ratio of 1.39, which may hinder the conversion of organic matter into methane, due to low availability of biodegradable substrate, further to this sulphates reduction remained a concern. The settled wastewater treated is indeed quite diluted and weak, factors such as the pandemic and storm water might have played a role on such a low carbon load.

Table 24 Characterisation of the influent settled wastewater, fed to the UASB reactor.

	T	pH	COD	soluble COD	BOD	TSS	VSS	CE
	°C		mg/L	mg/L	mg/L	mg/L	mg/L	mS/cm
Average	17.7	8.08	171	91	45	46	40	957
Standard deviation	0.6	0.53	27	9	13	14	13	57

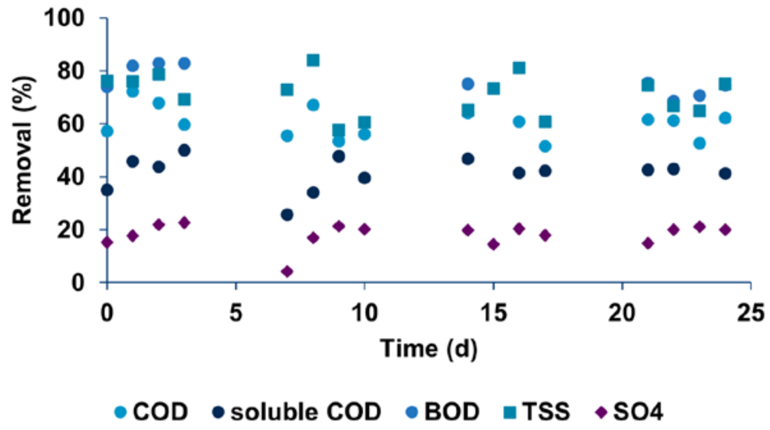
	NH_4-N	Total P	PO_4-P	SO_4	$COD:SO_4$	Alkalinity	VFAs
	mg/L	mg/L	mg/L	mg/L	-	mg $CaCO_3$/L	mg/L
Average	23.7	3.0	1.9	124	1.39	308	100
Standard deviation	2.1	0.5	0.2	9	0.25	14	16

*VFAs: Volatile fatty acids

The data presented in Figure 33 shows the pollutant removals in the AnMBR from 13/06/2022 to 12/07/2022, which can be considered the start-up period, of special relevance for the biological reactor. During this period the removals were, in average 60% COD, 76% BOD and 71% TSS (Figure 33). The methane content in the biogas was observed to increase steadily, reaching values of 60% and a production of 63 L/h (Figure 33). The AnMBR is still going through the start-up phase. Stable operation (i.e., after start-up) is considered when the COD removal is above 80% and methane concentration in the biogas is 70%. An odd value that is also being investigated is the TSS removal, which is expected to be 100% after the UF. A

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

potential explanation is the solids accumulation in the autosamplers and frequent cleaning has been advised together with spot samples to verify the data. Expected removals in the AnMBR once the issues have been solved and stable operation is reach are in the order of BOD >80%, COD>90% and TSS of 100%.



	COD	soluble COD	BOD	TSS	SO_4
Average removals (%) ± standard deviation	60±6	41±6	76±5	71±8	18±4

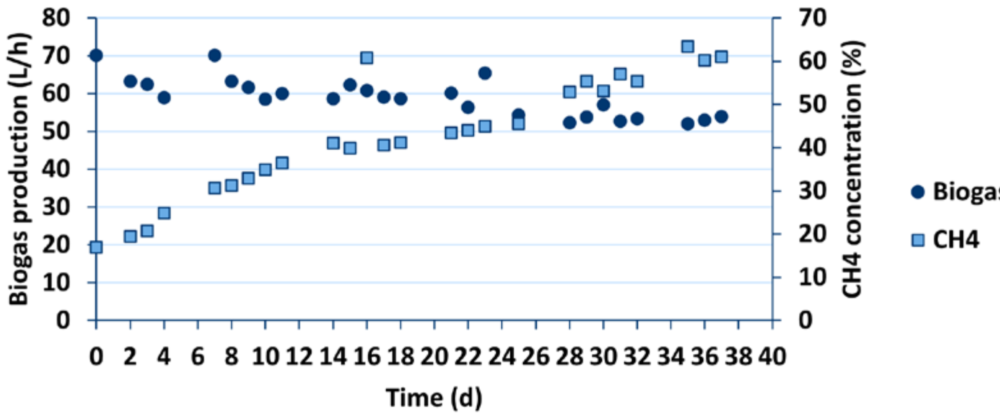


Figure 34 Pollutant removal (top) and biogas/methane content (bottom) in the AnMBR between Jun-July 2022, corresponding to the start-up period.

Solids management in the AnMBR is of vital importance, as these must be retained in the UASB reactor for as long as possible to go through hydrolysis followed by the 3 other stages of anaerobic digestion and ultimately result in biogas production. Further to this, the solids should not find their way to the UF to avoid fouling issues. The total solids concentration in the UASB is being carefully monitored (Figure 34) to help inform the reactor stability but also when the reactor needs to be de-sludge. So far, the UASB has not yet been de-sludge, which is one of its advantages of the system, i.e., a very low sludge production.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

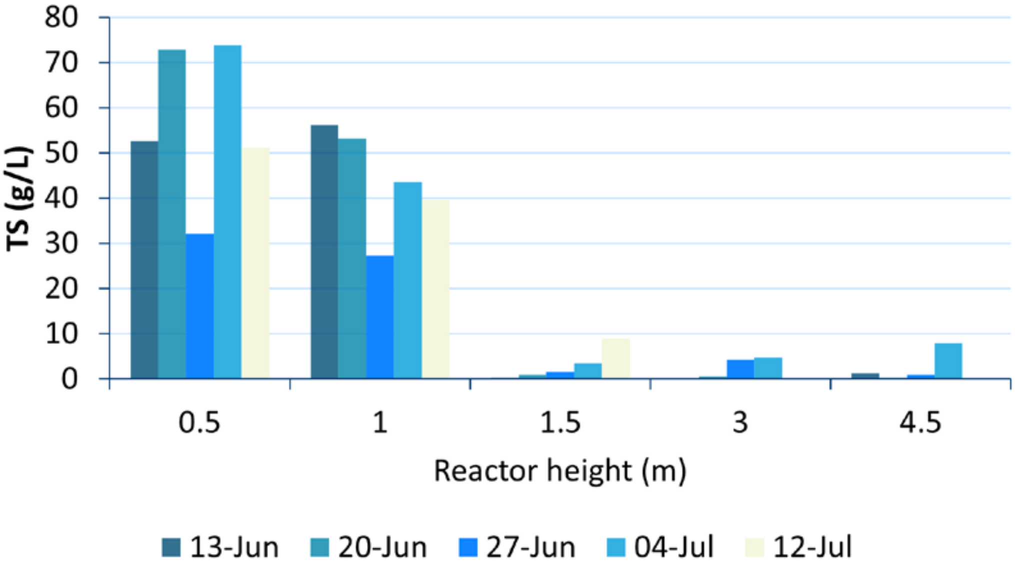


Figure 35 Total solids concentration in the UASB reactor to monitor the sludge blanket.

Discussion

The AnMBR operational efficiency was comparable to previous studies with variable influent municipal wastewater values for COD of 221 to 455 $mg.L^{-1}$ and TSS of 45 to 479 $mg.L^{-1}$ (Martin Garcia et al., 2013; Shin et al., 2014). The removal rates achieved for the COD and BOD_5 were similar to Wang et al. (2018), which obtained 83 ± 7% and 90 ± 6%, respectively. According to Ribera-Pi et al. (2020), a granular sludge inoculated AnMBR also achieved an sCOD removal of 43 ± 15%, once again very similar to this study. The removal efficiency of a self-forming hollow fibre dynamic membrane (i.e., membrane reactors made of materials with high pore size where the filtration cake enables the pore size of the reactor to be similar to ultrafiltration), analysed by Isik et al. (2019), was only around 42% and 34% for TSS and VSS, respectively. The correspondence of the reactors' parameters to previous studies promoted the validity of the results and performed work. The temperature upon which the experiments were conducted was also mentioned in other studies, where Gouveia et al. (2015) operated with a temperature of 18 ± 2°C and Wang et al. (2018) of 16.3 ± 3.7°C.

Regardless of the high COD influent in the systems, the methane yield reported was considered an average value. This was mainly because no solids could escape the system and hydrolysis was maximised during operation, which in turn impacted methane yields, ensuring they were high. In a study by Gouveia et al. (2015b), a municipal wastewater fed and pilot-scaled AnMBR that operated at a similar temperature of 18°C and a lower COD of 74 to 225 mg/L produced a methane yield of around 0.16-0.31 L CH_4/g COD removed, which is comparable to this study. Similarly, another two AnMBR from the study by Ribera-Pi et al. (2020), which had a lower temperature of 9.7 ± 2.4°C, had methane yields of 018 -0.20 L CH_4/g COD removed.

Membrane contactor for methane degassing

The dissolved methane concentration in the effluent of the AnMBR reached 7 mg/L in mid July 2022 (Figure 35).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

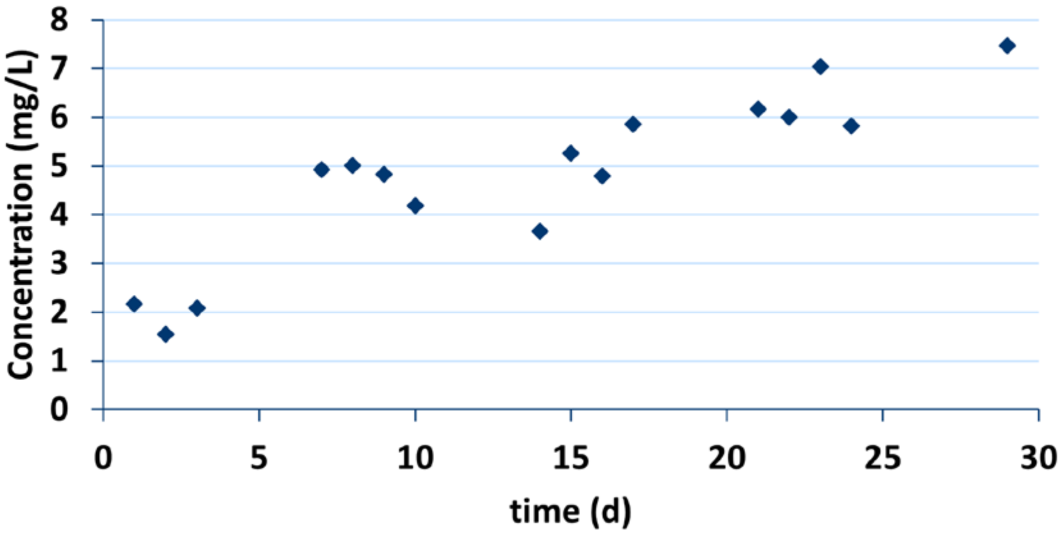


Figure 36 Dissolved methane concentration in the AnMBR effluent between Jun-July 2022.

The degassing plant is based around commercially sourced 3MTM Liqui-celTM industrial series membrane contactor units. This technology was selected following a feasibility assessment of other approaches including vortex and towers. Membrane degassing provides a vacuum and sweep gas to disturb the equilibrium of dissolved gases in the UF permeate.

The specifications for the degassing system were as follows:

- Membrane degas system capable of recovering methane from a UF membrane filtration system effluent to a dissolved methane concentration of 0.14 mg/L from an initial concentration of 20 mg/L (99% removal).
- To meet this, 12 No. Liqui-celTM Membrane contactors (EXF-8x20) with supports were supplied by 3MTM.
- The membranes are designed to operate at 2 Nm^3/h at 60 mbar (a).
- Liquid ring vacuum pump technology was chosen to generate the vacuum. The membrane contactors are not available as a package plant installation. This meant significant

Design was required to engineer the following aspects:

- Nitrogen generation for sweep gas
- Water system and cooling for vacuum pump operation. This additionally was complicated by the relatively low potable water supply available and the explosive atmosphere requirements.
- Clean in place (CIP) system using two separate chemicals and softened water for membrane cleaning
- Pipework installation that could satisfy the explosive atmosphere regulations.
- Detailed dangerous substances and explosive atmospheres (DSEAR) investigations around this design and the interface with the works. Given that this plant required multiple pieces of equipment from different suppliers, the interface required significant design input.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

- The interface with the UF plant and other works returns. A significant amount of instrumentation is required to maintain plant safety if monitors record errant readings for factors such as temperature, pH, gas flow.

The system was commissioned in August 2021. However, throughout the initial operation the following significant issues were identified:

1. Pressure testing of the contactors was not possible, therefore leaks during commissioning were encountered and were challenging to identify. Detailed testing of the membrane building for hazardous gases was required.
2. The complexity of the degassing process ensures that if the plant is offline, restarting the degassing system can be challenging. The contractor has advised that automation of the CIP and sweep gas systems would likely be required for larger scale systems to be operable.
3. The system is designed to shut down on instrumentation failures. This means that probe faults, caused a number of degassing plant shut downs. Similar interlocks on upstream processes also caused degassing plant shutdowns.
4. Degassing systems remove the gases in solution. The higher than anticipated presence of H2S in the UF permeate means that high levels of H2S were removed in the offgas. This increased the likelihood of corrosion. Corrosion of the water trap seals (for the liquid ring vacuum pump) has been observed in this trial.
5. Many of the items are therefore bespoke or require site specific integration. Replacement of these items is therefore not a straightforward process.

Initial results (not presented here) showed that the degassing system was functional. However, multiple issues with operating the pilot plant between Aug 2021 and Dec 2021 mean that any data from this period is not reliable. Some of these plant shut downs are attributable to specific instrumentation or equipment issues with the degassing plant. For example, the nitrogen generator required a replacement of the internal thermometer.

The AnMBR pilot was taken offline between January and March 2022. Re-commissioning of the AnMBR plant demonstrated very poor performance with minimal methane production as discussed elsewhere in this report. This was attributed to bacterial community changes associated with a long period of non-operation.

The decision was taken to re-seed the AnMBR UASB on the 8th of June 2022. Unfortunately, during the period between March and June 2022, the aforementioned corrosion of the water trap seals occurred. As such, the degassing plant had to be taken offline whilst a replacement and fix for the problem could be found. The water trap has not been replaced since June 2022 and as such the degassing plant has been non-operational during the data period presented in this report.

As such, there is no reliable and representative degassing plant data available to assess the viability of this approach for methane recovery.

Severn Trent have continued to try and to fix the water trap mechanical fault preventing degassing plant operation since June 2022. Simultaneously, the membrane solids removal

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

performance has declined. If the degassing was reinstated, it is likely that the residual solids deposition on the membrane contactor would undermine the performance of the membrane. Similar issues around fouling as found elsewhere on the plant may occur as well if not addressed. The membrane performance is therefore being investigated as a pre-requisite for degassing plant reinstatement.

In addition, a review of the AnMBR pilot plant overall has identified twenty items (including the water trap replacement and membrane performance issues previously raised) that need to be changed or fixed to maintain consistent operation. Severn Trent are investigating these items and progressing them if amenable. When consistent operation of the three constituent parts (UASB, UF, degassing) can be achieved, a further review of the efficacy of the degassing system will be viable.

3.2.8. Comparison of the baseline situation and the NextGen KPIs

The existing Spernal WWTP constitutes the base case to provide a comparison to the NextGen Spernal demonstrators.

The baseline case (Table 24):
The Spernal WWTP is a medium sized plant and treats an average daily flow of 27 ML/d to a 10 mg BOD/L, 25 mg TSS/L, 5 to 10 mg NH_4/L and 2 mg P/L standard. The plant includes a preliminary treatment (6 mm screening and grit removal), conventional primary settlement tanks with iron dosing for P removal, secondary treatment comprising of trickling filters for 33% of the flow and activated sludge for the remainder and tertiary sand filters.

Effluent from the plant presents COD of 44.6 ± 11.5 mg/L, BOD of 3.6 ± 2.7 mg/L total suspended solids (TSS) of 9.8 ± 6.8 mg/L; a total nitrogen (TN) content of 34.5 ± 5.18 mg/L, and a total phosphorous (TP) of 1.18 ± 0.3 mg/L. In this case, the quantity of microorganisms for both influent and effluent is not shown as it is not measured regularly. The overall quality of both influent and effluent is better during the winter period.

Around 14.62 ton/day (1.061 kg VS/m^3·d) sludge produced from primary settlement tanks is treated by anaerobic digestion process. It produces about 13,156 m^3/day biogas containing 40.2-63.7% methane (average 53.6%). The total methane gas production ranges from 216.4 to 999.9 L·CH_4/kg VS (average 507.25 L·CH_4/kg VS). Dewatered sludge of 0.297 ton/day is reused for farmlands and industries.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

Table 25 Base case Spernal WWTP flow rates, standard influent and effluent parameters.

Parameter		Units	Mean value	Standard deviation	Frequency of the measures	Summer mean value	Standard deviation	Winter mean value	Standard deviation	Considered years for the analysis
Influent	Flowrate	m^3/h	1267	447	Daily	1114	344	1422	484	2018
Effluent	Flowrate	m^3/h	1097	324.7	Daily	921.4	195.8	128	330.7	2018
Influent to the Spernal WWTP	COD	mg O_2/L	861.2	520.8	Twice per month	947.7	604.5	759	405.1	2018
	BOD_5	mg O_2/L	276.1	172.3	Twice per month	322.7	192.8	221.1	132.3	2018
	TSS	mg/L	515.2	300.6	Twice per month	536.9	358.3	489.6	228.9	2018
	TN	mg N/L	32.6	7.1	twice per month	34.7	4.3	30	9	2018
	NH4-N	mg N/L	31	8.2	Twice per month	34.2	4.6	27.2	10	2018
	TP	mg P/L	7.5	3.3	Twice per month	8.46	3.5	6.3	2.9	2018
Effluent from the Spernal WWTP	COD	mg O_2/L	44.6	11.5	Twice per month	43.69	11.1	45.7	12.4	2018
	BOD_5	mg O_2/L	3.6	2.7	Twice per month	4.2	2.7	2.9	2.6	2018
	TSS	mg/L	9.8	6.9	Twice per month	7.2	3.6	12.8	8.6	2018
	TN	mg N/L	34.5	5.2	Twice per month	34.1	5.6	35	4.9	2018
	NH4-N	mg N/L	2.4	1.1	Twice per month	2	1	2.8	1.1	2018
	TP	mg P /L	1.2	0.3	Twice per month	1.2	0.3	1.1	0.3	2018

The demonstration scale at Spernal was overdesigned in relation to energy consuming equipment, such as pumps, blowers, compressors, instrumentation, standby and duty equipment, etc. This was necessary to have high flexibility of operation within the plant operation to allow for a wide range of conditions to be investigated during the study and reduce risk. As such the energy consumption at Spernal was significantly higher than the expected in an efficiently design full-scale plant without the need for extra redundancy. To overcome this, the energy balance at Spernal was estimated using standard equations.

Energy consumption:

The pumps energy was estimated according to Equation 6 (Kong et al., 2021):

$$Ec = \frac{\rho * g * H}{1000 * 3600 * \eta}$$ Equation 6

The density of wastewater ρ was considered 1000 kg/m^3, with the pump's efficiency η being set to 80% and a hydraulic pressure head (H) of 3 m.

