# A multi-criteria analysis of building level graywater reuse for personal hygiene

Citation for the original published paper (version of record):

Wallin, J., Knutsson, J., Karpouzoglou, T. (2021). A multi-criteria analysis of building level graywater reuse for personal hygiene. Resources, Conservation and Recycling Advances, 12.
http://dx.doi.org/10.1016/j.rcradv.2021.200054

12 (2021) 200054

Contents lists available at ScienceDirect

Resources, Conservation & Recycling Advances

journal homepage: www.sciencedirect.com/journal/Resources-Conservation-and-Recycling-Advances

# A multi-criteria analysis of building level graywater reuse for personal hygiene

Jörgen Wallin [a,*], Jesper Knutsson [b], Timos Karpouzoglou [c]

[a] Royal Institute of Technology (KTH), Department of Energy Technology, Division of Applied Thermodynamics and Refrigeration, Brinellvägen 68, 100 44 Stockholm, Sweden
[b] Chalmers University of technology, Department of Architecture and civil engineering, Chalmersplatsen 4, 412 96 Gothenburg, Sweden
[c] Royal Institute of Technology (KTH), Department History of Science, Technology and Environment, Teknikringen 74b, 100 44 Stockholm, Sweden

A R T I C L E I N F O

*Keywords:*
Graywater recoveryGraywater reuseHeat recovery in graywaterEnergy conservation
Water savingWater reuseRecycled water

A B S T R A C T

Globally an increasing number of people are facing water scarcity. To address the challenge, measures to reduce water demand are investigated in the world. In the present paper, a novel approach to reuse bathroom graywater for shower and bathroom sink hot water is investigated. The investigation focuses on water and energy savings, water treatment, economic benefit and investigates the main actors and institutions that are involved.

The main results are that there is significant potential for water and energy savings with a positive economic benefit. Water savings of domestic hot water up to 91 % and energy savings up to 55 % were observed. The investigated treatment plant produces recycled graywater with a quality close to drinking water standards.

The investigation also presents that the reason for the positive economic benefit will depend on the utility tariffs. Therefore, two locations with different utility rate structures were investigated, Gothenburg, Sweden and Settle, USA. In Gothenburg, the utility cost for energy was the driver of economic benefit and in Seattle it was the water and wastewater cost that was the driver. The return of investment for the system and installation was shown to be 3.7 years in Gothenburg and 2.4 years in Seattle.

## 1. Introduction

Globally an increasing number of people are living under conditions of water scarcity. Due to increasing demand and anticipated climate changes, 4.8–5.7 billion people could be living in areas with potential water scarcity at least one month per year by 2050 A (Burek et al., 2016). Water supplies are already strained in many places and withdrawals are exceeding sustainable levels, thus the potential for mitigation on the supply side is limited.

Because of this, water reuse schemes have been gaining increased attention as an alternative approach to provide water to support human activities (Oteng-Peprah et al., 2018).

Graywater reuse for various applications have been previously demonstrated and there is a significant number of papers describing graywater reuse for non-contact purposes. Commonly encountered applications include irrigation, groundwater recharge, industrial use, recreational use, non-potable urban use and, less commonly, direct potable reuse, (Jimenez and Asano, 2015; Makropoulos and Butler, 2010; Pidou et al., 2008), while the most common in-building reuse is toilet flushing (Ren et al., 2020; Sharifi et al., 2020). There is a lack of both regulatory and public support for potable reuse of recycled graywater which is a significant obstacle to novel in-building reuse applications (Oteng-Peprah et al., 2018; Vuppaladadiyam et al., 2019).

Shower and bathroom sink water use typically represents a significant share of total household water consumption both in terms of volume and energy. The share of household water used in showers and bathroom sinks vary greatly depending on user habits. In the literature values of 29% for shower, bath and sink has been reported (Memon et al., 2007), while the corresponding number for the apartment building in the present study was 42.8% of total water consumption and 63.6% of the total DHW consumption (Knutsson and Knutsson, 2021), The energy consumption associated with water use will correlate closely to the hot water use, in the present case around 60%. By reclaiming the water and its latent heat content the savings in consumption of municipal drinking water and electrical energy for heating the water can be significant.

Graywater from personal hygiene use sources potentially contain a range of contaminants, including microbial pathogens in the form of bacteria and virus, oil and grease, surfactants, dissolved and particulate

---

* Corresponding author.
*E-mail addresses:* jorgen.wallin@energy.kth.se (J. Wallin), jesper.knutsson@chalmers.se (J. Knutsson), timothy.karpouzoglou@abe.kth.se (T. Karpouzoglou).

https://doi.org/10.1016/j.rcradv.2021.200054
Received 5 January 2021; Received in revised form 13 May 2021; Accepted 20 June 2021

**Nomenclature**

| | |
|---|---|
| *TOC* | Total organic carbon |
| *DHW* | Domestic hot water |
| *DOC* | Dissolved organic carbon |
| *EDI* | Electrodeionization |
| *EAOP* | Electrochemical advanced oxidation process |

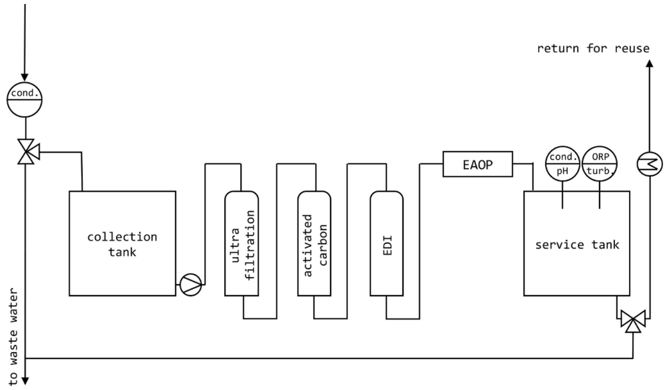


**Fig. 1.**. Schematic of Graywater treatment and recovery system.

organic matter as well as inorganic salts. The main concern for reuse is the risk of pathogen exposure, but the recycled water also needs to fulfil other quality criteria to be acceptable in terms of appearance, odor, health risk and physicochemical properties. Achieving long term cost-effective and adequate treatment of personal hygiene graywater requires the alignment of several factors, including process design, user behavior and social acceptance, as well as a regulatory framework that will facilitate graywater reclamation systems to be installed or retrofitted in buildings (Asano, 2007).

The concept of graywater reclamation has been described previously from technical and economic perspectives (Christova-Boal et al., 1996; Dixon et al., 1999; Li et al., 2009), showing that there is significant water saving potential and economic feasibility under certain conditions.

However, for the specific reuse application which this paper address, where graywater is collected from showers and bathroom sinks and reutilized as hot water for the same micro-component use points (referred to as *personal hygiene* use in this paper), there is a lack of publications, as the existing literature examine this scenario only partially (Chaillou and C. Gérente, 2011; Fountoulakis et al., 2016; Gross et al., 2015; Lu and Leung, 2003; Najm et al., 2017).

In Gothenburg, Sweden a pilot plant for graywater recovery has been installed in a multifamily building situated in the campus of Chalmers University of Technology. The building is a living lab, which provides a great opportunity to investigate this type of installation. The present investigation draws on a multi-criteria analysis of this graywater recovery pilot plant and a specific reuse application. The analysis explores different aspects of graywater reuse by addressing treatment factors, energy savings, water savings, economical parameters, and stakeholder aspects. In addition to social parameters a mapping of the relevant actor groups and institutions is also examined.

The aim of this paper is to provide a multi-criteria analysis with a holistic view on the potential, challenges, and possibilities for onsite graywater reuse systems for personal hygiene purposes.

Previous literature is typically focusing on single criteria (e.g., technology performance or social acceptance). Instead, we have identified multiple criteria that can determine the feasibility for implementation of these types of systems. Our methodology therefore follows a systematic process of evaluation of these multiple criteria. The objective with the present paper is to develop broader insights into the specialized field of reused graywater for personal hygiene purposes and contribute new insights based on a multi-criteria analysis.

