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Industrial Electrical Engineering and Automation

# Sustainability Analysis for Wastewater Heat Recovery – Literature Review

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HÅA
HÅLLBARHETSANALYS AV
VÄRMEÅTERVINNING UR AVLOPPSVATTEN

TECHNICAL REPORT

# Sustainability Analysis for Wastewater Heat Recovery
# Literature Review

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energy systems, heat recovery, mathematical modelling, performance assessment, sustainability, urban water systems, wastewater treatment

# Preface

This report is the first deliverable from the project Sustainability Analysis of Wastewater Heat Recovery, running from 2016 to 2019. The project is funded by grants from The Swedish Research Council Formas and The Swedish Water and Wastewater Association along with financial and/or in-kind contributions from partnering organisations: Sweden Water Research, VA SYD, Tekniska Verken in Linköping, Käppalaförbundet and Stångåstaden. The authors would like to thank the following persons for contributing and reviewing the manuscript of the report: Selim Stahl and Emma Rex, RISE; Robert Sehlén and Jenny Nordenberg, Tekniska Verken in Linköping; Stefan Nielsen and Stefan Erikstam, Käppalaförbundet; Mårten Danckwardt Lillieström and Ulrica Melin, Stångåstaden; David Gustavsson, Sweden Water Research and Maria Jonstrup, VA SYD.

Magnus Arnell
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# Sammanfattning

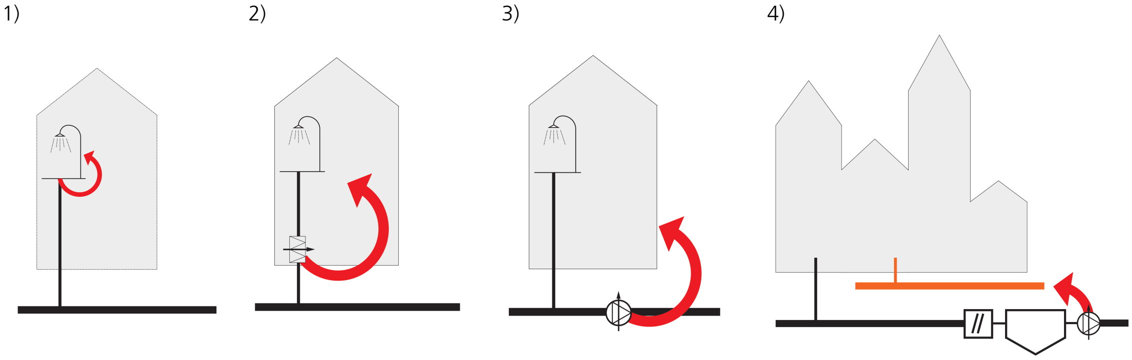
Denna rapport beskriver en litteraturstudie om värmeåtervinning ur avloppsvatten som gjorts inom ramen för forskningsprojektet Hållbarhetsanalys för värmeåtervinning ur avloppsvatten, HÅVA. Uppvärmning av tappvarmvatten hos slutanvändarna utgör lejonparten av den totala energianvändningen i den urbana vattencykeln, upp till 90 %. Uppskattningar visar att 780 till 1 150 kWh per person och år används i svenska hushåll i form av varmvatten. Varmvattenanvändningen är inte jämnt fördelad över tiden vilket bidrar till variationer i flöde och temperatur för avloppsvatten. Denna energi hamnar huvudsakligen i avloppsvattnet. Variationerna i varmvattenanvändning är stora och potentialen för besparingar är generellt stor. En kompletterande möjlighet för att minska energianvändningen för varmvatten är att återvinna delar av den värme som går ut via avloppet.

Tillämpningen av värmeåtervinning ur spillvatten är lovande ur ett energiperspektiv men det finns också utmaningar på systemnivå där motstridiga målsättningar inte fullt ut undersökts. Om värmeåtervinningen resulterar i en lägre inloppstemperatur för avloppsvattnet till reningsverket kan det leda till försämrad rening och ökade utsläpp – av framförallt kväve – till recipienten samt till ökade driftskostnader för energi och kemikalier. Tillgänglig forskning som identifierats i denna litteraturstudie har inte kunnat ge svar på frågan hur stor påverkan värmeåtervinning uppströms reningsverket har på inloppstemperaturen med hänsyn till värmeförluster och tillskottsvatten i ledningsnätet. Det finns ett behov av att göra en systemövergripande hållbarhetsanalys som analyserar effekten av värmeåtervinning på olika delsystem samt ger en samlad bedömning av konsekvens och nytta med denna praxis.

Energi i avloppsvatten kan återvinnas med hjälp av värmeväxlare eller värmepumpar (eller en kombination av båda). Värmeväxlare är en enklare och mer robust teknik. Värmeåtervinningen i värmeväxlare är begränsad av differenstemperaturen mellan avloppsströmmen och det kalla mediet. I litteraturen har många installationer av värmeväxlare som återvinner avloppsvärme för att förvärma inkommande tappvarmvatten före varmvattenberedaren hittats. Värmepumpar kan lyfta värmen från en låg temperatur upp till en högre vilket möjliggör bättre användning av värmen. Priset för detta är en insats av elenergi. Effektiviteten beror huvudsakligen på temperaturskillnaden och mäts i en värmefaktor, COP. För värmepumpar i avloppsvatten har värmefaktorer på 3 till 7 redovisats i litteraturen, ju högre avloppstemperatur – d.v.s. högre uppströms i avloppssystemet – desto effektivare. Värmepumpar kräver ett jämnare flöde och ofta någon form av avskiljning av partiklar för att fungera bra. Vissa installationer av värmeåtervinnande utrustning har varit i drift under lång tid och både teknisk funktion och ekonomisk lönsamhet har utvärderats vilket redovisas i rapporten. Exempel finns både i Sverige och utomlands.

När spillvattnet lämnar en bostadsfastighet har det en temperatur på omkring 20 °C och när det når reningsverket har det sjunkit till ca. 8 till 12 °C. Inloppstemperaturen till reningsverket varierar med säsongerna och över dygnet. Skillnaderna mellan olika reningsverk är stor beroende på kallvattentemperatur, ledningsnätets funktion och status samt klimat (snösmältning, etc.). Tillskottsvatten i form av dagvatten och inläckage har visat sig sänka temperaturen på avloppsvattnet påtagligt. Av den energi som går till avloppet visar studier att ca. 800 kWh per person och år går att återvinna. Det motsvarar ca. 7,5 TWh per år för hela Sveriges befolkning. Principiellt kan spillvattenvärmeåtervinning implementeras i fyra olika positioner från komponentnivå och fastighets nivå uppströms ner till reningsverkets utlopp, Figur I.

I litteraturen finns ett stort antal installationer av spillvattenvärmeväxlare av olika slag och i olika positioner beskrivna. För värmeåtervinning i fastigheter har studier visat att 3 till 9 kWh per $m^2$ boarea och år kan återvinnas. Det kan jämföras med att energiförbrukningen för tappvarmvatten uppvärmning i ett flerfamiljshus är ca. 25 kWh/$m^2$/år. Andra studier visar att ca. 10 till 30 % av



Figur I. Möjliga positioner för spillvattenvärmeåtervinning: 1) komponentnivå (t.ex. duschar), 2) fastighetsnivå, 3) kvartersnivå (i avloppsledningsnät eller -pumpstationer) och 4) på reningsverkets utlopp.

energin i avloppsvattnet kan återvinnas, vilket är i samma storleksordning. I Sverige och utomlands finns också flera installationer av värmepumpar på utgående avloppsvatten från avloppsreningsverk. Totalt återvinns 2 till 3 TWh årligen vid framförallt större reningsverk med befintligt fjärrvärmenät i närheten. Värmepumpar på utgående avloppsvatten har en förhållandevis låg COP, 3 till 4.

Modellering är ett kraftfullt verktyg för att utvärdera prestanda på avloppssystem. Det ger möjlighet till att utvärdera de integrerade effekterna på systemnivå och utvärdera och jämföra olika målsättningar, t.ex. energi, ekonomi och reningsprestanda. De väsentliga delsystemen för att utvärdera värmeåtervinning ur avloppsvatten kan modelleras.

- Varmvattenanvändning och den energianvändning som kopplas till det har modellerats tidigare i syfte att utvärdera besparingar. Modellerna inkluderar också tidsvariationer över dygn och vecka. Metodiken för detta kan anpassas för att modellera det större systemet, inklusive värmeåtervinning.
- Prestanda och resultatvariabler för värmepumpar och värmeväxlare är standardmässiga beräkningar och användbara ekvationer har sammanställts.
- Energibalansen i avsnitt av ledningsnät och variationer i avloppsvattentemperatur har tidigare modellerats på olika sätt för specifika syften. Befintliga modeller bedöms svåra att skala upp till ett helt avloppssystem. Koncept från identifierade modeller kan tillämpas med nyutveckling kommer att krävas för projektets vidare syften.
- Temperaturens påverkan på avloppsreningsverkets biologiska processer kan modelleras med befintliga bioprocessmodeller. Eventuellt kan temperaturvariationer längs reningsverkets vattenväg att behöva inkluderas.

I de fall ett fjärrvärmesystem finns i samhället där spillvattenvärme återvinns bör interaktion med energisystemet beaktas. Minskat värmebehov i fjärrvärmenätet kan i vissa fall leda till ökade växthusgasutsläpp om integration med den europeiska el- och avfallsmarknaden beaktas. Detta gäller framförallt om värmebehovet minskar under den varma årstiden och i mindre grad om värme återvinns när effektbehovet är högt under vintern.

I Sverige finns det olika regelverk som påverkar tillämpningen av värmeåtervinning ur avloppsvatten. Varmvattensystem i byggnader är reglerade i Boverkets byggregler för att förebygga legionellautbrott. Vidare så begränsas värmeåtervinningen i byggnader av de avtalade bestämmelserna mellan kund och VA-huvudman i majoriteten av Sveriges kommuner (ABVA). Dels krävs tillstånd från VA-huvudmannen för dylika installationer samt att värmeuttaget begränsas till att utgående avloppstemperatur från byggnaden inte får understiga inkommande kallvattentemperatur.

# Abstract

This technical report describes the literature review conducted on wastewater heat recovery (WWHR). As part of the urban water cycle, domestic hot water consumes the lion share – up to 90 % – of the total energy requirement for water management. Individual energy consumption of 780 to 1 150 kWh/cay/yr has been estimated in Sweden. Energy can be recovered from wastewater, in buildings close to the source or further downstream in the wastewater system. Depending on wastewater flow and temperature heat exchangers or heat pumps (or a combination of both) can be used for extracting heat the energy. Obstacles for utilizing this potential are for example: clogging and fouling of equipment, potentially negative system impacts and economic feasibility. Examples of various WWHR implementations have been found in Sweden, Switzerland and North America. Some installations have been running for a long time and technical function and financial viability has been evaluated and are reviewed in the report. Generally, heat pumps reach a coefficient of performance of 3 to 7, better the higher the wastewater temperature is, i.e. further up-stream.

WWHR application in a wastewater system can be modelled. The domestic hot water requirement and associated energy use has been modelled previously and concepts can be adapted for modelling the larger system. Equations for calculating performance and output variables from heat recovery equipment have been reviewed and is presented. For the purpose of assessing single WWHR installations in sewers, detailed models have been developed and presented. There are reviewed in the text. Concepts for estimating temperature variations in sewers are essential to assess the impact on wastewater treatment plants. Performance of wastewater treatment plants and their temperature dependence can be modelled with existing process models. Temperature variations along the course of the treatment plant might be important to consider.

In Sweden, there are currently some regulations related to WWHR. The temperature of hot water systems in buildings are regulated to prevent Legionella outbreaks. Furthermore, the practice of WWHR is limited in extent and requires a permit from the utility as by the contract between the consumer and the utility. Currently, this limits the implementation of WWHR in Sweden.