The energy demand of the MBR permeate pumps can be calculated by accounting for the average transmembrane pressure (TMP) kPa in every operational condition in Equation 7 (Kong et al., 2021):

$$Ec = \frac{TMP \cdot Q}{\eta}$$ Equation 7

The gas blowers in MBR also had a significant energy demand and were considered in this study, using Equation 8 and Equation 9 (Verrecht et al., 2008, Judd, 2010):

$$k = \frac{P_{A,1} T_{A,1} \lambda}{2.73 \cdot 10^5 \eta (\lambda - 1)} \left[\left(\frac{P_{A,2}}{P_{A,1}} \right)^{(1-(\frac{1}{\lambda}))} - 1 \right]$$ Equation 8

$$Ec = \frac{k \cdot SGD_m \cdot 1000}{J \cdot 3600}$$ Equation 9

The energy factor k was calculated considering the absolute temperature $T_{A,1}$, which was 293 K. The inlet or atmospheric pressure and outlet pressures $P_{A,1}$ and $P_{A,2}$, respectively, were calculated using the expressed membrane height. Furthermore, the efficiency of the blower η was defined as 60% and the heat capacity ratio of biogas λ (Martin et al., 2011). Using this factor, the consumption E_c was estimated by including the flux J and specific gas demand per unit of membrane area SGD_m at the condition operated.

Energy production:

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

Concentrating on the pumps as the primary source of energy demand for every operated reactor, the consumption of the feeding and recirculation pumps (Ec) was estimated according to Equation 10 (Kong et al., 2021):

$$Ec = \frac{\rho * g * H}{1000 * 3600 * \eta}$$ Equation 10

The density of wastewater ρ was considered 1000 kg/m^3, with the pump's efficiency η being set to 80% and a hydraulic pressure head (H) for the reactor.

The energy demand of permeate pumps can be calculated by accounting for the average TMP kPa in every operational condition in Equation 11 (Kong et al., 2021):

$$Ec = \frac{TMP \cdot Q}{\eta}$$ Equation 11

The gas blowers in MBR also had a significant energy demand and were considered in this study, using Equation 12 and Equation 13 (Verrecht et al., 2008, Judd, 2010):

$$k = \frac{P_{A,1} T_{A,1} \lambda}{2.73 \cdot 10^5 \eta(\lambda - 1)} \left[\left(\frac{P_{A,2}}{P_{A,1}} \right)^{(1-(\frac{1}{\lambda}))} - 1 \right]$$ Equation 12

$$Ec = \frac{k \cdot SGD_m \cdot 1000}{J \cdot 3600}$$ Equation 13

The energy factor k was calculated considering the absolute temperature $T_{A,1}$, which was 293 K. The inlet or atmospheric pressure and outlet pressures $P_{A,1}$ and $P_{A,2}$, respectively, were calculated using the expressed membrane height. Furthermore, the efficiency of the blower η was defined as 60% and the heat capacity ratio of biogas λ (Martin et al., 2011). Using this factor, the consumption E_c was estimated by including the flux J and specific gas demand (SGD) per unit of membrane area SGD_m at the condition operated.

The energy consumption per each process unit is as follow:

- UASB influent feed pump: 0.023 kWh/m^3
- Membrane reactor recirculation to UASB pump: 0.025 kWh/m^3
- Degas influent feed pump: 0.010 kWh/m^3
- Membrane permeate pump: 0.024 kWh/m^3
- Membrane backwash: 0.052 kWh/m^3
- Biogas blower to control membrane fouling: 0.25 kWh/m^3
- Methane degas system: could not be estimated as not enough data was collected
- Ion exchange process for ammonia removal and recovery: 0.08 kWh/m^3 *
- Ion exchange process for ammonia removal and recovery: 0.06 kWh/m^3 *

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

(*the IEX is operated in sequence for N and P removal, and it is challenging to separate the 2 regarding energy consumption, as only one feed pump is used, regenerant recovery not included in the estimation)

The energy production on the Spernal demonstrator originates from the biogas produced in the AnMBR. On average the biogas yield recorded was 0.15 $m^3 \cdot CH_4$/kg COD removed, this includes the dissolved methane part of the biogas production

The energy balance for Spernal demonstrator is described in Figure 36. Overall, the energy demand for all the process units (i.e.: UASB, UF, IEX-N, IEX-P, N recovery, P recovery) was estimated at 0.52 kWh/m^3 and the energy production from the biogas in average 0.09 kWh/m^3. The overall energy balance was estimated at 0.43 kWh/m^3, which is lower for the combination of a a biological nutrient removal (BNR) and tertiary filter with 0.65 kWh/m^3 (Long et al 2016, Siatou et al 2020) (Figure 36). As the COD of the influent was particularly low in this trial, the energy balance was significantly impacted and energy neutrality was not achieved. Further to this, there is biogas production in the anaerobic digester of primary sludge and wasted UASB solids hat was not estimated due to lack of data but it would help the overall energy balance.

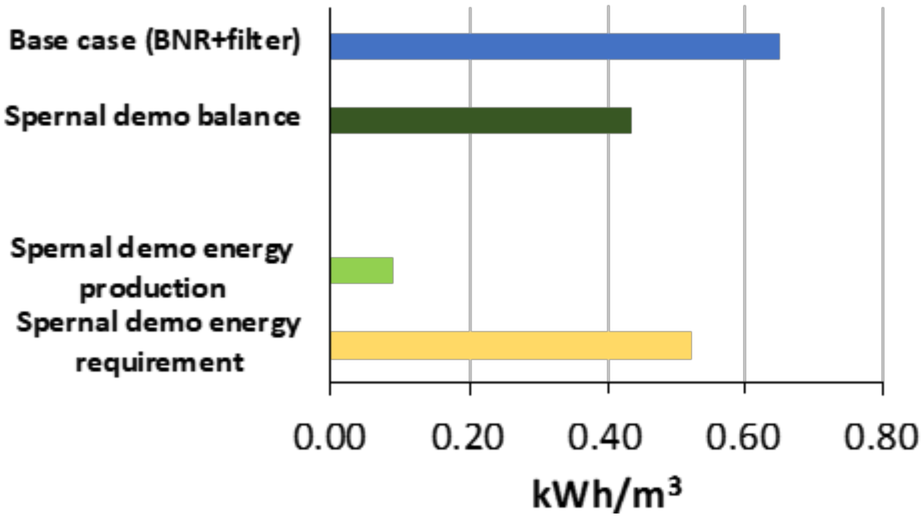


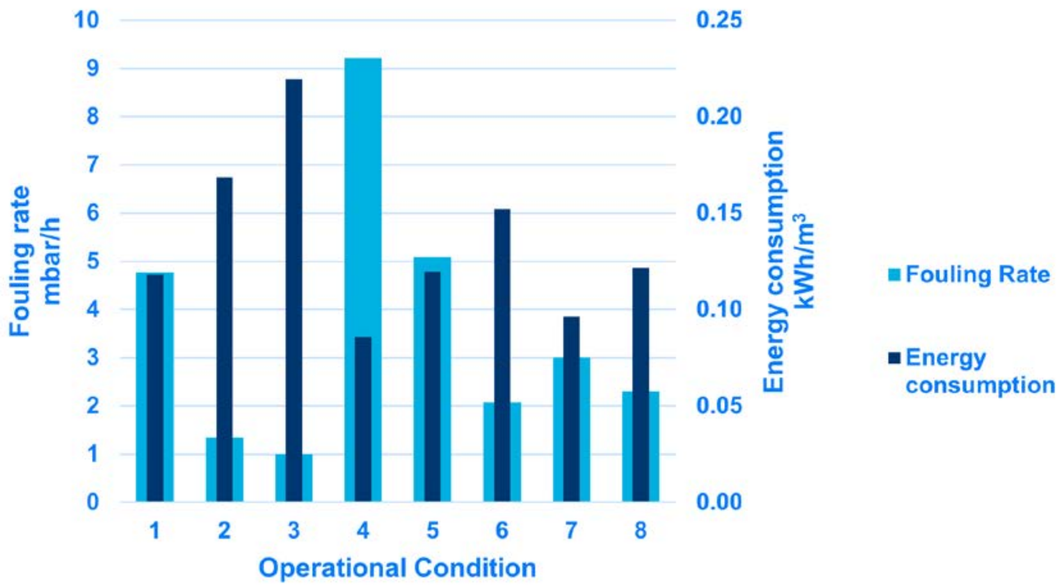
Figure 37 Spernal demonstration plant energy balance, including UASB, UF, IEX-N, IEX-P, N recovery, P recovery.

Key questions that need to be addressed include the challenge of membrane fouling and the required energy demand, as this has a high estimated energy demand (biogas blower to control membrane fouling: 0.25 kWh/m^3). Membrane fouling risks damaging the adopted membranes and system components, thus restricting the flux. The fouling cannot be avoided during long-term operation, requiring very effective mitigation cycles that decrease the fouling rate. Gas flushing or sparging plays a vital role in reducing membrane fouling by promoting the movement of foulants from membrane surfaces (Wang et al., 2018). Relaxation or membrane zero-flux operation is the part of the cycle where processes are stopped, providing for the exploitation of natural processes such as sedimentation. Backwashing refers to the backwards pumping of water through a membrane or filter media resulting in a high energy draw (Hu et al., 2021). Strategies such as sparging cause one-third or more of the energy demand in wastewater treatment (Robles et al., 2012). There is also a

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

paradox in the applied antifouling strategies, which are currently energy intensive, yet produce methane from the production of biogas resulting in energy production (Aslam et al., 2022).

To better understand how to control fouling in the AnMBR, a parallel pilot-plant was operated at Cranfield University, also combining a UASB fed with settled wastewater and the sidestream membrane module, that was the same as applied in Spernal. By varying the flux and specific gas demand (SGD) fouling can be controlled efficiently and energy consumption improved (Figure 37). These results would need to be duplicated in Spernal and the optimised energy balance verified.



Operational Condition	1	2	3	4	5	6	7	8
Flux, LMH	8	8	8	12	12	12	16	16
$SGD_{m\text{-}net}$, $m^3/m^2 \cdot h$	0.08	0.12	0.16	0.08	0.12	0.16	0.12	0.16

Figure 38 MBR energy consumption optimisation at pilot-scale by investigating fouling rates (top) by varying membrane flux and specific gas demand per unit of membrane area (SGDm) (bottom).

The energy production and consumption for Spernal base case is defined in Table 25 and compared to the NextGen technologies tested.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

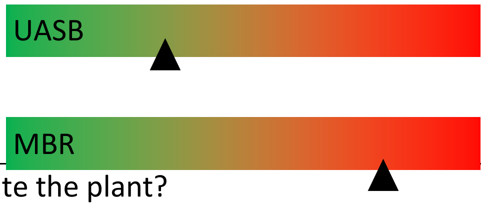
Table 26 Energy related balances for base case and NextGen system.

Parameter			Units	Mean	Min-Max	Standard deviation	Frequency and number of measurements
Base case		Energy demand	kWh/d	9,000			
		Energy production*	kWh/d	15,000			
	Digester	Total throughput	ton/day	14.6	2.15-23.88	3.24	
		Organic loading rate to Digester	kg $VS/(m^3 \cdot d)$	1.06			
		Methane yield (calculated)	L CH_4/(kg VS)	507.2	216.4-999.9	200.22	57/13.44%
NextGen system	Digester	Organic loading rate to Digester	kg $VS/(m^3*d)$	no sludge from AnMBR wasted went to the digester			
		Digester Volume	m^3	10800			
	UASB + UF	Energy consumption	kWh/m^3	0.374			
		Energy production	kWh/m3	0.09			3 times a week
	Degas system	Energy consumption	kWh/m^3	To be determined			
	Energy balance	Biogas production rate	m^3/d	1400			3 times a week
		Methane content	%	60%	Expected to reach 80%		3 times a week
		Dissolved methane production	mg/L	7			Daily
		Recovery of dissolved CH4 from Degas	%	To be determined			

*Sludge imports from nearby WWTPs are digested in Spernal generating energy the anaerobic digester

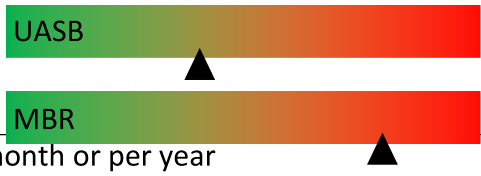
3.2.9. Lessons learned

Anaerobic membrane bioreactor (AnMBR)

Required competence	LOW  HIGH

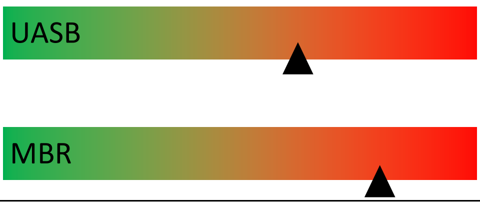
LOW HIGH

- Which knowledge is required to operate the plant?
  - UASB: Biological processes (aerobic effluent treatment processes and anaerobic sludge treatment processes) are widely used and understood by utilities. Operation of the UASB is little different to activated sludge plants and anaerobic digesters that are widely used.
  - MBR: UF membranes are a complex piece of equipment, however, operation is largely automated and water utilities are familiar with operating the e.g. aerobic MBRs.
- What kind of training is necessary?
  - UASB: Key operational set points - up flow velocity, sludge banket levels
  - UASB: Key performance metrics - biogas yields, sulphide level
  - MBR: Principles of operation - e.g., membrane flux rate
  - MBR: Cleaning requirements - scour, back pulse and chemical

Maintenance	LOW  HIGH

LOW HIGH

- Frequency of plant maintenance per month or per year
  - UASB: Monthly
  - MBR: Regular (weekly) chemical cleans (as per design, might not be needed, but installed by commercial company)
- Duration of a normal maintenance procedure
  - UASB: 1 day/month
  - MBR: 2h/week
- Duration of active process control per day (manual process control, unforeseen events)
  - UASB: 2h/day
  - MBR: 1h/day
- Are external experts required to conduct the maintenance procedure?
  - UASB: No
  - MBR: No

Technological risks	LOW  HIGH

LOW HIGH

- Reasons for downtimes or technical risks
  - UASB: Septicity – sulphate reducing bacteria affecting biogas yield and causing elevated H2S concentration in effluent – reseed required
  - UASB: Mechanical failures (compressor)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

- UASB: Blockage of inlet feed
- MBR: Membrane leak

- Frequency of plant downtimes per year
  - UASB: 3 issues over 1 year – Septicity of the influent, blockage and mechanical failure of compressor
  - MBR: 1 Issue
- Duration of plant downtimes
  - UASB: 3 months
  - MBR: 3 months
- Are external experts required to restart the plant?
  - UASB: Yes
  - MBR: No
- Which measures can avoid such downtimes?
  - UASB: Routine maintenance, better management of inlet conditions
  - MBR: Membrane leak was a manufacturing or commissioning issue

Membrane contactor for methane degassing

Required competence	LOW  HIGH

- Which knowledge is required to operate the plant?
  - New technology for the water sector – complex operation.
  - Optimal degassing procedure still to be determined – vacuum degas, sweep degas or a combination?
- What kind of training is necessary?
  - Operation and maintenance procedures

Maintenance	LOW  HIGH

- Frequency of plant maintenance per month or per year
  - 2 day/month
- Duration of a normal maintenance procedure
  - 2h
- Duration of active process control per day (manual process control, unforeseen events)
  - 1h
- Are external experts required to conduct the maintenance procedure?
  - No

Technological risks	LOW  HIGH

- Reasons for downtimes or technical risks
  - Leaks in vacuum pipework
  - Membrane cleaning
- Frequency of plant downtimes per year
  - 3 since start up
- Duration of plant downtimes

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

- 3 months
- Are external experts required to restart the plant?
  - No
- Which measures can avoid such downtimes?
  - Better understanding of the technology/process

3.2.10. Best practice guideline to design and operate the technology

Anaerobic membrane bioreactor (AnMBR)

- What is important to consider during the construction of the plant?
  - Working with commercial suppliers has been seen favourable, but the integration of the different technologies as single flowsheet has been challenging.
  - Health & Safety considerations dealing with biogas and H_2S
- What is crucial for the start-up of the plant?
  - Having a fresh influent (i.e., redox potential > 0)
  - Understand sulphate fate
  - Having nitrogen gas available to sparge the membrane whilst biogas production starts
- Which parameters are crucial for the optimization of the production process?
  - Having a fresh influent
  - Organic loads and hydraulic retention time
  - Solids management
  - Membrane flux, sparging and cleaning routines
- Which ranges for the crucial parameters delivered the best removal and production results?
  - Still to be clarified

Membrane contactor for methane degassing

- What is important to consider during the construction of the plant?
  - Working with commercial suppliers has been seen favourable, but the integration of the different technologies as single flowsheet has been challenging. The degassing unit is the first of its kind and there is a steep learning curve.
- What is crucial for the start-up of the plant?
  - Still to be clarified
- Which parameters are crucial for the optimization of the production process?
  - Still to be clarified
- Which ranges for the crucial parameters delivered the best removal and production results?
  - Still to be clarified

3.2.11. Literature references

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

Aslam, A., Khan, S. J., Shahzad, H. M. A. (2022). Anaerobic membrane bioreactors (AnMBRs) for municipal wastewater treatment-potential benefits, constraints, and future perspectives: An updated review. Science of The Total Environment, 802, 149612.

Martin Garcia, I. M., Mokosch, M., Soares, A., Pidou, M., Jefferson, B. (2013). Impact on reactor configuration on the performance of anaerobic MBRs: treatment of settled sewage in temperate climates. Water research, 47(14), 4853-4860.

Gouveia, J., Plaza, F., Garralon, G., Fdz-Polanco, F., Peña, M. (2015). Long-term operation of a pilot scale anaerobic membrane bioreactor (AnMBR) for the treatment of municipal wastewater under psychrophilic conditions. Bioresource Technology. J. 185, 225–233.

Gouveia, J., Plaza, F., Garralon, G., Fdz-Polanco, F., Peña, M. (2015b). A novel configuration for an anaerobic submerged membrane bioreactor (AnSMBR), Bioresource Technology, 198, 510–519.

Hu, Y., Du, R., Nitta, S., Ji, J., Rong, C., Cai, X., ... & Li, Y. Y. (2021). Identification of sustainable filtration mode of an anaerobic membrane bioreactor for wastewater treatment towards low-fouling operation and efficient bioenergy production. Journal of Cleaner Production, 329, 129686.

Isik, O., Abdelrahman, A.M., Ozgun, H., Ersahin, M.E., Demir, I., Koyuncu, I. (2019). Comparative evaluation of ultrafiltration and dynamic membranes in an aerobic membrane bioreactor for municipal wastewater treatment. Environmental Science and Pollution Research, 26(32), 32723-32733.

Judd, S. (2010). The MBR Book: Principles and applications of membrane bioreactors in water and wastewater treatment. 2nd ed., Elsevier.

Kong, Z., Li, L., Wu, J., Wang, T., Rong, C., Luo, Z., Pan, Y., Li, D., Li, Y., Huang, Y., Li, Y. (2021). Evaluation of bio-energy recovery from the anaerobic treatment of municipal wastewater by a pilot-scale submerged anaerobic membrane bioreactor (AnMBR) at ambient temperature. Bioresource Technology, Vol. 339, 125551.

Longo, S., D'Antoni, B.M., Bongards, M., Chaparro, A., Cronrath, A., Fatone, F., Lema, J., M., Mauricio-Iglesias, M., Soares, A., Hospido, A., (2016). Monitoring and diagnosis of energy consumption in wastewater treatment plants. A state of the art and proposals for improvement. Appl. Energy 179, 1251–1268.

Martin, I., Pidou, M., Soares, A., Judd, S., Jefferson, B. (2011). Modelling the energy demands of aerobic and anaerobic membrane bioreactors for wastewater treatment. Environmental technology, Vol. 32, No. 9, 921–932.

Paissoni, E., Sakar, H., Vale, P., Pitt, S., Smith, R., Jefferson, B., Soares, A. (2022). Demonstration-scale anaerobic membrane bioreactor and degassing unit for resource recovery in temperate climates. 17th IWA World Conference on Anaerobic Digestion, Ann Arbor, MI, United States.

Ribera-Pi, J., Campitelli, A., Badia-Fabregat, M., Jubany, I., Martinez-Llado, X., McAdam, E., Jefferson, B., Soares, A. (2020). Hydrolysis and methanogenesis in UASB-AnMBR treating municipal wastewater under psychrophilic conditions: Importance of reactor configuration and inoculum. Frontiers in Bioengineering and Biotechnology, 8, 1-14.