## 2. Methodology

The investigation of the graywater recovery system is a multi-criteria investigation. There are three main criteria we have investigated which are 1) greywater treatment performance analysis (including environmental performance), 2) energy and water savings and 3) social actors influencing the system. We have used different methods for the different investigated areas. How the different criteria have been investigated is described in more detail in the following sections.

### 2.1. *Performance analysis of graywater treatment*

The performance analysis included several aspects of the treatment process; characterization of untreated graywater, treated graywater quality, use of process chemicals and maintenance materials consumption.

To gather data for performance analysis of the graywater treatment samples of both untreated and treated graywater were over a period of 4 weeks collected in bottles washed in a laboratory dishwasher using deionized rinse water. Samples were collected during normal operation of the system from the collection tank and service tank respectively (see Fig. 1), while graywater was collected and treated, but not reused due to regulations that restrict reuse of graywater without consent from the tenants.

Analysis of samples were performed in a laboratory at Chalmers university of technology. Determination of DOC and TOC were done using a SHIMADZU TOC-$V_{CPH}$ analyzer following standard analytical method SS-EN 1484. Anionic and cationic species were determined using a Dionex ICS-900 system, following standard analytical method ISO10304-1. Turbidity was measured using a TurB 430 IR meter. Conductivity and pH and were determined using calibrated laboratory instruments. *Escherichia coli* and *Legionella Pneumophila* was determined by IDEXX reagent kits with subsequent incubation and plate counting giving the result as the most probable number (MPN).

Odor was determined by three test subjects in a blind test where three samples of tap water and three samples of treated graywater were placed in glass beakers at room temperature. The test subjects were then told that one or several beakers containes something other than tap water and were asked to identify which beaker or beakers by smell.

### 2.2. *Performance analysis of energy and water saving*

The graywater treatment plant was set up in such a way that the recovered graywater can be recirculated to the building in the domestic hot water (DHW) system, using a pump, after being heated to around 45°C. The recirculated water is then mixed to the desired temperature in the facets of the apartments.

To evaluate the energy and water consumption performance of the graywater recovery system measurements of temperatures, electric power and flow rate was performed.

Two test occasions were arranged, where test 1 consisted of 8 test subjects using the shower under one day. The aggregated shower time was approximately 25 minutes. Test 2 was arranged to evaluate the energy performance of the system in which water was treated and reused with one shower continuously flowing at full flow for approximately 2 hours. Both tests are described in detail in the results section below. Temperatures of supplied DHW, untreated graywater, treated graywater before entering the storage tank and treated graywater before entering the DHW electrical boiler was measured and logged with a ten-minute interval. Electric power to the DHW electric boiler, the total electric power to the treatment plant and electric power to the DHW pump was measured and logged with a one-minute interval using a logger. Flow of DHW was read and noted at the start and finish of every shower event.

### *2.3. Social actors influencing the system*

We have conducted a stakeholder mapping which allowed us to identify and describe some of the most influential actors of this graywater reuse project. Furthermore, using additional qualitative data from interviews, a workshop and a social survey conducted with residents we gained insights into a range of considerations which are discussed by relevant actors involved in the process of implementing graywater reuse for personal hygiene purposes.

## 3. Case study

### *3.1. Building and system description*

The case study was performed in HSB Living Lab, a joint research venture in the residential building sector, Gothenburg, Sweden. The built-up area of the facility is 400 $m^2$ and consists of 29 apartments with 32 tenants at the time of conducting this study. The HSB living lab has been described in further detail elsewhere (Hagy and Balay, 2014; Knutsson and Marx, 2016).

### *3.2. Graywater treatment and recovery system description*

In the current installation setup, graywater is collected from bathroom sinks and showers, in six shared bathrooms (of a total of eight shared bathrooms in the building). To protect the system from highly contaminated flows, the incoming untreated graywater is screened using a conductivity sensor. If the conductivity value exceeds a set limit, a pneumatic valve opens and the graywater is rejected to the municipal wastewater for a set period of time. If the conductivity is below the set limit, water is diverted to the collection tank, which is a feed buffer to the treatment system.

The graywater treatment and recovery system consist of several components each commercially available. In Fig. 1, a schematic of the system layout is presented.

The treatment system consists of five process components: coarse filtration, ultra-filtration (Aqualine GAUF 16, ESLI, Turkey), granulated active carbon (GAC) filter, electro deionization (EDI, CapDI Module C-5, Votea Ltd., Netherlands) unit and an electrochemical advanced oxidation process (EAOP, Condiapure®, Condias GmbH, Germany) which combine UV and hydroxide radicals disinfection. The coarse filtration stage is intended to catch large debris from the graywater and consist of a bag filter with a 1 μm nominal cut-off. The ultrafiltration stage nominally removes solids larger than the cut-off size, which is 0.01μm, which is sufficient to remove all bacteria and some viruses.

Treated water is collected in a service tank, from which treated water is supplied back to users as hot water on-demand. The treatment capacity of the system was determined to be 3.8 liters per minute and a tankless boiler was used for heating the water to the desired temperature.

### *3.3. Relevant actors for graywater re-use at HSB living lab*

Three levels of organization are of interest in understanding the actors that are relevant to graywater reuse at HSB Living Lab:

1) ***Building level:*** The property owner (HSB); The water technology development company (Graytec AB); The scientists that are maintaining the research infrastructure (namely linked to Chalmers University); the residents of HSB Living Lab (mainly students of Chalmers University).
2) ***City level:*** The city authority which also has the mandate for water and energy (Gothenburg Municipality and Gothenburg Energy). Gothenburg environmental department (Gothenburg municipal environmental administration), the key contact authority that had to approve the installation of the pilot plant.
3) ***National level:*** The National Board of Housing, Building and Planning (Boverket); the Swedish Institute for Standards (S.I.S); the Swedish Environmental Protection Agency (Naturvårdsverket); Sweden's Innovation Agency (Vinnova). The first three are important as important regulators of building norms and standards while the latter agency had a role as a co-founder of the plant.

In Section 4.4 we look at some of these actors and the way they have supported the development of the HSB Living Lab.

### *3.4. The performance indicators*

Performance indicators were developed for the different investigated areas to evaluate, and in the future be able to compare different system configurations. The indicators are described under the headings of relevant categories.

#### *3.4.1. Environmental indicators*

The environmental indicators were selected to include waste streams that were generated during the operation of the treatment system, as well as production chemicals and parts routinely replaced for maintenance of the system. The waste streams consist of reject and backwash water, mixed with chemical agents that facilitate cleaning and regeneration of system components and treatment stages.

The graywater treatment system described in the present work, consists of the following treatment stages: coarse filter (1), ultrafilter (2), active carbon filter (3), EDI (4) and EAOP (5). The operation of the system requires the use of chemicals for maintenance cleaning and regeneration of the various stages, as outlined in Table 1.

In total there are three waste flows (EDI reject, UF backwash and global system disinfection), three chemicals (NaOH, citric acid and hypochlorite) and three components that needs to be replaced (coarse filter bag, UF filter cartridges and active carbon filter mass). Together these aspects of the system operation comprise the environmental impact of the treatment system which, together with system components, can serve as input for complete LCA to be performed in future work.

#### *3.4.2. Graywater treatment indicators*

It is important that the reclaimed and treated water is of high enough quality so that reuse does not pose elevated health risks to the users, including both microbial and physicochemical risks. Furthermore, to improve user acceptance the treated water must be aesthetically appealing, i.e., colorless, odorless, and clear (as in non-turbid).

Currently there are no quality criteria for reclaimed hot water intended for personal hygiene purposes. Thus, we chose to utilize the Swedish national drinking water quality criteria to derive performance indicators. Conforming to existing water quality standards also facilitated the process of attaining the necessary permits from local authorities to conduct the study. In the future it is expected that water quality standards specifically for various reuse scenarios will be established. As placeholder quality indicators the parameters and levels outlined in Table 2 are proposed.