# Nomenclature

**Abbreviations**

| | |
|---|---|
| ABVA | Customer agreement on water services. In Swedish, Allmänna bestämmelser för VA-anläggning |
| ADM1 | Anaerobic Digestion Model No. 1 |
| ASM | IWA Activated Sludge Models No. 1 to 3 |
| ASU | Activated sludge unit |
| BLDG | Building |
| BRE | Building Research Establishment (company) |
| BREEAM | BRE Environmental Assessment Method |
| COP | Coefficient of performance (for heat pumps) |
| DHW | Domestic hot water |
| DOE | Department of energy |
| EPA | Environmental Protection Agency |
| EPD | Environmental product declarations |
| EU | European Union |
| GHG | Greenhouse gas |
| HEX | Heat exchanger |
| HH | Household |
| HP | Heat pump |
| HWC | Hot water circulation |
| IWA | International Water Association |
| KTH | The Royal Institute of Technology KTH |
| LEED | Leadership in energy and environmental design |
| ODE | Ordinary differential equation |
| PDE | Partial differential equation |
| RMSE | Root mean square error |
| SCB | Statistics Sweden (Statistiska centralbyrån) |
| SDG | Sustainable Development Goal |
| STEM | The Swedish Energy Agency (Energimyndigheten) |
| STEP | Sustainable Technologies Evaluation Program |
| UN | United Nations |
| WW | Wastewater |
| WWH | Wastewater heat |
| WWHR | Wastewater heat recovery |
| WWT | Wastewater treatment |
| WWTP | Wastewater treatment plant |

**Parameters and Variables**

| | | |
|---|---|---|
| COD | Chemical oxygen demand | $g/m^3$ |
| SRT | Solids retention time | d |
| T | Temperature | $^oC$ |
| Q | Flow | $m^3/d$ |

# 1 Introduction

This is an internal report in the research project Sustainability Analysis of Wastewater (WW) Heat Recovery (WWHR) – Hållbarhetsanalys av värmeåtervinning ur avloppsvatten (HÅVA), in Swedish – coordinated by the Division of Industrial Electrical Engineering and Automation at Lund University, Lund, Sweden. Key partners in the project are RISE Research Institutes of Sweden, the wastewater utilities VA Syd, Tekniska Verken in Linköping and Käppalaförbundet, and the real estate company Stångåstaden.

Smarter infrastructure is required to make our cities more resource-efficient and at the same time more liveable. This study should be seen as part of a broader goal of reaching sustainable cities through evaluating technology and design of urban local systems, hand in hand with the concept of Urban Metabolism (Ferrão & Fernández, 2013).

## 1.1 Aim and Goal of the Project

The aim of the whole project is to gain knowledge about the system-wide effects of wastewater heat recovery (WWRH). A broad sustainability analysis will provide the foundation to determine if the benefits exceed the risks when introducing WWHR. The overarching goal is to enable sustainable recovery of the large energy resource in wastewater that is currently wasted.

One of the project outputs is a system-wide model tool including components for heat recovery in different positions, heat losses in sewers and the effect of inlet temperature on the WWTP efficiency and resource requirements. The model will be used as part of a sustainability analysis. In three case studies, simulation of scenarios for different options will provide insights about the system-wide effects of WWHR.

This report is the first output from the project and it aims to clarify the state of the art in modelling waste water heat recovery and to provide an overview of the existing WWHR installations, the existing techniques and suppliers.

## 1.2 Delimitations for the Project

- Storage of recovered heat from wastewater is not included in the study.
- Other heat sources than wastewater is not part of the study.
- Industrial WWHR is not considered.
- No other heat recovery at WWTPs than from the main water train will be considered.

## 1.3 Project Contributions to UN Sustainable Development Goals

In 2015, 193 countries in the United Nations (UN) agreed on a resolution for global sustainable development – Agenda 2030. The agenda sets 17 goals to achieve a social, environmental and economic sustainable world by 2030. For the 17 Sustainable Development Goals (SDGs), 169 quantifiable and measurable targets have been defined. The Agenda 2030 is truly global and, in contrast to the previous UN Millennium Development Goals, they challenge all countries to step up and work for a more sustainable world nationally and internationally.

This project on WWHR has been identified to address four of the SDGs and contribute to improve seven targets.

*SDG 6 – Clean Water and Sanitation*
6.3.1 Proportion of wastewater safely treated
6.3.2 Proportion of bodies of water with good ambient water quality

*SDG 7 – Affordable and Clean Energy*
7.1.2 Proportion of population with primary reliance on clean fuels and technology
7.3.1 Energy intensity measured in terms of primary energy and GDP
*SDG 9 – Industry, Innovation and Infrastructure*
9.4.1 $CO_2$ emission per unit of value added
9.5.1 Research and development expenditure as a proportion of GDP
*SDG 14 – Life Below Water*
14.1.1 Index of coastal eutrophication and floating plastic debris density

## 1.4 Scope of the Literature Review and Layout of the Report

This technical report describes the literature review conducted for the project. The scope of the literature review has the same focus as of the overall project, which involves looking at heat recovery at mainly four different locations in the wastewater system, i.e. at component level, at property level, at precinct level and at system level after a wastewater treatment plant (WWTP). Also, some alternative measures, such as hot water conservation measures for households has been included.

The literature review includes: academic publications, reports (technical, consultancy, etc.) on installation and testing as well as information and specification of technical equipment. The literature was retrieved from search in academic databases (Scopus and Web of Knowledge), search on the Internet and collected from project partners. For the background, a few interviews were conducted to collect information relevant for the project, e.g. about other on-going projects in the same area. Key review articles and reports with extensive reference listings have also been a source for finding relevant literature. The material has been reviewed to collect and compile the present state of knowledge related to the area of the project.

In Chapters 2 to 6 in this report the literature review is presented with extensive referencing. Chapter 2 presents some general background on WWHR. In Chapter 3, studies on relevant wastewater characteristics for WWHR are presented. Furthermore, in Chapter 4 literature on WWHR systems are thoroughly described, e.g. the technology used, examples in installations and reported performance. Chapter 5 focuses on the modelling of WWHR systems and in Chapter 6 the relations between WWHR and the energy production is described. In Chapter 7, literature on regulation and financial viability of WWHR systems are briefly touched upon.

# 2 Background

According to several international studies the energy use in the urban water cycle adds up to 10% or more of the total national energy use (Olsson, 2012). Out of this only about 10% (corresponding to 1% of the total energy use) is used for withdrawal, treatment and distribution of tap water and collection, treatment and discharge of wastewater. The remaining part – the absolute majority – is used by the customers mainly for heating tap water for showers, dishwashers and laundry (Olsson, 2012). The Swedish Energy Agency (2009) has estimated the heat requirement in households for domestic hot water (DHW) to 1,150 kWh/cap/yr. These statistics is often used to argue for saving DHW but also to motivate recovery (or recycling) of heat from wastewater. Wastewater heat recovery (WWHR) is also known as sewage (or sewer) heat recovery, drain water heat recovery, water heat recovery, greywater heat recovery or even shower water heat recovery.

There are many reasons to recover heat from domestic wastewater, such as water from the dishwashing, laundry and shower that otherwise goes down the drain. Typically, 80-90% of the energy used to heat water in an American home goes back down the drain (U.S. Department of Energy, 2017). By installing a WWHR system the energy used for heating water can be reduced. Energy Saver – the U.S. Department of Energy's (DOE) consumer resource on saving energy and using renewable energy technologies at home – state that WWHR systems have a pay-back range from 2.5 to 7 years. This is dependent on how often the system is used. In the USA, many municipalities have an upper limit of temperature, 120-140 degrees Fahrenheit (= 49-60 °C), on drain water entering the sewer system. This means that many larger facilities such as hospitals that have kitchens or laundry, might have to cool there drain water. For these special situations heat recovery would seem extra appropriate.

In Sweden, there are still very few installations of WWHR and one reason for this is that property managers and owners are hesitant to how much energy that can actually be recovered and if the investment will pay off (Blomsterberg, 2015). Due to the few installations, there are few best practise examples to take after and there is uncertainness around the functionality and robustness of such systems.

Heat recovery through heat exchange from one liquid to another is a well-known approach within many fields and industries. In chemical engineering heat exchange reactors (HEX), compact heat exchangers and microchannel heat exchangers are all well-known examples of process-intensifying equipment with the potential impact of making the overall processes more energy-efficient and environmentally sustainable (Stankiewicz & Moulijn, 2000). There are several types of heat exchangers, such as plate, tube, plate-fin, plate-and-shell, spiral heat exchanger and many more (de Vries, 2015). When it comes to recovering heat from wastewater however, the approach of heat exchange is quite underutilised and disputed.

Obstacles for introducing wastewater heat recovery can simply be the measures taken to decrease hot water consumption, a much cheaper measure than the implementation of a WWHR system (The Swedish Energy Agency, 2006). If the hot water consumption goes down then the benefit from WWHR is decreased. Aside from achieving environmental certifications, the financial aspect is highly important, including the comparison of space and investment costs for example (Nykvist, 2012). Some heat exchangers are only suitable for greywater and not for wastewater from toilets and kitchen, which require a source separating wastewater system.

Constructing hot water systems in buildings requires considering regulations and norms to provide safe water on tap as well as minimizing the energy loss in the heat transfer. According to the Swedish standards, the hot water must be at least 50° Celsius at the tapping point as well as in the hot water circulation (HWC) system in order to prevent Legionella outbreaks (Olsson, 2003). HWC systems are built with the purpose to deliver hot water on tap quicker upon request, thereby saving water. This demands that the hot water out from the water heater has to be higher; however, the water at the tapping point has to be below 65° Celsius to avoid scalding (Olsson, 2003). These figures form some boundaries also for the implementation of heat exchangers on wastewater.

## 2.1 Knowledge Gap

The application of WWHR holds great promises but there are also effects on system level with potential conflicting objectives that have not been investigated in detail in the previous studies of the different components of the system. A significant reduction of the WWTP inlet temperature will reduce the treatment efficiency leading to deteriorated effluent quality, increased use of energy and chemicals, or need for expansion of the plant. However, it is not evident how large the impact on inlet temperature is from upstream heat recovery when also the energy losses in the sewers and by extraneous water are taken into account. One area that has not previously been researched is the connection between WWHR and WWTP nitrogen load. While the temperature reduction will decrease the efficiency of the nitrogen removal, this might partially be compensated if the nitrogen load at the same time is reduced. Reduction in nitrogen load can be accomplished by, for example, source separating wastewater systems (black water or urine separation).

There is a need to do a holistic sustainability analysis that evaluates WWHR from a system-wide perspective and investigates the influence and impact of the different components and subsystems. The results and conclusions will by necessity be site specific since the city density and location, capacity and design of the WWTP will determine the impact of different measures. Therefore, there is a need for developing a general system-wide model tool for evaluating WWHR locally and provide decision support for various stakeholders.

## 2.2 Modelling of Wastewater Treatment Plants and Temperature Effects on Treatment

A wastewater treatment plant (WWTP) usually combines mechanical, biological and chemical treatment processes in different treatment steps. In the biological treatment processes the biological material is reduced and the bound organic nitrogen is decomposed into nitrogen gas. The biological nitrogen removal normally occurs in two steps, nitrification and denitrification. The biological rate in the nitrification process, i.e. the speed at which the bacteria converts ammonium to nitrate, is dependent on temperature. The rate increases exponentially to the temperature in the range of 0-32 degrees Celsius and then stays constant between 32-40 (Henze *et al.*, 2002). The same relationship applies for the second step on biological nitrogen removal, denitrification.

To evaluate performance of WWTPs detailed mechanistic process models are used (Gernaey *et al.*, 2014). The models describe the hydraulic, chemical and biological process of the treatment processes by a set of – mostly ordinary differential equations, ODEs – equations that can be implemented in a computer platform for simulations of various cases.