Robles, A., Ruano, M. V., García-Usach, F., Ferrer, J. (2012). Sub-critical filtration conditions of commercial hollow-fibre membranes in a submerged anaerobic MBR (HF-SAnMBR) system: the effect of gas sparging intensity. Bioresource Technology, 114, 247-254.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

Shin, C., McCarty, P. L., Kim, J., Bae, J. (2014). Pilot-scale temperate climate treatment of domestic wastewater with a staged anaerobic fluidized membrane bioreactor (SAF-MBR). Bioresource Technology, 159, 95–103.

Siatou, A., Manali, A., Gikas, P. (2020). Energy Consumption and Internal Distribution in Activated Sludge Wastewater Treatment Plants of Greece. Water, 12, 1204.

Verrecht, B, Judd, S., Guglielmi, G., Brepols, C., Mulder, J.W. (2008). An aeration energy model for an immersed membrane bioreactor, Water Res. 42, 4761–4770.

Wang, K. M., Martin Garcia, N., Soares, A., Jefferson, B., McAdam, E. J. (2018). Comparison of fouling between aerobic and anaerobic MBR treating municipal wastewater. H2Open Journal 1(2), 131-159.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement N°776541

4. Heat storage and recovery

4.1. Aquifer thermal energy storage in Westland (NL)

Authors: Martin Bloemendal, Stijn Beernink, Steven Ros, Niels Hartog, Jos Frijns (KWR)

4.1.1. Description of the demo site

The Westland Region in the Province of South Holland, the Netherlands, are dense urban and industrial areas and greenhouse horticulture complexes. Spanning in a total area of 410 km^2, the region is one of the most densely populated spaces in the Netherlands, with approximately 1.2 million inhabitants living and working in a total of approximately 0.5 million households and 40,000 businesses and industries.

Westland is well known for its greenhouse horticulture, where mainly vegetables (tomatoes, peppers, cucumbers etc., mostly on hydroponics), flowers and potted plants are grown. The geographical scope of NextGen activities is Delfland (which is similar to the area of the Water Authority of Delfland) and contains the Westland horticulture area and other rural areas and part of the urban regions of Rotterdam, Delft and The Hague.

The NextGen circular water-energy solutions are assessed on the following levels:

- Province of South Holland: heat balance and HT-ATES application conditions
- Polanen greenhouse cluster in Westland: feasibility of HT-ATES
- Koppert Cress greenhouse company at Westland (part of Polanen cluster): performance of HT-ATES system.

State of play at the start of NextGen

Energy use in greenhouses

Natural gas is used for heating of the greenhouses and producing electricity through Combined Heat & Power (CHP) engines. The electricity is used in the greenhouses for high intensity lighting (24 h per day) to grow the crops. CO_2 of the CHP engine is used to enrich the atmosphere of the greenhouses, again to increase crop yields.

Several clusters of greenhouses in the Westland already have, or are developing, a geothermal well as an alternative sustainable heat source. However, none of these clusters have a large-scale heat buffer. ***Aquifer Thermal Energy Storage (ATES) systems*** could provide for this heat storage. In Westland, a number of ATES systems are in operation and at the horticulture company Koppert Cress the current system is being converted to a High Temperature-ATES.

Block diagram of the pre-existing treatment scheme in horticulture

In the current greenhouses water, gas, and power are utilised as shown in Figure 38.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

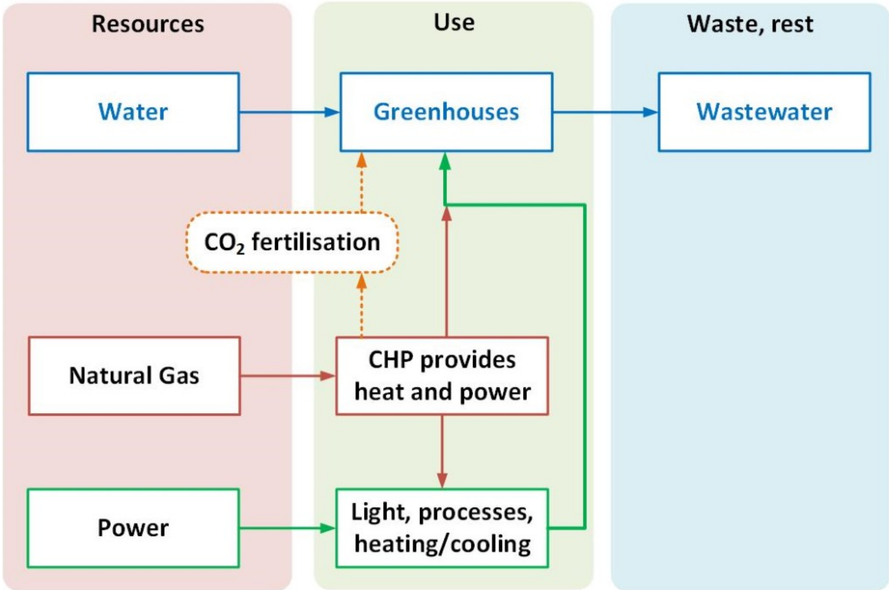


Figure 39 Diagram of the current system of Westland horticulture

4.1.2. Motivation of implementing circular economy solutions

The Province of South Holland aims at strategies towards wiser, more circular water management in the coming decades, in light of challenges such as a variable climate and changing population. Within the Westland Region, various projects, activities, and initiatives are already running that contribute to the objectives that have been set at national and provincial level, and from the Hoogheemraadschap Delfland and the municipality of Westland. The report 'Delfland Circular', written by Dijcker et al. (2017) on behalf of Hoogheemraadschap Delfland, states that there is still a lack of an integral and overarching strategy, with which an optimal mix of cost-effective measures can be realized together with the environment. It is important to develop such a strategy, because different objectives can sometimes conflict with each other when closing material, water, and energy cycles (for example, it takes energy to recover raw materials), and therefore considerations must be made with regard to these trade-offs.

The NextGen assessment addresses the following circular water technologies:

- Aquifer Storage & Recovery / water banking systems and reuse of WWTP effluent for the horticulture sector
- Circular urban water management solutions (rainwater harvesting, grey water recycling green roofs and domestic water saving)
- High Temperature-Aquifer Thermal Energy Storage system (HT-ATES) at the horticulture.

Specific for the horticulture in Westland (Figure 39), alternatives to improve the water and energy system in the horticulture sector are demonstrated by rainwater storage and effluent reuse (subtask 1.2.1), and by High-Temperature Aquifer Thermal Energy Storage (HT-ATES) at the horticulture Koppert Crest (subtask 1.3.5, this report).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

Heat storage through ATES
In the horticulture area of the Westland there is a large demand for heat. Traditionally this demand is met by using gas fired boilers and/or combined heat and power units. Due to the energy transition, also greenhouses transition to sustainable sources of heat. The two main available alternative sources of heat in the Westland are: geothermal heat and waste heat from industry in the Rotterdam harbour. An important characteristic of both sources of heat is that their availability is constant throughout the year. Because demand concentrates in the winter months, large scale seasonal heat storage is needed to be able to fully utilise the available heat.

Several clusters of greenhouses in the Westland already have, or are developing, a geothermal well. However, none of these clusters have a large-scale heat buffer to overcome the temporal mismatch, allowing them to also supply peak heat demand with sustainable heat, via seasonal storage. Aquifer Thermal Energy Storage is a cost-effective method for large scale heat storage in areas where aquifers are available, like in the Westland. Therefore, this study explored the role ATES can play in the heat supply of the Westland.

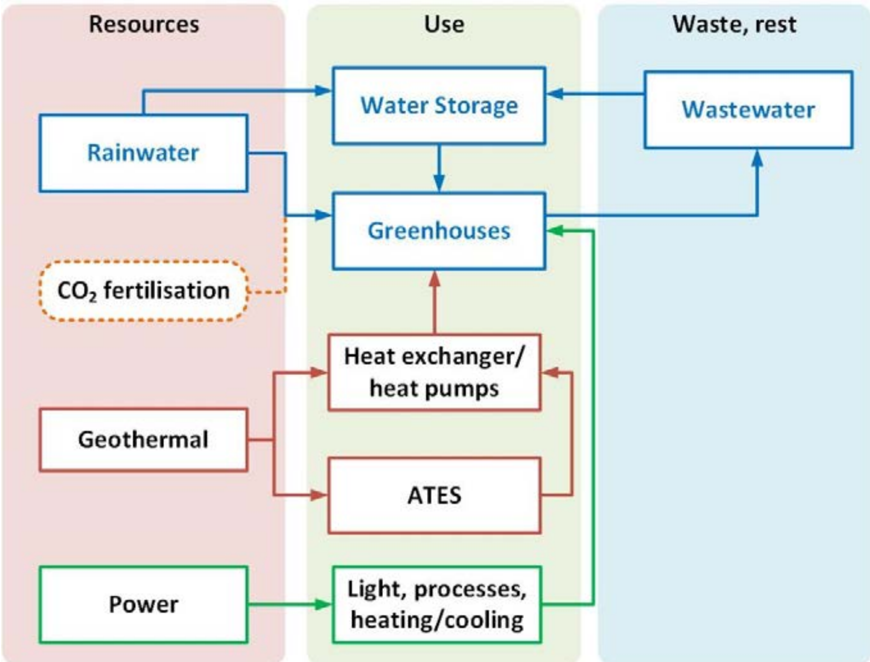


Figure 40 Diagram of the NextGen system for Westland horticulture

4.1.3. Actions and case study objectives

The main objective of the Westland demo case is the demonstration of an integrated approach for the regional evaluation of the conditions for implementing High Temperature Aquifer Thermal Energy Storage systems (HT-ATES) to the overall sustainable thermal energy transition of the Westland area (Table 26). Compared to ATES, the main advantages of HT-ATES are that high temperature heat can be used directly for heating and more energy can be stored per volume groundwater.

The following actions have been undertaken:

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

- Characterization of the thermal energy supply and demand in the region, and the application conditions for HT-ATES in the Province of South Holland
- The technical and financial feasibility of HT-ATES at the Westland greenhouse cluster of Polanen
- The performance monitoring of the HT-ATES system at the horticulture company Koppert Cress.

Table 27 Technical details for Westland demo case according to energy components.

Case Study number & Name	#3 Westland region
Subtasks	1.3.5 Aquifer Thermal Energy Storage
Technology baseline	Pilot set-up
NextGen intervention in circular economy for water sector	High Temperature-Aquifer Thermal Energy Storage system (HT-ATES)
TRL	TRL 4 → 6
Capacity	Pilot location: - Heating demand from 8 to 23 TJ/year; - Cooling demand from 6 to 16 TJ/year
Quantifiable target	Heat recovery factor

4.1.4. Unique selling points

Aquifer Thermal Energy Storage (ATES) systems use groundwater as a carrier for heat to transport the heat to and from the underground. ATES is used to overcome the temporal discrepancy between energy demand and availability. ATES systems have been operating in the Netherlands since the early 1980s. They usually operate at low temperatures, max. 25°. However, often heat is available at higher temperatures, e.g., solar heat, geothermal heat or waste heat. Storing this heat in a high temperature HT-ATES system allows to utilize this high quality heat during demand (winter time).

In the Province of South Holland heat at these higher temperatures is available, e.g., waste heat from industry in Rotterdam harbour. In the Westland region, e.g., at the Polanen cluster, geothermal wells provide for heat at high temperature as well. At the Koppert Cress horticulture company in the Westland, an existing ATES system is converted to an HT-ATES system.

Unique selling points of (High Temperature) Aquifer Thermal Energy Storage (ATES)

Storing heat in ATES systems can potentially save fossil energy (i.e., reduced greenhouse gas emissions). In addition, besides being economically feasible and scalable, the unique selling points are:

- Seasonal and/or long-term energy storage of thermal energy
- Subsurface heat storage with long-term heat recovery efficiencies up to 83%
- Subsurface cooling capacity with long-term cooling efficiencies up to 93%

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

The potential to save fossil energy is even larger for High Temperature ATES as higher temperatures (such from geothermal wells) can be efficiently stored. HT-ATES has a higher storage capacity with the same infrastructure and no heat pump.

4.1.5. Principal and main characteristics of the technology

Description of the technology

In an aquifer thermal energy storage (ATES), excess heat is stored in subsurface aquifers in order to recover the heat at a later stage. The thermal energy is stored as warm groundwater. The groundwater is also used as a carrier to transport the heat to and from the subsurface. Hence, the thermal energy is stored and recovered via the production and injection of groundwater from an aquifer through wells. The capacities of ATES systems range from 0.33 MW to 20 MW (Fleuchaus, et al., 2018).

Usually, the ATES is operated seasonally. In summer, the excess heat from gas or coal fired power plants, from solar plants or from cogeneration plants is transferred via heat exchangers to the cold groundwater. The resulting warm groundwater transports the heat into the aquifer, where the heat is stored. In winter, the ATES is operated the opposite direction by reversing the flow in the production and injection wells. Now, the stored heat is recovered from the warm groundwater via heat exchangers and used for heating purposes, while the resulting cold groundwater is reinjected in the aquifer.

Usually, the distance between the injection and production wells is between 1000 m and 2000 m. The depth of the aquifer also varies. In the Netherlands, most of the ATES systems use aquifers in depths between 20 m and 150 m in the subsurface.

Corresponding to the depth, heat storages are operated at different temperatures. Low temperature (LT) ATES are operated below 30°C and are usually located in shallow aquifers, medium temperature (MT) ATES refer to a temperature range between 30°C and 50°C and high temperature (HT) ATES are operated at 50°C and higher.

In contrast to MT- and HT-ATES, due to the low temperature in LT-ATES, a heat pump is used to increase the temperature to the level required to heat the associated building such as 40 °C. Simultaneously, the extracted groundwater is cooled to a temperature between 5 °C and 8 °C. Subsequently, the cold groundwater is reinjected in the cold well. In summer, buildings can be efficiently cooled using groundwater from the cold well. This water is heated due to the cooling process by the heat pump to a temperature range between 14 °C and 18 °C. Subsequently, the heated groundwater is stored via the warm well in the LT-ATES for its later recovery in winter. If the cooling requires no facilities next to the low-temperature groundwater stored in the previous winter season, it is called free cooling. When excess heat is available, e.g., from solar collectors, or waste heat, this can be added to the warm well to reduce heat pump operation or make it even redundant.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

In the Westland Region of the NextGen project, the solar heat, geothermal heat or waste heat is stored in an aquifer by the HT-ATES system (depth between 50 m to 180 m below surface) so that it can be recovered in winter period for heating purposes.

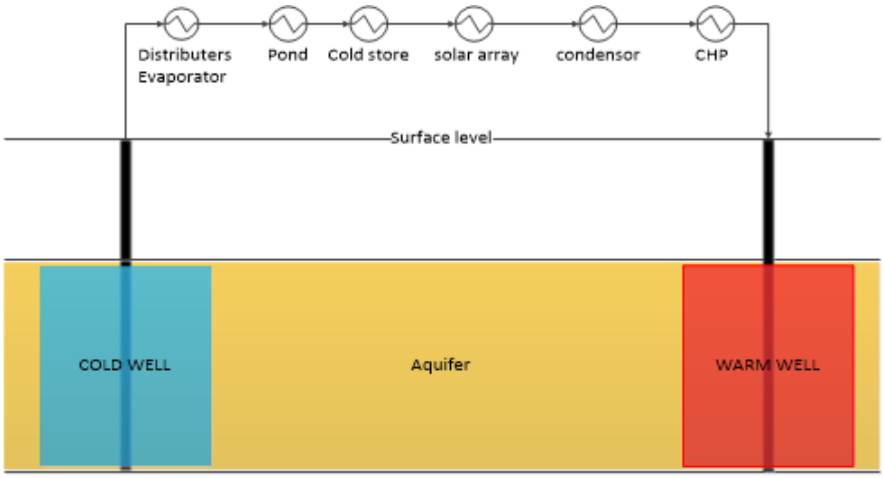


Figure 41 ATES-system.

Synergetic effects and motivation for the implementation of the technology

- Excess heat can be stored over a long time period e.g., a season or even longer
- An ATES stores the heat over a long time period ranging between several months up to several years. The heat can be recovered, whenever it is needed.

High storage capacity
Due to the high storage mass of an ATES, its storage capacity is high compared to other thermal storages. Storage capacity is even higher for HT-ATES.

Heating and cooling dependent on the season
Simultaneously to the storage of waste heat from industrial processes and its recovery for heating purposes, also, the cold groundwater can be used for cooling processes in the summer. Thus, it can replace for example conventional air conditioning and heating units.

Reduction of CO_2 emissions
The ATES system allows to store and recover waste heat or to provide cool groundwater for cooling purposes. This significantly reduces the amount of fossil fuels needed for heating in winter or for cooling in summer.

Sewer heat recovery
Temperature levels in LT-ATES are ideally matching with sewer heat recovery. Therefore, LT-ATES is a perfect match for decoupling heat availability and heat demand in sewer heat recovery systems.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

4.1.6. Requirements for the implementation of the technology and operating conditions

ATES systems obviously require the availability of heat and the presence of appropriate aquifers. For optimal functioning of ATES systems an equal need for heat and cold on an annual basis is necessary. The best operating condition for ATES is when there are large seasonal differences in demand and availability for heat. Geological suitability is based on the presence of adequate aquifers. Detailed soil stratification information is needed, especially to avoid mixing of groundwater from different layers with varying geochemical characteristics, which can potentially cause clogging problems. It has been estimated that about 1/3 of the total urban area in Europe has appropriate aquifers available for applying ATES. Those high potential urban areas are mainly concentrated in North-Western and Eastern Europe, with some local hotspots in Central Europe as well. In southern Europe suitability is less generic but local opportunities are nonetheless significant. More research is ongoing on the applicability in different type of aquifers: fine sand, sandstone, chalkstone, karsts. It seems that ATES is possible in much more regions then assumed before. In Westland, a sand aquifer with suitable thickness is available (see next chapter).

4.1.7. Results obtained

This section presents the results obtained of sub-task 1.3.5 Aquifer Thermal Energy Storage for the demo case (#3) Westland Region. It consists of three parts:

- Characterization of the thermal energy supply and demand in the region, and the application conditions for HT-ATES in the Province of South Holland
- The technical and financial feasibility of HT-ATES at the Westland greenhouse cluster of Polanen
- The performance monitoring of the HT-ATES system at the horticulture company Koppert Cress.

In this report emphasis is put on the third part, HT-ATES at Koppert Cress. More detailed information on applied methods and results are described in the informal NextGen report: Bloemendal, M., Beernink, S, Ros, S. & Hartog, N (April 2022), Regional potential of HT-Aquifer Thermal Energy Storage in the Westland: Assessment of Financial and Technical feasibility.

4.1.7.1. The role of HT-ATES in the regional heat demand

In the horticulture area of Westland there is a large demand for heat. Traditionally this demand is met by using gas fired boilers and/or combined heat and power units (CHP's). Due to the energy transition, also greenhouses transition to alternative sources of heat. The two main available alternative sources of heat in the Westland are: geothermal heat and waste heat from industry in the Rotterdam harbour. An important characteristic of both sources of heat is that their availability is constant throughout the year. Because demand concentrates in the winter months, large scale seasonal heat storage is needed to be able to fully utilise the available heat.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

Many greenhouses join forces to transition to these sustainable sources of heat. As a result, several clusters of greenhouses already have, or are developing, a geothermal well. However, none of these clusters have a large-scale heat buffer to overcome the temporal mismatch, allowing them to also supply peak heat demand with sustainable heat, via seasonal storage. High Temperature Aquifer Thermal Energy Storage (HT-ATES) is the most cost-effective method for large scale heat storage in areas where aquifers are available (Hartog et al., 2017), like in the Westland.

