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Is on-property heat and greywater recovery a sustainable option? A quantitative and qualitative assessment up to 2050

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ABSTRACT

This article deals with ongoing attempts to recover heat and greywater at property level, based on an in-depth study of Stockholm, Sweden. We explore different socio-technical development paths from now up until 2050 using a novel combination of on-property technology case-studies, actor studies and system-level scenario evaluation, based on Artificial Neural Networks modelling. Our results show that the more conservative scenarios work in favour of large-scale actors while the more radical scenarios benefit the property owners. However, in the radical scenarios we identify disruptive effects on a system level due to disturbance on wastewater treatment plants, where incoming wastewater can be critically low for up to 120 days per year. At the same time, net energy savings are relatively modest (7.5% of heat demand) and economic gains for property owners small or uncertain. Current policies at EU and national level around energy-efficient buildings risk being counter-productive in cases when they push property owners to install wastewater heat recovery technology which, in places like Stockholm, can create suboptimal outcomes at the system level.

1. Introduction

Cities around the world are struggling to reduce their energy consumption and their ecological footprint. One of the strategies that has been used to achieve this goal is heat recovery at property level. Globally, the housing sector generates 38% of the world's emissions of greenhouse gases and stands for 35% of global energy use (UNEP, 2020), underlining its centrality in the transformation towards fossil-free and energy-efficient societies, and reaching global sustainability goal on energy (SDG7). Major actors like the European Union place much emphasis on how to save energy in urban housing, where heating, cooling, ventilation and domestic hot water (DHW) make up a substantial share of the energy consumption (Arriazu-Ramos et al., 2021; Longo et al., 2019). Demand for heating and cooling differ vastly between climate zones. The energy consumption for keeping our homes, offices and public buildings at a comfortable temperature can be five times higher in a cold climate zone than in temperate zones (He et al., 2020) and as climate change progresses, cities will face new challenges, prompting different and locally adapted response strategies (Shen et al., 2020). Retrofitting, renovation, improved designs and building envelopes are common measures to improve energy efficiency, and to move towards "near-zero emission buildings" (Pasichnyi et al., 2019; He et al., 2020; Arriazu-Ramos et al., 2021; Savvidou and Nykvist, 2020). In cold climates, recovering heat from sewage water has recently become increasingly popular as a way of increasing the energy efficiency in urban areas, with applications in many countries, such as Germany, Switzerland, Austria, China and the Scandinavian countries (Chen et al., 2022; Golzar et al., 2020; Ichinose and Kawahara, 2017). Water and energy are two vital resources that are intimately linked under what often is called the "water-energy nexus" (Fang and Chen, 2017), but seldom is this connection as conspicuous as in wastewater heat recovery (WWHR). Around 15% of the energy consumed in European homes in 2020 was used for heating of DHW (Eurostat, 2022). In the absence of heat recovery this energy practically speaking goes down the drain, when it leaves the buildings in the form of warm wastewater. Technologies to recover the heat in wastewater, as well as to recover and re-use hot water from for example showers, can directly reduce both energy and water consumption (Chen et al., 2022; Golzar et al., 2020;

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Wallin et al., 2021).

However, a range of complications and conflicts have previously been identified, including optimisation of heat extraction points and lack of documentation of economic and technical performance (Wallin, 2021a; Ichinose and Kawahara, 2017). In particular, the potential downstream negative effects in the wastewater treatment plant (WWTP), where reduced sewage temperature causes the process to remove nitrogen to be less efficient, has attracted much attention. Wanner et al. (2005) found that for every degree of temperature drop in the incoming sewage water, the nitrification level in the treatment was reduced by 10%. A reduction of temperature from 20 °C to 10 °C is likely to halve the maximum nitrification rate in the WWTP (Arnell et al., 2021). This means that the treatment capacity will be lower than designed for, and in the long run, WWTP may have to be re-designed and reconstructed at great cost.

Moreover, competition between actors in the system may potentially create "winners and losers" (Karpouzoglou et al., 2020) if WWHR technologies applied in upstream properties reduce the possibility to extract heat in downstream facilities, for example at the WWTP. In all, a range of controversies may arise at the system level if WWHR is applied in an un-coordinated fashion which could create sub-optimisation and even negative system-level effects (Golzar and Silveira, 2021; Saagi et al., 2021). As policy-makers and city managers try to steer urban development towards a resource-efficient path, knowledge about risks and possible goal conflicts will be crucial. In this case, should policy facilitate the recovery of water and heat at the property level, or through central facilities? It is important though, not to fall into the old "Big vs Small" dichotomy (cf. Schumacher, 1973) which could be an over-simplified binary. Instead we argue that policy must be based on a context specific and in-depth understanding of the system, its components and actors.

Our aim in this paper is to explore different scenarios for large-scale uptake of WWHR and assess the benefits as well as risks at system level. We wish to analyse the trade-offs faced by urban actors such as city leaders, property owners, technology providers and users under these scenarios, and evaluate what they mean at a systems (city) level. Specifically, we have developed five future scenarios of WWHR technology uptake which we have evaluated quantitatively and qualitatively. To make our analysis and resulting insights concrete and specific, these scenarios are evaluated using an in-depth application on a real case. We have studied Stockholm, a city in a cold climate with well-developed centralised water, sewerage and district heating systems, and where property owners have begun installing private WWHR technology. In Stockholm, there is already a central wastewater heat recovery facility in place at the main WWTP, which allows evaluating system-level trade offs between heat recovery at property level and at the central level.

By applying our study to Stockholm, results from case studies of local WWHR installations together with participatory and actor-centred future scenario planning, have been available as input to a novel data-driven conceptual model that allows quantifying the effects of the different strategies and scenarios at city level. Based on this comprehensive approach we derive tangible and surprising insights for policy-makers to consider, where efficiency measures in one sub-system of a larger (city-level) energy system can have negative consequences for other sub-systems.