For the plant-wide process modelling the Benchmark Simulation Model No. 2 (BSM2) was developed (Gernaey *et al.*, 2014). The BSM platform is a general simulation platform for benchmarking of operational and control strategies at WWTPs. It consists of: *i)* a general plant layout; *ii)* a set-up of sub-models for the included processes; *iii)* models for sensors, controllers and actuators to allow implementation of various control strategies; *iv)* a specified simulation procedure including an influent profile; and, *v)* an evaluation procedure including two aggregated indices: Effluent Quality Index (EQI) and Operational Cost Index (OCI). The EQI measures the effluent water quality as a weighted average of effluent COD, BOD, ammonia, nitrate and total solids loads whereas the OCI provides a relative comparison for the operational costs including, power for mixing, aeration and pumping, carbon source addition, heating of the digester, utilisation of biogas and disposal of sludge.

Energy modelling and energy recovery has been a topic well incorporated in plant-wide WWTP models. Most commonly the aeration in the activated sludge treatment consumes the largest amount of energy at a WWTP (Frijns *et al.*, 2013). By using different modelling approaches, such as dynamic mathematical models and dynamic analysis approaches, one can identify where there are aeration deficiencies and margins, for the purpose of optimising the energy use. Energy footprint modelling is a way to identify how to minimise costs and environmental impact (Rosso *et al.*, 2012). This approach focuses on the energy consumption used by equipment in the different units of a WWTP. However, modelling heat recovery from heat transfer systems is not seemingly to be found.

## 2.3 Related Research Projects

The topic of WWHR is of high interest in Sweden currently. There are several parallel research projects.

E2B2 – The project aims to investigate the long-term system effects of WWHR. The team at The Royal Institute of Technology, KTH, will carry out long-term measurements in three different locations: a multi-family house, an apartment complex with a total of 350 apartments, consisting of both new and renovated properties as well as a hotel. The hotel is located in central Stockholm, has small rooms and is expected to have high occupancy, which means that it will use large amounts of tap water. The project will also carry out laboratory measurements with simulated operating conditions. They also aim at developing a method for evaluating the performance and maintenance needs of waste water heat exchangers under different conditions.

BeBo – the Swedish Energy Agency's network for residential property owners committed to energy efficiency – BeBo – has investigated WWHR for many years. They concluded an innovation procurement in 2015 with a very limited outcome due to the few technical solutions that were competing. Now BeBo has started a new development project that will try out 5 different types of equipment in full-scale operation for one year.

KTH – at The Royal Institute of Technology, KTH, the research group Fluid and Climate Technology works with CFD modelling and simulation to increase the efficiency in energy recovery systems in buildings. At KTH also the building development lab – KTH Live-in lab – are projecting to pilot WWHR in their building.

IVL – The EU funded research project Reuse Heat aims to demonstrate four different scalable systems designed to reuse and recycle unused heat streams in urban environments. These systems utilize heat from, for example, subway systems and wastewater flows in residential buildings and offices. 16 players from a number of European countries participate in the project, which is led by IVL Swedish Environmental Research Institute.

Fortum and Ecoclime – The two companies are planning to do a pilot test of WWHR in a number of buildings in a joint project.

# 3 Wastewater Characteristics

For the objective of the project HÅVA, several parameters of the wastewater characteristics are of interest. Firstly, flow and temperature are critical to assess heat recovery but also impact of temperature variations. Secondly, other parameters, such as concentration of COD and fat, could be relevant as in-sewer processes related to these (and potentially other) components might be affected by temperature changes. On a general level Larsen (2015) makes a rough estimation of the energy content in wastewater in three categories: heat energy and calorific energy in organic matter and calorific energy in nutrients. The values are presented in Table 1 and Figure 1. It is evident that heat energy dominates in terms of energy content. To calculate the heat energy content of water a temperature difference must be assumed and the specific heat capacity for water considered.

Table 1. Typical energy content in wastewater. Values from Larsen (2015).

| | kWh.pe$^{-1}$.yr$^{-1}$ |
|---|---:|
| Heat | 800 |
| COD | 150 |
| N and P | 50 |

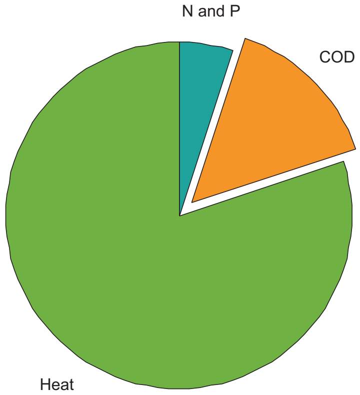


Figure 1. Illustration of values in Table 1. Figure from Arnell (2016)

## 3.1 Domestic Water Temperature

When wastewater leaves the building, without HEX it has an average temperature of around 20°C in Sweden and when it reaches the WWTP it has a temperature of about 12 to 8 °C after heat losses to the ground. There is a standard value for energy consumption for DHW of 25 kWh/m$^2$/yr for multi-family buildings, 20 kWh/m$^2$/yr for single family houses and 2 kWh/m$^2$/yr, in premises and schools in Sweden – so called $A_{temp}$, (Boverket, 2016). The value is not dependent on chosen heating system and heat losses through hot water heating recirculation has to be accounted for additionally.

Text books on WWT does not contain much information on wastewater temperature (Henze *et al.*, 2002; Metcalf & Eddy, 2014). Neither have many academic studies been published specifically on wastewater temperature. Cipolla and Maglionico (2014) analysed variability in flow (Q) and temperature (T) of municipal wastewater in Bologna, Italy. In the paper, daily patterns for Q and T are presented normalised to the average daily value. For Q, the variation around the normalised value (1) is in the range 0.25 to 1.5 for the five measurement stations in the sewer network. The variations in T are smaller, 0.90 to 1.05 but show a similar daily profile with a minimum early morning and a peak around mid-day. However, there is a small shift as the min and max points are 1 to 3 hours delayed compared to the flow. The sewer system of Bologna is combined and the measured parameters are affected by rain events. This impact is not quantified in the publication, but an increase in Q and consequent decrease in T is reported. The wastewater temperature in Bologna never falls below 11 °C. A couple of studies evaluating the applicability of WWHR have reported isolated measurements of wastewater temperature (Dürrenmatt & Wanner, 2008; Abdel-Aal *et al.*, 2014; Kretschmer *et al.*, 2016) and find the same pattern for diurnal variations as reported by (Cipolla &

Maglionico, 2014). Abdel-Aal *et al.* (2014) measured temperature of wastewater, sewer air and soil at three locations in Antwerp for modelling.

## 3.2 Domestic Hot Water Use

Water usage patterns can be useful for modelling heat recovery having only samples of heat and flow data. In a survey study from China described by Wong and Mui (2009), 597 respondents amongst 1300 households in 14 high-rise residential buildings in China, provided information though a face-to-face interview on their hourly shower usage patterns. All the winter showers and 97 % of the summer showers were hot water ones. On a summer day (June-August) an occupant would take 1.6 showers (standard deviation = 0.6) and on a winter day (December- February) 1.1 showers (standard deviation = 0.3). It would be relevant in a modelling study to make accurate assumptions on the hot water usage patterns in order to justify the potential of the heat exchanger effectiveness (Ligman *et al.*, 1974; Hall *et al.*, 1988; Wong & Mui, 2008; The Swedish Energy Agency, 2009; Wong & Mui, 2009).

Domestic hot water use has been measured and analysed (Ellegård & Cooper, 2004; The Swedish Energy Agency, 2009). The Swedish Energy Agency (2009) measured the total and hot water use in 44 households in Sweden. Out of those 35 were single household dwellings and 9 were apartments in an apartment block. Furthermore, total consumption for all 110 apartments in the same block was measured and used for estimation. In the study, the average total water consumption in the apartments was 184 l/p/d of which 58 l/p/d was hot water at an average temperature of 57 °C. The corresponding value for single household buildings was 130 l/p/d of which 42 l/p/d was hot water at 52 °C. The hot water consumption corresponds to an energy use of 1150 kWh/p/yr in the apartments and 781 kWh/p/yr in single household buildings. The variations between households are large. For the hot water use the variation is a factor 2 to 3.5 between different houses with the same number of residents. For the energy use for DHW the variation is even larger, up to a factor 4.5 in variation. The study concludes that the water use, both cold and hot water, is higher for multi dwelling buildings than for single household ones. However, in both types of dwellings objects with low respectively high consumption are found. The hypothesis is that the fact that single HH buildings have individual measurement and payment of water and energy (for heating water) – in contrast to apartment blocks that measures the overall consumption and debit by template – are more restrictive in their use. Pilot projects with individual measurement and payment of hot water for apartments support this conclusion (Boverket, 2002; Berndtsson, 2005; Hjerpe & Krantz, 2006).

Based on measurements, models predicting domestic hot water use have been developed. Widen *et al.* (2009) used the time series data from SCB and STEM to make time series for use of electricity and hot water on person and household level. The model is based on different activities consuming these commodities in households reported, in detail, in diary form during one weekday and one weekend day. The model assumes specific power use for each activity and multiplies with usage time which adds up to the total consumption in time series on an aggregated level. They conclude that good accuracy can be achieved if the number of households in the data is large enough. The work is continued by Bertrand *et al.* (2017). They take a somewhat different, more fundamental, approach by calculating power requirements for each activity from water temperature difference and heat capacity in combination with usage statistics data.

# 4 Wastewater Heat Recovery Systems

Wastewater heat recovery systems are mainly based on exchanging heat from outgoing wastewater for pre-heating cold water and therefore decreasing the energy required for the system to produce hot water. The technology can be implemented in different positions in the wastewater system. Primarily there are four different positions, Figure 2.

1. At component level, i.e. household appliances, showers etc. with internal heat (and possibly even water) recycling.
2. At property level, i.e. heat is recovered from collected wastewater (or separated greywater) from the property and recycled for pre-heating tap water or heating/cooling the building.
3. At precinct level, i.e. in the sewer network where heat can be recovered by, for example, heat pumps.
4. At system level, i.e. at the wastewater treatment plant (WWTP) where heat pumps are used to recover heat from the treated plant effluent.

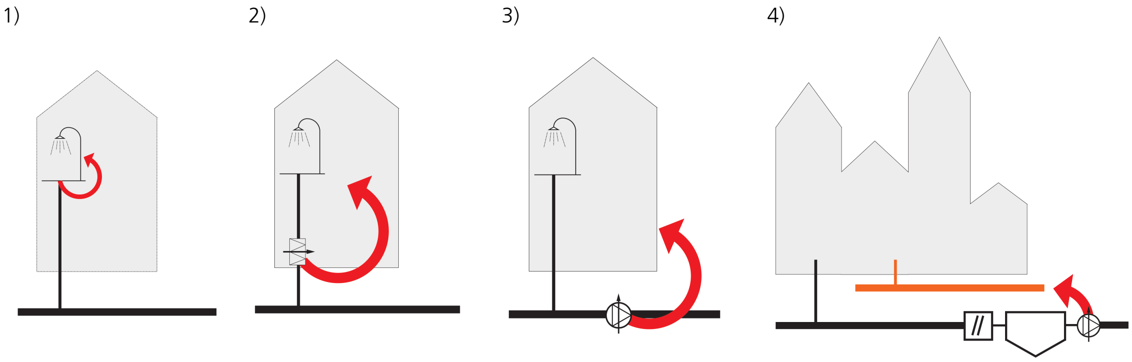


Figure 2. The four different positions (1 to 4) for implementing wastewater heat recovery in the wastewater system. From the left: at component level, at property level, at precinct level and at system level.