Description of the ATES technology

Concept and specifications

Across the world ATES systems usually operate at low temperatures, max. 25°C due to legislation (Haehnlein et al., 2010). However, often heat is available at higher temperatures, e.g., geothermal heat, Combined Heat and Power (CHP) or waste heat. Storing this heat in periods of excess (summer) allows to utilize this high-quality heat during winter time, . The same concept of ATES can be used to store and recover this heat in a high temperature (HT-)ATES system (> 25 °C). The main advantages of HT-ATES are that a) high temperature heat can be used directly for heating (e.g., buildings, utility, greenhouses) and is therefore useful for more applications and b) more energy can be stored per volume groundwater (and therefore also per m^3 of available subsurface space (Drijver et al., 2012)).

Performance of (HT-)ATES systems

The performance of the ATES system is defined by how much of the stored heat can be recovered after storage. Bloemendal et al. (2018) describe the impact of storage conditions on the recovery efficiency of low temperature ATES systems and provide a generic overview of the most important processes affecting low temperature ATES systems. For HT-ATES, at temperatures generally ranging from 25-90°C, the physical characteristics (as well as the chemical composition) of the groundwater can be affected considerably. Due to the density decrease of heated water, density-driven (buoyancy) flow can therefore become an important factor when storing at high temperatures which can negatively affect the recovery efficiency (Schout et al., 2013; van Lopik et al., 2016). HT-ATES systems have been used in the past in the Netherlands (1980s), but most of these systems failed due to technical difficulties. Currently a few operational/pilot HT-ATES systems exist worldwide (Holstenkamp et al., 2017; Schout et al., 2013). In NextGen, the technical operation and performance is assessed the pilot HT-ATES system of Koppert Cress horticulture company in Monster (Westland Region), the Netherlands.

Heat balance of the Province of South Holland

A summary table of the heat supply and demand in the Province of South-Holland is shown in Table 27, which includes seasonal differences in thermal energy surpluses caused by a varying seasonal demand and the relative contribution of the most relevant sectors to the overall heat supply and demand. The estimated heat availability covers the annual thermal energy demand. During summers, overall, about 16% (ca. 18 PJ) of the annual baseload thermal energy demand will be available for seasonal storage.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

Table 28 Summary sheet of energy supply and demand, incl. current and planned geothermal energy systems. High estimate of residual heat surplus (i.e., twice the low estimate).

		Autumn/Spring	Winter	Summer	Annual	Annual contribution
		(PJ)	(PJ)	(PJ)	(PJ)	(%)
Demand$	Heating of houses	15.3	24.5	6.1	61.2	60.7%
	Greenhouses	9.9	15.9	4.0	39.7	39.3%
Supply	Residual heat (from industries)	26.9			107.7	95.2%
	Geothermal energy*	1.3			5.2	4.6%
	Data centres	0.06			0.2	0.2%
Overall	Total demand	25.2	40.4	10.1	100.9	-
	Total supply	28.3			113.2	-
	Total surplus	3.1	-12.1	18.2	12.2	-

*$Industrial heat demands are not included in the analyses. This could be a topic of further research. *Existing and planned systems (in 2035: 13 geothermal systems)*

Surpluses in heat from the area around the Rotterdam harbour can be used to cover the heat demand of the greenhouse regions in the Westland area and major urban areas such as Rotterdam and The Hague. In these regions large-scale HT-ATES systems can be used to cover nearby peak heat demand.

The total storage requirement for HT-ATES in the area is nearly 120 million cubic metres to store and recover about 15 PJ (see Figure 41). This is the amount of heat required to cover the winter demand using summer surpluses of heat, i.e., 15 % of the annual total heat demand.

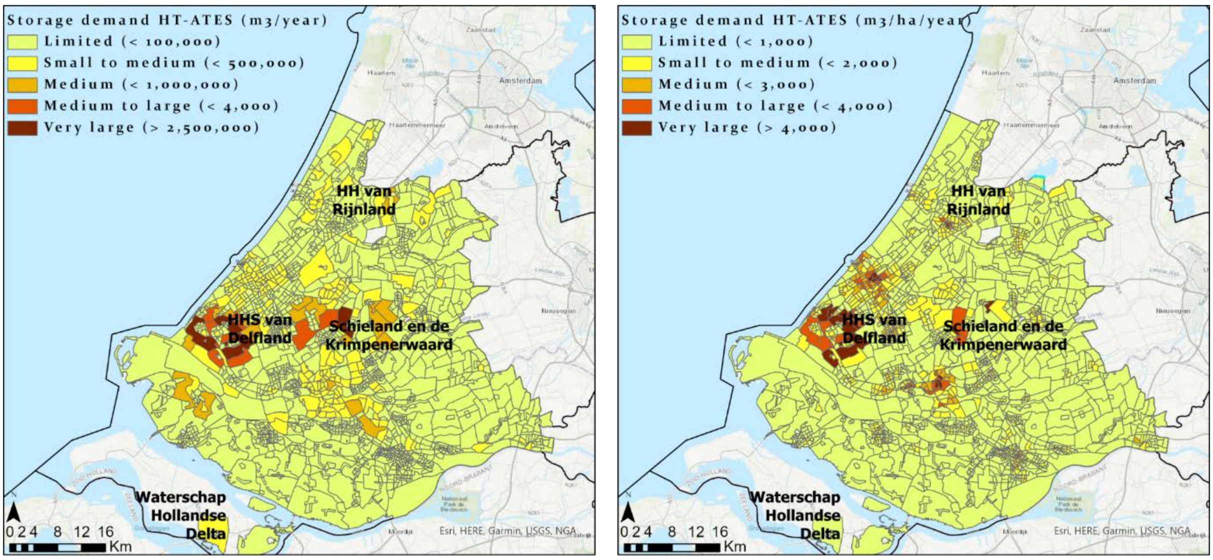


Figure 42 Required storage volume to cover the winter peak demand with summer surplus of base load heat supply. The mismatch between summer and winter heat demand is 30 % of the total annual heat demand, thus 15 % of the annual base load can potentially be stored. The figure assumes a 30-degree temperature difference between infiltration temperature and aquifer temperature during storage.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

Please note that when sources of heat from sustainable sources for example from solar or wind using power to heat, the demand for storage may increase considerably due to the variable nature of these sources.

Application conditions for HT-ATES

Up until depth horizons of 200m the 1st and combined 2nd-3rd aquifer have suitable storage conditions for HT-ATES across whole province of South-Holland. Heat losses due to ambient groundwater flow are expected to be small, as groundwater flow velocity in these aquifers is limited. HT-ATES well designs can be optimised for limiting losses via heat conduction and buoyancy, for specific aquifer thickness, storage volume and storage temperature.

4.1.7.2. Technical and financial feasibility of HT-ATES at the Westland greenhouse cluster of Polanen

To illustrate HT-ATES suitability in Province of South Holland, a case study was carried out to address the specific local details which cannot be assessed in a regional spatial analysis as was described in the previous chapter. The analysis of technical and financial feasibility of HT-ATES was carried out for a case of the Westland greenhouse cluster of Polanen comprising of 43 greenhouses, in the process of developing a geothermal well, from which they want to store excess heat in summer, to be utilised in winter.

Next to a permit for the HT-ATES activity also several other permits are needed. This analysis indicates that a HT-ATES for both Polanen and the Westland region is possible. The province will first issue a temporarily permit, which may be converted into a permanent one after some years of operation without problems/negative effects.

The feasibility study included two scenario's to assess how the Polanen district heating network and geothermal well may benefit from a HT-ATES. For both scenario's it is determined how much groundwater will be injected and extracted each season and the maximum required flow capacity. These are the basis for the initial design and aquifer selection, used for a cost estimate.

The HT-ATES recovery efficiencies are 68 and 60% for the 15 and 18 MW scenarios respectively (see Figure 42). Application of HT-ATES helps to reduce shortage from 25 to 10% of the 15 MW and 15 to 1% for the 18 MW case. The required storage volume of the HT-ATES is 500,000 and 650,000 m^3 for the 15 and 18 MW scenarios respectively, and both would deliver about 80 TJ of heat per year.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

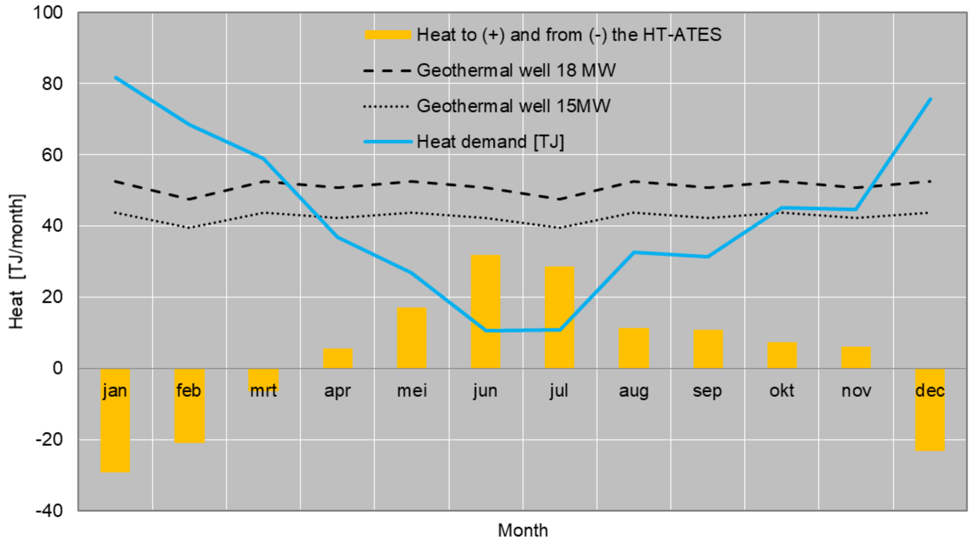


Figure 43 Approximate monthly supply and demand of heat and monthly HT-ATES injection extraction of heat.

Table 28 shows the aggregated results of the simulations for both the 15 and 18 MW geothermal well scenarios. These results show that application of the HT-ATES helps to better utilise the geothermal well.

Table 29 Yearly average heat flows during the 15y simulations.

	15MW	18MW	
Heat demand	524	524	[TJ/y]
Total produced from geothermal well	514	573	[TJ/y]
Directly used from geothermal well	393	438	[TJ/y]
Stored in HT-ATES	121	135	[TJ/y]
Delivered by HT-ATES	82	81	[TJ/y]
Recovery efficiency HT-ATES	0.68	0.60	[-]
Total delivered	475	519	[TJ/y]
Utilisation of geothermal well			
Without HT-ATES	0.76	0.76	[-]
With HT-ATES	0.92	0.91	[-]

Regarding costs related to the 18 MW geothermal well, 4 hot and 4 warm wells (at about 200 m depth) are needed for the required capacity of 250 m^3/h. The total HT-ATES costs are: 0.8 M€/y (375 k€/y capital cost and 427 €/y operational cost). With a heat delivery of 80 TJ, the heat price is 10 €/GJ. This is within the price range for heat from gas for large users (prices range from 9-14 €/GJ).

Having the HT-ATES provide 80 TJ of heat, saves 2.6 Mm^3 natural gas, which accounts for a yearly reduction of 4.800 tonnes of CO_2 emission.

It is concluded that with an 18 MW Geothermal well the Polanen greenhouse cluster can potentially meet 99% of their heating demand by using an HT-ATES. Thus, HT-ATES can

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

optimize the utilisation of heat available from a geothermal well at a competitive price, with a reduction of the carbon footprint through gas savings.

The Province of South Holland is the governing authority for HT-ATES permits. The rules allow application of HT-ATES, but there is no specific policy or streamlined permit procedure. However, the Province of South Holland currently welcomes pilot HT-ATES projects.

HT-ATES potential Westland
The positive technical, legal and financial feasibility of HT-ATES at the site of Polanen in the Westland shows perspective for large scale adoption of HT-ATES.

Using HT-ATES to meet the total demand heat of the entire Westland area, about 100 times as much heat needs to be stored that is the case for Polanen. Individual HT-ATES size could be 2 to 3 times larger than is designed for Polanen. Hence, about 50-75 HT-ATES systems are needed for the Westland. Of course, the exact number and size strongly depend on local conditions related to ΔT and size of DHN.

4.1.7.3. Performance monitoring of HT-ATES at the Westland horticulture company Koppert Cress

The Koppert Cress HT-ATES system

Koppert Cress is a horticulture company situated in the Westland region of the Netherlands. It is one of the companies in the greenhouse cluster Polanen. To provide sustainable heating and cooling, an ATES system was installed with 4 warm and 4 cold wells (Figure 43). This ATES system is operational since 2012. As part of a Dutch research project the normal ATES was converted to a HT-ATES pilot (Bloemendal et al., 2020; Bloemendal et al., 2019). To obtain insights in the effect of higher storage temperature on the performance, heat spreading and water quality changes associated to the ATES, the site is intensively being monitored.

The greenhouses of Koppert Cress have a large heat demand in winter, compared to their cooling demand in summer. Therefore, excess heat, harvested from (around) their greenhouses is stored in the warm wells in summer to be used in winter. This comprises of multiple ‘passive’ heat sources from e.g., solar panels, aquathermal heat and waste-heat from a CHP plant. After the start of the transition from LT-ATES to HT-ATES in 2015, these heat sources were gradually added to the heating and cooling system (Bloemendal et al., 2020). The performance of the HT-ATES is being monitored (from 2018 as part of the NextGen activities), and the results are presented in this chapter.

In the Westland region where Koppert Cress is situated, multiple geothermal projects are currently initiated. Possibly, Koppert Cress will be able to obtain heat from one of these geothermal wells in the near future (see previous chapter). This will have a big impact on the total amount and temperature of yearly stored heat; effectively resulting in an increase of storage volume and the injection temperature in the warm wells.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement N°776541

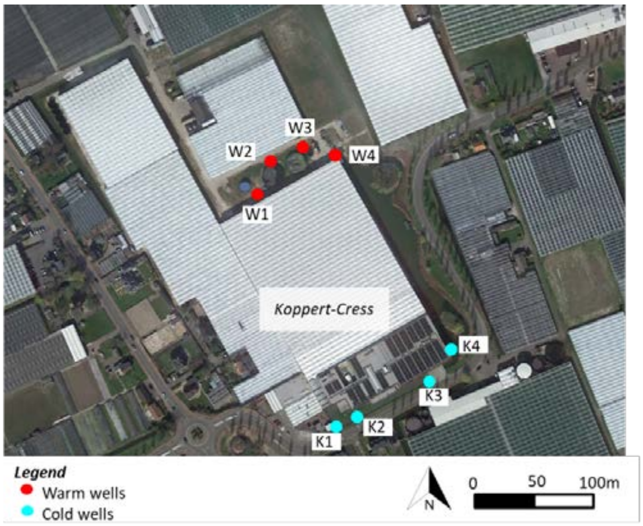


Figure 44 Overview of Koppert cress site with the warm and cold well locations. The individual warm and cold wells are placed apart 40 to 50m. The distance between the cold and warm wells is ~250m.

Hydrogeological characterization

The first aquifer in the subsurface at the Koppert Cress location is not available for the ATES system because this aquifer is reserved for application freshwater storage and recovery, a technology many greenhouse also use for their fresh water supply. The deeper formations Oosterhout and Maassluis are less frequently used compared to the shallow aquifer, resulting in limited and uncertain data on their characteristics. The ATES system utilizes 2 aquifers of 20m thickness with screens up to 170m depth. This means that, in total, 16 well screens are used for the ATES system, divided over 8 wells and 2 aquifers. The horizontal (K_h) and vertical (K_v) hydraulic conductivity of both aquifers are estimated to be K_h=35 and K_v=7 m/d. The national subsurface model REGIS (TNO, 2017) was used to determine this.

Groundwater flow

The regional groundwater flow direction is West, towards the sea. However, at the pilot site the groundwater flow direction is stagnant due to a large groundwater extraction in Delft. This extraction is being stopped over the course of a period of about 10 years. As a result, over time, the groundwater flow direction in the Westland area will be West everywhere. However, in both situations the head gradients in the Westland area are limited resulting in relatively small groundwater flow velocities, usually <1 m/y. It is therefore expected that these relatively low groundwater flow velocities do not have a significant influence on the performance of the ATES systems in this area (Bloemendal et al., 2018).

Methods

Monitoring program

Figure 44 and Figure 45 show the locations and depth of the Distributed Temperature Sensing (DTS) temperature monitoring installed. This allows to closely monitor the temperature profile and heat distribution around the warm well. Next to that also 3 monitoring wells are installed, from which periodically water samples are taken to analyse the water quality. Figure 7.4 also shows the locations of these 3 monitoring wells (PB in the figure), 1: at 20m distance from W3, 2: at 75 m distance from W4 (as a reference, without any influence of the warm well) and 3: at 5m distance from W1.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

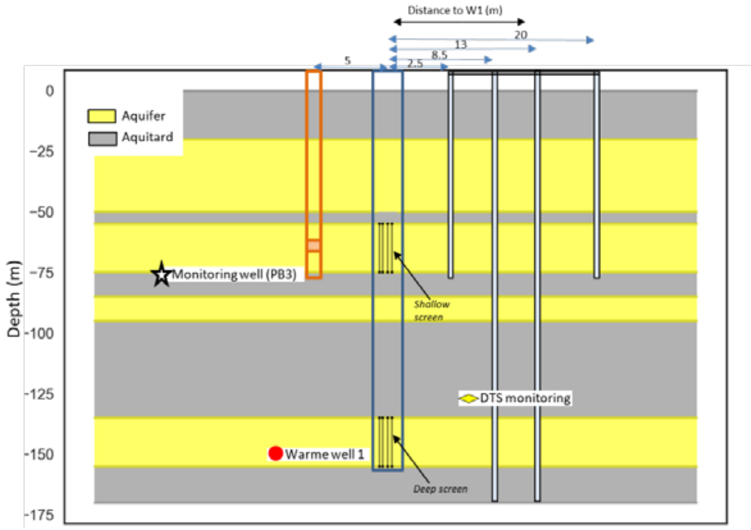


Figure 45 Subsurface composition and monitoring infrastructure at warm well 1.

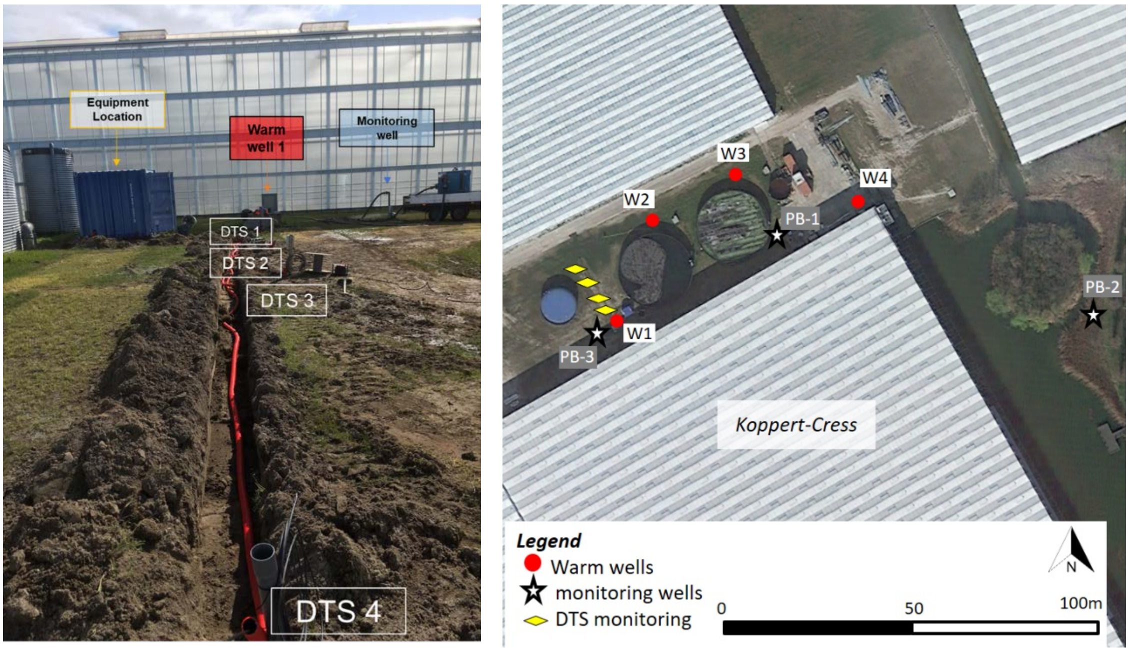


Figure 46 Overview of the monitoring facilities around 'warm well 1'.