In the next section we explain our investigative approach more in detail, including the methods and data used. After that we present and discuss our results from assessments of future scenarios. In the final section, we conclude with a message to policy-makers on how to better balance decisions to account for both actor-perspectives, as well as systemic effects, when leading sustainability shifts in their cities.

2. Overall conceptual approach and methods to collect data

2.1. Conceptual approach

In this paper we conceptually draw on the tradition of Technology Assessment (TA); the study of the development of, and effects from, new technology in society. TA draws on the field of future studies and particularly its methods of *scenario planning* and *back-casting,* typically characterised by its interdisciplinary approach, and the use of participatory methods (Carlsson-Kanyama et al., 2008; Carlsen et al., 2010).

In our study we have used mainly scenario planning, a method developed during WW2 and refined in the 1970s. It is a means to inform decision-making in face of major uncertainties and typically involves developing and evaluating three to five scenarios together with stakeholders (Carlsen et al., 2010).

The importance of involving key societal actors in scenario planning has been underscored in earlier studies. Not only does a close actor-collaboration improve the quality of the scenarios, it may also facilitate knowledge uptake and strengthen the legitimacy of the future visions developed (Gunnarsson-Östling and Höjer, 2011; Svenfelt et al., 2011; Carlsson-Kanyama et al., 2008). The role of actors in technology change should not be underestimated. Large institutional actors like states, municipalities or utility companies have historically played an influential role in technology shifts (Vleuten, 2019). Large incumbent actors can resist innovation and try to keep competitors out, or they can act as facilitators, both in the area of energy (Brisbois, 2018; Green and Newman, 2017; Mignon and Bergek., 2016) and in water and sewerage (Ampe et al., 2021; Blomkvist et al., 2020). Mignon and Bergek (2016), in their study of energy transitions in France and Sweden, conclude that different actors face very different types of challenges, and that non-commercial actors may be crucial in the early stages of technology shift, something that policy must better acknowledge. Morever, technology shifts driven by individual property owners are unlikely to be neutral for today's water and energy utilities (Green and Newman, 2017) and could potentially present them with a "disruption from below" (Egyedi and Mehos, 2012). Kivimaa et al. (2021) defines disruption in the context of sustainability transitions as " […] unlocking the stability and operation of incumbent technology and infrastructure, markets and business models, regulations and policy, actors, networks and ownership structures, and/or practices, behaviour and cultural models." (119). Therefore, also qualitative aspects are key, since potential disruptions may not be easily captured in quantitative studies.

Our approach requires carrying out the analysis applied to a real case, such that actors can be included. Whereas some specific parts of the results are context specific, this concept still makes it possible to deduce important insights from a general point of view. This is further discussed below.

Our conceptual approach has been to, in a step-wise fashion, combine data from existing on-property installations in Stockholm, with city-wide future scenarios developed with key city actors (see Fig. 1). The scenarios were evaluated using a computer-based quantitative

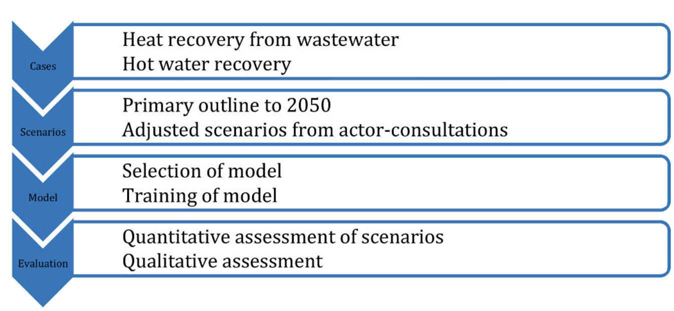

Fig. 1. The sequential development of our study from individual case studies to system level evaluation.

model combined with an analysis of the qualitative aspects in a multidisciplinary research team.

We have established a close collaboration with key actors through a Reference Group, and collaborated with several of them in the on-property installation case studies. The Reference Group has consisted of highly experienced professionals from real estate, city development, heat and water utilities, technology suppliers and municipal authorities, as shown in Table 1.

Our approach is highly inter-disciplinary, involving a team of scientists from applied thermodynamics, energy systems, social sciences, and history of technology. In the following we provide more detail on key methods and materials.

2.2. Method

2.2.1. The case of Stockholm

For the overall concept of scenario planning, we need to apply it to the case of a real city. In this study, the city of Stockholm is chosen, that is the capital of Sweden with a population of 2.3 million people in the greater metropolitan area (RUFS, 2018). Stockholm is interesting from several viewpoints. As mentioned, the city is located in a fairly cold climate, has a well-developed district heating system and ambitious policies for energy-efficient housing, and the city has set a target for being fossil-free by 2040 (Pasichnyi et al., 2019). Sweden has set national goals for improved energy efficiency, further enhanced by local building codes, meaning that total energy demand in all new buildings in Stockholm must be less than 55 kWh per square metre and year (City of Stockholm, 2020). A wastewater heat recovery facility is already in place at the largest WWTP Henriksdal, with installed effect of 225 MW (Stockholm Exergi, 2021). This means that applying our study on Stockholm provides us with ample opportunity to analyse the dynamic interactions between various technical systems, key stakeholders per sector, under a seemingly ambitious set of policies designed to promote energy efficiency and conservation.

2.2.2. On-property heat recovery installations

For making realistic assumptions in scenario development and for the system modelling, we have used data from five case studies of existing on-property installations for heat recovery, as presented earlier (Wallin, 2021a; Wallin et al., 2021). These include four installations of heat recovery from wastewater with various technical configurations, involving heat exchangers as well as heat pumps (Wallin, 2021a). One installation of graywater recovery was also studied, where water from showers in an apartment building is being treated locally and recycled in a closed loop (Wallin et al., 2021). For two examples of the configuration schemes of the installations, see Fig. 2 (a) and (b).