There are different technologies and solutions for recovering heat from wastewater. These should be installed depending on facility and how the living habits affects the wastewater characteristics, mainly volume and flow (Nykvist, 2012). Possible WWHR appliance systems are summarized in Table 1 and further elaboration through examples of installations and other experiences of heat recovery from the four different positions in Sections 4.1-4.4. Nykvist (2012) summarizes existing installations as a pre-study to a technology competition reported by Blomsterberg (2015), who also points out that the few existing installations are due to the lack of knowledge and the few selections of total system solutions. None of the competing solutions in the competition met the set criteria set by the purchasing group, to separate drinking water and waste water in a sufficient manner. However, it was indicated that there were interesting solutions with potential for the future. RISE has tested and evaluated at least 6 different wastewater heat exchangers with varying efficiency between 5-50 % (Nordling, 2017). The highest efficiency was reached by an appliance based on plate heat exchanger (PHE) to be mounted under a bath tub for example. Nordling (2017) pointed out that the tests were not performed in order to evaluate what happens over time, e.g. potential fouling or clogging. A pipe with more geometry, creating more turbulence and therefore increased heat exchange efficiency, could possibly prevent clogging.

Table 2. WWHR appliance systems described by technical specification, what scale that it is suitable for, its specific features and the different companies that deliver such a solution.

| **Technical system description** | **WWHR level** | **Features** | **Examples of model and supplier** |
|---|---|---|---|
| Horizontal wastewater heat exchanger | BLDG (Pos. 2) | • Suitable for pre-heating cold water that will become hot water<br>• Installed in basement, close to water heater<br>• For either blackwater or sorted systems<br>• Some pipes are designed to create turbulent flow for increased heat exchange efficiency<br>• Passive installation<br>• Many examples of installations<br>• Contact surface limited to the bottom of the pipe<br>• Consists of a central pipe carrying wastewater surrounded by a coiled cold water pipe or a larger pipe | SPUAB's värmeväxlare-Sandvikens Projektutveckling AB (Sweden), Effektiv Energiåtervinning AB; B1000 EcoDrain (Canada); Super Singlex, Power Products - Europé AB; iNEX Power-Pipe® Spillvattenvärmeväxlare, iNEX Internationell Exergi; MM-växlare, Rörmontage I Borås.; Renewability Inc.; Power-Pipe, Ekologiska byggvaruhuset |
| Vertical wastewater heat exchanger | BLDG (Pos. 2) | • Consists of a central pipe carrying wastewater surrounded by a coiled cold water pipe or a larger pipe<br>• Suitable for villas and smaller apartment complexes<br>• Available in different lengths<br>• Suitable for pre-heating cold water that will become hot water<br>• Few examples of installations<br>• Higher efficiency than horizontal due to larger contact surface | V1000 Vertical Drain Water Heat Recovery, EcoDrain (Canada); Thermodrain, EcoInnovation; Recoup Pipe+ HE, Recoup Energy Solutions Ltd (UK); iNEX Power-Pipe® Spillvattenvärmeväxlare, iNEX Internationell Exergi; MM-växlare, Rörmontage I Borås |
| HEX with storage tank | BLDG (Pos. 2) / WWTP (Pos. 4) | • Wastewater is accumulated in a tank<br>• Heat recovery is facilitated in a coarse plate HEX | Evertech by Ecoclime. Approx. 10 installations in Sweden. |
| Dishwater heat exchanger | Unit (Pos. 1) | • Suitable for commercial dishwashing applications | A1000 Food Service, EcoDrain; |
| Shower heat exchanger | Unit (Pos. 1) | • Suitable to implement on shower floor<br>• Heat exchange close to source means less temperature loss<br>• About 1 meter of the wastewater pipe is replaced by a copper pipe and the cold water pipe twists around it<br>• Few examples of installations | Recoh-Tray, Hei-Tech Energisystemen (Nederland, certified by RISE);<br>CCF Spillvattenväxlare, iNEX International Energy; Closed loop showers, Orbital Systems; A1000, EcoDrain (Canada); Recoup Drain+, Recoup Energy Solutions Ltd (UK); Caruzo, ReCalor (Sweden), Showerheat - Kattfotsbacken AB (Certified by RISE); Miljödusj, Ekologiska byggvaruhuset; duschvärmeväxlare, ReCalor; WWRX duschvärmeväxlare, Ayma |
| Heat pump for greywater | BLDG (Pos. 2), System (Pos. 3) | • More heat can be recovered than from a passive heat exchanger, the system will however be more complex<br>• A storage tank is needed in order to secure that the pumps do not run dry (therefor suitable only for greywater)<br>• A course filter is needed before the storage tank. Not suitable for kitchen wastewater<br>• Suitable for, for ex. swimming pools<br>• The evaporator needs to be able to handle slightly contaminated water | AquaCond 44, Menerga |

| | | | |
|---|---|---|---|
| Heat pump combined with HEX | BLDG (Pos 2), System (Pos.3) | • Can generate a higher degree of heat recovery<br>• Suitable for swimming pools | AquaCond, Menerga |
| Heat pump for greywater and pre-exchanger | BLDG, (Pos 2), System (Pos.3) | • Suitable also for highly polluted water<br>• Heat exchange from accumulation tank<br>• Still no full-scale implementation<br>• Significantly lowers the temperature of the wastewater and clogging due to that fats hardens is a challenge | |
| Heat pump for sewage water | BLDG, (Pos 2), System (Pos.3) | • Wastewater is collected in an isolated well outside of building<br>• A heat exchanger wraps around a filter that collects particles and transfers the heat from the filtered wastewater to a heat exchanger<br>• Demands quite a lot of space | FEKA (Switzerland), Nibe (Sweden) |
| HEX and / or HP with pre-screening | BLDG(Pos 2), System (Pos.3) | • Wastewater passes through a screen to remove course solids and pumped through a heat exchanger. Can be combined with a heat pump following the HEX<br>• Demands quite a lot of space | ThermWin® Solution (Huber Technology, Germany).<br>Sharc Energy Systems. Approx. 5 pilot installations in N. America. 5 projects planned in UK. |

## 4.1 WWHR at Component Level

WWH can be recovered directly from household appliances. Heat exchangers can be mounted in adjacent to, for example, showers in order to recover heat from the shower wastewater and directly pre-heat the cold tap water running to the shower. Wastewater from showers is relatively clean and can be used efficiently for heat exchange as a large transmitting surface can be used (Nykvist, 2012). The temperature of the shower water will decrease from the shower head to the floor.

A Canadian evaluation study of two residential DWHR units showed that the seasonal temperature variations effects on the incoming cold water has a substantial impact on the heat recovered in practise from the wastewater (Toronto and Region Conservation Authority, 2015). In the winter, the difference between inlet temperatures and desired shower temperatures is large and a larger amount of energy is recovered. During a 400 seconds long shower the average heat recovery during winter was 4.55 kW and during summer 3.75 kW. Also, the time of the shower event affects the heat recovery rate as the power generation is achieved quicker when the unit is warmed up. The summer heat recovery reaches a steady-state after 150 seconds at 4-4.5 kW while the winter heat recovery continues to increase beyond 150 seconds and reaches a steady-state at 6-7 kW. The effectiveness remained at approximately 50 % all year around with only a 2 % increase during winter. The effectiveness is rather a result of the unit configuration, improved for example when the drain water flow rate is higher than the coiled cold-water flow rate. According to a study using a calculator tool developed by Natural Resources Canada, a WWHR unit in a home with 4 occupants, showering every day for 10 minutes each, will reduce annual greenhouse gas emissions by approximately 126 kg $CO_2$, based on an estimated release of 0.16 kg $CO_2$/kWh for an electric water heater. The payback time under Canadian circumstances was estimated to 3 to 5.1 years compared to electric heating, 6 to 10 years compared to standard natural gas heating and 7-12 years compared to high efficiency natural gas (Toronto and Region Conservation Authority, 2015).

Many component WWHR appliances are based on the same concept of a copper coil wrapped around a copper pipe section. Most WWHR appliances heat cold water so that less hot water is needed in the water mixer. However, having room tempered water standing in the pipes is never good, enabling growth of legionella bacteria (Nykvist, 2012); this must be acknowledged and solved in order to meet Swedish legislation.

One example of a component appliance is the Recoh-vert 2.1 meter long heat exchangers that can be mounted vertically in spaces under wastewater drainage, making it suitable for showers on upper floors (Hei-Tech Energiesystemen, 2010). The manufacturer describes the necessity to avoid that the water temperature in the Recoh-vert goes above 25 °C when there is no flow of cooling water. The inlet can be connected to the household's drinking water distribution system while the outlet of heated water can be connected in different ways. Either in a combined connection to both the cold-water connection of the shower's mixing faucet and the water heater, or separately to the cold-water connection on the water heater or the shower's mixing faucet. The solution is recognized by BRE. There are many manufacturers that supply similar system solutions.

Recoh-tray is a shower floor with heat exchange functionality that can be mounted on top of the existing floor. Both the Recoh-vert and Recoh-tray have received certification of approval (Certificate number SP SITAC SC0906-09) by RISE Research Institutes of Sweden provided that the heat exchangers and connection couplings should be possible to inspect, be exchangeable and be positioned so that possible leakages can quickly be detected and not cause further damage.

Another appliance is the shower heat recovery solution CCF wastewater exchanger, which can be implemented for both greywater and combined grey- and blackwater (iNEX, 2017). There are both pros and cons with these two options according to Jonsson (2015). Combining toilet water with the greywater decreases the temperature and therefor the potential heat recovery, however, it has a mechanical cleaning effect inside the pipe (Jonsson, 2015).

Orbital Systems offers showers with closed loop systems, recirculating water to save both water and energy. The shower Oas saves up to 90 % of water and energy (Orbital Systems, 2017). However, technically this is "only" savings of DHW and not an example of WWHR.

For examples of installations one can look at Hong Kong, where many high-rise residential buildings have installed WWHR, most commonly through a "shell-and-tube" heat exchanger (Wong *et al.*, 2010). Typically, instantaneous water heaters are installed in wash rooms in Hong Kong, meaning that the heat exchanger pre-heats cold water going directly into the water heater adjacent the shower, compared to central heating more often found in Sweden.

## 4.2 WWHR at Property Level

Many multi-apartment and office buildings have hot water circulation (HWC) to provide the user with hot water quicker on request (and thereby also saving water). This system can cause great heat losses in buildings (Termens, 2017). Heat exchangers on the wastewater system can be an opportunity to decrease the heat losses in a building overall and decrease the energy needed to heat the hot water in the water heaters. On a property level, it is implied that the heat exchanger is installed on a mixed and combined wastewater outlet, however there are cases when greywater is separated from toilet water and the heat exchanger is mounted on the greywater outlet.

Moore (2013) describes how drain water heat recovery simply can be comprised by exchanging a part of the existing wastewater outlet pipe with a 3-inch-diameter copper drainpipe coiled by a ½-inch-diameter copper water supply pipe. With this setup, the incoming cold water is naturally heated through the principle of gravity film heat exchange (GFX). The article presents numbers for reduced water heating costs by 20 to 35 % and an overall reduction of energy costs by about 10 %.

In a study from 2015 an efficiency measurement campaign was performed on a 6 meter long heat exchanger manufactured by SPUAB- Sandvikens Projektutveckling AB, which was installed in the basement of a multi-purpose building in Stockholm (Wallin, 2015). The study is based on collected data from a 30.5-hour period in December so the overall conclusions drawn from the study are quite limited. The measured effectiveness of the heat exchanger revealed that the relative recovery of heat was better at low flow periods. Overall, the degree of heat recovery was lower than the systems effectiveness, showing that the flow of wastewater was higher than the cooling flow. During the evening and morning, when showers and laundry were running the recovery effect was increased following the increased flow rates [l/s]. However, considering the relative recovered effect of 18.3 kW out of 298 kW available at peak hour compared to 2.3 kW recovered effect of the available 6.5 kW at the lowest flow, it is clear that the relative efficiency decreases as the flow increases. The results show that the potential and efficiency depend on the wastewater and cooling water temperatures as well as flows. If the cooling water flow would have been constantly high, the heat recovery would have been 10.1 % of the theoretically available energy. With the existing cooling water flow the recovery was, however, 26.7 % of the maximum possible energy recovery.