Results of temperature monitoring

Aquifer temperature

Figure 46 shows the temperature profiles measured by the Distributed Temperature Sensing (DTS) from October 2019 until September 2020. The temperature increase is apparent in the two aquifers employed by Koppert Cress, with the strongest temperature changes near to the well, while at the DTS location at 18m distance a limited change in temperature is observed. This corresponds with the expected reach of the thermal radius of about 15 m. The middle 2 DTS monitoring locations show a difference in spreading of heat between the upper and the lower aquifer. The heat has a larger reach in the shallow aquifer, indicating that this aquifer is more productive and contributes more to the total flow of the well compared to the deeper aquifer. The temperature variations at about 40m depth is caused by a thin sandy layer, from which heat conduction for the well is transported into this layer.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

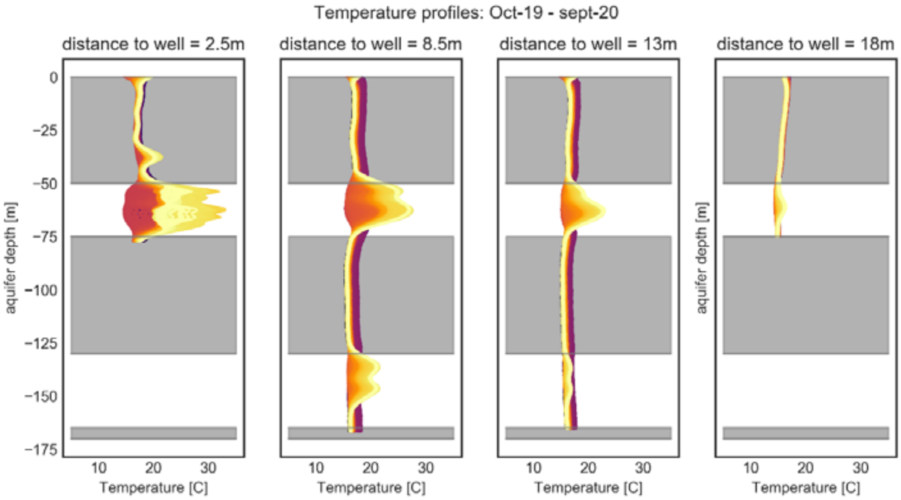


Figure 47 DTS temperature monitoring results at 4 different locations from the warm well. Each line is a moment in time, purple is in the beginning, yellow half-way and red at the end of the time series

The DTS measurements do not show considerable heating of the clay layers covering the aquifer employed for heat storage. The measurements at 2.5 and 8.5 m distance show heating at the bottom of the clay layer, but at lower temperatures than measured in the aquifer and almost returning to ambient like is also the case in the aquifer at the end of winter. Figure 47 shows the temperature increase over time. This confirms the observation that the temperature inside the aquifer as well as in the confining layers returns towards ambient conditions during winter, due to the imbalanced use of the ATES system. the temperature change contour of 5°C illustrates how the confining layers slowly heat-up during summer and cool down during winter.

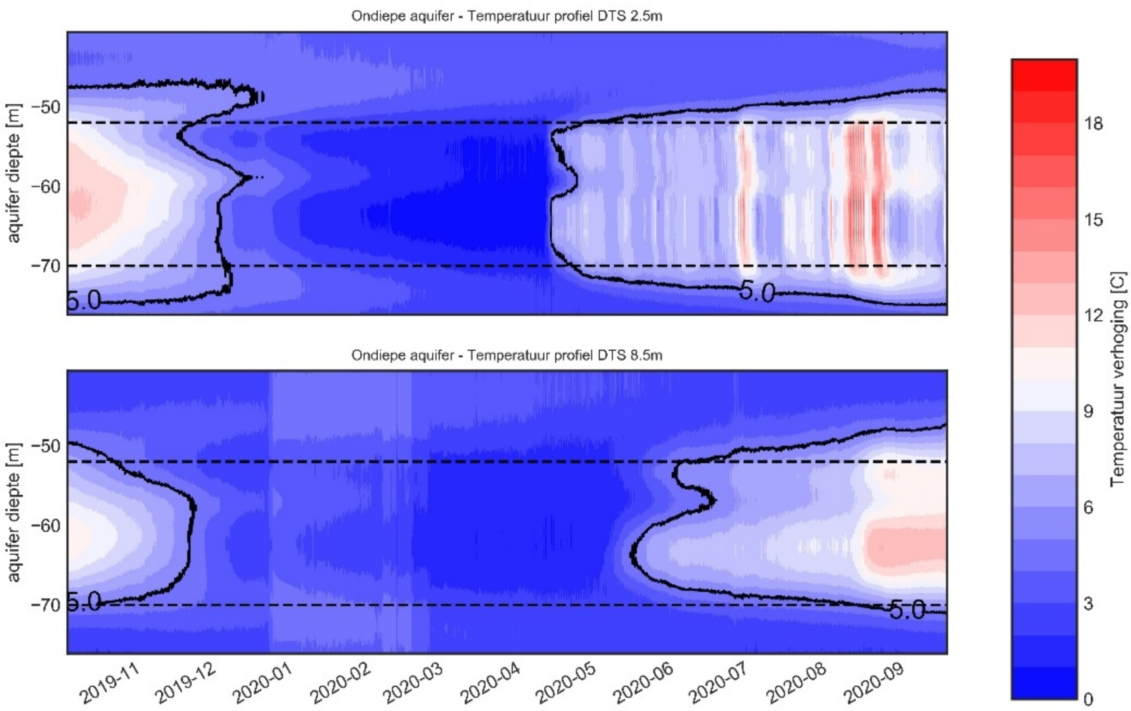


Figure 48 Temperature increase in the shallow aquifer over time, at 2.5 and 8.5 m distance.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

Aquifer heterogeneity affects the temperature distribution in the subsurface, Figure 48 shows that some layers show better conductivity as they respond quite well to injection and extraction (e.g., 52-55 m and 62-67 m). While at around 60 m depth the response is much slower and less strong as well, indicating that this layer has a lower hydraulic conductivity and hence contributes less to the total flow of the well.

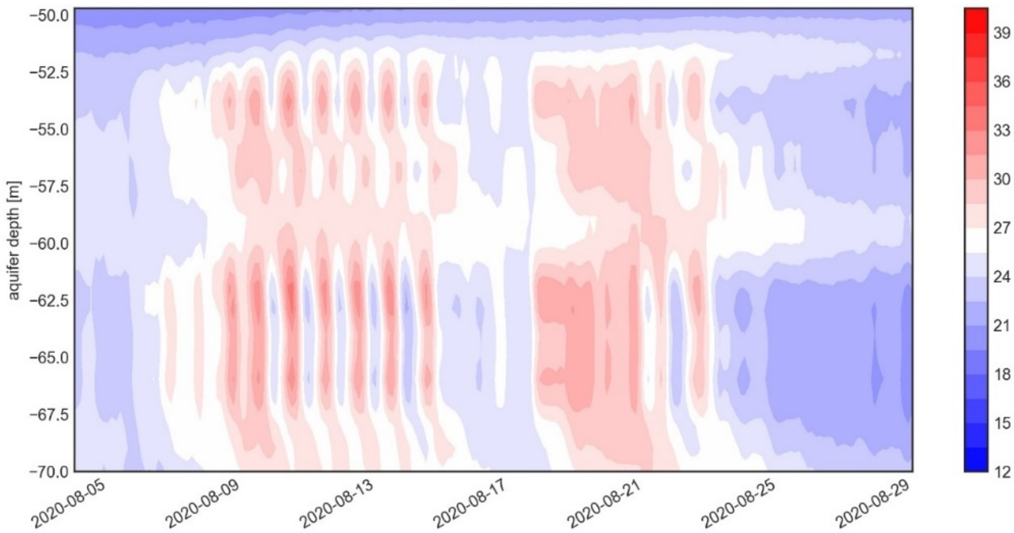


Figure 49 Heterogeneity made visible via the temperature distribution over the full aquifer thickness at 2.5m distance from the warm well.

ATES system operational data analysis

Temperature of ATES wells

Figure 49 and Figure 50 show the well temperature of the warm and cold wells respectively. These plots include both the raw hourly data as well as the daily weighted average temperatures. The weighted temperature is calculated according to:

$$T_{day} = T_{ambient} + \frac{\sum_{n=24} (T_{hourly} - T_{ambient}) \cdot V_{hourly}}{\sum_{n=24} (V_{hourly})} \qquad \text{Equation 14}$$

An ambient temperature of 12.5°C was estimated based on the extraction temperatures measured at the start of available monitoring data. However, the system was already operating a couple of months when the monitoring dataset started, so there is an uncertainty in the exact value for ambient temperature.

The diurnal variation in the use of the wells causes the warm well to be charged during the day and discharged during the night. As a result, the daily average temperatures show a less spiky pattern. Also, the heat which is stored seasonally is stored at a lower temperature, due to this operation strategy. Another cause of the strong variations in the raw data is the way heat is collected from the environment, i.e., partly with solar heat collectors, which provide high temperatures during short moments in time when radiation is high.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

Warm wells

The start of the transition from normal ATES to HT-ATES is indicated in Figure 49 and reflected in the temperature levels. In 2015 and 2016 the maximum infiltration temperature is 30°C, while from 2017 onwards also groundwater temperatures of >30°C are registered, due to the addition of the solar collectors to the system. The relative mild increase of the injection temperatures is a result of the environmental sources of heat (from the green house, surface water, solar collectors) which are charged into the warm well. The temperature data of sub-ambient temperature is caused by the diurnal variation and sometimes very low flow rates. The last years this happens more frequently and is associated with the strong imbalance at which the system is operating: over the course of the years the cold well has grown and starts interacting with the warm wells from 2017 onwards.

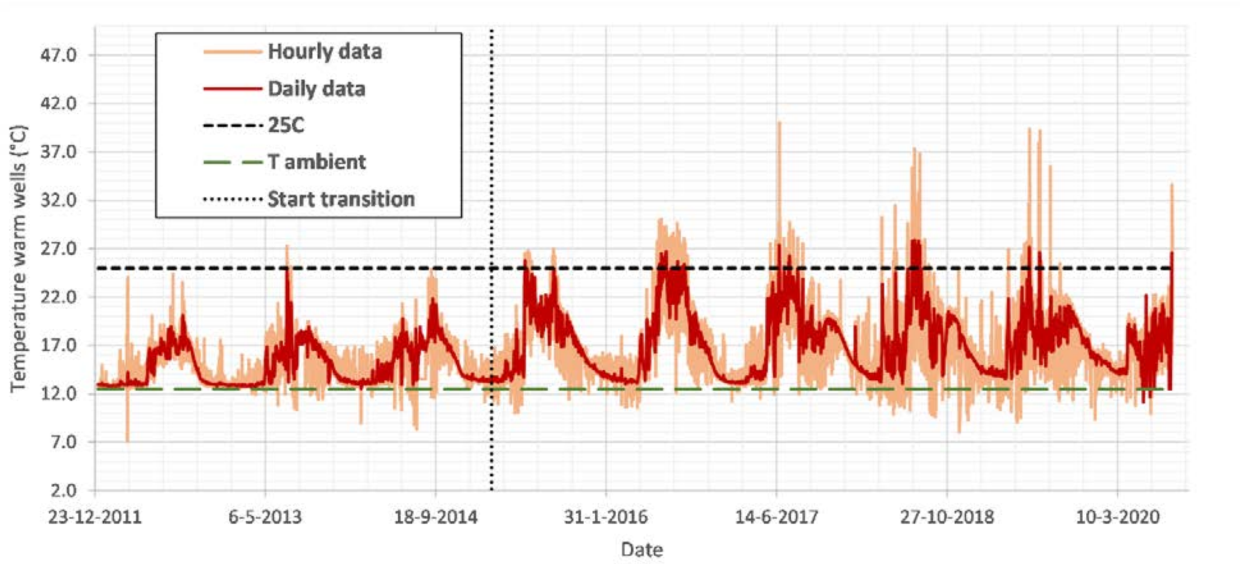


Figure 50 Warm well temperature of the 4 warm ATES wells of Koppert Cress (2012-sept 2020). Transition to higher storage temperature from 2015 onwards.

The maximum injection temperature

To illustrate the warm well temperature responses, the injection and extraction data of the well are analysed during a series of the warmest days in the hot summer of 2018. Figure 50 shows the daily injection and extraction temperature and volume of the warm wells. This shows that the daily average injection temperature is >30°C during some of the days, while at the same time, the extraction temperature during the night is <25°C in almost all cases, and always <30°C. The strong variation in injection temperature is caused by the way of heat collection, depending on the weather conditions.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

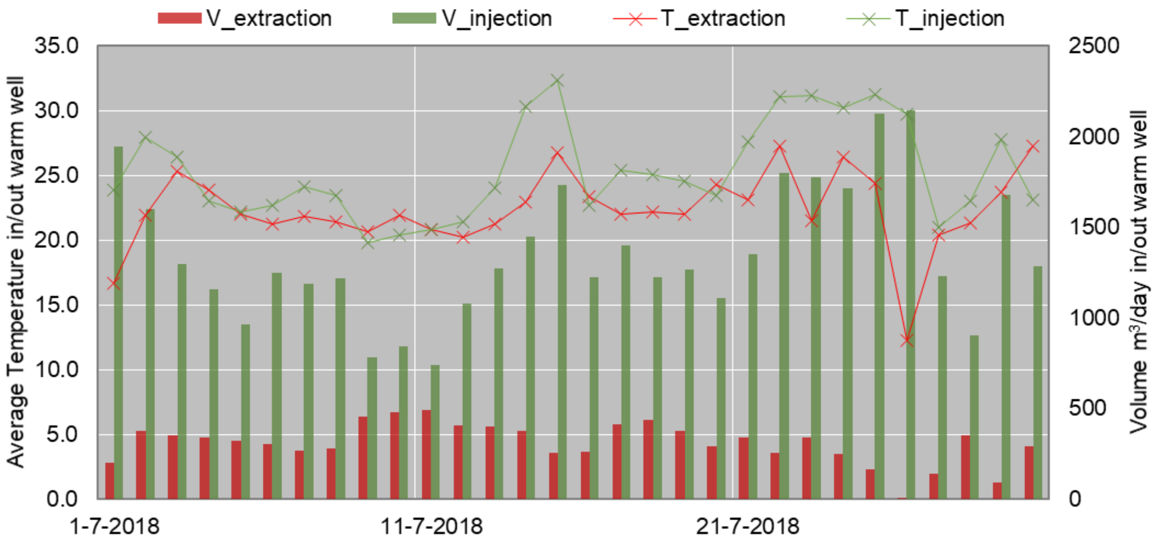


Figure 51 Daily total injection and extraction volume and daily average injection and extraction temperature for the warm wells.

Figure 51 shows the raw 5 min data for temperature and well flowrates. It shows that when warm wells inject heat (negative flow from cold well) during the day, warm water with high temperature is injected, >40°C. But when subsequently water is extracted during the following night, the extraction temperature from the warm well is mostly <30°C. Figure 49 and Figure 50 show that the daily average extraction temperature exceeds 25°C incidentally. Figure 51 now also shows that during early mornings the extraction temperature exceeds 30°C incidentally.

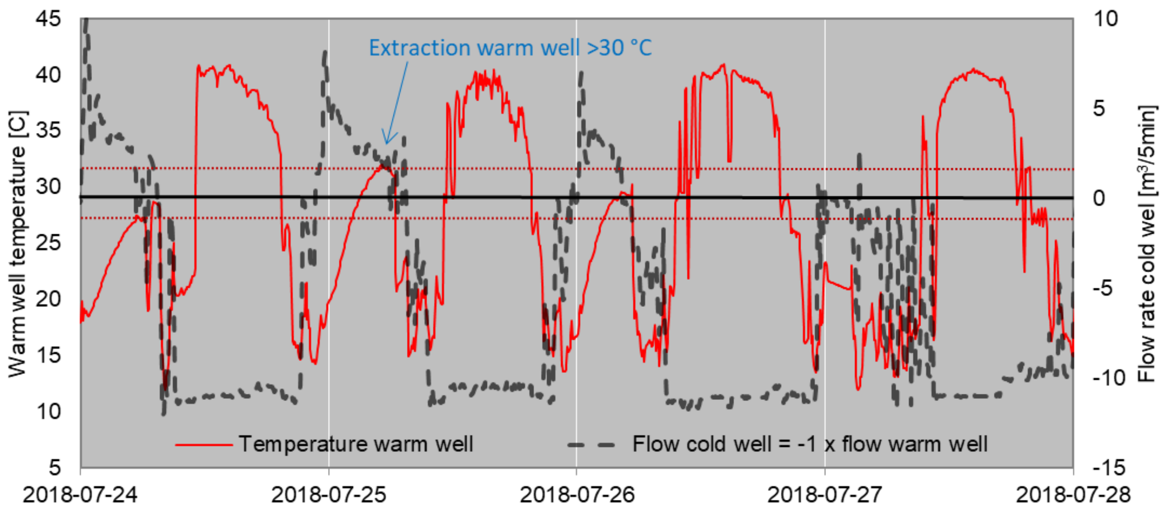


Figure 52 Discharge of cold wells and temperature warm wells from 24-7-2018 to 28-7-2018.

Cold wells

The cold well temperature is affected less by the transition to a HT-ATES. From early 2017 the cold well temperature decreases, which is caused by the installation of a second heat pump. Despite the strong imbalance towards a large surplus in the cold well, still relatively high temperatures are monitored incidentally. This is during low flow rates, and caused by heating

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

of the water in the pipes in the plant room, these are no longer visible in the weighted average daily temperatures.

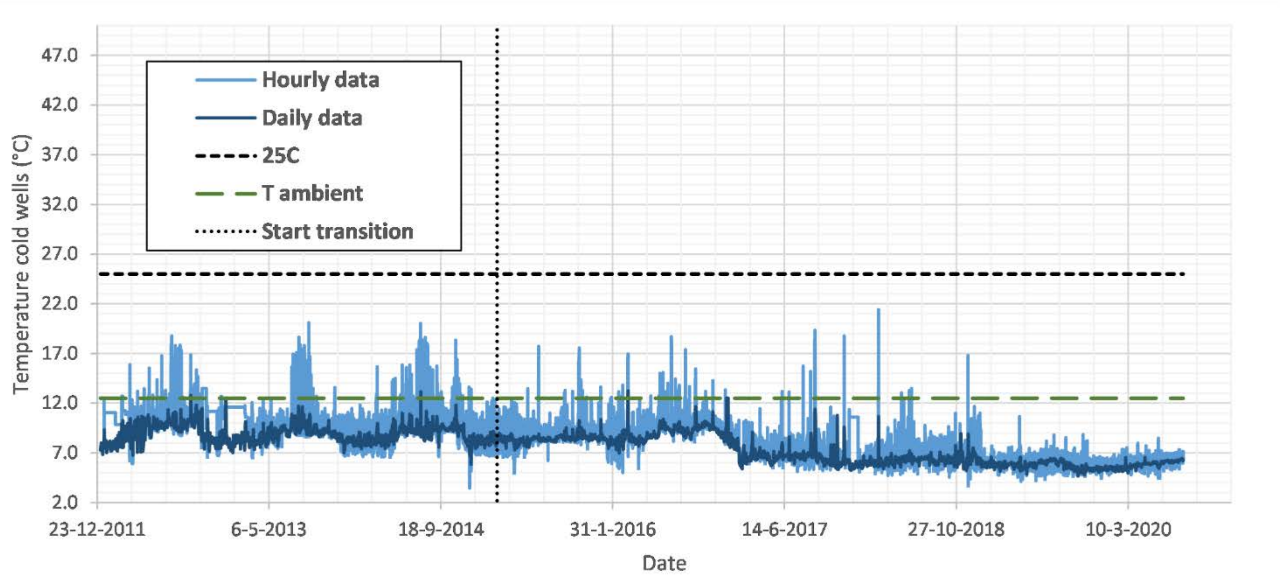


Figure 53 Well temperature of the 4 cold ATES wells of Koppert cress (2012-sept 2020). Transition to higher storage temperature from 2015 onwards.