In the proposed performance indicators total organic carbon (TOC) is included as a possible substitution parameter for chemical oxygen demand (COD), which is also proposed in the Swedish drinking water standard. This was mainly proposed since legacy methods to determine COD typically used environmentally toxic compounds such as mercury or dichromate. Novel methods for DOC determination overcome most of these problems, but TOC is still proposed as an alternative quality control parameter for the sake of completeness.

The standard instructs that TOC to be measured alongside COD for an extended period of time to establish a correlation which can be used to calculate a guideline value for TOC. Measurements in graywater has

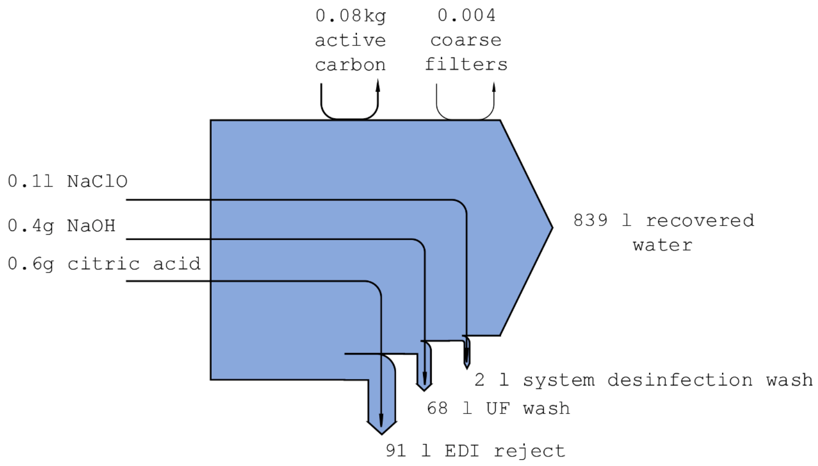


**Fig. 2.** Graphical representation of environmental impact indicators and their values expressed per $m^3$ of treated water.

indicated this relationship to be TOC = 0.247 COD ($r^2 = 0.724$, $n=12$), which is why we propose 1 mg/l TOC as a possible substitution quality parameter. More data points may yield a higher coefficient of correlation.

### 3.4.3. Energy and water saving indicators

The performance of the graywater recovery system in terms of energy is valued using kWh/$m^3$ of produced domestic hot water (DHW) as the main key performance indicator. The indicator is used to describe both system performance including and excluding the auxiliary equipment demand. The system performance is also indicated by comparing the energy demand for produced DHW with how much energy that should have been used if no graywater recovery was installed. Also, the energy used for auxiliary equipment as the treatment plant and the DHW pump is analyzed using energy demand per m3 of treated graywater (treatment plant) or pumped DHW (DHW pump).

Water performance is described by comparing how much of the total DHW is reclaimed graywater.

### 3.4.4. Economic indicators

The economic benefits of the installed and investigated system is analyzed based on a consultancy report regarding an installation serving 80 people (Karlsson, 2020) and the energy performance of the investigated system in the present report. The economic performance is calculated using data from the mentioned investigations and presented as cost and cost saving per person. To widen the scope of the economic analysis, the calculations are done for two locations with differing prerequisites regarding cost of energy and water. The locations chosen were Gothenburg, Sweden, where the pilot plant was installed and Seattle Washington, USA. The location of Seattle was chosen due to the fact that Seattle has one of the highest combined water and wastewater costs in the USA (MWRA Advisory Board, 2018).

As the economic indicator, savings per person and year was chosen. Also, system pay-off time is used as an indicator of investment profitability.

### 3.4.5. Social indicators

Social acceptance of the reused water is a critical factor shaping success of water reuse projects. Studies looking at social acceptance of recycled water provide useful background about psychological factors as determinants of success for water reuse. Studies have found for instance that even if the recycled water is considered clean, by means of testing against scientific water quality standards, the fact that it is often linked to a psychological perception of disgust, or the so-called “yuck factor”, that means that it may be ultimately considered unacceptable regardless of the level of treatment (Ching, 2010; Christen, 2005; Fielding et al., 2019). Water authorities and public health organizations can have a central role in terms of shifting social acceptance from negative to positive through initiatives such as public outreach campaigns, promoting better awareness of benefits and risks of recycled water (namely health risks).

In Section 4.4 we also discuss some of the results of an online survey conducted with residents of HSB Living Lab (in total 7 residents participated in the survey). Using a 10-point Likert-type response scale, HSB residents ranked their level of agreement to statements about graywater reuse (1 Strongly Disagree – 10 Strongly Agree). Residents could also provide independent comments about their experiences with using recycled graywater for personal hygiene purposes.

## 4. Results and discussion

Presentation of results and discussions related to the different areas of investigation are split into different categories and presented under relevant heading.

### 4.1. Environmental performance

Based on these process settings the system volume recovery was determined to 83.9%. Based on intermittent system operation over the course of several months and a total of 16 $m^3$ treated greywater the EDI reject volume was determined to 9.1% using 0.6 g/$m^3$ citric acid, UF backwash volume was 6.8% using 0.4 g/$m^3$ NaOH and the global disinfection volume was 0.2% using 0.1 l/$m^3$ of 10% NaClO solution. Furthermore, 0.08 kg/$m^3$ granulated active carbon and 0.004 $m^{-3}$ coarse filter bags were consumed, see Fig. 2.

The UF waste flow consists of treated graywater together with contaminations from the UF membrane surface that is washed off and amounts to 68 liters per $m^3$. The EDI reject consists of a concentrate of the partially treated graywater as charged species are flushed from the electrode cells in the EDI unit. The EDI reject volume comprises approximately 9.1% of the treated graywater volume, and the physicochemical properties of the reject is shown in Table 3. The fact that average TOC values for the EDI reject was 9.73 mg/l while COD was 0 mg/l is attributed to residual citric acid in the effluent, which is detected by the TOC analysis but not with the COD analysis.

The results for environmental indicators presented here should primarily be viewed as benchmark values as there are presently no relevant comparisons to be made. However, it can be expected that further process development will reduce the environmental impact by optimization of process operation conditions.

No comparable treatment systems were found in the literature, but (Opher and Friedler, 2016) described a decentralized system for

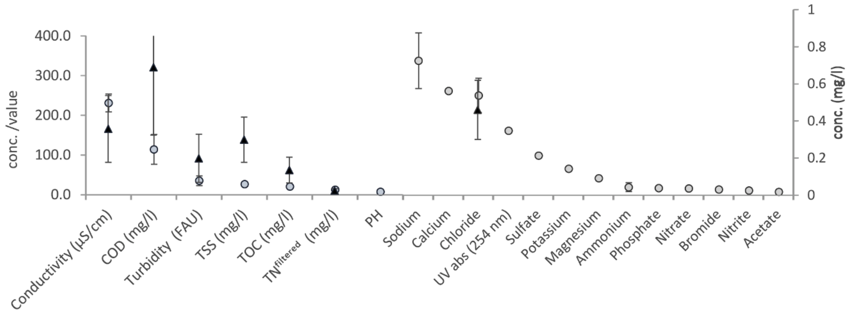


**Fig. 3.** Graph showing values for selected parameters for untreated graywater from this study (gray circles, n=7) and values found in the literature (Eriksson et al., 2002) (black triangles). Bars show standard deviation of the population.

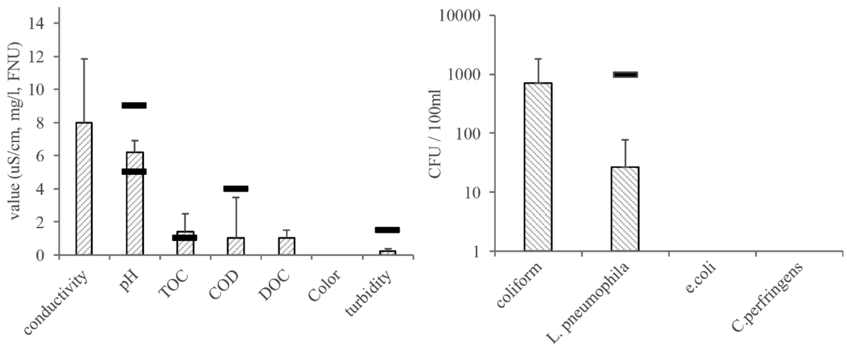


**Fig. 4.** Graphs showing average values for water quality key performance parameters for physicochemical parameters (left) and microbial parameters (right). The error bars show the standard deviation of the population (n=28) and the black horizontal bars show upper (and for pH also lower) control limits as described above. The control limits for conductivity and color are not shown since they are higher than the maximum scale (8000 µS/cm and 30 mg Pt/l respectively).