The municipal housing company in Växjö, Växjöbostäder, in 2009 built two apartment buildings, together holding 64 apartments, with “passive house technique” in the neighbourhood Portvakten Söder. In between the two buildings is a WWHR installation, a “CCF Spillvattenväxlare” from iNEX International Exergi, to recycle the energy from the outgoing wastewater. The goal of reusing 5 kWh/m$^2$ was not reached according to an evaluation study performed by Vändal and Lowentoft (2014). A theoretical calculation of the estimated expected energy saving of 35 818 kWh/year made in 2008 by NCC, in practise turned out to result in a fourth of the saving, 8 960 kWh/year. This was, however, likely to be a result of groundwater rising above the heat exchanger. The hot water use in the two buildings clearly differed as one of the buildings had around 50 % higher hot water use than the other. The study pronounces how the water consumption has great influence on the efficiency and also the distance between heat exchanger and water heater – here about 35 meters – is of great importance for the results (Vändal & Lowentoft, 2014). A similar installation, with the Super Singlex, mafrom Powers Products Europes been installed in Stockholm, by Stockholmshem in the Måseskär neighbourhood for a building with 50 apartments to pre-heat the incoming cold water prior to the water heater (Nykvist, 2012). It is placed 10 meters from the water heater and according to Vändal and Lowentoft (2014) the hot water consumption is close to double the consumption in the Vaxjö building. For these reasons and perhaps others the WWHE in Måseskär has a significantly higher recovery of energy than in Växjö, differing between 570 and 2000 kWh depending on the season, saving 5.15 kWh/m$^2$ using the heat exchanger (Nykvist, 2012).

The swimming pool Sydpoolen in Södertälje has a combination of HEXs and heat pumps, called AquaCond by Menerga. A measurement campaign during one week in 2004 revealed that the wastewater temperature was decreased by 14.8 °C and increased the incoming cold water by 22.8 °C, in total recovering 4 800 kWh and using 840 kWh in electricity for the heat pump (Nykvist, 2012).

There are international experiences of central WWHR installations in buildings in for example North America. Nykvist (2012) mentions a WWHR installation with two HEX supplied by Renewability called Power-Pipe C4-40 and C4-42 in Québec (Canada) in a three-story building with six apartments. The energy saving was reduced by 14.5 %. In Eulachhof (Switzerland) two multi-function buildings built as zero-energy housing, use in a combination with other energy solutions, a heat pump solution using the wastewater as a source of heat and solar energy to run the compressor. The heat recovery reaches 6.56 kWh/m$^2$.

Nykvist (2012) suggests comparing different installations through recovered energy dependent and relating it to hot water consumption. A comparison of 6 different HEX system installations in multi residential buildings shows energy savings in the range of approximately 3 to 9 kWh/m$^3$ hot water.

EcoDrain, a company based in Montreal (Canada) has developed both a vertically and horizontally oriented product. It is a heat exchanger that captures the energy directly through installation both on the main drain line, from the shower drain or on dishwasher applications. A technical brief, prepared by the Toronto and Region Conservation Authority's Sustainable Technologies Evaluation Program (STEP) reflects the assessment of the capacity of drain water heat recovery in general (DWHR)(Toronto and Region Conservation Authority, 2015).

## 4.3 WWHR at Precinct Level

Heat can be recovered from a collecting sewer pipe and used for the heating of buildings in the proximity. Recovering heat at precinct level implies a homogenised and continuous flow to the advantage of the WWHR.

The company Huber Technology supplies the ThermWin® Solution. The heat exchanger can be put above ground. A portion of the wastewater is used. The course solids are removed and lifted through a vertical pipe with a screw and then returned to the sewer. The screened wastewater is pumped through a compact heat exchanger and then the cooled wastewater is returned to the chute (Huber Technology, 2017). The Huber company expresses the importance of investigating the effect that cooling of the sewage could have on the operation of the wastewater treatment plant.

## 4.4 WWHR on Treatment Plant Effluent

Heat energy in wastewater can be recovered from the WWTP effluent, i.e. position 4 in Figure 2. In this position, the flow is as large as possible and more constant compared to any up-stream position. Recovering the heat from treated wastewater with heat pumps at the WWTP has several benefits (Frijns *et al.*, 2013; Elías-Maxil *et al.*, 2014).

- The variations in flow and temperature are small, which is beneficial for the heat pump.
- Using treated wastewater reduces the problem with fouling and clogging of WWHR equipment.
- No risk for negative effects on the biological wastewater treatment.

However, at the same time the temperature is lower and some of the energy has been lost in the sewer network. Usually heat pumps are used for heat recovery at WWTPs. The lower temperature affects the efficiency of any heat recovery technology. For heat pumps the COP factor is reduced (Olsson, 2008). Meggers and Leibundgut (2011) report that heat pumps installed at building level recovering heat from hot wastewater can achieve a COP of 5.5 to 7.3 depending on release temperature, while COP factors for WWTP effluent around 3 to 4 are reported. The recovered heat can be used internally at the WWTP but the amount often exceeds the internal heat requirements and delivering excess heat to a local district heating system, if available, is feasible.

In Sweden, heat recovery from WWTP effluent has been applied at several treatment plants. Lingsten and Lundkvist (2008) report that 2 to 3 TWh of heat were recovered at Swedish WWTPs in 2006. Primarily, it is the larger Swedish WWTPs that feature heat recovery, e.g. the WWTPs: Käppala in Lidingö, Henriksdal in Stockholm and Rya in Gothenburg, but also a few medium sized WWTPs: e.g. Koholmen in Karlskrona, Kungsängen in Västerås and Kungsängsverket in Uppsala. Furthermore, examples of WWHR from effluent wastewater are found around the world. In this literature review several examples were found from Switzerland and Russia (Schmid, 2008; Alekseiko *et al.*, 2014). Hepbasli *et al.* (2014) made an extensive review of application of heat pumps for WWHR listing 33 installations, many implemented at WWTPs, mostly in China, North America and Turkey.

## 4.5 Impact of material use in heat recovery equipment

No specific LCA study comparing copper with stainless steel in heat exchanger has been found. Copper is the usual choice for biofouling and antimicrobial related applications (Schmidt *et al.*, 2012), whereas it is in antifouling paints or heat exchanger material (Trepos *et al.*, 2014). Therefore, it is the metal of choice for drain water heat recovery (US Department of Energy, 2017). Hence the comparison with other materials, like stainless steel, which would require additional protection against biofouling is tricky.

The choice of alloys in heat exchanger is mostly dictated by design factors like heat conductivity, corrosion, biofouling, water quality, etc. (Farhami & Bozorgian, 2011). Generally and historically (Rodriguez, 1997), the environmental factor is not looked at from a system analysis perspective. It is mostly considered from a heat exchange performance perspective since a better heat conductor will perform better and save fossil fuel energy. Most of the studies and articles on this matter are usually related to performance and cost review (Malavasi, 2015) even though copper production has a higher environmental impact. Environmental impact is rarely addressed in the choice of heat exchanger materials, even from governmental sources (U.S. Department of Energy, 2017). The fact that both copper and stainless steel are recycled in large amount today could explain this lack of interest/studies about the difference in environmental impact to produce copper vs. stainless steel heat exchangers (Evans & Foster, 2016). Environmental impact of including copper in heat exchanger is usually addressed via Environmental Product Declarations (EPD) and sustainability reporting, e.g. Alfa Laval EPD (Alfa Laval, 2017). It is indeed possible to combine copper and steel by having thin copper foils on top of metal plates or to use copper only in pipes whereas the heat exchanger sheets are made of steel (Beccali *et al.*, 2014). This is usually promoted and used as green marketing when relevant.

Because the performance of heat exchangers is at the core of research interest, even the few comparative LCA that exist on the matter are normally comparing heat exchanger designs with the same material (Adolfsson & Rashid, 2016). It may theoretically be possible to extrapolate data from different studies with different materials, though it is not recommended by LCA academics (Baumann & Tillman, 2004).

Since copper production has a higher environmental impact than steel per kg, copper often contributes the most to the environmental impact of the heat exchanger product/system in a life cycle perspective (Watkins & Tassou, 2006; Oliveira, 2012).

# 5 Modelling of Wastewater Systems Facilitating WWHR

Modelling has been used to assess WWHR systems in various ways. There is a large span from simple empirical calculations to advanced mechanistic models. Table 3 summarize the, mostly academic, literature found describing various types of models. In the following description, the models are divided based on which parts of the system that is modelled, i.e. models of WWHR systems, models of sewer temperature and models of temperature impact of WWTPs.

Table 3. Models of WWHR or relevant systems found in literature.

| **Model** | **System Modelled** | **WWHR Pos.** | **Model Features** | **Key Conclusion** | **Reference** |
|---|---|---|---|---|---|
| DHW use – detailed mechanistic | DHW use | n/a | • Dynamic modelling of DHW<br>• Activity based approach<br>• Dynamic profile | • Energy use can be modelled from time series data.<br>• DHW use is highly influenced by showering habits and appliances. | Widen *et al.* (2009); Bertrand *et al.* (2017) |
| WWHR – static Eq. | WWHR eqipment | 1, 2 | • Generalized equations for calculating energy recovery.<br>• Dynamic if varying T | • Large variations in WW Q and T.<br>• Recovery efficiency varies with Q and T | Wallin (2015); Rask (2012) |
| HEX – static Eq. | HEX | 1, 2 | • Static equations for calculating heat recovery and efficiency.<br>• Dynamic if varying T | n/a | Geankoplis (1993) |
| HP – static Eq. | HP | 2, 3, 4 | • Static equations for calculating energy recovery with HP.<br>• Dynamic if varying T | • COP in range 1.8 to 10.6.<br>• main challenge of WWHR with HP y is fouling and clogging | Hepbasli *et al.* (2014) |
| Sewer temp – detailed mechanistic (called TEMPEST) | Sewer network | 3 | • Detailed mechanistic model. PDE formulation<br>• Models temperature changes along sewer line with branches. Heat energy exchange with soil and air<br>• Includes COD degradation and associated heat generation | Temperature and thermal resistance of soil are, together with distance from pipe to undistributed soil, the most relevant parameters. | Dürrenmatt and Wanner (2008, 2014); Sitzenfrei *et al.* (2017) |
| Sewer temp – simplified mechanistic | Sewer network | 3 | • Simplified mechanistic model<br>• Natural sewer increments modelled based on thermal resistance instead of full PDE<br>• Heat transfer to soil and air. | RMSE of 0.37 °C. Most sensitive parameters are, temperature of in-sewer air and soil. | Abdel-Aal *et al.* (2014) |
| In-sewer WWHR recovery – static | Sewer WWHR site | 3 | • Two equations to calculate heat recovery potential and effect on WWTP influent temp | Framework for deciding on in-sewer WWHR with 4-step method. | Kretschmer *et al.* (2016) |
| Sewer temp – detailed mechanistic | WWTP | n/a | • Plant-wide process model for WWTPs<br>• Includes ASM1 for ASU biological reactions<br>• Temperature correction with Arrhenius equation | n/a | Gernaey *et al.* (2014) |

| | | | | | |
|---|---|---|---|---|---|
| Sewer temp – detailed mechanistic | ASU | 3 | • ASM3 used to assess effect on nitrification by reduced influent temp<br>• Temperature correction with Arrhenius equation | Long term temperature reduction has negative effect on nitrification. 1 °C lower influent temp leads to 10 % lower nitrification capacity. | Wanner *et al.* (2005) |

A sewage heat energy balance model was created for each of Metro Vancouver's four WWTPs to evaluate the implications of sewage heat recovery on wastewater treatment plants (Wong, 2014).

## 5.1 Modelling Domestic Wastewater Temperature

From investigations of domestic hot water use (DHW), such as The Swedish Energy Agency (2009), the DHW has been modelled for simulation purposes (Widen *et al.*, 2009; Bertrand *et al.*, 2017). The basic approach is to use data on temperature (or power requirement) and flow for different household chores together with their respective frequency. Bertrand *et al.* (2017) propose the following equations for the power requirement of DWH in households:

$$\dot{q}_e = \rho \cdot c_p \cdot Q_e (T_e - T_c)$$

$$q_e = \dot{q}_e \cdot d_e \cdot f_e$$

where,

$\dot{q}_e$ is the thermal power requirement for DHW end-use for a specific HH activity;
$\rho$ is the density of water;
$c_p$ is specific heat capacity of water;
$Q_e$ is volumetric flow of DHW for a specific HH activity;
$q_e$ is daily energy demand for a specific HH activity;
$d_e$ is duration time for a specific HH activity; and
$f_e$ is the daily use frequency for a specific HH activity.