Data on energy use, water recovery rates, water quality and temperatures on outgoing wastewater was collected for periods of between 14 and 115 days, depending on the installation. For the gray water recovery installation, user and actor surveys were also included. The results from the studies of these on-property installations formed necessary inputs to the subsequent steps, where essentially these results were used as input both to the scenario development, and to form some of the boundary conditions for the subsequent modelling. It should therefore be noted that while not all data collected for the installations have been used directly in the modelling step, it is used to inform the qualitative assessment. See Table 2 for an overview of the existing installations.

Table 1
Composition of actor Reference Group.

Actor Category	Organisation
Real estate & developer	Akademiska Hus
	Einar Mattsson AB
	HSB
	Vasakronan
	Stockholmshem
	Familjebostäder
Utilities	Stockholm Water and Sewerage company, SVOA
	Stockholm Exergi AB
	Svenskt Vatten
Technology supplier	GrayTech AB
	Skandinavisk Kommunalteknik
	Bengt Dahlgren AB
Authorities	City of Stockholm, Stockholm Stadshus AB
	Värmdö municipality

2.2.3. Scenario development

Similarly to earlier studies of Stockholm's sustainability futures we have developed scenarios up to 2050 (Gunnarson-Östling and Höjer, 2011; Svenfelt et al., 2011), which is also the planning period for the current regional metropolitan plan (RUFS, 2018). We have worked in a multi-phase approach to factor in quantitative results and experience from the case studies described in 2.2.1, and qualitative insights developed with our Reference Group.

Quantitative results include technical and economic performance of WWHR, including evaluations of actual on-site installations with system-level simulation of heat and water flows and temperature at the WWTP system level. Qualitative results include interviews with key actors in the city to evaluate perceived responses to different levels of technology diffusion, in terms of energy and water savings, its economic value, and the risk for disruption of WWTP operations.

The scenarios were developed through a slightly simplified version of the procedure applied by Carlsson-Kanyama et al. (2008) in three key methodological steps, see Fig. 3. In the first phase, we developed different scenarios in the form of 'story lines' that describe cause-effect relationships between different factors. In developing the storylines we have drawn insights from our own research with the case studies of on-property installations but also consulted relevant literature for the Stockholm region (Carlsson-Kanyama et al., 2008; Gunnarsson-Östling and Höjer, 2011; Svenfelt et al., 2011; Pasichnyi et al., 2019; Shen et al., 2020; Carlsen et al., 2010).

A Base scenario was used as a reference point, based on demographic changes and urbanisation as forecasted in official regional development plans (RUFS, 2018). Four draft Scenarios (H1, H2, HW1, HW2) representing different levels of technology diffusion of heat and water recovery were developed, see Table 3.

In the second phase, we received feedback on draft scenarios from our Reference Group using an online survey, generating a total of 9 responses from the members of the group. The responses were then discussed using an online session (this phase of the study was carried out during the COVID-19 pandemic, rendering physical meetings impossible).

In the third phase and based on the feedback, we revised the scenario storylines. In the final round, we decided to also include a sixth, post-COVID-19 scenario. This has a much lower population growth than all other scenarios, as there were signs of reversed population trends during and after the pandemic in the Stockholm region. The final storylines for our scenarios are presented in APPENDIX A.

2.2.4. Quantitative system model

A key goal in our research is to quantitatively analyse and compare the scenarios using a computer model at system level. The system defined for quantitative analysis is the drainage basin to Henriksdals WWTP, currently treating wastewater from around 760,000 people including the larger part of Stockholm city. Deciding on a modelling tool always involves making a trade-off between (i) accurateness of representation; (ii) computational cost, and; (iii) access to and cost of data to feed the model (Kuznik et al., 2022). Physical (deterministic) models can adequately represent different technical configurations but require very large amounts of data, are computationally demanding, and are therefore typically used for steady-state simulations or only short-term simulations (Chen et al., 2022; Saagi et al., 2021; Abdel-Aal et al., 2018). In

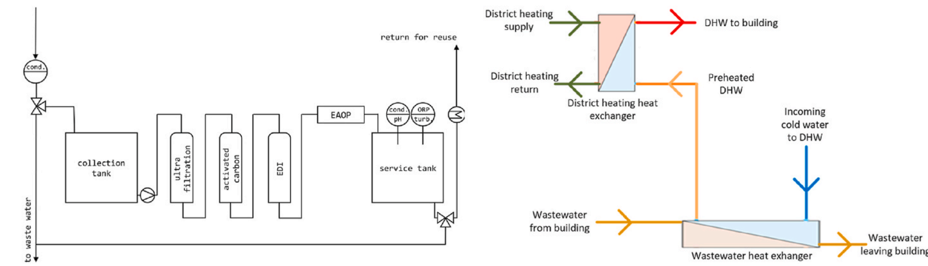

Figure 2. (a), installation configuration for graywater recovery and (b) waste water heat recovery by pre-heating of incoming water for DHW.

Table 2
Key characteristics of the case studies of existing on-property heat recovery installations.