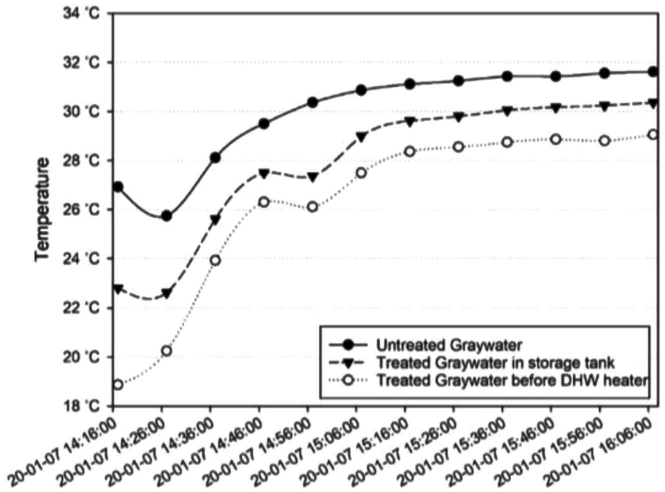


**Fig. 5.** – Temperatures at different locations in the treatment process during test 2.

graywater treatment and reuse, using a Rotating Biological Contactor (RBC) which consumed 14 g $m^{-3}$ chlorine during operation, but with different effluent quality demand a comparison is asymmetrical. Future work should include a complete LCIA where the complete water supply and treatment system is considered.

### *4.2. Graywater treatment*

Samples of the untreated graywater were extracted from the collection tank and characterized for an array of physico-chemical parameters. The results are shown in Fig. 3. Graph showing values for selected parameters for untreated graywater from this study (gray circles, n=7) and values found in the literature (Eriksson et al., 2002) (black triangles). Bars show standard deviation of the population..

Generally, the water quality of the treated graywater exceeds the drinking water criteria. Average results over the course of several weeks of operation for key performance parameters (*n=28*) are summarized in Fig. 4. Graphs showing average values for water quality key performance parameters for physicochemical parameters (left) and microbial parameters (right). The error bars show the standard deviation of the population (n=28) and the black horizontal bars show upper (and for pH also lower) control limits as described above. The control limits for conductivity and color are not shown since they are higher than the maximum scale (8000 µS/cm and 30 mg Pt/l respectively).

The notable exceptions are TOC and coliform bacteria. For TOC we see rather consistent results (1.38±1.10 mg/l) around the derived guideline value of 1.0 mg/l. For microbial parameters we observed large standard deviations which is due to a relatively low number of samples and analyses (n=3, 5 and 7 for *C.perfringens, L.pneumophila* and *E.coli/coliforms* respectively). It can also not be ruled out that the sampling procedure itself could have compromised the samples on some occasions, but we chose to disclose the results here for completeness. Since microbial safety is central to the reuse scenario investigated in the present paper, it is emphasized that more thorough and especially long-term investigations of microbiological quality are needed in future work before the proposed system is implemented widely.

Furthermore, the treated water was determined to be inseparable from samples of drinking water in terms of odor as test subjects were unable to beat the chance in picking out the beakers containing treated graywater (*p=0.468*).

The lack of water quality regulation for the type of non-potable reuse discussed here is a possible drawback, as both process setup and operation could benefit and operate more effectively if requirements were less stringent.

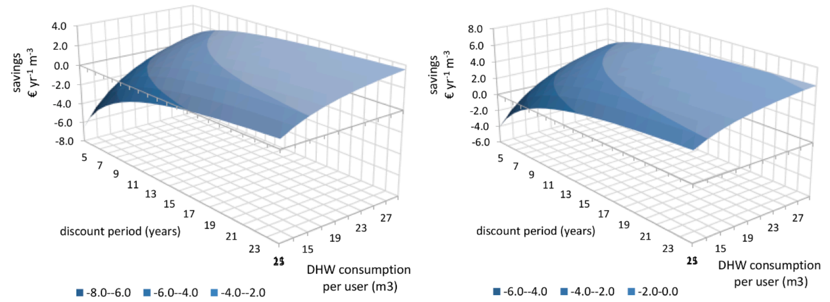


**Fig. 6.** - Water savings per $m^3$ and year as a function of depreciation period and annual DWH consumption per person for Gothenburg (left panel) and Seattle (right panel).

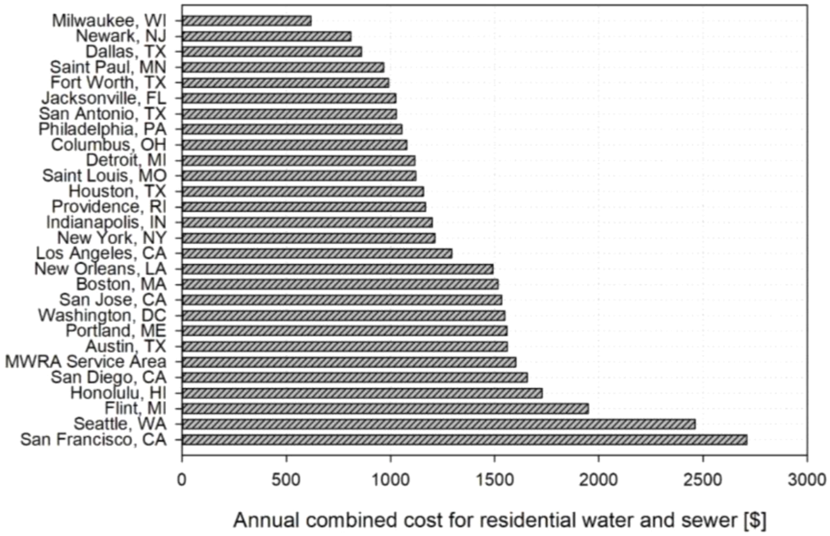


**Fig. 7.** – Annual combined cost for residential water and sewer 2018 (MWRA Advisory Board, 2018).

### 4.3. *Energy and water saving*

The tests show that there is significant potential in recovering graywater, between 82 to 91% of the total water demand of the showers was met by reclaimed water. The tests also show that the reduction of energy demand for DHW was between 50 to 55%, compared to a system with no heat recovery. For comparison, a traditional passive wastewater heat recovery system where the outgoing wastewater is heat exchanged with the incoming cold water to the building would recover 9-27 % (Zaloum et al., 2007). The conclusion from such a comparison is that the heat recovery ratio for the present system is significantly higher and less sensitive to the draw profile.

Table 4. Table showing the results for the two tests conducted using the pilot plant for graywater reuse in HSB Living Lab, Gothenburg. presents the results from the two individual test periods.

From the results it is seen that the system performed better in test 2 in comparison to test 1; 16.17 kWh/$m^3$ versus 18.98 kWh/$m^3$ for reheating the treated graywater before reuse. This is likely because of the continuous operation of the system in test 2 with one long (110 minutes) shower session, while test 1 consisted of 8 short shower sessions (effectively on average 3.7 minutes) separated by up to two hours.