The calculated daily power requirements for all household activities using DHW can then be summed up for a household, a building and for the time period of interest. A similar approach providing dynamic time series on power requirements include time series for the frequency data, see Figure 3 (Widen *et al.*, 2009). Input data on DHW use and specific power requirements for different household activities are presented in the publication.

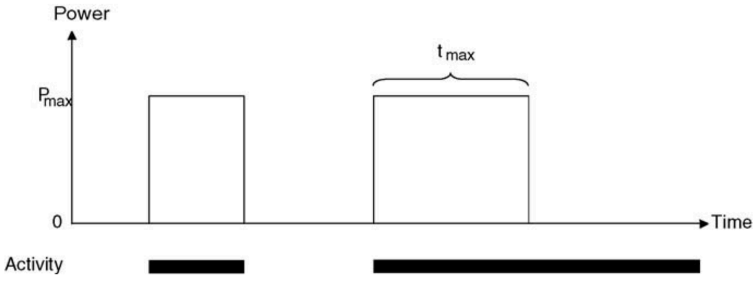


Figure 3. Example of modelling scheme for DHW for a specific HH activity. During the activity, power of level $P_{max}$ is demanded until maximum time $t_{max}$ has elapsed or the activity is finished. Figure from Widen *et al.* (2009).

## 5.2 Modelling of Energy Recovery from Wastewater

For the purpose of this project it is crucial to gain knowledge about the existing energy recovery models for wastewater, plant-wide models as well as specific heat transfer models and also understand the mathematical heat transfer equations that set the foundation.

The effectiveness, Ɛ, of a wastewater heat recovery system was expressed as (Rask, 2012; Wallin, 2015):

$$\varepsilon = \frac{T_{k2} - T_{k1}}{T_v - T_{k1}} = \frac{Actual\ recovery\ effect}{q_{max}}\ (eq. 1)$$

where $T_{k1}$is the temperature of the incoming cold is water, $T_{k2}$ is the pre-heated warm water that passes through the exchanger, $T_v$ is the drained wastewater and $q_{max}$ is the theoretical maximal recovery effect. The effectiveness of a heat exchanger, of any sort, is dependent on the actual recovery effect and the theoretical maximal recovery effect. $q_{max}$ can also be calculated as the lowest heat capacity at each moment for one of the fluids in the system ($C_{min}$), either the hot or the cold side of the exchanger, times the temperature difference between the hot wastewater ($T_{hot,\ in}$) and the cold water $T_{cold,\ in}$ entering the exchanger (eq. 2)(Wallin, 2015).

$$q_{max} = C_{min} \cdot (T_{hot,in} - T_{cold,in})\ (eq. 2)$$

Power consumption for pre-heating shower water can be expressed as (this relation applies to preheating of water for any use):

$$\dot{Q}_0 = m_c c_p (T_2 - T_0)$$
$$\dot{Q}_1 = m_c c_p (T_2 - T_1)$$

$\dot{Q}_0$ is the power consumption without heat recovery and $\dot{Q}_1$ is the power consumption with heat recovery, where $T_0$ [°C] is the cold-water temperature, $T_1$ [°C] the pre-heated water temperature and $T_2$ the shower head water temperature (Wong *et al.*, 2010). The drop in temperature between the shower head ($T_2$) and the shower drain ($T_3$) has been shown to correlate with the shower head water temperature and the air temperature following:

$$\Delta T_{2,3} = 3.6 \cdot 10^{-10} T_2^{6.673} T_a^{-0.530}$$

where $T_a$ is the outside air temperature (Wong *et al.*, 2010).

### 5.2.1 Modelling Heat Pumps

Heat pumps (HP) are used for to elevate a low temperature heat source to a useful higher temperature. A HP consists of four main components: evaporator, compressor, condenser and a throttle device. A refrigerant media circulates in the system. The basic HP cycle is as follows (see Figure 4). The temperature of the media is instantly reduced as the pressure drops when it passes through the throttle valve. The media then pass through the evaporator where is absorbs heat from the environment (e.g. wastewater) and evaporates. The evaporated media is compressed (pressure is increased) in the compressor and goes to the condenser. In condensation, energy is released to the environment in a controlled fashion and taken care of, e.g. in a heating system. From the condenser, the media flows through the throttle again and the loop is closed.

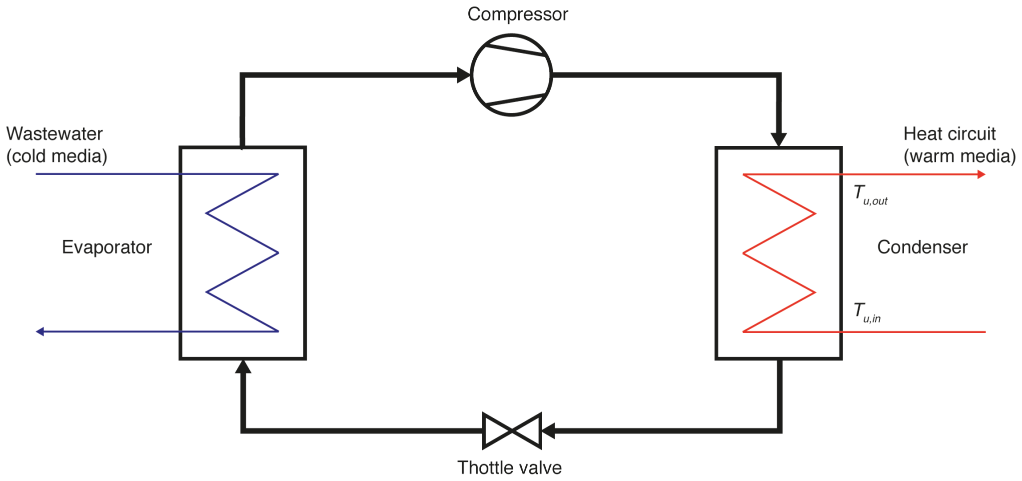


Figure 4. Schematic figure for a heat pump in heat recovery mode.

For calculating the performance of heat pumps the factor Coefficient of Performance (COP) is used. In steady state the COP is calculated as (Hepbasli *et al.*, 2014).

$$COP = \frac{q_u}{W}$$

The useful heat extracted, $q_u$, is calculated from the temperature difference on the user side of the HP,

$$q_u = \dot{m}_u \cdot c_p \cdot \left|T_{u,out} - T_{u,in}\right|$$

where,

$q_u$ is the quantity of useful heat from the heat pump;
$W$ is the work (e.g. electrical power) required by the considered system;
$\dot{m}$ is the mass flow of water, index *u* denotes the user side of the HP;
$c_p$ is the heat capacity of the water on the user side of the HP; and
$T_u$ is the temperature of the water coming in and out on the user side – index *in* and *out*.

The power requirement, $W$, varies with the temperature on both the user and wastewater side of the HP and is supplied by the manufacturer. For a total calculation, power for any additional pumps and support systems should be included. If the heat pump system is prone to fouling this should be included in the calculations.

### 5.2.2 Modelling Heat Exchangers

Heat exchangers are passive equipment for transferring heat energy from a warm media to a cooler. The two-media flow through the heat exchanger, most effectively in a counter current arrangement, on separate sides of a heat transferring surface, see Figure 5. The temperature difference of the media and the HEX area in relation to media flow governs the heat transfer.

For modelling heat exchangers, the following equations can be used (Geankoplis, 1993).

$$q = \varepsilon \cdot C_{min}(T_{h,in} - T_{c,in})$$
$$q = (\dot{m} \cdot c_p)_h\left(T_{h,in} - T_{h,out}\right) = (\dot{m} \cdot c_p)_c(T_{c,out} - T_{c,in})$$
$$C_{min} = (\dot{m} \cdot c_p)_c$$

where,

$q$ is the actual heat transfer;
$\varepsilon$ is the effectiveness of the HEX;

$C_{min}$ is the minimum heat capacity;
$T_h$ is the temperature on the hot media, – index *in* and *out* denote in and out temperature;
$T_c$ is the temperature on the cold media, – index *in* and *out* denote in and out temperature.

The effectiveness, $\varepsilon$, is a function of the area, $A$, and overall heat transfer coefficient, $U$, for the specific heat exchanger and is supplied in diagrams by the supplier. If fouling occurs this should be compensated for in the heat transfer coefficient, $U$.

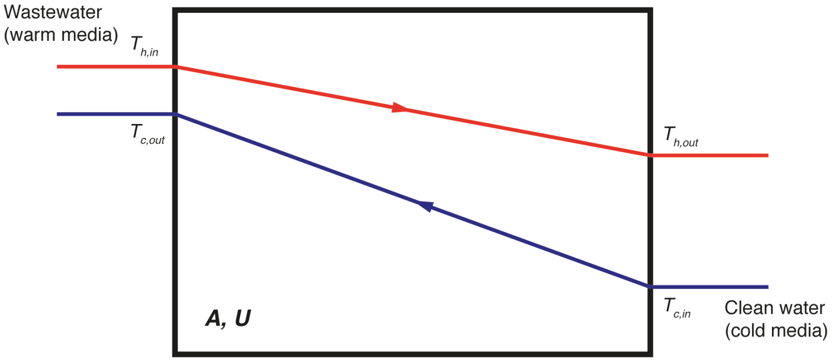


Figure 5. Principle description for counter flow heat exchanger processes.

## 5.3 Modelling Temperature in Sewers

For the present project, the temperature changes in the sewer network is a critical part to model. The literature has been reviewed specifically to identify existing models for this.

The simplest "models" found are linear relations of temperature loss per sewer length. Values from 0.1 to 4 °C per km have been reported (Sonakiya *et al.*, 2013; Abdel-Aal *et al.*, 2014; Hepbasli *et al.*, 2014). On the other end are detailed mechanistic models describing full mass and energy balances. The most detailed model found is the TEMPEST model (Dürrenmatt & Wanner, 2008, 2014). The model which was developed at the Swiss Research Institute for Aquatic Research (Eawag) is available on request (http://www.eawag.ch/en/department/eng/software/). In the TEMPEST model, all the relevant energy flows are considered. Energy exchange with both soil through the pipe wall and with air (depending on airflow) in gravity sewers are calculated with appropriate equations, Figure 6. Also, the humidity of the air, i.e. evaporation or condensation, is included as it affects the wastewater temperature. Consequently, the temperature of not only the wastewater but also the air, pipe wall and soil is modelled. At the pipe wall the energy transfer in the model is limited by turbulence, according to fluid dynamics and biofilm formation on the pipe wall. Lastly, the heat formation by biological degradation of COD is included with an empirical relation. The equations are modelled as a function of time and sewer length making the model a system of partial differential equations (PDEs). Following from this formulation, it is possible to model a network of sewers with branches connecting along the line as in Dürrenmatt and Wanner (2008). The TEMPEST model was also applied by Sitzenfrei *et al.* (2017), who modelled WWHR in household appliances and sewers (i.e. Pos. 1 and 3). From the application of the TEMPTEST model it was concluded that, quote: "the temperature of the undisturbed soil, the thermal conductivity of the soil and the distance between the sewer pipe and undisturbed soil are the most sensitive model parameters in steady state situations. The most dominant transfer process is the direct exchange of heat between wastewater and the pipe wall, but evaporation and convection at the water surface can also be relevant depending upon the environmental conditions. (Dürrenmatt & Wanner, 2014). Sitzenfrei *et al.* (2017) also applied the TEMPEST model and found it useful to evaluate the performance of WWHR systems in both Pos. 1 and 3 and their interactions. In areas with in-sewer heat recovery (Pos. 3) extensive application of heat recovery in bathrooms (Pos. 1) would lead to a 40 % performance drop for the sewer heat recovery.