Configuration	Property type	Data collected
Pre-heating of DHW – direct exchange	Multifamily house with 141 apartments, one preschool and two small stores	Temperature of wastewater before and after heat exchanger, incoming cold tap water and pre-heated DHW. Flowrate of pre-heated DHW.
Pre-heating of DHW – storage and pump	Multifamily house consisting of 300 student apartments.	Temperature of wastewater before and after heat exchanger, incoming cold tap water and pre-heated DHW. Flowrate of pre-heated DHW. Electric power of wastewater pump.
Pre-heating of DHW	Commercial building of 13,700 m2, used as office, hotel, and a supermarket	Temperature of wastewater before and after heat exchanger, incoming cold tap water and pre-heated DHW. Flowrate of pre-heated DHW.
Heat recovery to heating system using heat pump	Commercial building 12,010 m2, for offices and five restaurants	Temperature of wastewater before and after heat exchanger, heat pump cold side supply and return. Flow rate of heat pump cold side. Electric power of heat pump.
Graywater treatment and recovery	29 student apartments with 8 shared bathrooms	Temperatures, flowrate, heat recovery rate, treatment plant electric power. Water quality, user experience

our application, the key parameter to evaluate for the different scenarios is the temperature of the wastewater at the inflow to one and the same WWTP, and the amounts of heat and water that can be saved collectively in the upstream buildings. These we regard as the main parameters that can cause disruption at different levels of diffusion of the technology. For many types of studies, black-box types of model have been found to represent system behaviour just as adequately as physical models, at much lower computational and data cost (Abdel-Aal et al., 2015; Saagi et al., 2021).

The model we have used is a data-driven conceptual model which has previously been developed, validated and tested for the Henriksdal drainage area (Golzar et al., 2020; Golzar and Silveira, 2021). The model relates the temperature of wastewater at the entrance of the WWTP with a number of other parameters that can be measured or estimated. For each of our scenarios, the temperature and flow rate of wastewater leaving buildings are calculated using results from on-property case studies. The data-driven model is used to calculate the temperature of wastewater at the entrance of the WWTP on an hourly basis, for one reference year (2019). The model uses an Artificial Neural Network (ANN), where a computer algorithm is trained to “guess” the right value of the modelled parameter (in this case, temperature at WWTP), based on historical data series of the other variables: air temperature; temperature and flow of wastewater from buildings; storm water and infiltration; hour and day. See illustration of ANN setup in Fig. 4.

The ANN model has been trained for the Henriksdal WWTP in Stockholm, using data for a ten-year period. After training, the model was able to very accurately predict the temperature at WWTP, with a $R^2 = 0.946$ for the validation year 2019 (Golzar et al., 2020), see Fig. 5. The potential to use the model for evaluating scenarios at the city-level has been tested and confirmed (Golzar et al., 2020; Golzar and Silveira, 2021). In this study, we use the same model but take a more holistic approach, building on the more rigorous scenarios developed (2.2.3), and we emphasise more the qualitative aspects and the socio-technical dynamics in the actor- and policy landscape.

With regards to potential disruptive effects, such as for nitrogen removal in WWTP (Wanner et al., 2005), we pay particular attention to the number of days (compared to the reference year) when the temperature of incoming sewage will be lower than 10 °C. Below this temperature, the WWTP can expect significant disturbance of the treatment process (Bergstrand, 2020).

3. Results and discussion

3.1. Quantitative simulation of scenarios

The results for all scenarios are summarised and compared in Table 4. Below, we briefly outline the key findings and notable differences between the simulated scenarios.

3.1.1. Current condition

In the current condition, 752,700 people are connected to Henriksdal WWTP. Wastewater leaves the buildings at a yearly average temperature of 25 °C and reaches the WWTP at 16 °C. The temperature of wastewater is less than 10 °C only for 9 days during the year. The district heating company potentially recovers 520 GWh/year from treated water at the WWTP, and by a combination of other resources of energy, provides 1666 GWh/year in terms of heat to the buildings.[1] Heat loss in the district heating distribution is calculated as 10% of the total supply, leading to an annual loss of 166 GWh. The water company provides 66 Mm^3/year to the buildings while 13.2 Mm^3/year is lost in the network as leakage (20% of total supply).

3.1.2. Base Scenario 2050

In the base scenario, population growth by 2050 is considered, but there is no wastewater heat and water technology diffusion in the buildings. Due to population growth, the number of connected people to WWTP would increase to over 1,160,000. There is no heat or water recovered on the properties, and accordingly the average temperature of wastewater leaving buildings would be similar to the current condition as 25 °C. However, the total flow rate of wastewater would increase

[1] The actual heat from treated water was 750 $GWh.year^{-1}$ in 2020 (Stockholm Exergi, 2021). The reason of this difference is 1) we have assumed that the district heating company extracts heat from treated water when the ambient temperature is lower than 5 °C, while in practice, it depends on other economic parameters, 2) we have assumed a temperature of the effluent from the heat pump at 5 °C, while during the year it could be different.