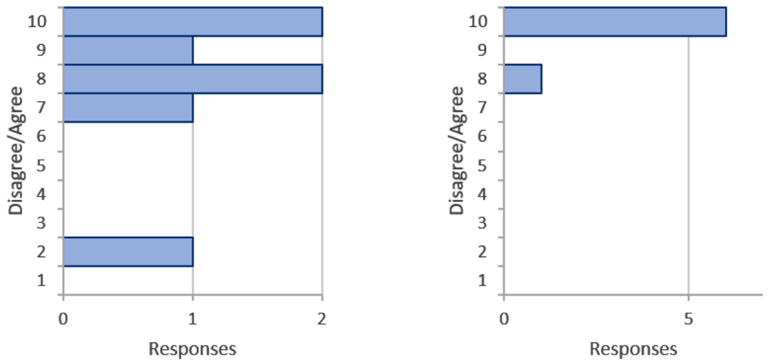
The effect of this can be observed in Fig. 5, where the temperatures in different stages of the treatment process during test period 2 is presented.

During the start-up of the test, a large difference was observed between the temperature of the untreated graywater and the temperature of the treated graywater before the DHW electrical boiler. The reason for this significant difference can be attributed to heat losses in the system. When there is no DHW demand, the treated graywater is stored in a service tank. In the pilot plant, there is no insulation of pipes and storage tanks, leading to heat loss to the surroundings. When there is a demand for DHW, the temperature drop of the graywater from untreated to treated before the DHW electrical boiler is lower, this is because the graywater is stored for a shorter period of time in the system. Reducing heat losses in the treatment plant is important to achieve maximum system energy performance.

Looking at active wastewater heat recovery systems for graywater using a heat pump and thermal storage, (Ni et al., 2012) created a theoretical model to investigate a heat pump assisted recovery system for a single-family house. The results from that investigation indicates that 33.9% of the heat in the graywater can be recovered using such a system setup for a building in New York City. The authors also concluded that the performance will be dependent on the climate zone, and therefore investigated 14 other cities with results varying between 17 and 57.9%. Wallin and Claesson, (Wallin and Claesson, 2013) concluded that an in-line wastewater heat exchanger boosted by a heat pump recovered between 32-50% of the available heat in the wastewater.

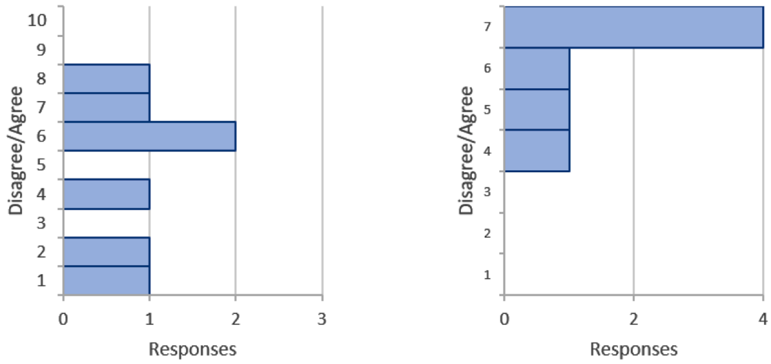
In the present investigation, the energy demand for auxiliary equipment was measured in the second test period, the auxiliary equipment accounts for about 10% of the total energy demand for DHW production. For the first test, no measurements of auxiliary energy were performed.

When analyzing data from the two test periods, it was noted that it will be important to consider the energy performance of the auxiliary equipment when designing the system. Otherwise there is a risk that a



I am positive about the idea of reusing water locally in our building

I am positive about the idea of reusing greywater for toilet flushing



I am positive about the idea of reusing greywater in the shower

I'm willing to change my habits in order to facilitate the recycling of gray water

**Fig. 8.** – Attitudes towards graywater reuse amongst residents of HSB Living Lab.

large portion of the energy saving potential is erased by the energy demand of the auxiliary systems. This is largely due to the fact that there is an intermittent demand of DHW and the auxiliary equipment operation needs to be adapted to this intermittent operation. In practice, this means that the auxiliary equipment only is running when there is a demand for DHW. In the pilot system, the system design requires significant pumping power to distribute the reclaimed DHW in the building.

In most buildings in Sweden there is a requirement of DHW circulation to satisfy the demand of maximum time to supply hot water to the services. In such a case, the continuous running time of a DHW pump could significantly decrease, or completely erase, the energy saving potential of the graywater recovery system.

#### 4.3.1. *Economic aspects*

Costs and savings for the installation can be divided into categories. On the cost side, the identified categories are:

- Treatment plant components cost
- Installation costs
- Operation cost
- Maintenance cost

On the savings side, the identified savings are:

- Water savings (consists of water and wastewater cost)
- DHW energy savings
- DHW power savings

To determine the potential savings from reusing graywater and recovering the latent heat and illustrate the impact of different water and energy tariffs we calculate the cost for DHW for two cases. In Gothenburg, Sweden, the cost of water and water treatment is low compared to many other regions in the world. For 1 $m^3$ of water (supply and treatment) the cost amounts to approximately 1.5 € (Göteborgs Stad, 2020). In Seattle, USA the cost for 1 $m^3$ of water (supply and treatment) is 7.5 € (City of Seattle, 2020).

The cost of energy for heating 1 $m^3$ DHW is on average about 1.7 € using district heating in Gothenburg and 0.8 € in Seattle using natural gas. However, this is only considering the direct cost of energy. Considering the fixed fees and feed in tariffs to get the full cost of the energy used, the cost for heating DHW per 1 $m^3$ in Gothenburg amounts to 7.2 € (Göteborg Energi AB, 2020) compared to 1.8 € in Seattle (Puget Sound Energy, 2020). This means that the total cost for water supply, wastewater treatment and DHW heating of 1 $m^3$ DHW accumulates to 8.7 € in Gothenburg and 9.3 € in Seattle.

An installation of a graywater reuse system in an apartment building for 80 tenant occupancy the extraordinary installation, operation, and maintenance costs (cost that exceed those of a standard installation with no source separation of graywater and no treatment system) installation in a new building development is presented in Table 5. Extraordinary costs for a graywater reuse installation, operation and maintenance designed for 80 people. It should be noted that the cost for the graywater treatment system is an estimate, which is not based on a commercially available product.

Using the costs from Table 5 the annualized cost of 10-year depreciation is 4 100 € and including the operation and maintenance cost the amount will be 6 400 € $yr^{-1}$.

In Sweden every person uses about 18-47 $m^3$ with an average of 30 $m^3$ of DHW per year (Energimyndigheten (Swedish Energy Agency), 2012) of which approximately 60% is used for shower and bathroom sink (unpublished data of the authors), which corresponds to an annual

**Table 6**
presents detailed data from the economical calculations.

| Appartment building with 80 pax | Gothenburg | Seattle |
|---|---|---|
| **Installation cost** | | |
| Drainpipes | 1 500 € | 1 500 € |
| Water heater | 5 000 € | 5 000 € |
| Treatment plant | 35 000 € | 35 000 € |
| Sum costs | 41 500 € | 41 500 € |
| Maintanence cost per year | 2 300 € | 2 300 € |
| Cost per person | 548 € | 548 € |
| **Cost for utility** | | |
| Water cost per m3 | 1,6 € | 7,5 € |
| Energy cost distric heating per kWh | 0,031 € | 0,033 € |
| Energy for heating 1 m3 to 55 gC | 55,9 kWh | 55,9 kWh |
| Energy Cost of heating per m3 | 1,7 € | 1,8 € |
| Total savings per m3 | 3,3 € | 9,4 € |
| DHW Water cost per person (30m3/year) | 48,0 € | 226,5 € |
| DHW Energy cost per person (30m3/year) | 52,0 € | 54,6 € |
| **DHW heating power demand** | | |
| Max DHW flow rate (aggreation affected) | 0,58 l/s | 0,58 l/s |
| Max DHW power 80 pax | 116,9 kW | 116,9 kW |
| Decrese of power demand 55 % recovery | 64,3 kW | 64,3 kW |
| New Installed power demand DH | 52,6 kW | 52,6 kW |
| Cost of power before | 9 991,3 € | - € |
| Cost of power after | 4 845,0 € | - € |
| Savings | 5 146,3 € | - € |
| Savings per person | 64,3 € | - € |
| **Cost for graywater recovery plant (yearly)** | | |
| Cost for Electricity for treatment per person | 2,0 € | 1,4 € |
| Cost for Electricity aux. equipment) per person | 3,0 € | 29,1 € |
| Cost for heating DHW | 28,1 € | 29,6 € |
| **Sum of cost savings (yearly)** | | |
| Savings of water 91 % savings | 43,7 € | 206,1 € |
| Savings of energy 55 % savings | 28,6 € | 30,1 € |
| Savings of power | 64,3 € | - € |
| Sum annual savings per person | 136,6 € | 236,1 € |
| Payback | 4,0 Years | 2,4 Years |

**Table 1**
Table outlining process settings and waste flows from the graywater treatment system.

| Stage | Operation/process | Agent |
|---|---|---|
| Coarse filter | Replacement | Filter bag |
| Ultrafilter | Backwash<br>replacement | NaOH<br>UF cartridges |
| Active carbon filter | Replacement | Active carbon |
| EDI | Regeneration | Citric acid |
| EAOP | None | - |
| Global | Disinfection | Hypochlorite |

use of 11-28 m$^3$ DHW (on average 18 m$^3$).