General view on well temperatures

From 2015 onwards higher temperatures are stored in the warm wells, gradually increasing over time, as operation is optimized, and more heat sources are added to the system. However, the daily average warm well temperature is only incidentally >25°C, due to the strong diurnal variations in mode of operation and outside air dependent heat production from the heat sources to be stored in the warm well. Due to thermal retardation and strong dispersion effect in the close vicinity of the well screen (Bloemendal et al., 2018), strong peaks in the injection temperature are flattened out and not visible in extraction temperature, both after short and long storage cycles.

Storage volumes and energy balance

The ATES wells of Koppert Cress have a capacity of 40 m^3/hr each, so 160 m^3/hr in total. During the day the wells can change flow direction multiple times, as a result the total measured injection volume in a well during the charging season has a net and gross storage volume which may differ. When these short cycle charging and extraction occurs more often, the difference between net and gross storage volume may differ considerably. The net volume in a well is calculated according to

$$V_{net} = V_{in\_gross} + V_{extr\_gross} \qquad \text{Equation 15}$$

Extractions have negative and injections have positive values. Figure 53 shows the difference between the net hourly and net daily volumes, indicating the diurnal pumping cycle executed by Koppert Cress. In July 2018 there is a net storage in the warm well, however, also heat is

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement N°776541

extracted during the night. Figure 54 shows the daily injection and extraction rates as well as the net daily rate, indicating that in general Koppert Cress is extracting more from the warm well than the cold well and the net volume in the warm well is considerably smaller than the gross volume injected in the warm well. This affects the size of the warm zone around the well.

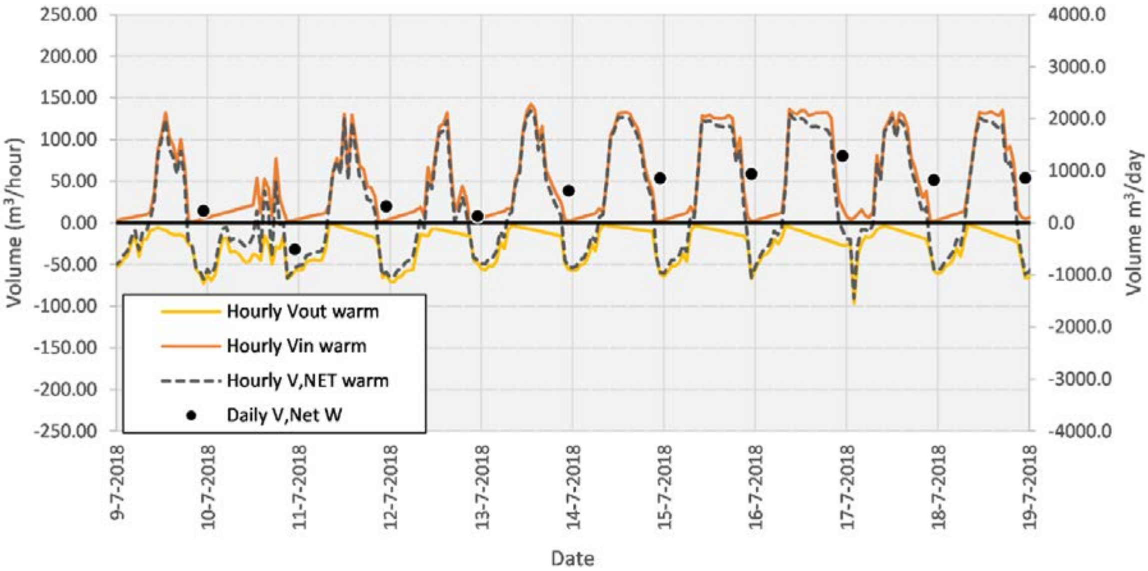


Figure 54 Net hourly flow rates of the warm well and resulting net daily volumes during the summer of 2018.

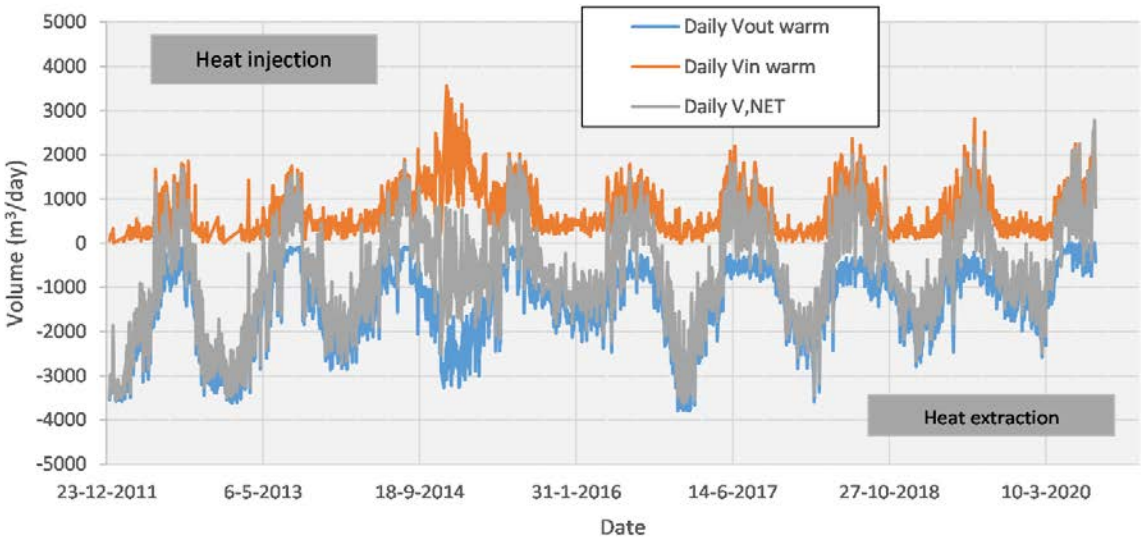


Figure 55 Daily gross injection and extraction in/from warm well and net total flows during monitoring period.

The diurnal storage cycles are typical for how the ATES system of Koppert Cress is operated during spring and fall. On top of the diurnal cycles, also a seasonal cycle is visible. To assess performance of the seasonal storage, the net storage volume provides insights on the volume of heat that is stored seasonally. This is the volume that needs to be analysed to assess the seasonal losses. Using the gross flow data the volume balance ratio (r_V) is identified according to Beernink et al. (2019):

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

$$r_V = \frac{V_{in\_gross} + V_{extr\_gross}}{V_{in\_gross} - V_{extr\_gross}}$$ *Equation 16*

Extractions have negative and injections have positive values. Similarly, this is done for the energy balance ratio (r_E), by taking into account the extraction and injection temperatures:

$$r_E = c_w \cdot \frac{\Delta T_{in} \cdot V_{in\_gross} + \Delta T_{extr} \cdot V_{extr\_gross}}{\Delta T_{in} \cdot V_{in\_gross} - \Delta T_{extr} \cdot V_{extr\_gross}} = \frac{E_{in\_gross} + E_{extr\_gross}}{E_{in\_gross} - E_{extr\_gross}}$$ *Equation 17*

Figure 55 shows that since both ratios are cumulative in time, their values are less subject to change as time proceeds. The following insights follow from this figure:

- The volume ratio is negative, meaning that the warm well is depleted each winter, and the cold well grows every year because cold groundwater is left behind at the end of each summer.
- The imbalance in energy ratio is smaller than for the volume ratio, this is cause by the fact that the temperature difference is larger during injection of the warm well, compensating a bit for the imbalanced flows. The temperature difference between the injection and extraction varies between 0-4°C, on average the difference is about 1°C.

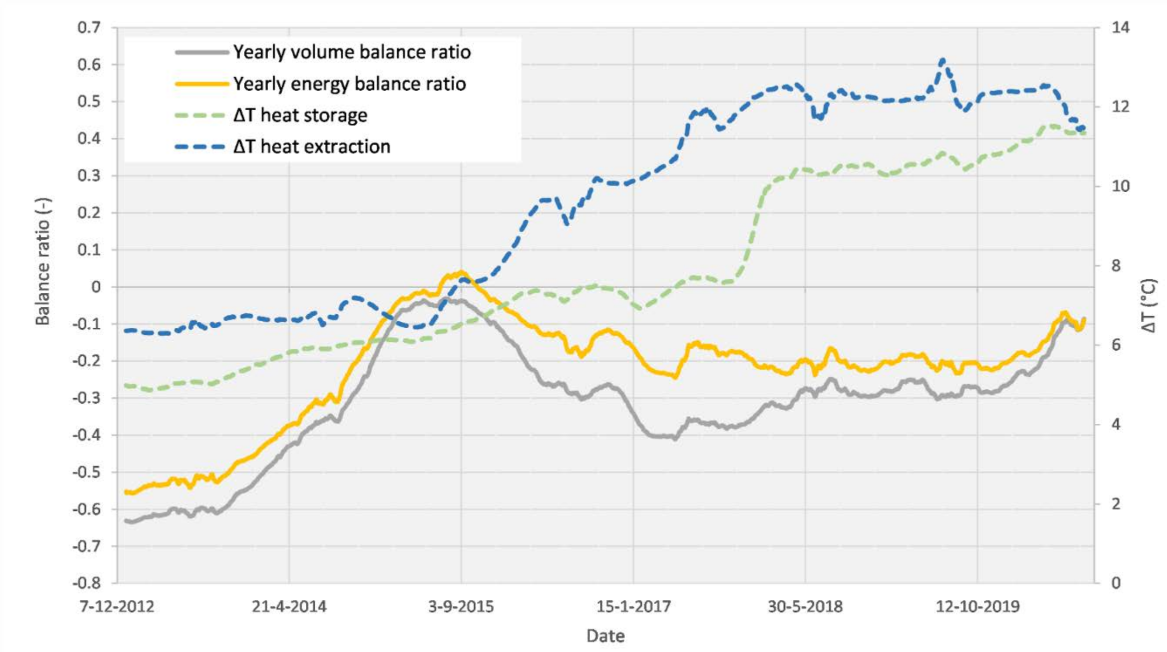


Figure 56 The yearly averaged volume and energy balance ratio of Koppert Cress warm wells and the yearly averaged ΔT (T_{warm} - T_{cold}) during heat storage and heat extraction.

The large energy/volume imbalance was also investigated with a simulation of a 3D model using the monitored data of the injected and extracted volumes and temperatures to identify

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement N°776541

the heat distribution in the subsurface. To do this, a relatively course model (5x5m grid) was used to simulate the temperature distribution in the upper and lower storage aquifer (Figure 56). As would be expected from the actual pumped data, these results show the large surplus of cold groundwater around the cold wells, due to the imbalance discussed previously.

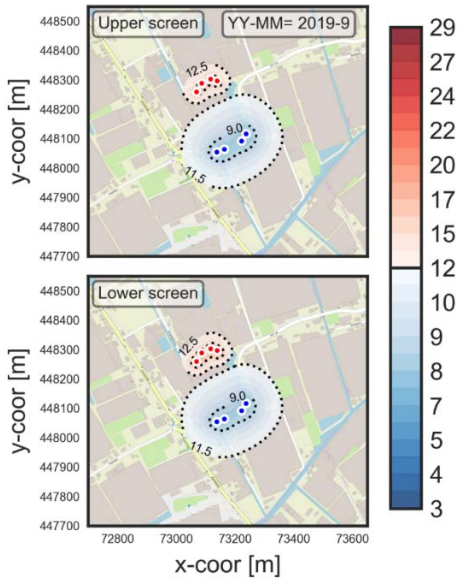


Figure 57 Temperature distribution in the top and deep aquifer at the end of the simulation period of the monitoring data: 2012-2019. Here, the temperature distribution is given at the end of summer; the thermal radius of the warm wells is at their maximal size. A course SEAWAT model (5x5m grid) was used to get insight in temperature distribution.

Warm and cold well recovery efficiencies

Following the energy balance ratio and the net storage volumes the total amount of warm/cold groundwater in the warm/cold wells is plotted in Figure 7.16, together with the temporal recovery efficiencies.

The following insights follow from this figure:

- Confirmation from Figure 57: the warm well is depleted each winter, and the cold well grows every year.
- Despite the net extraction of the warm well, still around 3% of the heat remains in the subsurface, as the maximum recovery efficiency of the warm well is 97% at the end of winter. These are losses that could be due to conduction into the confining layers.
- The cold well recovery efficiency is structurally low due to the volume imbalance, as 60% of the cold groundwater is left behind in the aquifer.
- As all heat is extracted from the warm well, the thermal impact caused by the heat storage is expected to be small. Over the course of 5 years 1.1 TJ of heat stays behind in the warm wells, while at the same time almost 23TJ of cooling capacity remains in the cold wells. As a result, most impact on groundwater temperature is expected at/around the cold wells.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

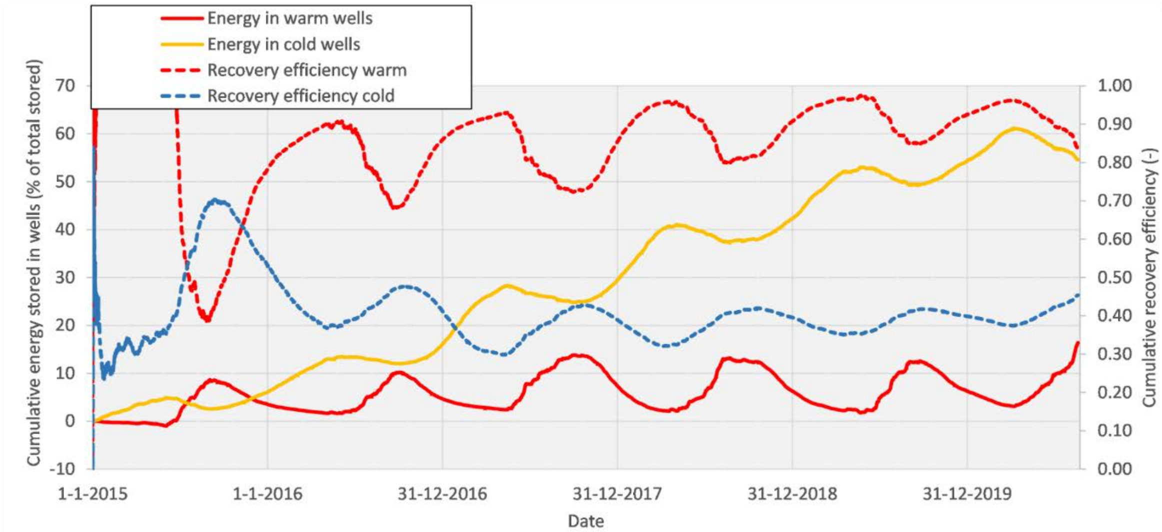


Figure 58 Fraction of total stored net volume in each well during 2015 till Sept 2020 and the warm and cold well recovery efficiency.

Diurnal storage cycle recovery

As about 25-30% of the heat extracted from the warm wells is stored on a diurnal cycle, it is also of interest to assess the short cycle recovered fraction. During these short cycles the difference in injection and extraction volumes may differ a lot, i.e., in summer, large amount of heat is stored, while at night small amounts are extracted and vice versa in winter. During short cycle storage heat may be lost to the aquifer, this is likely to be larger when the warm well is not charged much at the end of winter (net volume is low), and the opposite in summer. As a result, the short cycle recovery efficiency may vary strongly during the year. The short cycle recovery efficiency is calculated according to:

$$\eta_{shor-cycle} = \frac{\left(\frac{E_{extr}^{day}}{E_{in}^{day}}\right)}{\left(\frac{V_{out}^{day}}{V_{in}^{day}}\right)}$$

Equation 18

Figure 58 shows the short cycle recovery efficiency together with the temperature of the warm wells of Koppert Cress. This shows the positive effect of charging period during each summer on the efficiency after summer, resulting in efficiencies of 120% and higher. However, as the warm well temperature drops, also the short cycle recovery efficiency drops sometimes as low as 40%. The ratio in the short cycle injection and extraction volumes affect these numbers as well. When analysing the days at which same injection and extraction volumes only with different net storage volumes, the differences are less strong: around 100% for large net storage volumes and 70% for depleted warm well.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

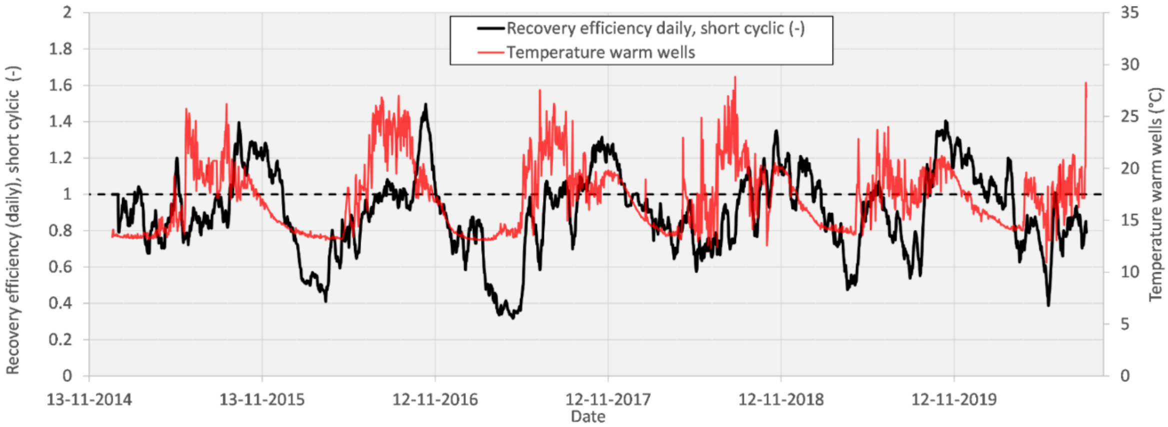


Figure 59 Short cycle daily recovery efficiency of the warm wells over the years. When the well temperature is relatively high, the short cycle daily recovery efficiency is also high, and vice versa.

Discussion and HT-ATES at Koppert Cress

From 2015 onwards, the transition from regular LT-ATES to HT-ATES started. Temperatures >30°C are injected irregularly. The increase in storage temperature results in a larger ΔT between the wells, reaching a yearly average ΔT of 12°C, which is twice as high compared to the Dutch ATES system average (Willemsen, 2016).

The imbalanced use of the warm and cold wells has a dominating influence on the recovery efficiencies of the warm and cold wells. Due to the larger amount of groundwater extracted than injected from/in the warm wells, almost all heat is recovered each year. The overall recovery efficiency is therefore almost 100%. Contradictory to this, much cooling capacity is left behind in the cold wells, resulting in poor cold well efficiency.

The short-cyclic use of the wells cause about 25-30% of the heat to be stored in the aquifer only for a short amount of time, as a result of this short storage time losses are small and recovery efficiencies relatively high. Especially when the warm well is reasonably charged, short-cyclic recovery efficiencies are high.

The analysis of the behaviour of the ATES wells of Koppert Cress shows that insufficient heat is stored in the warm well to meet the heating demand, resulting in an imbalance and a depleted warm well at the end of winter. Due to improvements to the system, more heat has been stored during the last years of operation, but this should be further increased to optimize performance of the system.

The expected future addition of a geothermal heat source (see previous chapter) can provide the required amount of extra heat. It is expected that this will subsequently lead to a more balanced system with higher and less variable storage temperatures in the warm wells. To evaluate the effect of this or other future changes, it is important to assess application of HT-ATES under various temperature levels, aquifer thickness and storage volume.