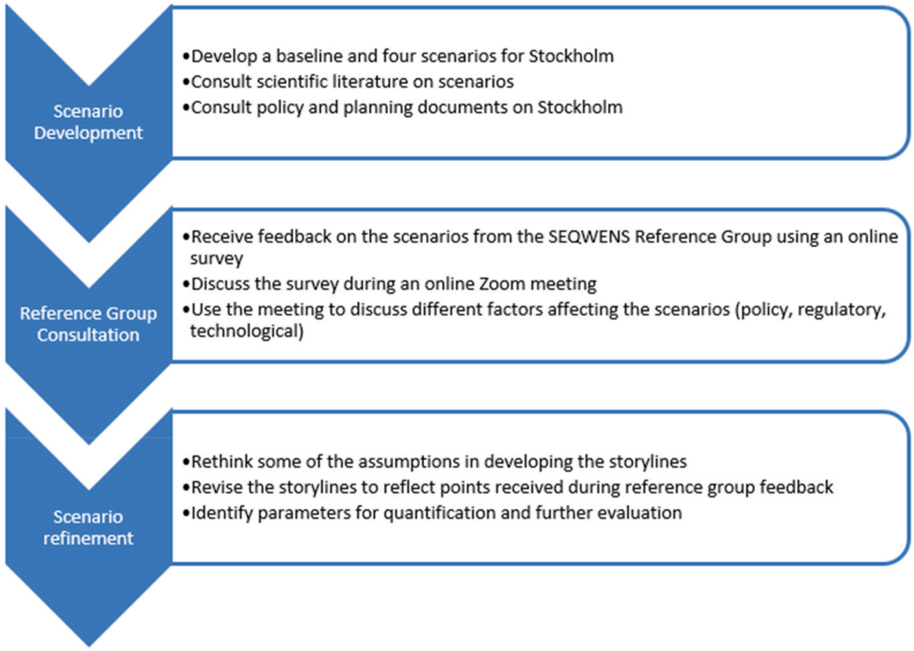

Figure 3. Methodological steps for the qualitative development of the scenarios. For more details about inputs and assumptions in the scenarios and for the modelling, see APPENDIX B.

Table 3
Six future scenarios for heat and greywater recovery for Stockholm region.

Scenario	Description
Current condition	This scenario represents the Stockholm region in 2020 in terms of population (2.3 million people), climate condition (temperature and rain in 2020), and diffusion of technology (0% of buildings have installed heat and water recovery technologies).
Base scenario	It is assumed that there is no on-property WWHR in Stockholm until 2050. The population of the region will increase to 3.4 Million people by 2050. The climate condition in 2050 is also considered for this scenario (the ambient temperature in 2050 for Stockholm will increase by 0.5 °C during summer, 1 °C during winter, and 0.75 °C during transitioning seasons in comparison with 2020 and average annual rainfall will increase by 5%).[1] This scenario helps to understand the impacts of population growth and climate change regardless of technology diffusion.
H1	This scenario investigates the impacts of moderate diffusion of WWHR as heat recovery in 45% of new buildings and 25% of existing buildings. The population and climate conditions of 2050 are considered in this scenario.
H2	This scenario investigates the impacts of radical diffusion of WWHR as heat recovery in 90% of new buildings and 50% of existing buildings. The population and climate conditions of 2050 are considered in this scenario.
HW1	This scenario investigates the impacts of moderate diffusion of WWHR technologies as heat and water recovery in 45% of new buildings, heat recovery in 25% of existing buildings, water recovery in 10% of existing buildings. The population and climate conditions of 2050 are considered in this scenario.
HW2	This scenario investigates the impacts of radical diffusion of WWHR technologies as heat and water recovery in 90% of new buildings, heat recovery in 50% of existing buildings, water recovery in 20% of existing buildings. The population and climate conditions of 2050 are considered in this scenario.
Post-covid-19	This scenario assumes no population growth in Stockholm after Covid-19. However, technology diffusion would happen as HW1 (heat and water recovery in 45% of new buildings, heat recovery in 25% of existing buildings, water recovery in 10% of existing buildings). Climate would also be changed by 2050.

[1] Gourhand Martin, 2021.

because of population growth and an increase in rainfall due to climate change. The model estimates that incoming wastewater at WWTP would have a temperature of less than 10 °C during 36 days per year, while in current condition it is only 9 days per year. The reason is that wastewater from buildings and rainfall are combined in the sewage system and transferred to the WWTP. Golzar et al. (2020) presented that the temperature at the WWTP entrance drops due to the cold temperature of the rain, especially when there is an increase in flow rate into the WWTP during the colder seasons. Therefore, more rainfall in 2050 would lead to more days with a temperature of lower 10 °C and consequently would slightly decrease the amount of heat recoverable at WWTP from 520 to 502 GWh per year.

3.1.3. Scenario H1, moderate heat recovery

In scenario H1, heat recovery is assumed in 45% of new buildings and 25% of existing buildings in addition to population growth. Due to local wastewater heat recovery, 175 GWh/year would be recovered locally (around 7% of the heat demand). Consequently, the temperature of wastewater at buildings and the WWTP would be lower than the current condition and base scenario. The district heating company would be able to extract 415 GWh from treated water, down from 502 GWh because of the decrease in the temperature of wastewater. Although there is 175 $GWh.year^{-1}$ heat recovery in the buildings, the total amount of heat demand in the buildings would increase from 1666 to 2401 GWh/year due to population growth. The local recovery of 175 GWh/year means less heat delivered to the properties, and a sales loss for the district heating company of 148 MSEK/year (approx. 14 M€) at current prices.[2]

3.1.4. Scenario H2, radical heat recovery

In comparison with scenario H1, the double amount of heat is recovered locally (around 15% of the heat demand). The temperature of wastewater would decrease and the volume of extracted heat at WWTP

[2] Average DH cost in Sweden is approx. 800–900 kr/MWh according to Swedish Energy suppliers, Swedenergy, https://www.energiforetagen.se/statistik/fjarrvarmestatistik/fjarrvarmepriser/.