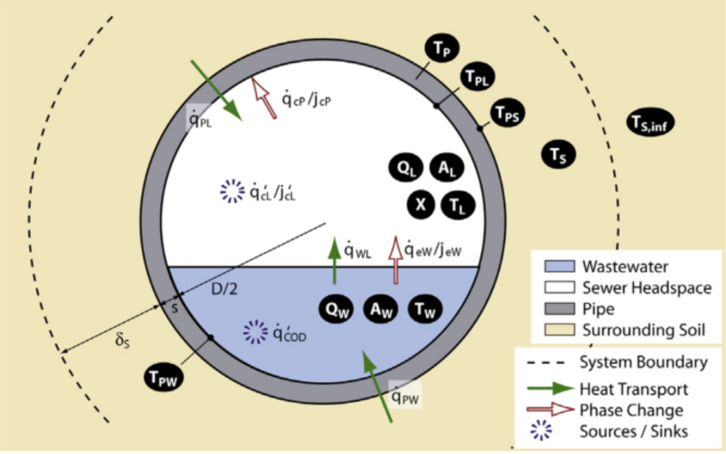


Figure 6. Compartments, processes and state variables considered in the TEMPEST model. Figure from Dürrenmatt and Wanner (2014).

Abdel-Aal *et al.* (2014) argues that the TEMPEST model is overly complicated and that the many details and parameters required about the sewer system makes it infeasible to use. Instead the authors present a simplified model for simulating the wastewater temperature in sewers. Instead of a full PDE formulation this model splits the sewer into natural segments, between branches and connection points. The temperature at the downstream end is calculated based on the inlet temperature for the segment and heat transfer in the segment. Heat transfer processes from wastewater to both soil and air are included. The transfer equations are governed by thermal resistivity, for which equations are given in the paper. The results from applying the model to three sites show that the accuracy varies between the sites but errors are random and within ±1 °C. The most sensitive parameters are, except the influent WW temperature, temperature of in-sewer air and soil.

WWHR in sewers, i.e. Pos. 3, is also assessed with modelling by Kretschmer *et al.* (2016). For the temperature modelling they focus on the maximum potential of heat to recover, which is assessed by a simple function of wastewater flow, heat capacity and temperature difference over the heat recovery equipment. Furthermore, they calculate the impact on the WWTP influent temperature by heat recovery at one site in Pos. 3. The influent temperature drop is calculated based on present flow and temperature and adjusted for the heat extracted up-stream. This approach is very simple. However, it neglects the potential impact of WWHR on heat losses in the sewer. For selecting a site for implementing in-sewer WWHR Kretschmer *et al.* (2016) recommend a four-step methodology:

1. Preselection of potential site – identify potential recovery site and potential heat consumer.
2. Processing WW data – collection and reconciliation of WW flow and temperature data for potential site.
3. Assessment of potential site – estimation of heat recovery potential and WWTP impact.
4. Decision making – comparison of heat demand and supply and appraisal of WWTP inflow temperature.

## 5.4 Modelling Temperature and Impact at WWTPs

Temperature is known to have a strong impact on wastewater treatment processes. Generally, the rates of biological and chemical reactions slows down at lower temperatures. For wastewater treatment plants (WWTPs) detailed mechanistic models with temperature corrected parameters exists. The model family developed within International Water Association (IWA) Activated Sludge Models No. 1 to 3 (ASM1 to 3) (Henze *et al.*, 2000) and Anaerobic Digestion Model No. 1 (ADM1) (Batstone *et al.*, 2002) are such examples. These models include the hydraulic, physico-chemical and biological reactions in the WWT processes to a various extent. The biological reactions are modelled as microbial growth on true substrate (COD, N and in some cases also P) using Monod functions. In common implementations of these models, the growth parameters are temperature adjusted to reflect that biological reactions are strongly temperature dependent (Gernaey *et al.*, 2014).

The temperature correction for microbial parameters in the model can be modelled with different functions. A common option is the Arrhenius equation (Henze *et al.*, 2000; Gernaey *et al.*, 2014), another option is the van't Hoff equation (Henze *et al.*, 2002). Principally, an equation inspired by Haldane kinetics (Guo & Vanrolleghem, 2014) could be used. It has the benefit of also featuring a rapid drop in activity at higher temperatures. When selecting temperature correction function, it is important to consider the temperature interval of relevance and verify that the selected model predicts the real temperature dependency within this interval.

Wanner *et al.* (2005) presented a study explicitly investigating the effect of reduced influent temperature (by WWHR) on WWTP performance, more specifically on nitrification and nitrogen removal. For simulations, the ASM3 in the software ASIM including the Arrhenius equation for temperature correction of nitrification was used. The nitrification process was simulated under steady-state conditions at different influent temperatures. Diagrams are presented showing how the solids retention time (SRT) and subsequently effluent nitrogen are affected. They present a methodology in 10 steps to determine the residual nitrification capacity and the effect of reduced influent temperature. The study concludes that long-lasting (more than a few hours) temperature drops affect the nitrification and leads to elevated effluent ammonium concentrations if no measures are taken. The validation of the model with measured data provides evidence that the ASM3 is suitable to predict temperature effects on nitrification performance.

The effect of temperature on growth of anammox bacteria is reported by Lotti *et al.* (2015). They show that the growth as function of temperature cannot be properly modelled by a simple Arrhenius equation as for traditional nitrifying bacteria as the decrease in growth increases at lower temperatures, i.e. < 15 °C.

The temperature in an activated sludge basin can be calculated with an energy balance over the basin. Models based on varying levels of detail have been presented in literature (Eckenfelder, 1966; Ford *et al.*, 1972; Argaman & Adams Jr., 1977; la Cour Jansen *et al.*, 1992; Sedory & Stenstrom, 1995; Makinia *et al.*, 2005; Lippi *et al.*, 2009; Fernandez-Arevalo *et al.*, 2014). The typical phenomena contributing to temperature change in an activated sludge tank was tabulated by la Cour Jansen *et al.* (1992). The information is re-printed in Table 4.

Table 4. Typical range of contributions to temperature changes in treatment plants. Table from la Cour Jansen *et al.* (1992).

| **Energy Transfer Phenomena** | **Temperature Change (°C/day)** |
|---|---|
| *Significant energy contributions:* | |
| Short-wave radiation (increase) | 0.5-2.5 |
| Long-wave radiation (decrease) | 0.5-1.0 |
| Sensible heat (decrease/increase) | 0.5-3.5 |
| Evaporation (decrease) | 0.5-2.5 |
| Process energy (increase) | 0.5-2.0 |
| *Insignificant energy contributions:* | |
| Mechanical energy (increase) | <0.1 |
| Geothermal energy (decrease/increase) | <0.05 |
| Precipitation (rain/snow at surface) (decrease/increase) | <0.2 |

One model approach is to start with the overall energy balance over one tank,

$$\phi_{net} = \rho \cdot Q_{in} \cdot C_p(T - T_{in})$$

where:

$\rho$ = density of water [kg/m3];
$Q_{in}$ = flow [m3/s];
$C_p$ = heat capacity of water [J/kg/ °C];
$T$ = in-tank temperature [°C];
$T_{in}$ = influent temperature [°C] and
$\phi_{net}$ = net heat exchange flux. [W].

The net heat exchange equals the sum of the different heat exchange phenomena as follows.

$$\phi_{net} = \phi_{sr} + \phi_{ar} + \phi_c + \phi_e + \phi_a + \phi_m + \phi_{bp}$$

Indices denote: solar radiation (sr), atmospheric radiation (ar), conduction and convection (c), evaporation (e), aeration (a), mechanical energy from mixing (m) and biological processes (bp). The different heat exchange variables are calculated from separate individual functions that are somewhat differently defined in different models (Makinia *et al.*, 2005; Lippi *et al.*, 2009). The study by Makinia *et al.* (2005), modelling the temperature of an activated sludge unit (ASU) reactor in USA shows that – besides the influent temperature being the most influential variable – the biological reactions have a significant impact. Seasonal, also the solar radiation is significant during summer as well as the and atmospheric radiation and conduction/convection during winter. These conclusions are supported by the results from Lippi *et al.* (2009). This model for calculating temperature variation also allows for longitudinal in-tank gradients to be calculated with PDEs or a "tanks in series" formulation. This was tested by Makinia *et al.* (2005) and very little difference was seen between the two approaches. Furthermore, this temperature model can be combined with traditional bioprocess models, such as the ASM family models. This was not presented in any of the referred publications. A combined framework for temperature modelling and bioprocess models in multi-phase (liquid, solids, and gas) is presented by Fernandez-Arevalo *et al.* (2014). The work expands the plant-wide methodology (Grau *et al.*, 2007) with an energy balance using Hess's law of change of entropy for all reactions. The paper presents the energy balance equations, integration with bioprocess models and a case study exemplifying the approach.

# 6 Energy System Relations

Wastewater heat recovery is naturally closely interlinked with the energy systems. The purpose of heat recovery is to reduce the requirement for primary energy for heating. Weather the recovered heat is used for spatial or tap water heating, it replaces energy otherwise used for this purpose. Therefore, the present energy system is important to consider.

## 6.1 District Heating

In Sweden, it is common with district heating. A centrally located power plant produces heat with a circulating hot water network as condenser. In large and modern power plants of this type, combined heat and electrical power production is facilitated by having a gas turbine connected to an electrical generator before the condenser. All common fuels can be used, biofuels (eg. chips or beads of wood), gas (CNG or biogas), oil or waste fuels. In larger district heating systems, it is common to have a power plant utilizing combustible waste as fuel.

WWHR in an area with district heat distribution will influence the energy nexus of the overall system. Co-generation of heat and electrical power with waste incineration makes a complex system to evaluate. The driving force for the production is the heat requirement. The heat requirement sets the limit for how much power can be dumped in the condenser and subsequently for how much waste can be fed to the boiler. The amount of electrical power produced is a consequence of the heat generation and is thereby also fully controlled by the heat requirement. Profu has on behalf of Tekniska Verken in Linköping studied the climate impact of the company, where such a system is the major part of the business (Profu, 2017). As illustrated in Figure 7, not only the direct emissions from the power plant is affected when varying the load but also both the up- and downstream processes and other compensatory systems. To the compensatory systems count production of commodities, or handling, that would have been replacing the goods produced by the company if they were not available. Equivalently, these are the goods that the products of the company replace. This system view is well corresponding to the urban water system framework presented by Malmqvist *et al.* (2006).

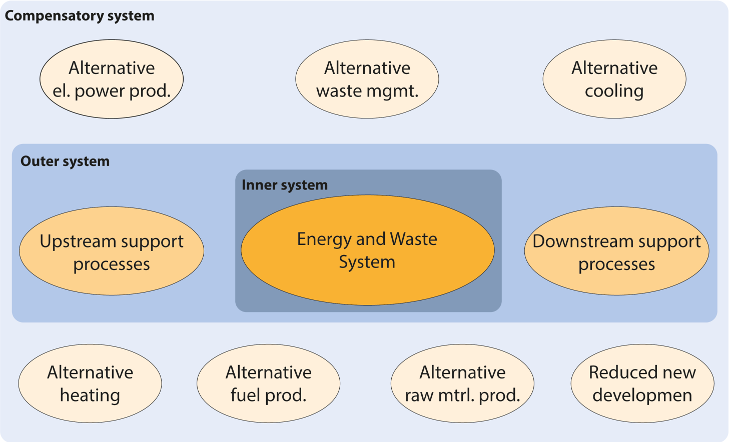


Figure 7. Illustrations of internal and external processes that directly or indirectly affect the climate impact from the operation of the businesses at Tekniska Verken in Linköping. Figure inspired from Profu (2017).