This calculates to a cost of recycled DHW of 6.23-10.65 € and 4.34-8.76 € per m$^3$ for Gothenburg and Seattle respectively including operation and maintenance, assuming 55% reduction in energy for heating, 91% reduction in municipal water consumption, as reported above in this work, and 10 year depreciation period of investment. See supplementary material for details on the calculations.

A sensitivity analysis shows that for the scenario outlined here that graywater reuse is cost reducing for certain depreciation periods and annual DWH consumption averages. The higher DHW consumption the shorter depreciation period is required for the reuse scheme to be cost reducing, see Fig. 6 for a graphical illustration of how savings per m$^3$ and year depends on depreciation period and annual DWH consumption per person. Details on the calculations for the sensitivity analysis can be found in the supplementary material.

The graphs in Fig. 6 also illustrate the difference between the two cases of Gothenburg and Seattle and the impact on savings potential. Due to the much higher cost of municipal water in Seattle and the 91% reduction in municipal water use, graywater reuse is profitable in a greater range of scenarios for this case. The payback for the installation

**Table 2**
Water quality indicators for non-potable graywater personal hygiene reuse.

| Indicator parameter | Permissible level | Criteria source |
|---|---|---|
| ***Microbial indicators*** | | |
| Ecoli | 0 cfu/l | [a] (literal wording in standard is "detected") |
| Legionella | 1000 cfu/l | EWGLI |
| Coliform | 100 cfu/l | [a] |
| ***Physical indicators*** | | |
| Turbidity | 1.5 FNU | [a] |
| Color | 30 mg Pt/l | [a] |
| ***Chemical indicators*** | | |
| pH | 5-8 | Process control |
| Conductivity | 2500 uS/cm | [a] |
| COD-Mn | 4 mg/l | [a] |
| TOC | 1 mg/l | Possible substitution parameter for COD-Mn |
| Odor | None | [a] |

[a] Swedish drinking water quality directive (SLVFS 2001:30)

**Table 3**
Average values for physicochemical parameters of EDI reject water (n=3).

| Parameter (unit) | Value |
|---|---|
| pH | 6.95 |
| Conductivity (µS) | 1266 |
| Turbidity (NTU) | 2.3 |
| COD (mg/l) | 0 |
| TSS (mg/l) | 8.3 |
| TOC (mg/l) | 9.73 |
| DOC (mg/l) | 9.41 |

**Table 4**
Table showing the results for the two tests conducted using the pilot plant for graywater reuse in HSB Living Lab, Gothenburg.

| | Unit | Test 1 | Test 2 |
|---|---|---|---|
| Hot water consumption [l] | l | 134 | 545 |
| Cold water consumption [l] | l | 29 | 55 |
| Time [s] | s | 21540 | 6600 |
| DHW energy demand with graywater recovery (only water heating) | kWh | 2.53 | 8.81 |
| DHW energy demand with graywater recovery (including auxiliary systems) | kWh | - | 9.75 |
| DHW energy demand without graywater recovery | kWh | 5.02 | 19.45 |
| Specific energy demand DHW production with graywater recovery (only water heating) | kWh/$m^3$ | 18.98 | 16.17 |
| Specific energy demand DHW production with graywater recovery (including auxiliary systems) | kWh/$m^3$ | - | 17.89 |
| Energy to DHW production without graywater recovery | kWh/$m^3$ | 37.60 | 35.69 |
| Energy to Treatment plant | kWh/$m^3$ | - | 0.66 |
| Energy to DHW pump | kWh/$m^3$ | - | 1.00 |
| DHW heating demand reduction | % | 50 | 55 |
| Recovered graywater | % | 82 | 91 |

**Table 5**
Extraordinary costs for a graywater reuse installation, operation and maintenance designed for 80 people. (Karlsson, 2020).

| Component | Cost |
|---|---|
| Drainpipes | 1 500 € |
| Water heater | 5 000 € |
| Treatment system | 35 000 € |
| Operation and maintenance, annual | 2 300 € |

with these numbers will be 4.0 years in Gothenburg and 2.4 years in Seattle if the cost of installation and the amount of DHW used would be the same in both locations. A more extensive presentation of the economical calculations can be found in Appendix 1.

Looking at the cost for water service (water and waste) in different major cities of the USA, it is apparent that the cost varies quite a lot. In the following graph, the combined cost for water and wastewater for major cities in the USA is presented.

The average cost for water and sewer was about 1358 USD in 2018, about 45% lower than the cost for Seattle. Considering this, if the rate for water and sewer was at the average price presented in the graph above was valid in Seattle, the payback time would increase from 2.4 to 4.0 years, i.e. a significant increase of the payback time.

It is worth noting that the cost per person used in the above calculations is not valid for very small or very large installations. But as a reference for a mid-sized multi-family building with around 40-120 people these numbers can be used as a cost estimate.

### 4.4. *Discussion of social aspects*

HSB Living Lab operates as a form of protective space for the early development phase of a new water innovation, graywater recovery for personal hygiene purposes (Mignon and Bergek, 2016). In that sense the living lab offers a valuable space at this point given that it shields graywater recovery as an innovation from certain kinds of market pressures and incumbent socio-technical regimes for water and energy (Smith and Raven, 2012).

A survey conducted with student residents at HSB Living Lab shows that attitudes towards the reuse of graywater in general are positive. An important motivation for the residents is related to a sense of contributing to more sustainable practices related to water consumption. For instance, one resident explained “If we are to have a sustainable existence in society, we must begin to act”, highlighting a deeper societal motivation underpinning residents’ attitudes towards graywater reuse.

In addition, specific uses that are more related to personal hygiene also ranked positively, except for the use of graywater for showering where we see some more variety in the responses (Fig. 8). The reasons for this are not entirely obvious to the authors yet but as one resident explained “You are thinking maybe a bit extra on what the water contains - what if I swallow it? But I understand that the water is clean!”. This statement alludes a sense of novelty associated with showering with graywater which in turn can create a sense of uneasiness with graywater reuse for certain personal hygiene purposes.

This protective space has been made possible through strong interaction and cooperation of a relatively small group of actors at this point and mainly at the property level. That is the property owner (HSB), the technology developer (Graytec AB) and the research environment (Chalmers University) have formed a network that has been able to track and assess performance across technical and social parameters. This network has also been catalytic in fostering a certain level of engagement with the innovation by more established socio-technical regime actors at the national level. For instance, S.I.S has actively participated in the project to develop appropriate standards for graywater reuse. Other forms of dialogue are in place with Boverket to understand how building regulations and wider developments in the housing market can affect the type of technology studied here for graywater reuse. Further dialogue with Livsmedelsverket (Swedish Food agency) that deals with food safety (including drinking water) and Folkhälsomyndigheten (the Public health agency of Sweden) are also being carried out.

While there are certain benefits with graywater recovery indicated by our analysis (namely associated with water and energy savings) what is going to be important moving forward is to understand how to move the innovation out of the protective space and into the main market.