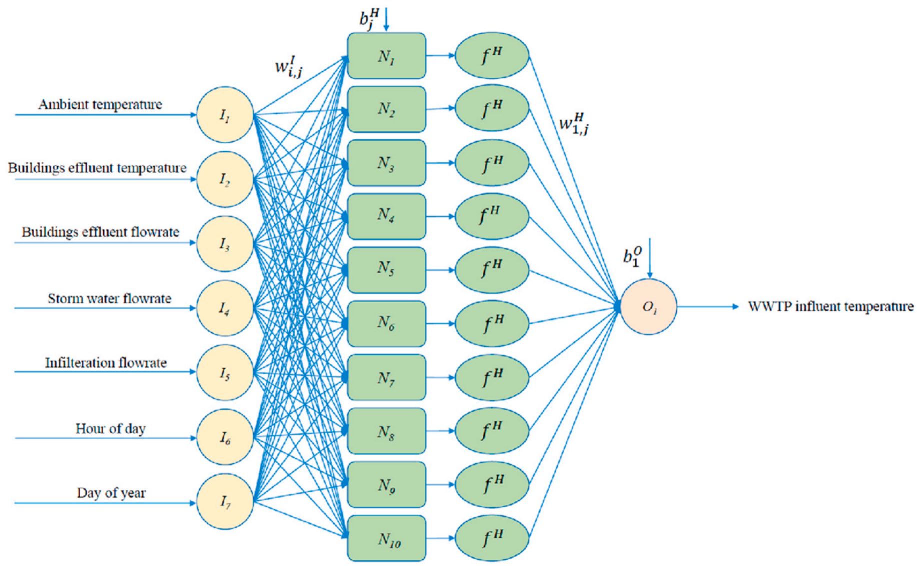

Figure 4. The input and output parameters of the ANN (from Golzar et al., 2020).

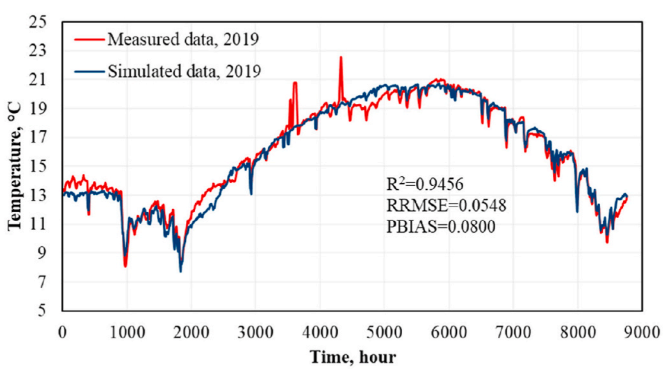

Figure 5. Comparison of simulated and observed temperature at WWTP Henriksdal for the ANN model (from Golzar et al., 2020).

level water would thereby decrease by 33%–339 GWh. Wastewater would have a temperature of less than 10 °C for as much as 122 days per year. This clearly would have a very dramatic effect on the treatment process, with extended periods of very poor conditions for nitrification, hence disturbed nitrogen removal, in the treatment plant.

3.1.5. Scenario HW1, moderate heat and hot water recovery

In scenario HW1, in addition to local wastewater heat recovery, water would also be recovered. In this scenario, in addition to 175 GWh/year recovered heat in the buildings, 5.4 Mm^3 water would be recovered locally per year. In comparison with scenario H1, the temperature of wastewater released from buildings is higher. The reason is that the total amount of wastewater in HW1 is less than H1 because a part of the wastewater is recovered. Therefore, from an energy point of view, this scenario has less impact on WWTP and district heating company in comparison with H1. However, in this scenario, the amount of domestic water supply would decrease by around 5%. It also results in a decrease in the leakage in the network compared to base scenario, since less water is distributed, but would still increase compared to the present conditions due to population growth.

3.1.6. HW2, radical heat and water recovery in buildings

Scenario HW2 is a radical version of scenario HW1, where double the amount of heat and water is saved at property level (350 GWh per year), while only 368 GWh of heat can be extracted at the WWTP level, a reduction with 27% from the base scenario. Also in scenario HW2 there will be significant effects on the nitrogen removal process in the WWTP, although not as severe as in H2. The model estimates there may be up to 94 days in a year when incoming sewage water has a lower temperature than 10 °C, which is less than H2 due to a warmer water leaving the buildings.

Table 4
Results from simulated future scenarios for heat and greywater recovery up to 2050.

Parameter	Scenarios						
	Current	Base	H1	H2	HW1	HW2	Post-covid
Recovered heat in buildings (GWh/year)	0	0	175	350	175	350	88
Recovered water in buildings (Mm^3/year)	0	0	0	0	5.4	10.7	1.6
Average temperature of wastewater at buildings (°C)	25	25	23.1	21.2	23.4	21.6	23
The minimum temperature at WWTP entrance (°C)	7.2	7.6	5	2.9	5.5	3.5	5.9
The average temperature at WWTP entrance (°C)	16	15.6	13.9	12.2	14.2	12.8	14.4
Days with temperatures less than 10 °C (days)	9	36	78	122	60	94	49
Potential heat from treated water (GWh/year)	520	502	415	332.8	420	339	368
Heat loss in the district heating system (GWh/year)	166	258	240	222	240	222	150
Water leakage in water system (Mm^3/year)	13.2	20.3	20.3	20.3	19.3	18.2	12

3.1.7. Post-COVID scenario

The comparison of current condition and post covid-19 scenario, which assumes the same technological diffusion as in HW1, shows that when there is no population growth, even moderate local wastewater heat and water recovery could affect the temperature of wastewater considerably. The average temperature of wastewater at buildings would decrease from 25 to 23 °C. It would lead to a decrease in extracting heat from wastewater from 520 to 368 GWh/year.

3.2. Discussion of results

On the whole, our simulations of the different scenarios do not show drastical savings of heat and water even in the most radical scenarios H2 and HW2, despite very high levels of WWHR technology uptake. Under the assumptions made, which are informed by actual case studies of existing WWHR technologies, up to 350 GWh can be saved on an annual basis within the concerned housing units, corresponding to a future population of 1,16 million people in Henriksdal WWTP catchment area.[3] These savings amounts to around 15% of the total heat demand in these buildings, when other energy efficiency improvements are not considered. In comparison, Abdel-Aal et al. (2018) found, in a study of a city in Belgium, that up to 18% of heat demand could be covered by WWHR. Their study evaluated optimal (theoretical) WWHR configurations in the sewer network, not considering heat recovery at the property-level. Our study, on the other hand, takes a point of departure in the system-effects resulting from changes at the property level.