A relevant example for the evaluation of WWHR is illustrated in Figure 8. Here, each process is drawn and labelled, the arrows indicate how each process affects others – amplifying or diminishing. In the case of WWHR the heat requirement decreases, leading to less heat produced and thereby lower direct greenhouse gas emissions. Consequently, less waste is incinerated and must be landfilled instead, which causes higher indirect emissions from the landfill. The reduced heat production furthermore leads to lower internal electricity production, which must be covered by external marginal production of electricity, which in turn also leads to higher carbon dioxide equivalents ($CO_2e$) emissions. In summary, WWHR implies a lower heat requirement, which reduces the direct emissions from internal production of heat and electricity but increases the indirect emissions from external power generation and landfilling of waste. Calculations show that the direct emissions – per power unit – is much less than the indirect emissions from the compensatory system (Profu, 2017). Therefore, if WWHR is introduced – without compensation from another heat sink – the climate impact is increased. However, if reduced climate impact, rather than heat power, is considered the product from the system, the society should be considered the customer and fund any heat sink additional to the system customers' core need.

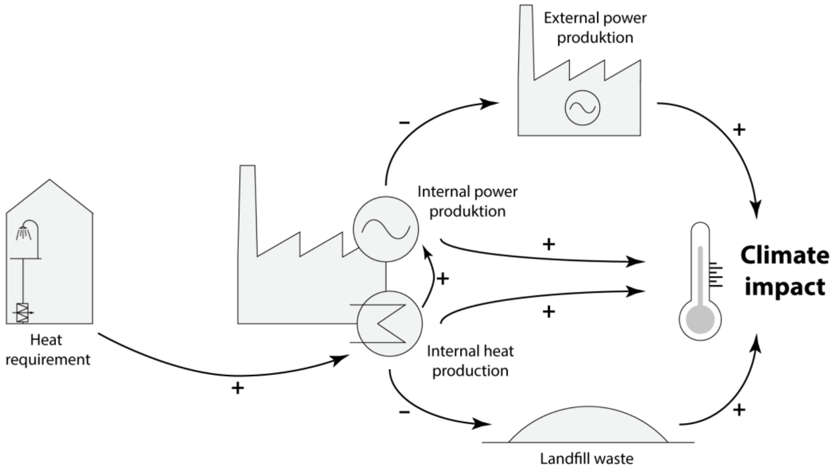


Figure 8. Stella type scheme for the district heating energy system. Each process is drawn and labelled, the arrows indicate how some processes affect others. A plus-sign indicates that a process has an amplifying effect on the other – e.g. an increased heat requirement demands an increased heat production – a minus-sign means a diminishing effect on the other process – e.g. increased heat production from waste leads to less waste to landfill.

The impact on the district heating system from residential energy conservation measures has been studied (Difs *et al.*, 2010; Åberg, 2014; Gustafsson *et al.*, 2016; Lundström & Wallin, 2016). The results show that different energy conservation measures have different impacts. Mainly because they affect the heat load profile of the district heating system differently. For the operations – cost and GHG emissions from the district heating system – it is a major difference if the energy savings arise in winter, summer or both (Difs *et al.*, 2010). Generally, heat demand reductions in the coldest period reduce the expensive, and potentially dirty, peak load production while in summer reductions mean less co-generated electricity than preferred – i.e. less expensive and cleaner – base load fuels. For the district heating system and its GHG emissions it is good if the heat demand profile is more balanced over the year (Lundström & Wallin, 2016). Depending on the type of power plants and the specific fuel mix, each district heating system is unique and will respond differently to any heat demand reduction. However, Åberg (2014) concluded that for four typical systems most energy conservations are beneficial from a GHG emission perspective. It has been shown that electricity savings has the largest impact on GHG emissions of all compared residential energy conservations (Difs *et al.*, 2010; Gustafsson *et al.*, 2016; Lundström & Wallin, 2016). For estimating the impact of any heat demand affecting action in a district heating system Lundström and Wallin (2016) propose a six-step method. The core of the method is to calculate a new heat demand profile for the whole system to compare with the base case, see example in Figure 9. They investigated the impacts of seven different actions, saving on DHW use being one. They assumed that the DHW savings reduced the heat demand linearly over the whole year. It is not evident that WWHR will act identically to this.

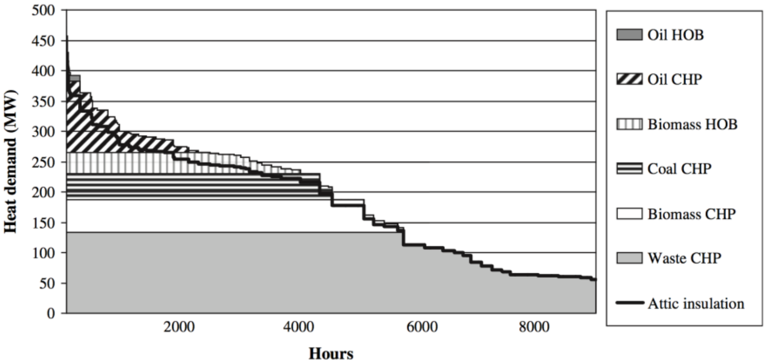


Figure 9. Heat demand profile for the district heating system of Linköping with an alternative profile including residential heat conservation with attic insulation. Figure from Difs *et al.* (2010).

## 6.2 Direct Electrical Power

Both domestic and industrial hot water heat requirements can be supplied through direct heating with electrical power. In this case, there is no connection to any other heating system, as for the case of district heating. WWHR has the positive effect of reducing the amount of electricity used for heating and thus less electrical power needs to be produced. How to estimate the environmental benefit from a reduced production of electrical power is debated. A legitimate argument is that all changes in electricity generation, positive or negative, acts on the margin. It is always the most expensive and dirty production that is used to react to changes in demand. Profu (2017) apply a complex mix of marginal electrical power generation with a $CO_2e$ emission of 778 kg $CO_2e$/MWh. WWHR will lead to lower GHG emissions as less electricity is needed for DHW heating.

### 6.2.1 Green Electricity

All electricity produced in the EU is labelled by origin and production method according to the Guarantees of Origin as described in EU directive 2009/28/EC. These certificates then follow from producer to the trading company and on to the consumer when the electricity is sold. Thereby, it is possible for power trading companies to buy and sell electricity of a specific kind, for example: locally produced, fossil free, only from wind, water or solar power production. The intention of the system is to empower customers to influence the electricity production (Colnerud Granström *et al.*, 2011). If enough customers contract fossil free power sources the power companies will “need” to expand the capacity and in due time a shift towards more fossil free power production can be achieved. However, when consuming electricity, it is not possible to direct any electrons from a specific power supplier to a consumer. In northern Europe, we all draw power from the same grid and consume a mix of what is currently produced. So, when evaluating the impact of electricity use for any consumer – whether fossil free electricity is contracted or not – the current power production mix must be used. For any change in electricity use, the marginal electrical power generation referred to in Section 6.2 should be applied (Profu, 2017).

A consumer who installs, or invests in, local fossil free electricity production, such as solar panel on the roof or a share in a wind mill, and claims the Guarantees of Origin for this production will have a larger share of fossil free electricity consumption. Depending on how well the production and consumption match, the consumer might need to buy some power from the grid when the “own” production does not meet the consumption. In that case, the consumer should be including some residual or marginal mix energy when assessing GHG impact from electricity use (Profu, 2017).

## 6.3 Heat Pump

Heat pumps use electricity to elevate a low temperature energy source to a useful level. For heating of buildings both liquid–water, air–water and air–air heat pumps are used. Heating of tap water can be built in to the heat pump, performed in a separate heat pump or in a separate DHW boiler. The efficiency (COP factor) varies between type of heat pumps and individual installations but in any case, the power source is electricity. Thereby, the system considerations for WWHR in buildings with heat pumps are the same as for direct electrical heating (see Section 6.2). WWHR will lead to lower GHG emissions as less electricity is needed for DHW heating.

## 6.4 Local Boiler

The heat required at a property can be provided by a local boiled fuelled by solid, liquid or gas fuels. In the case when DHW is provided by the same system (and not in a separate electrical water heater) the system perspective is still very similar to the one for electricity (Section 6.2). However, the greenhouse gas (GHG) emissions depend on the type of fuel. Wood-based biofuels have quite small GHG emissions while fossil fuels, such as oil, coal and natural gas, have a larger impact. WWHR will lead to lower GHG emissions as less fuel is needed for DHW heating.

# 7 Legal and Economic Feasibility of WWHR

## 7.1 Regulation of WWHR in Sweden

The Swedish legislation on water services does not regulate energy recovery from municipal water or wastewater (SFS, 2006). The utility joint organization, The Swedish Water & Wastewater Association (in Swedish, Svenskt Vatten) has in its proposal for customer agreement on water services (in Swedish, Allmänna bestämmelser för VA-anläggning, ABVA) proposed recommendations on installations for energy recovery from water at customer properties (The Swedish Water and Wastewater Association, 2007). The document provides recommendations for both tap water (cold) and wastewater. For a customer to use tap water as a source for energy, it is recommended that the utility require the customer to get a permit from the utility. Furthermore, tap water used for energy purposes is considered outside the general use and requires another permit to be wasted to the municipal sewer system. Also for wastewater, the recommendation is to require the customer to request a permit. Furthermore, the text recommends utilities to limit energy recovery from wastewater so that the temperature of the wastewater leaving the property never gets below the temperature of the actual drinking water supplied. Many municipalities apply these recommendations. Furthermore, municipalities are restrictive giving the required permits, which in practice place a ban on WWHR. Regardless of permits, these restrictions do in practice make upstream heat recovery unfeasible in many cases.

## 7.2 Building Standards and Green Certifications

The National Board for Housing, Building and Planning (Boverket in Swedish) in Sweden has published recommendations on building standards in general. The guidelines do not specifically cover installation of equipment for WWHR. However, recommendations for plumbing to avoid growth of Legionella bacteria in the hot tap water system are provided (Boverket, 2011). The general requirement is that the heated tap water must be at least 50 °C in all parts of the system. This will impact how recovered heat can be utilised since it is in many cases used for pre-heating tap water in many cases.

One driver for wastewater heat recovery (WWHR) over the past years have been the conquest of achieving different certifications for buildings of international standard trademarks. The first multi-unit residence in California that received Passive House certification (Passive House Institute, 2016) had incorporated heat recovery through the principle of gravity film heat exchange (GFX) according to Moore (2013). For this unit, the showers consumed most of the energy used for heating the building and the project architect stated that GFX helped to reach the overall goal of sustainability. It seems from this experience that the installation is straight forward and that the primary design challenge is associated with space.

The technology of wastewater heat recycling is recognized in Canada and the USA by LEED (Leadership in Energy and Environmental Design) for homes and by Energy Star for New Homes Canada. Wastewater heat recovery has also been tested independently by the multi-disciplinary building science centre, BRE. BREEAM (BRE Environmental Assessment Method) is a world leading sustainability assessment method for planning projects, infrastructure and buildings (http://www.breeam.com/) and describes a building's environmental performance. LEED is one of many international standards for benchmarking design, construction and operation of structures, from hotels to healthcare. The latest version of LEED, LEED v4, (http://www.usgbc.org/leed-v4) includes water efficiency and evaluates total building use. It also rewards renewable energy. WWHR can be input into SAP-modelling (Systems Applications Products) to increase a buildings energy performance.

## 7.3 Economic Feasibility of WWHR

The economic viability of any practical WWHR installation will be case specific. Life Cycle Cost (LCC), return on investment and pay-back time are examples of tools that have been used in literature and can be calculated as (The Swedish Energy Agency, 2017):

$$LCC = INV + NV_{energy} + NV_{maintenance}$$

where $NV_{energy}$ is the "present value" for energy and $NV_{maintenence}$ is the "present value" for maintenance. For more information on how to calculate the "present values" see The Swedish Energy Agency (2017) or Nykvist (2012) for a condensed overview.

The economic viability of some existing installations is reported in Chapter 4.

# 8 REFERENCES

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