We identify both opportunities and risks associated with a larger uptake of graywater recovery that can be identified across property, city and national level levels of the socio-technical system. Hence innovation strategies need to focus across all these levels to initiate a wider diffusion process.

At the property level two types of actors that are influential are the property owners and residents that are mostly directly affected by graywater recovery. Property owners need to trust the technology enough to make larger investments into graywater recovery. That means that technical operation and maintenance needs to be optimized over time so that the costs do not exceed the investment capital. At the same time as our survey also suggests dealing with some possible mistrust by residents of the reused water is going to be another important factor. Generally, previous studies suggest that dealing with negative perceptions of reused water is to be expected in the early phases but can be resolved over time through different awareness campaigns that focus on improving public understanding of the reused water.

At the city level the most critical actors will be the water and energy utility company associated with the city of Gothenburg. The municipality is moving towards a more resource-efficient water supply system in different ways. There is for instance a strong interest in blue-green solutions that can reduce the volume of stormwater that reaches the treatment plants through managing stormwater more locally at the property level. Therefore, at the moment, there is a certain degree of openness associated with testing new water innovations that can reduce dependence on freshwater but also contribute to achieving ambitious environmental regulations. As narrated by one of the municipal officers of Gothenburg working with the Sewerage and Water department, “recirculation within the property should be encouraged since that means that less water is returned to the sewage treatment plant which in turn means less emissions of toxic substances”.

At the national level we see perhaps the most important area of work in terms of creating a clear regulatory framework for the reuse of graywater. For instance, although standards for drinking water quality are clearly defined through Swedish water regulation (Livsmedelsverket, 2017), no regulation specifies the desired quality of reclaimed water used for personal hygiene purposes. As part of a stakeholder workshop, we conducted on graywater recovery for personal hygiene purposes, technology designers in particular voiced their concerns about the lack of a clear regulatory framework for water reuse for personal hygiene purposes. As one technology developer stated, “the design of tap water systems in properties today is locked to drinking water quality and maintaining the warm water at 50°C to avoid the spread of legionella bacteria in the pipes and water outlets”. On the other hand. “making adjustments to functional requirements (e.g., level requirements for legionella instead of temperature requirements) and differentiating the quality standards of water depending on the type of use would open up new solutions”. In the current context therefore the established drinking water quality guidelines are used as a reference in the HSB Living Lab and that can prohibit a faster acceleration of the innovation since confusing or inappropriate standards can create barriers for investment in the technology by the property owners.

Currently, Graytec AB, the technology developer, is in dialogue with the The National Board of Housing, Building and Planning (Boverket) and the Swedish Institute for Standards (S.I.S) in order to identify a mechanism for establishing clear regulatory norms for graywater recovery. What is seen by Graytec as a clear priority is related to developing the right incentives and knowledge within relevant agencies about graywater reuse for personal hygiene purposes. This is an area where there is a lack of knowledge and sources of guidance and that this is a challenge not only confined to the Swedish context alone but as mentioned it is a global challenge when it comes to water recirculation.

Moving forward with this process will be important for establishing confidence in the innovation across the users, the market actors (such as the property owners) and the public agencies (namely the water and energy companies). It is important to emphasize here also the role of the technology developers, such as Graytec AB as key actors in this early phase in terms of not only building the systems but also developing the necessary fora for actors positioned differently in the socio-technical system to enter a dialogue.

## 5. Conclusions

From a technical point of view, it is straightforward to treat graywater from wash basins and showers to reach potable water quality or better. The challenge lies in ensuring long time safety of water quality as one of the most significant threats to end user health are microbial pathogens, such as *L.pneumophila*, as this and other bacteria can multiply and grow in the clean water part of the reuse system. It is therefore of utmost importance that the research community establish procedures or measures that reliably inhibit pathogen growth post treatment. In the present work we show that good microbial quality can be achieved, but more thorough and long-term investigations are needed to validate our results. We also identify a need to develop appropriate standards that differentiate across different types of water uses. Currently, the closest framework applicable is the one which relates to drinking water quality use. However, the drinking water quality standards create exceedingly high demands on the reuse treatment process which are not necessary for other personal hygiene uses.

Environmental indicators have been identified and quantified and can be used as benchmark values. To assess environmental performance of the proposed graywater reuse for DHW a full life cycle assessment would need to be done in future work, and the foundation for this has been performed in the present paper. The overall conclusion is that graywater reuse is a promising route to reduce both water- and energy use in buildings.

From the two test periods that was investigated, there are indications of a significant potential to reduce energy by 55 % and water demand in a multifamily building by 91 % using a graywater reuse system where the graywater is recycled to the DHW. The tests also point to the importance to tailor the system design to the demand. Meaning that the auxiliary equipment needs to be especially addressed and optimized to ensure an efficient system. This was results from initial testing with a pilot installation so there are still many system related details to improve to have a system that is mature and ready for the market.

The investigation also shows that the economic result of the installation is depending on the rate structure in the specific geographic location. In the present study, the two locations have different prerequisites. In Gothenburg, the results are more depending on the energy and power reduction than on the water savings, indicating that the heat recovery parameter is the most important to consider. In Seattle, the situation is the opposite, here, the water saving is the most important parameter.

The economic viability is shown for both investigated locations, but for different reasons. In Seattle, the extremely high cost of water and water treatment is the main reason for the economic success of the installation. In Gothenburg, the effects of the reduced heating demand for DHW is the main reason for success.

These facts lead to the conclusion that the economic viability of graywater recycling will depend on the rate structures of the installation location.

When it comes to the social analysis, the conclusions are that in the current phase there is significant potential to strengthen the dialogue across a range of public and private actors and institutions so that trust in the technology is established. Currently Graytec AB, the technology developer, has been an important facilitator of the dialogues taking place around the Living lab (installation site). Moving forward, it will be important to deepen trust in graywater recovery across a wider range of water users and a greater diversity of market actors and public agencies.

## Credit author statement

Conceptualization: Jörgen Wallin, Jesper Knutsson, Timos Karpouzoglou

Methodology: Energy and measurements, Jörgen Wallin. Water treatment and reuse, Jesper Knutsson. Social analysis and investigation, Timos Karpouzoglou

Formal analysis: Energy and measurements, Jörgen Wallin. Water treatment and reuse, Jesper Knutsson. Social analysis and investigation, Timos Karpouzoglou

Investigation: Energy and measurements, Jörgen Wallin. Water treatment and reuse, Jesper Knutsson. Social analysis and investigation, Timos Karpouzoglou

Resources: Jesper Knutsson

Data Curation: Energy and measurements, Jörgen Wallin. Water treatment and reuse, Jesper Knutsson. Social analysis and investigation, Timos Karpouzoglou

Writing - Original Draft: Energy and measurements, Jörgen Wallin. Water treatment and reuse, Jesper Knutsson. Social analysis and investigation, Timos Karpouzoglou

Writing - Review & Editing: Energy and measurements, Jörgen Wallin. Water treatment and reuse, Jesper Knutsson. Social analysis and investigation, Timos Karpouzoglou

Visualization: Energy and measurements, Jörgen Wallin. Water treatment and reuse, Jesper Knutsson. Social analysis and investigation, Timos Karpouzoglou

Supervision: Jörgen Wallin

Project administration: Jörgen Wallin

Funding acquisition: Jörgen Wallin, Jesper Knutsson

## Declaration of Competing Interest

Jesper Knutsson is, apart from his main employment at Chalmers University of technology, also co-owner at Graytec AB, which is the company that owns and markets the graywater treatment system that was used in the case study described in the present paper.

## Acknowledgment

The authors would like to acknowledge Formas SEQWENS project (Dnr. 2018-00239) for funding the case studies. HSB Living Lab consortium for funding the installation of the pilot system. The National Board of Housing, Building and Planning (Boverket) for funding a part of Dr. Knutssons activities (Dnr. 6479/2018). A special acknowledgement to Per Ericson of Graytec AB for helping in administering and running the treatment system during the tests.

## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rcradv.2021.200054.

## Appendix 1 Economical calculations

## References

Asano, T., 2007. Water Reuse: Issues, Technologies, And Applications. McGraw-Hill, New York.

Burek, P., Satoh, Y., Fischer, G., Kahil, M.T., Scherzer, A., Tramberend, S., Nava, L.F., Wada, Y., Eisner, S., Flörke, M., Hanasaki, N., Magnuszewski, P., Cosgrove, B., Wiberg, D., Cosgrove, A.P.D.W.B., 2016. Water Futures and Solution - Fast Track Initiative. IIASA, Laxenburg, Austria.

Chaillou, K., Gérente, C., Y.A., D.W., 2011. Bathroom Graywater Characterization and Potential Treatments for Reuse. Water, Air, Soil Pollut 215, 31–42.

Ching, L., 2010. Eliminating "yuck": A simple exposition of media and social change in water reuse policies. Int. J. Water Resour. Dev. https://doi.org/10.1080/07900620903392174.

Christen, K., 2005. Water Reuse: Getting Past the "Yuck Factor.". Water Environ. Technol. 17, 11–15.

Christova-Boal, D., Eden, R.E., McFarlane, S., 1996. An investigation into graywater reuse for urban residential properties. Desalination 106, 391–397.

City of Seattle, 2020. Seattle Public Utilities - Water and Sewer rates [WWW Document]. Drink. Sewer water rates. URL. https://www.seattle.gov/utilities/services/rates/water-rates.

Dixon, A., Butler, D., Fewkes, A., 1999. Water saving potential of domestic water reuse systems using graywater and rainwater in combination. Water Sci. Technol. 39, 25–32.

Energimyndigheten (Swedish Energy Agency), 2012. Vattenavändning i hushåll - Water use in dwellings.

Eriksson, E., Auffarth, K., Henze, M., Ledin, A., 2002. Characteristics of grey wastewater. Urban Water 4, 85–104. https://doi.org/10.1016/S1462-0758(01)00064-4.

Fielding, K.S., Dolnicar, S., Schultz, T., 2019. Public acceptance of recycled water. Int. J. Water Resour. Dev. 35, 551–586. https://doi.org/10.1080/07900627.2017.1419125.

Fountoulakis, M.S., Markakis, N., Petousi, I., Manios, T., 2016. Single house on-site graywater treatment using a submerged membrane bioreactor for toilet flushing. Sci. Total Environ. 551–552, 706–711.

Göteborg Energi, AB, 2020. Fjärrvärmepriser [WWW Document]. Fjärrvärmepriser. URL. https://www.goteborgenergi.se/foretag/fjarrvarme-kyla/fjarrvarmepriser.

Göteborgs Stad, 2020. Göteborgs Stad - VA Taxan [WWW Document]. Göteborgs Stad VA Taxan. URL. https://goteborg.se/wps/portal/start/vatten-och-avlopp/avgifter/vatten–och-avloppstaxa/.

Gross, A., Friedler, E., Alfiya, Y., Maimon, A., 2015. Graywater Reuse. CRC Press, Boca Raton, FL.

Hagy, S., Balay, P., 2014. Adaptable Design for the HSB Living Lab - flexible, co-created spaces in student housingg.

Jimenez, B., Asano, T., 2015. Water Reuse: An International Survey of current practice, issues and needs. Water Intell. Online 7 https://doi.org/10.2166/9781780401881, 9781780401881–9781780401881.

Karlsson, A., 2020. Chalmers Tekniska Högskola SYSTEMANALYS AV LOKAL GRÅVATTENRENING. Bengt Dahlgren AB.

Knutsson, J., Knutsson, P., 2021. Water and energy savings from greywater reuse: a modelling scheme using disaggregated consumption data. Int. J. Energy Water Resour. 5, 13–24.

Knutsson, J., Marx, C., 2016. The Habitation Lab as a platform for sustainable innovations in the built environment: a case study. In: 16th International Multidisciplinary Scientific GeoConference. Albena, Bulgaria, SGEM2016 Conference Proceedings. Book 6, pp. 317–324.

Li, F., Wichmann, K., Otterpohl, R., 2009. Review of the technological approaches for graywater treatment and reuses. Sci. Total Environ. 407, 3439–3449.

Livsmedelsverket, 2017. Livsmedelsverkets föreskrifter om ändring i Livsmedelsverkets föreskrifter (SLVFS 2001:30) om dricksvatten.

Lu, W., Leung, A.Y.T., 2003. A preliminary study on potential of developing shower/laundry wastewater reclamation and reuse system. Chemosphere 52, 1451–1459.

Makropoulos, C.K., Butler, D., 2010. Distributed water infrastructure for sustainable communities. Water Resour. Manag. 24, 2795–2816.

Memon, F.A., Ton-That, L., Butler, D., 2007. An investigation of domestic water consumption through taps and its impact on urban water flows. Water Sci. Technol. Water Supply 7, 69–76.

Mignon, I., Bergek, A., 2016. System- and actor-level challenges for diffusion of renewable electricity technologies: an international comparison. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2015.09.048.

MWRA Advisory Board, 2018. Annual Water and Sewer Retail Rate Survey.

Najm, M.A., Hasan, H., Alameddine, I., El-Fadel, M., 2017. Onsite graywater reclamation towards alleviating water shortages at the household level. WIT Trans. Ecol. Environ. 216, 87–99.

Ni, L., Lau, S.K., Li, H., Zhang, T., Stansbury, J.S., Shi, J., Neal, J., 2012. Feasibility study of a localized residential grey water energy-recovery system. Appl. Therm. Eng. 39, 53–62. https://doi.org/10.1016/j.applthermaleng.2012.01.031.

Opher, T., Friedler, E., 2016. Comparative LCA of decentralized wastewater treatment alternatives for non-potable urban reuse. J. Environ. Manage. 182, 464–476. https://doi.org/10.1016/j.jenvman.2016.07.080.

Oteng-Peprah, M., Acheampong, M.A., DeVries, N.K., 2018. Greywater Characteristics, Treatment Systems, Reuse Strategies and User Perception—a Review. Water, Air, Soil Pollut 229, 255. https://doi.org/10.1007/s11270-018-3909-8.

Pidou, M., Avery, L., Stephenson, T., Jeffrey, P., Parsons, S.A., Liu, S., Memon, F.A., Jefferson, B., 2008. Chemical solutions for greywater recycling. Chemosphere 71, 147–155. https://doi.org/10.1016/j.chemosphere.2007.10.046.

Puget Sound Energy, 2020. Rates sheduled summaries [WWW Document]. URL. https://www.pse.com/pages/rates/schedule-summaries#sort=%40fdocumentdate43883descending.

Ren, X., Zhang, Y., Chen, H., 2020. Graywater treatment technologies and reuse of reclaimed water for toilet flushing. Environ. Sci. Pollut. Res. 27, 34653–34663.

Sharifi, F., Nourouzi, M.M., Tahmourespour, A., 2020. Effect of gray water reuse on toilet flush tank bacterial and scum formation. Sustain. Water Resour. Manag. 6, 1–8.

Smith, A., Raven, R., 2012. Reconsidering niches in transitions to sustainability. Res. Policy. https://doi.org/10.1016/j.respol.2011.12.012.

Vuppaladadiyam, A.K., Merayo, N., Prinsen, P., Luque, R., Blanco, A., Zhao, M., 2019. A review on greywater reuse: quality, risks, barriers and global scenarios. Rev. Environ. Sci. Bio/Technology 18, 77–99. https://doi.org/10.1007/s11157-018-9487-9.

Wallin, J., Claesson, J., 2013. Investigating the Efficiency of a Vertical In Line Drain Water Heat Recovery Heat Exchanger in a System boosted with a Heat Pump. Submitt. to Energy Build.

Zaloum, C., Lafrance, M., Gusdorf, J., 2007. Drain Water Heat Recovery Characterization and Modeling. Ottawa Sustain. Build. Communities Nat. Resour. Canada 38–40.