From the existing on-property installations studied we know that on an individual basis, some property owners can make much larger energy savings from WWHR in their building; up to 55% of the heat demand (Wallin et al., 2021). However, on the system level, the total saving is less impressive when upstream-downstream trade-offs are considered. The saved 350 GWh on properties upstream reduces potential heat extraction downstream at WWTP level with up to 170 GWh. The net saving at system level even in the most radical scenario H2 therefore will be just 180 GWh, or 7.5% of the heat demand.

What is also evident from the simulation results, is that radical scenarios where WWHR technology becomes more or less standard in new and renovated buildings would lead to extended periods of very low sewage temperatures at the WWTP. Temperatures would go below the critical temperature of 10 °C over one hundred days in a year, effectively prompting a re-design of the centralised treatment process or a substantial expansion of the treatment works to allow longer retention times. These negative effects and external costs are not included in the individual property owners' balance sheets but do pose concerns for the utilities.

In fact, each scenario suggests a different distribution of risks and benefits to the involved actors. More broadly, the more conservative scenarios (H1 and HW1) tend to work more in favour of incumbent actors (primarily the district heating company and the water and sewerage utility) because in these scenarios these actors need to make the least adjustments to their operations. On the other hand, the more radical scenarios such as H2 and HW2 tend to work more in favour of the property owners since they can take advantage of more benefits from heat and water recovery. Meanwhile, the incumbent actors will experience disruptive effects such as the disturbance of the wastewater treatment, but also loss of energy and water sales, and thereby loss of revenue. Hence, we foresee that they would need to make serious adjustments to their operations in scenarios such as H2 and HW2.

We consider scenarios H1 and HW1 as being more likely to occur given current conditions. But with changes in policy, regulation and other changes in society more broadly we may be able to see changes occurring such as those described under the more disruptive scenarios H2 and HW2. In particular, regulatory factors and economic incentives were ranked highly by the actors who participated in the Reference Group in terms of their impact on the scenarios. As described by one of the actors during the elaboration of scenarios: "*energy requirements in new construction can force new technology to be tested. If it works it can spread to existing buildings*" noting the importance of building regulation as a precursor for higher diffusion of the technology.[4]

Again, for the heat and water system to go towards more radical scenarios (H2, HW2) it is regarded that it might be less an issue of technology, and more of policy and regulation. As another actor remarked "*much will depend on government and other incentives*" in the case of the more radical scenarios. The consumer perspective is also of significance for the radical scenarios. In particular, water recycling for domestic uses will depend on how attitudes and overall acceptance will shift amongst consumers (Wallin et al., 2021; Fielding et al., 2019). Overall, we see that these findings correlate well with other studies, placing policy and consumer behaviour in a driver's seat for enabling more radical changes in energy and sustainability (Svenfelt et al., 2011; Mignon and Bergek., 2016; Savvidou and Nykvist, 2020).

One interesting finding from our study concerns the motivation of the actors. There are currently no strong economic incentives for property owners to invest in WWHR, since economic savings are small or uncertain. Local heat and water recovery will lower the consumption of heat and water and thus reduce some operational costs, but increase the capital costs for installations of wastewater heat and water recovery technologies, and lead to more unpredictable operational costs for maintenance. Hence, property owners may end up with very small net economic gains, or none at all (Wallin, 2021b). Instead, property owners seem to be motivated more by policy and regulation. In our Reference Group discussions, one large property owner admitted to "taking chances with the economy" but that WWHR could help them to meet regulatory requirements of energy performance of buildings.[5] Clearly, we observe a shift in property owners strategies towards more energy efficient options, but not mainly due to economic motives.

The changing motives of property owners can bring controversial outcomes for actors operating at the city level. As we have shown, relatively modest energy savings can be made on system level even with the highest investment pace in our most radical scenario, but at the same time, risking critically low temperatures at WWTP. Moreover, while not possible to elaborate further here, a study by Pektas (2021) indicates that from a Life-Cycle Analysis point of view, the centralised heat recovery at WWTP has a lower environmental impact than a decentralised configuration with on-property WWHR installations. However, as we have described centralised systems are much more sensitive to even small changes in inlet wastewater temperature, as well as heat loss. Hence we see that innovation at the centralised system level will be needed in order to better integrate both on property and centralised heat recovery options.

3.3. Dealing with uncertainty

Simplifications are always necessary, and for instance, due to added complexity we have refrained from making a full-scale modelling of the WWTP behaviour (c.f. Arnell et al., 2021; Bergstrand, 2020), and instead focussed on the temperature of WWTP influent, based on literature and in dialogue with our key actors. We have accounted for the range of assumptions made (Appendix B) which we argue stand out as reasonable

[3] Currently there is a major re-construction of the sewage network and the Henriksdal WWTP in Stockholm where water currently leading to another WWTP (Bromma) will be transferred to Henriksdal before 2030. This means that the population served by Henriksdal will in reality reach 1.16 million earlier than 2050. We have not factored in this structural re-configuration of the Stockholm sewer system in our simulations since the ANN would have to be re-trained for this new network.

[4] Scenario survey, 2020-04-29.

[5] municipal property owner, 2021-03-25.

in comparison to other similar studies. Furthermore, scenario planning should not be understood as a method to predict the future, but a way of exploring and preparing for different pathways, and with dynamic interactions among sub-systems of the overall system. Political frameworks are not only influential, but also unpredictable. This does not mean that scenarios should factor in all kinds of political developments. But as pointed out by Carlsen et al. (2010), scenarios need to be relevant from a policy perspective and outline controversies that require political attention, which we have tried to do.