Energy savings and CO_2 intensity

The energy monitoring of the components and heat flows in the system of Koppert Cress are used to calculate the costs and emission associated with the ATES system. These same energy

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

flows are used to evaluate costs and emission for different alternative heating and cooling supply systems:

1) Gas fired boiler and compression chiller
   delivered heating and cooling is delivered with a boiler with an efficiency of 95% and a chiller with a COP of 3.
2) LT-ATES with a normal warm well temperature
   The following operations are carried out to identify energy use of a normal ATES system:
   a. Heat pump capacity scales with the available heat from the wells and the flow rates between the wells stay the same
   b. The heat available from the well scales down by a factor 2 as the yearly average ΔT between wells is a factor 2 lower for all ATES systems in NL (6°C, (Willemsen, 2016)), compared to current practice for Koppert Cress (12°C).
   c. Due to lower warm well temperature, the heat pump has a lower COP, proportional to the change in Carnot efficiency.
   d. Cooling by wells is also smaller, due to lower ΔT between the wells.
   e. Power use of the circulation pumps is the same as in current practice (due to lower temperature levels COP's are smaller)
3) ATES as applied at Koppert Cress.
   Electricity use of the different components is monitored (and presented in Figure 59, showing the relative contribution of the circulation pumps, well pump and heat pump). Also, gas use of the peak boiler. These data are used to assess the performance of the system, given the amount of heating and cooling delivered.
4) Higher temperature of the warm well for the existing ATES at Koppert Cress.
   The following operations are carried out to assess the performance as if Koppert Cress would have an even warmer warm well temperature.
   a. Heat pump capacity scales according to the heat available from the wells.
   b. Heat available scales up with a factor 1.5 as we assume a yearly average ΔT increase of 6°C, so 18°C instead of the 12°C under current operation.
   c. Heat pump COP scales according to the Carnot efficiency associated to the increased warm well temperature.
   d. Cooling by wells is also more, due to higher ΔT between the wells.
   e. Power use of the circulation pumps is the same as in current practice (due to higher temperature levels COP's are larger)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

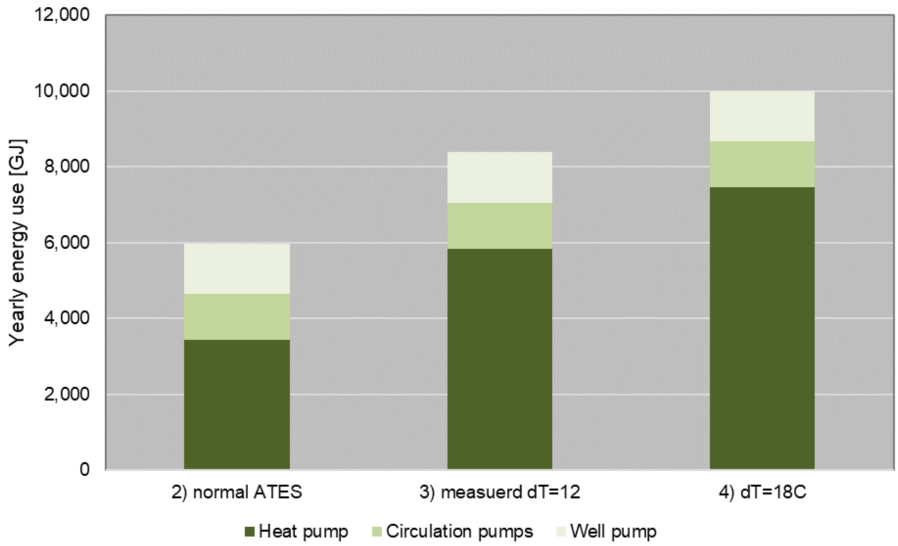


Figure 60 Electricity use distribution across different components of the ATES systems. Because only the dT's change considerably across the different cases, the energy use for well and circulation pumps are practically the same for each case.

Koppert Cress buys renewable electricity at a €0.093/kWh rate and gas €0.19/m^3. The gas emission factor is 1.77 kg CO_2/m^3. For the electricity use two electricity emission factors are used, A) one for the total chain emission for the sustainable power bought by Koppert Cress: 0.05 kg CO_2/kWh, and B) the mix at the power grid of the Netherlands: 0.32 kg CO2/kWh (Bloemendal et al., 2020; Vreede and Groot, 2010).

Figure 60 shows the results of the comparison. The higher the temperature of the warm well the better the system performs. Electricity use increased due to more heat pump electricity use. Gas use decreases considerably, resulting in lower overall GHG emissions, because more heat is delivered derived from sustainable sources. Overall, the transition from LT-ATES to HT-ATES resulted in a considerable increase in contribution of the ATES system to the total heat delivery, and as a result also a decrease of 30-70% of GHG emission (depending on the electricity source).

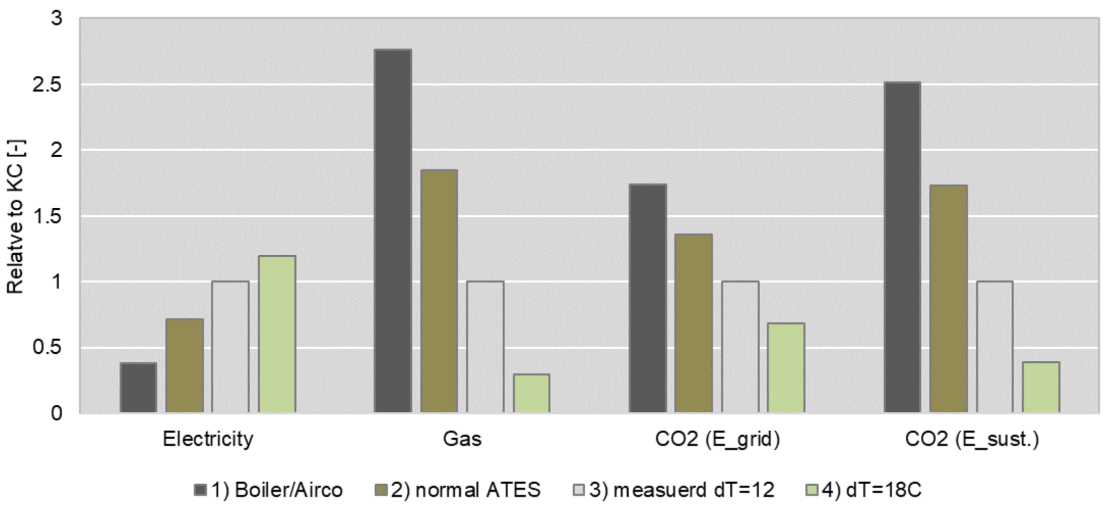


Figure 61 Relative change in energy use and associated CO_2-emissions and operational costs relative to the current Koppert Cress system (gray bar = 1 everywhere)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

Conclusion of HT-ATES performance at Koppert Cress

When the Koppert Cress HT-ATES pilot was initiated, it was expected that over the years enough additional heat sources would be available to seasonally store large amounts of heat, resulting in storage of heat at temperatures between 30-40 °C. However, analysis of the system showed that the yearly heat demand of the greenhouses of Koppert Cress exceeds the amount of heat stored in the wells. Also, the temperature of the available heat is limited because it is harvested mainly from environmental sources. This results in an imbalanced ATES system that only stores heat at temperatures >25 °C during the warmest days of the year. A considerable part (20-25%) of the stored heat is retrieved within a day or week.

In spite of these conditions, with respect to energetic performance and greenhouses gas emissions savings the Koppert Cress (HT-)ATES system is highly successful. By allowing storage temperatures >25°C, Koppert Cress is able to use their heating and cooling system more efficiently. More sources of heat were included over the years, which resulted in more heat storage in the warm wells. The increase in ΔT between the cold and warm wells led to a strong increase in yearly produced heat. Overall, the transition from LT-ATES to HT-ATES resulted in a decrease of 30-70% of GHG emission (depending on the electricity source). While the GHG emission decreased significantly, the costs of operating the ATES system decreased with about 10%.

The following main observations/conclusions follow from the analysis of this ATES system

- Upgrade ATES to HT-ATES: maximum infiltration temperatures from 25°C up to 45 °C, as a result the average ΔT between wells increases from 6°C to 12°C.
- Thermal effects are negligible. All heat is extracted; hence no continuous heating of aquifers or confining layers occurs. This may be different for other systems when heating/cooling demand is less imbalanced.
- Temporal high infiltration temperatures of >30°C disperse to <30°C in the subsurface and subsequent extraction.
- Higher storage temperatures results in larger amounts of heat to be stored and delivered, hence lower GHG emissions.

4.1.7.4. Conclusions for the ATES Westland Region demo case

This study explored the role HT-ATES can play in sustainably matching available heat with the heat demand of the Westland area.

The main conclusions are:

- The estimated heat availability in the Province of South Holland covers the annual heat demand. In principle there is sufficient residual heat available (mainly from the industries in the Rotterdam harbour) for the heat demand of the horticulture companies in Westland. During summers, overall about 16% (ca. 18 PJ) of the annual baseload thermal energy demand will be available for seasonal storage.
- ATES systems could facilitate the required storage of heat to overcome the temporal discrepancy between energy demand and availability. Down depths of 200 m the 1st and

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

combined 2nd-3rd aquifer have suitable storage conditions for HT-ATES across whole Province of South Holland.

- A feasibility study for the Polanen greenhouse cluster in Westland, showed that a HT-ATES system combined with an 18 MW geothermal well (in development) can potentially meet 99% of their heating demand. Moreover, having the HT-ATES provide 80 TJ of heat, saves 2.6 Mm^3 natural gas, which accounts for a yearly reduction of 4.800 tonnes of CO_2 emission. It is concluded that HT-ATES can optimize the utilisation of heat available from a geothermal well at a competitive price (10€/GJ).
- At the horticulture company Koppert Cress, the existing ATES system is being converted to an HT-ATES system by gradually adding heat sources. The performance monitoring, however, shows that insufficient heat is stored in the warm well to meet the heating demand, resulting in an imbalance and a depleted warm well at the end of winter. The expected future addition of a geothermal heat source can provide in the required amount of extra heat. Nonetheless, the transition to HT-ATES resulted in a decrease of 30-70% of GHG emission, and a decrease of 10% in the costs of operating the system.

All in all, the results show that A) the heat availability and demand conditions demand for seasonal storage of heat and B) the aquifers exist for application of HT-ATES. The case study for Polanen shows that at individual project/site level HT-ATES is technically, legally and financially feasible. The experiences of applying ATES at high temperatures, illustrate the potential of HT-ATES by show-casing the increase in energy performance and CO_2 emission reductions of the greenhouse of Koppert Cress.

4.1.8. Comparison of the baseline situation and the NextGen KPIs

Table 29 and Table 30 present the baseline conditions and reached KPI values for ATES in Westland Region. The recovery factor is a typical key performance indicator showing the recovery efficiency of warm or cold stored thermal energy over the whole charge and discharge cycle (normally referred to one year). The recovery factor is defined by the ratio between the annually discharged and charged energy. Typical recovery factors:

- For warm thermal energy: min 0.57, max 0.89
- For cold thermal energy: max 0.93

For Koppert Cress, the average recovery factor (warm well) is 0.89 (energy discharge 3,750 MWh/y/energy charge 4,200 MWh/y) (Bloemendal et al., 2020).

The feasibility assessment of the regional potential of HT-ATES in the Westland Region showed:

1. Residual heat in the Province of South Holland could contribute 100% of the heat demand of the horticulture companies in Westland.
2. ATES systems can secure 10-15 PJ seasonal storage, which is sufficient for 10-15% of the demand.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

3. The currently expected number of geothermal wells combined with HT-ATES can meet about 5% of the heating demand of the horticulture cluster Polanen.
4. The performance of the HT-ATES system at Koppert Cress in the current situation shows that, although the heat recovery factor for the warm well is good (0.7-0.95), the heat demand is not reached. Adding a geothermal well heat source will improve the performance.
5. Large scale adoption of HT-ATES in the Westland could potentially save ~250 Mm^3 gas, which reduces the GHG emissions with ~500 kt per year.

Table 30 Baseline conditions for ATES (Westland Region).

ATES		Parameter	Mean value for 2018
Aquifer Thermal Energy Storage (ATES) at Koppert Cress	**Primary energy**	Reduction of consumption (%)	50
	Thermal	T cold well (°C)	5
		T warm well (°C)	18
		Heat demand warm well (TJ)	6
		Cooling demand cold well (TJ)	8

Table 31 KPIs for ATES (Westland Region).

Objectives	Specific Key Performance Indicator (KPI)	Current value	Expected value	Reached value
Storage of heat in HT-ATES	Contribution of HT-ATES to heat demand of horticulture (in Province) ^	0	10 – 15 PJ	Implemented: 0 ˣ Potential: 10 – 15 PJ
Provide heat through renewable sources with HT-ATES	Percentage of heating demand (Polanen cluster) *	0	5 %	Implemented: 0 ˣ Potential: 5% *
To develop a HT-ATES system	Efficiency comparison with ATES (at Koppert Cress)	T: < 20°C Cooling demand 6 TJ Heating demand 8 TJ Heat recovery factor: 0.6-0.7	T: 45-80°C Cooling demand 16 TJ Heating demand 23 TJ Heat recovery factor: 0.8-0.9	T: 20-45°C Cooling demand 11 TJ Heating demand 20 TJ Heat recovery factor: 0.7-0.95 (warm well) 0.3-0.5 (cold well)

^ based on continuous/constant supply of heat during the year
** this is based on the current projections for geothermal heat as a renewable source of heat. However, this number could be larger when more geothermal heat is deployed and/or other sources of heat are used (e.g., solar thermal, power to heat)*
x objective of NextGen was not to implement regional HT-ATES but to assess its feasibility and potential

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

4.1.9. Lessons learned

The ATES feasibility study confirmed the potential to meet the heating demand of the horticulture sector in Westland. The conversion to HT-ATES, with a higher potential, however requires sufficient external heat sources to improve the performance.

Although ATES systems are economically feasible, it requires high upfront investments. Related to (the division of) costs, but also in general, collaboration between the different stakeholders (residual heat providers, (clusters of) horticulture companies, engineering firm, research organization) is essential. This also refers to the relationship with governmental organisations, i.e., for authorization and the required permits. As a summary, the main lesson learned for the implementation and upscaling of ATES is the need for active collaboration of all stakeholders, in particular related to legislative requirements and division of costs and risks.

<table>
<tr><td>Required competence</td><td>LOW</td><td>HIGH</td></tr>
<tr><td colspan="3">Which knowledge is required to operate the plant?
Technical skills to read and process monitoring data, steer energy balance, fix issues/or ask specialists to fix issues, change settings on various components or controls to optimize comfort, energy performance, energy balance.
Information regarding aquifer conditions, soil stratification, heat balance.

What kind of training is necessary?
In the Netherlands a special training and legal certification is needed to be allowed to operate an ATES plant. There is a vocational training available that lines up to acquiring this certification.</td></tr>
<tr><td>Maintenance</td><td>LOW</td><td>HIGH</td></tr>
<tr><td colspan="3">Frequency of plant maintenance per month or per year:
An ATES system consists of various components with different large/small maintenance intervals:
Heat pump: ~bi-yearly large maintenance, regular checks on settings, wear etc.
Wells: yearly
Drycooler: regular checks on wear and clogging
Heat exchanger: every 25 years
(well)pump: every 10/15 year

Duration of a normal maintenance procedure:
Heat pump: 1 day
Wells: 1 day
Drycooler: 1hr
Heat exchanger: 3-5 days (depending on size/capacity
(well)pump: 1day</td></tr>
</table>

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

Duration of active process control per day (manual process control, unforeseen events): 1hr Are external experts required to conduct the maintenance procedure? Yes. A building owner usually can only do very basic operational and maintenance tasks. Professionals do most of it. There are more and more companies who do the operation and maintenance for building owners to unburden them and ensure better performance.	
Technological risks	LOW  HIGH
Reasons for downtimes or technical risks: There are many possible reasons such as in-partial load, frequently turning on and off of pumps/heat pump, poor temperature settings, too low pressure in the groundwater system resulting in dissolution of gas. Most impact: clogging of wells, There is risk of imbalance and interference. Although environmental risks are considered a barrier, the actual risks are limited. Frequency of plant downtimes per year: This doesn't happen often. Duration of plant downtimes: Depending on cause. Building facilities related: 1-2 day or less. Well related: several working days. Are external experts required to restart the plant? No. Which measures can avoid such downtimes? Frequent maintenance and frequent monitoring of energetic, thermal and hydraulic performance of the system.	

4.1.10. Best practice guideline to design and operate the technology

Most important during the construction of an ATES system is the health and safety of people working. Ensure installation according to plan (sounds trivial, but plant rooms are usually full, a wrong connection, sensor or valve is easily made, no matter how small a mistake, but this can seriously disrupt the operation of the system).

The operating conditions for ATES system are location specific. In the previous chapters, the parameters relevant for Westland are described.

In general, the benefit of ATES is the optimal utilisation of available heat, and its main limitation is the required presence of an adequate aquifer.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

For optimal functioning of ATES systems an equal need for heat and cold on an annual basis is necessary. The best operating condition for ATES is when there are large seasonal differences in demand and availability for heat. Crucial for the optimisation of the process are temperature levels according to design, and use of buffers (no frequent turning on/off of pumps).

Other points to consider for future implementations/transferability of the technology:

- extensive and innovative monitoring to increase efficiency and counteract possible imbalances and interference
- uneven distribution of costs and benefits
- legislative procedures.

4.1.11. Literature references

Beernink, S., Hartog, N., Bloemendal, M., Meer, M.v.d., 2019. ATES systems performance in practice: analysis of operational data from ATES systems in the province of Utrecht, The Netherlands, European Geothermal Congress, The Hague, Netherlands.

Bloemendal, M., Beernink, S., Bel, N., Hockin, A.E., Schout, G., 2020. Transitie open bodemenergiesysteem Koppert-Cress naar verhoogde opslagtemperatuur. Evaluatie van energiebesparingen en grondwatereffecten. KWR Water Research Institute, Nieuwegein.

Bloemendal, M., Beernink, S., Hartog, N., Van Meurs, B., 2019. Transforming ATES to HT-ATES. Insights from Dutch pilot project, European Geothermal Congress EGC, Den Haag, p. 6.

Bloemendal, M., Hartog, N., 2018. Analysis of the impact of storage conditions on the thermal recovery efficiency of low-temperature ATES systems. Geothermics 17, 306-319.

Bloemendal, M., Olsthoorn, T., van de Ven, F., 2015. Combining climatic and geo-hydrological preconditions as a method to determine world potential for aquifer thermal energy storage. Science of the Total Environment 538 621-633.

Bloemendal, M., Beernink, S, Ros, S. & Hartog, N., 2022, Regional potential of HT-Aquifer Thermal Energy Storage in the Westland: Assessment of Financial and Technical feasibility. NextGen report.

Buscheck, T.A., Doughty, C., Tsang, C.F., 1983. Prediction and analysis of a field experiment on a multilayered aquifer thermal energy storage system with strong buoyancy flow. Water Resources Research 19, 1307-1315.

Caljé, R., 2010. Future use of aquifer thermal energy storage inbelow the historic centre of Amsterdam, Hydrology. Delft University of Technology, Delft.

Courant, R., Friedrichs, K., Lewy, H., 1967. On the partial difference equations of mathematical physics IBM Journal of Research and Development 11, 215–234.

Dataportaal, N., 2020. National hydrological Model (LHM) version 3.4.

Dijcker, R., Roemers, G., van Nieuwenhuiijzen, A., van Tuinen, E., Veldhoen, A., & Kennedy, E. (2017). *Delfland Circulair: Bouwstenen voor een strategie voor kringloopsluiting en zelfvoorzienendheid*.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

Doughty, C., Hellström, G., Fu Tsang, C., 1982. A Dimensionless parameter Approach to the Thermal Behavior of an Aquifer Thermal Energy Storage System. Water Resources Research 18, 571-578.

Drijver, B., Aarssen, B., De Zwart, B., 2012. High-temperature aquifer thermal energy storage (HT-ATES): sustainable and multi-usable, Innostock 2012. IF Technology.

Fetter, C.W., 2001. Applied Hydrogeology, 4th ed, Upper Saddle River, NJ, USA.

Fleuchaus, P., Godschalk, B., Stober, I., & Blum, P. (2018), Worldwide application of aquifer thermal energy storage – A review, *Renewable and Sustainable Energy Reviews*, 94, 861-876,

Graaf, A.d., Heijer, R., Postma, S., 2016. Evaluatie Wijzigingsbesluit bodemenergiesystemen. Buro 38 in commission of Ministry of Infrastructure and Environment, Cothen.

Haehnlein, S., Bayer, P., Blum, P., 2010. International legal status of the use of shallow geothermal energy. Renewable and Sustainable Energy Reviews 14, 2611-2625.

Harbaugh, A.W., Banta, E.R., Hill, M.C., McDonald, M.G., 2000. Modflow-2000, the U.S. Geological survey modular ground-water model—user guide to modularization concepts and the ground-water flow process in: USGS (Ed.). US Geological Survey, Virginia.

Hecht-Mendez, J., Molina-Giraldo, N., Blum, P., Bayer, P., 2010. Evaluating MT3DMS for Heat Transport Simulation of Closed Geothermal Systems. Groundwater 48, 741-756.

Hartog, N., Bloemendal, M., Slingerland, E., van, W.A., 2017. Duurzame warmte gaat ondergronds. VV+ sept-okt 17.

Holstenkamp, L., Meisel, M., Neidig, P., Opel, O., Steffahn, J., Strodel, N., Lauer, J., Vogel, M., Degenhart, H., Michalzik, D., Schomerus, T., Schönebeck, J., Növig, T., 2017. Interdisciplinary review of medium-deep Aquifer Thermal Energy Storage in North Germany, 11th International Renewable Energy Storage Conference, IRES, Dusseldorf, Germany.

Kruit, K., Schepers, B., 2017. Warmtevraag en- aanbod in Zuid-Holland: toelichting op database (in Dutch), incl. dataset / Heat demand and supply South-Holland: supplementary information on database, incl. dataset. CE Delft (17.5M31.173). Delft.

Langevin, C.D., 2008. Modeling Axisymmetric Flow and Transport. Ground Water 46, 579-590.

Langevin, C.D., Dausman, A.M., Sukop, M.C., 2010. Solute and heat transport model of the Henry and hilleke laboratory experiment. Ground water 48, 757-770.

Langevin, C.D., Thorne, D.T., Dausman, A.M., Sukop, M.C., Guo, W., 2008. SEAWAT Version 4: A computer program for simulation of multi-Species Solute and heat transport. USGS, Reston, Virginia.

Lopik, J.H., Hartog, N., Zaadnoordijk, W.J., Cirkel, D.G., Raoof, A., 2015. Salinization in a stratified aquifer induced by heat transfer from well casings. Advances in Water Resources 86, 32-45.

Lopik, J.H.v., Hartog, N., Zaadnoordijk, W.J., 2016. The use of salinity contrast for density difference compensation to improve the thermal recovery efficiency in high-temperature aquifer thermal energy storage systems. Hydrogeology Journal

Oude Essink, G. H. P., Van Baaren, E. S., & De Louw, P. G. B. (2010). Effects of climate change on coastal groundwater systems: A modeling study in the Netherlands. *Water Resources Research*, 46(May), 1–16.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

Possemiers, M., Huysmans, M., Batelaan, O., 2015. Application of multiple-point geostatistics to simulate the effect of small-scale aquifer heterogeneity on the efficiency of aquifer thermal energy storage. Hydrogeology Journal 23, 971-981.

RVO, 2021. Warmtetransitieatlas (WTA) Zuid-Holland / Heat Atlas South-Holland. Rijksdienst voor Ondernemend Nederland (RvO).

Sanchez, M.F., Klein, J., Essink, G.O., Raat, K., Paalman, M., 2012. Effecten van brijninjectie op de grondwaterkwaliteit en functies in het Westland Deltares / KWR, Delft / Nieuwegein.

Schout, G., Drijver, B., Gutierrez-Neri, M., Schotting, R., 2013. Analysis of recovery efficiency in high-temperature aquifer thermal energy storage: a Rayleigh-based method. Hydrogeology Journal 22, 281-291.

Sharqawy, M.H., Lienhard, J.H., Zubair, S.M., 2012. Thermophysical properties of seawater: a review of existing correlations and data. Desalination and Water Treatment 16, 354-380.

Sommer, W., Valstar, J., van Gaans, P., Grotenhuis, T., Rijnaarts, H., 2013. The impact of aquifer heterogeneity on the performance of aquifer thermal energy storage. Water Resources Research 49, 8128-8138.

Thorne, D.T., Langevin, C.D., Sukop, M.C., 2006. Addition of simultaneous heat and solute transport and variable fluid viscosity to SEAWAT. Computers & Geosciences 32, 1758-1768.

van Lopik, J.H., Hartog, N., Zaadnoordijk, W.J., 2016. The use of salinity contrast for density difference compensation to improve the thermal recovery efficiency in high-temperature aquifer thermal energy storage systems. Hydrogeology Journal 24, 1255-1271.

Voss, C.I., 1984. A finite-element simulation model for saturated unsaturated, fluid-density-dependent groundwater flow with energy transport or chemically reactive single-species solute transport. USGS, Reston, Va.

Willemsen, N., 2016. Rapportage bodemenergiesystemen in Nederland. RVO / IF technology, Arnhem.

Xynogalou, M., 2015. Determination of optimal separation well distance for Single Borehole ATES systems in the Netherlands, implementing an axisymmetric numerical model. Delft University of Technology, Delft.

Zheng, C., Wang, P.P., 1999. MT3DMS: A Modular Three-Dimensional Multispecies Transport Model for Simulation of Advection, Dispersion, and Chemical Reactions of Contaminants in Groundwater Systems; Documentation and User's Guide.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement N°776541

5. Conclusions

5.1. Benefits and challenges of the NextGen technologies

This report addressed three energy recovery practices across different NextGen demo cases, including (1) heat recovery from wastewater and local reuse, (2) biogas production from sewage sludge and (3) heat storage and recovery. The main benefits and challenges of the NextGen technologies are summarised in Table 31.

Table 32 Benefits and challenges of the NextGen technologies/approaches for energy recovery

Energy recovery	Case study	Technology/ Approach	Benefits	Challenges
(1) Heat recovery from wastewater and local reuse	Athens (GE)	Heat exchanger and heat pump	- Small, decentralised system - Easy to operate - Competitive capital cost - Return on investment can be less than 1 year	- Relatively low coefficient of performance (COP) values (4.5-5.5) - Requirement of high treated water quality with very low suspended solid content
	Filton Airfield (UK)	Feasibility study of low-grade heat recovery and local reuse	- Provide practical insight on the applicability of local heat recovery and reuse	- Require more accurate data collection to simulate wastewater profiles, flow rates and temperature - Heat storage required to overcome temporal variations of heat availability and demand
(2) Biogas production from sewage sludge	Braunschweig (GE)	Thermal hydrolysis and two-stage digestion	- Higher biodegradation and enhanced biogas production - Better dewaterability of digest and	- High maintenance technology - Risk of methane leakages

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

Energy recovery	Case study	Technology/ Approach	Benefits	Challenges
			reduction of disposal costs	- Temperature sensitive
	Spernal (UK)	Decentralised energy recovery from anaerobic membrane bioreactor	- Great potential for energy neutrality - Low carbon footprint - Compact system	- Use of energy and cleaning chemicals - Complex to operate - High capital cost
(3) Heat storage and recovery	Westland (NL)	Aquifer thermal energy storage	- Energy saving potential and low greenhouse gas emissions - Optimal utilization of available heat, overcoming temporal discrepancy between demand and availability	- Require presence of suitable aquifers - Require extensive monitoring to increase efficiency and counteract possible imbalances and interference

5.2. Best applications of the technologies

Four energy recovery technologies have been demonstrated in NextGen. Three technologies have been used to recover energy from treated wastewater and sewage sludge as an energy source while one technology is applied for heating and cooling supply.

In Athens, traditional centralised sewage heat recovery used raw sewage as a thermal energy source and showed good efficiencies in heating and cooling modes. However, they require additional processes including a pre-treatment system and often cause corrosion and biofouling. As a NextGen solution, a combination of the heat exchanger and heat pump was applied as an energy-efficient alternative to boilers or air conditions. In particular, the decentralised, commercially available small-heat recovery unit used in the pilot produces lower but acceptable efficiencies (COP heating 4.0-5.12 and EER cooling 3-4.85) without severe corrosion and biofouling as the system used the treated wastewater produced from MBR. This set-up was operated in the 1-10 kW range. However, the system still needs to be more operated to evaluate maintenance required, i.e., feed water quality control. For such smaller systems, water tanks or phase transition heat storage systems can be used in Filton Airfield. During the NextGen project, the Filton case investigated heat recovery potential and

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement N°776541

theoretically assessed recovered heat reuse for space heating and water heating. Results showed that the total heat recovery potential was in the 3.54-7.85% range, depending on house water use scenarios. Although the system highly depends on the conditions such as temperature etc, the system can contribute to reducing greenhouse gas emissions by replacing cooling and heating systems operated with fossil fuels. Through the NextGen demonstration, the system has been proven to be capable of performing all the functions even though the long-term operation is still required. In order to make this heat recovery technology feasible, there are some issues that need to be resolved. The piloted implemented thermal energy recovery solution showed that it is possible to use commercially available mass-produced heat pump equipment for decentralized energy recovery solutions. In order to spread the use of small-scale decentralized heat recovery units, pre-programmed, multifunctional switch options should be made available in order to address different potential uses such as technology boosting in decentralized solutions and residential heating /cooling/ hot water. A standardized heat recovery unit and switch should be made available for the market, with an easy-to-use installation and operation manual. Partners for production finalization and a distribution network are needed to upscale at the EU implementation level. A bundle option for water, thermal energy, and nutrient recovery is also recommended as a decentralized solution for urban parks and green areas. The water treatment unit, the thermal recovery unit, and the composting reactor unit should be fully integrated into one unit. This option should be pre-manufactured and readily available for installation and integration into any urban green area.

Another NextGen energy recovery technology that can be applied to a decentralised system is an anaerobic membrane reactor (AnMBR) combined with a methane degassing system. Coupling AnMBR with a methane degassing system for wastewater treatment allows for the recovery of the dissolved methane, and clean water rich in valuable nutrients. Methane has a high greenhouse gas potential, and its recovery and management are crucial to ensure the technology's low environmental impact. In order to make this technology feasible there are numerous and outstanding issues we need to resolve:

1. Effective and cost-efficient removal of the dissolved methane in the AnMBR effluent. The technology trialled at Spernal while having significant potential, remains at a low TRL, we had issues of leaks and corrosion during the trial that limited run-time. We also need to deal with the fundamental challenge of methane recovery – the two options evaluated were i) using a nitrogen sweep gas (energy efficient but leads to a recovered gas stream dilute in methane and therefore hard to valorise, or ii) vacuum degassing – this gives a high concentration of methane in the gas stream but is energy intensive. Recommended next steps are to evaluate other recovery processes for example biological degradation of the methane or scrubbing towers.

2. Influent wastewater quality – particularly sulphate. The wastewater at Spernal is largely representative of UK municipal wastewater, nonetheless, it contains levels of sulphate that cause issues for the anaerobic reactor and the downstream equipment. In the reactor the sulphate is reduced to hydrogen sulphide by sulphate reducing bacteria (SRB) – this generates odorous and corrosive hydrogen sulphide/sulphuric acid and reduces the gas yield as some of the COD is used by the SRB rather than converted to methane by the

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

methanogens. Recommended next steps investigate pre-treatment options to remove, sequester the sulphate/sulphide in the influent wastewater.

3. Nutrient (Ammonia & Phosphorus) recovery This aspect of the flowsheet requires additional development (particularly the ammonia recovery) in terms of the technology but also the ‘end of waste’ regulations and the market development for the nutrient products. Recommended next steps – Engage with and influence regulators and markets to ensure these two pillars of the implementation plan are developed in parallel with the technical development.

4. Long asset lifes of existing technology (ASPs) This technology is designed to replace energy, chemical and carbon intensive aerobic treatment technologies such as activated sludge plants. Despite the obvious advantages of the AnMBR flowsheet it is likely that full scale adoption will be a slow process even when the above technical challenges have been resolved. Recommended next steps – identify early opportunities for implementation of part or all the flowsheet e.g., if utilities have asset expired activated sludge plants or old fixed film processes that require upgrading to meet tight new standards.

A hybrid TPH and two-stage digestion system is promising to enhance biogas production, as demonstrated in the Braunschweig case. The system can be applied in a centralized wastewater treatment plant (WWTP) - the conventional WWTP with TPH being incorporated in the sludge line as a pre-treatment for anaerobic digestion. The TPH breaks down complex organic carbon compounds such as microbial cells into soluble compounds. In a subsequent anaerobic digester, microorganisms degrade those soluble compounds resulting in an increase in the biogas production of about 20% compared to anaerobic digestion without TPH. This system has been proved at a full-scale level (TRL 9) and showed successful operations and applications during the NextGen project. However, high maintenance technologies and further operation under the full range of operating conditions are more required for full commercial development.

An aquifer thermal energy storage (ATES) can provide an adequate solution as this system allows longer-term seasonal energy storage. Residual heat in the Province of South Holland could contribute 100% of the heat demand of the horticulture companies in Westland. In terms of energy storage capacity, an ATES can secure 10-15 PJ seasonal storage (10-15 % of the annual total energy demand). In addition, the currently expected number of geothermal wells combined with HT-ATES can meet about 5% of the heating demand of a cluster of 43 horticulture companies. From the environmental aspect, the ATES system can reduce the use of fossil fuels for heating in winter or cooling in summer. Large scale adoption of HT-ATES in the Westland could potentially save ~250 Mm^3 gas, which reduces the GHG emissions with ~500 kt per year. The performance of the HT-ATES system at horticulture company Koppert Cress in the current situation shows that, although the heat recovery factor for the warm well is good (0.7-0.95), the heat demand is not reached. The expected future addition of a geothermal heat source can provide in the required amount of extra heat. Overall, the findings drawn during the NextGen show the applicability of the ATES system to other regions but specific geohydrological conditions (i.e., system location/integration, groundwater flow and quality, legislation etc.) need to be investigated.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement N°776541

5.3. Transferability: application at other sites

Energy recovery technologies in NextGen are applied at different scales from city to regional levels. Although transfer and scaling studies are more needed for transferring each technology to other sites, the findings from the NextGen project offer insights into a direction for further research on the transferability and scalability of those technologies. This section addresses the main challenges and key requirements that need to be considered to adapt and implement technologies at other sites.

Heat exchanger and heat pump

In NextGen, a decentralised heat recovery system (25 m^3/day) has been successfully demonstrated. The results showed that more than 80% of energy recovery can be credited and used for general heating and/or cooling purposes while the remaining 20% can be used for composting/nutrient recovery boosting (refer to D1.5). Key parameters for heat recovery from wastewater and local reuse are wastewater flow rate and temperature. It has been shown that the decentralised heat recovery system can have a higher volume of wastewater and accumulation of multiple hot water activities. In addition, the temperature in the wastewater can be maintained at 24 °C (Section 2.1.7). Thus, before planning and adapting this technology, it should be carefully investigated which flow, temperature and feed quality will result in the influent to the system and its effect on the overall system efficiency (e.g., COP and energy saving).

In order to spread the use of small-scale decentralized heat recovery units, pre-programmed, multifunctional switch options should be made available in order to address different potential uses such as: technology boosting in decentralized solutions and residential heating /cooling/ hot water. A standardized heat recovery unit and switch should be made available for the market, with an easy-to-use installation and operation manual. Partners for production finalization and a distribution network are needed in order to upscale at EU implementation level.

A bundle option for water, thermal energy, and nutrient recovery is also recommended as a decentralized solution for urban parks and green areas. The water treatment unit, the thermal recovery unit, and the composting reactor unit should be fully integrated into one unit. This option should be pre-manufactured and readily available for installation and integration into any urban green area.

Biogas production from wastewater or sewage sludge

In NextGen, two different energy recovery configurations have been demonstrated at the WWTP level – (1) TPH and two-stage digestion and (2) AnMBR combined with a methane degassing system.

The TPH is used as a pre-treatment for anaerobic digestion at WWTP with a capacity for 350000 population equivalents. By coupling TPH and anaerobic digestion, higher degradation during digestion and thus enhancing biogas production by up to 20%. This NextGen technology is in TRL 9, meaning that it is a final form and operated under the full range of operating and maintenance conditions. Thus, the results obtained during the NextGen project

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

show high transferability potential of TPH at existing WWTPs since anaerobic digestion is the dominant sludge treatment technology in most countries' WWTPs.

Pilot-scale operation of an anaerobic membrane reactor (AnMBR) combined with a methane degassing system with a capacity of 200 m^3/day is a first step to investigate its technical-economic feasibility before confirmation in long-term full-scale operation. This means that the methane yield assessments at a pilot scale could investigate uncertainties of the system. However, during the NextGen project, continuous experiments for the pilot scale have been challenged mainly due to the technical issues with the membrane degassing system (i.e., membrane operation and cleaning and feed water quality control). Nevertheless, the expected methane yield based on batch experiments is assumed to be around 33 m^3 CH_4/day by assuming 90% COD removal and on average 11 m^3 CH_4/day. This batch-mode experiment data could be used to predict full-scale methane yield. In parallel, long-term continuous experiments for the pilot scale should be done. Therefore, this will provide a high data quality for the transferability and scalability of the system for other sites.

Heat storage and recovery

Heating and cooling using aquifer thermal energy storage (ATES) have been demonstrated in NextGen. The key requirement of the ATES system is to have an equal need for heat and cold on an annual basis. In addition, if there are large seasonal differences in demand and availability for heat, the ATES system can have high storage efficiency. Based on the project results, the key outcome is the optimal utilisation of available heat, and the ATES system can be a promising solution for heat storage from larger scale wastewater heat recovery systems (i.e., combining ATES with sewer heat recovery for Filton Airfield). However, its main challenge is the required presence of an adequate and suitable aquifer. In this context, it is crucial to conduct pre-investigation on technical (subsurface and climate conditions) and organisational/legal barriers. Thus, for future transferability of the technology, extensive and innovative monitoring to increase efficiency and counteract possible imbalances and interference, uneven distribution of costs and benefits and legislative procedures.

5.4. Recommendations for future implementations

This report focused on maximising the recovery of energy and heat intrinsically linked to the water cycle by either transforming the organic waste into biogas or taking advantage of temperature differences from wastewater streams.

In order to encourage energy recovery at different levels, various countries can introduce NextGen energy recovery technologies in their respective regulatory frameworks and guidelines aimed at improving the energy efficiency of existing or new development areas.

More studies with direct attention to list technical specifications should be performed to clearly highlight the advantage of energy recovery and reuse over conventional technologies in the future with the increasing cost of traditional energy sources. In addition, the decentralisation of heat recovery systems can be a promising method to enhance local energy recovery and reuse, reduce reliance on extensive sewer networks, and reduce the intensity

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

of economic and environmental impacts from centralised systems. Thus, more studies should be dedicated to this direction.

Although during the NextGen project, new approaches and technologies have been developed and demonstrated, the robustness of NextGen technologies for energy recovery and its broader implementation is still limited by energy, economic and environmental aspects. Further clarification on key features in relation to technical issues for long-term operations, monitoring and maintenance should be discussed between operators, developers, property owners and public and private organisations. In this context, further research should focus on policy and decision-making to improve understanding that the reuse of heat recovered from wastewater or sewage sludge provides energy savings.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541