The strength of our approach is the ability to evaluate scenarios quantitatively, but this also depends on the robustness of our ANN model. Our model's predictive reliability for the present system is arguably high, but its ability to simulate the behaviour of a future system is more uncertain. The ANN model is trained based on historical data collected in the sewage system in Stockholm. Hence, it can simulate the present system with high accuracy since the input data like temperature and rainfall are not outside of the range of historical data. However, when it comes to the behavior of the future system (in 2050 in this case), some inputs like the ambient temperature on the coldest day of year or the highest value for rainfall per year could go beyond the range of historical data. As a result, the ANN results will be associated with uncertainties. As all machine learning algorithms, the farther from its training domain it is used, the larger uncertainty in its prediction. Golzar et al. (2020) made substantial sensitivity tests on the model and concluded that stormwater flowrate and building effluent temperature are the most influential input parameters, followed by ambient temperature and the flowrate from buildings. Flowrate from buildings increases proportionally to population, thus pushing the model partly outside the training regime. Sensitivity analysis cannot fully compensate for the uncertainty of making predictions for an altered system which may in reality respond differently. This is the main drawback of using conceptual models for prediction (Abdel-Aal et al., 2015; Saagi et al., 2021) and conclusions should be drawn with these uncertainties in mind. Moreover, it points to the need for increased field measurement and data collection in areas where WWHR has been installed, in order to validate effects downstream and improve temperature prediction at system level. We have treated the entire drainage area to Henriksdal as one unit but recent studies indicate that WWHR in more remote areas within a system may have negligible effect on the WWTP downstream (Walllin and Dalgren, 2021; Arnell et al., 2021). Again, field measurement will be needed to map these urban energy geographies of wastewater more in detail, and render a better understanding of heat loss and transport. On the whole, given the data available, we believe we have struck a reasonable balance in the trade-offs necessary between accuracy and detail, computational cost and manageability of data, and predictive capacity. Our results should be significant enough for policy makers and actors to consider and for others to further elaborate upon.

4. Conclusion and policy implications

The results derived in this study are based on one specific application to a city, as described. Therefore, actual numbers presented on energy saved (GWh- and %- figures) are context specific. However, some general conclusions can be drawn about the dynamic interactions between all the sub-systems in an overall city-wide heating sector as follows, viewing our study of Stockholm as a demonstrator of such interactions and resulting goal conflicts in policy.

Our study shows that there are only modest energy savings (order of 15% of heat demand) to be made at system (city) level even with high diffusion of currently available on-property recovery solutions. However, energy savings at system level will be considerably less where there is already a central facility for heat recovery from wastewater. In Stockholm, the net energy saving was only 7.5% and was accompanied by severe disturbances in existing sewage infrastructure. The wastewater treatment process would be seriously disrupted, with temperatures going critically low a significant amount of days (100+ days for the system conditions of Stockholm) per year. Low sewage temperature at the wastewater treatment plant slows down the nitrogen removal process, leading to severely reduced treatment capacity. From an economic point of view, heat recovery at property level currently has little to offer as property owners can barely justify the local investments from a financial point of view. However we identify both policy and regulatory incentives for on-property actors to invest in these technologies. While it is possible that in more remote areas of the city adoption of local heat recovery could have less negative downstream effects, this will require investigation from time to time and will need more research on the geography of heat flows. On-property heat and water recovery is likely to be much more viable in cities with no or limited district heating, or where central WWHR is not feasible. The relative large scale of conventional centralised systems makes them very sensitive to even the smallest perturbations. Hence, we identify a need for studies that the can address options for retrofitting and innovation development in centralised systems as a way to address some of the existing conflicts with the spread of on property options, as well as seriously exploring decentralised solutions for energy and water in new development areas.

The most striking policy implication of our study is that - somewhat counter-intuitive - policies that force property owners to meet certain energy efficiency standards can have unintended and negative effects on the overall system. As shown here, Swedish energy regulations calling for near-zero energy buildings now seem to push actors to adopt WWHR solutions, which turns out to have negative outcomes on other technical sub-systems in the city, and its surrounding environment. Policy agendas within (and beyond) the European Union encourage (or force) property owners to save energy whenever they can. While this drive towards energy efficiency is absolutely crucial for a sustainable society, policy-makers at local and regional level need to steer and adapt city-level development to avoid conflict goals and sub-optimal outcomes, and chart a way forward within their specific geographic, social and technical conditions. We believe that in the case of heat recovery from wastewater, policy-makers at city-level hold the key to balancing and mitigating goal conflicts and cross-sector effects, once they have been identified. We have here shown that these goal conflicts exist for Stockholm. Although certain results are context specific, this overall insight is applicable in many places since it is common that the housing, waste water treatment and district heating network sub-systems are connected.

Policy at national level guides the overall direction of actors, but national policy also need to be informed by grounded and disaggregated evidence which account for the diversity of actors, and their respective strategies and goals. Here, our study serves as a demonstration of how policy areas like energy, urban housing, water and environment overlap and affect each other in a very real, but not always simple, way. As stressed by Kern et al. (2019), it will be necessary for policy makers to acknowledge that making policy is an ongoing and complex process, where a meta-perspective is needed to constantly reflect upon how policy plays out in a multitude of (sometimes unintended) ways, seldom confined to a single sector.

CRediT authorship contribution statement

David Nilsson: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Timos Karpouzoglou:** Methodology, Supervision, Investigation, Writing – review & editing. **Jörgen Wallin:** Methodology, Investigation, Resources, Supervision, Formal analysis, Validation, Writing – review & editing. **Pär Blomkvist:** Investigation, Writing – review & editing. **Farzin Golzar:** Methodology, Investigation, Formal analysis, Software, Resources, Data curation, Validation, Writing – review & editing. **Viktoria Martin:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary data

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