Research article

Screening innovative technologies for energy-efficient domestic hot water systems

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ABSTRACT

Domestic hot water systems are large energy consumers. With the aim of reducing the energy footprint of these systems, we selected and simulated five technologies across a wide range of technology readiness levels: established technologies – pipe insulation and low-flow faucets –, relatively new technologies – shower drain heat exchangers and an innovative pipe system –, and a novel experimental technology – a heat exchanger connected to membrane bioreactor for on-site greywater treatment. Using the WaterHub modeling framework, we simulated the technologies alone and in combination and compared the energetic performance of fifteen scenarios with a validated reference domestic hot water system. Low-flow appliances as standalone technologies performed best with 30% less energy required for the boiler tank, but combining low-flow appliances with a membrane bioreactor heat exchanger performed best overall (50% reduction). Deep insights into the temperature dynamics at all locations in the system led to the identification of technological competition patterns to prevent and synergies to exploit. Through our results, we are able to discuss and recommend further investigations regarding critical aspects like hygiene and economic performance.

1. Introduction

Domestic hot water (DHW) systems are often large energy consumers in modern buildings, representing as much as 50% of the total energy consumption in specific cases (Frijns et al., 2013; Meggers and Lembundgut, 2011). DHW systems may thus become the next bottleneck towards truly low-energy buildings. The retrofitting of existing buildings is also a burning question as DHW is estimated to consume about 13% of the total residential energy in Europe (Bundesamt für Energie, 2019; European Commission; Pérez-Lombard et al., 2008).

In order to reduce the energy footprint of DHW systems in the residential sector, optimizing strategies aim at (i) decarbonizing and increasing the efficiency of hot water production technologies (Ahmadi et al., 2018; Fabrizio et al., 2014; Shukla et al., 2013), (ii) reducing losses through hot water distribution systems within buildings (Bahl, 2013; Cholewa et al., 2019), (iii) decreasing hot water use through technological or behavioral measures (Binks et al., 2017; Tiefenbeck et al., 2016) and (iv) recovering heat from wastewater at multiple levels, from the household drain to the wastewater treatment plant (Frijns et al., 2013; Nagpal et al., 2021). However, it is not yet clear which strategy has more potential and what combinations may yield the best results for the least effort. While many studies focus on the integration of multiple technologies for the heating system – mostly in the realm of solar and heat pump technologies – (Fabrizio et al., 2014), there is little no research on the topic of DHW-specific technology combinations and how their integration influences the rest of the system. Some studies focus on the interactions between building-level and sewer-level heat recovery technologies (Sitzenfrei et al., 2017) or impacts on the wastewater treatment processes (Hadengue et al., 2021; Huber et al., 2020; Saagi et al., 2022), but few analyze the in-building interactions. One example is the interaction between hot water production and wastewater heat recovery highlighted in a previous study, in which we quantified the performance boost of shower drain heat recovery as the boiler set point temperature increases (Hadengue et al., 2020). This synergy is especially important in the context of the current push from regulators towards higher boiler temperatures to prevent the growth of Legionella pneumophila in domestic hot water systems (Van Kenhove et al., 2019).

The WaterHub modeling framework, developed in previous works (Hadengue et al., 2019, 2020), is designed for the assessment of DHW...
technologies – and combinations thereof – with the aim of reducing the energy footprint of DHW systems. The framework is a software tool that combines process-based technological models with a stochastic water demand model to allow for modular investigations of domestic hot water systems. Its strength lies in the rapid (virtual) prototyping of scenarios and new technologies allowing for rough performance assessments, as well as preliminary analyses of their impact on the rest of the system. The WaterHub can be used in combination with other tools for deep thermodynamic investigations of a single technology, as showcased in a previous study (Hadengue et al., 2022). Alone, the framework allows for the straightforward modeling of a real system and the dynamic simulation of its overall performance under varying scenarios, all of which using realistic water demand profiles.

In this work, we use the WaterHub framework to assess the performance of DHW-specific technologies and identify potential interactions when they are combined. We have selected five technologies across a wide range of technology readiness levels. We test well established technologies – pipe insulation and low-flow faucets –, relatively new technologies – shower drain heat exchangers and the 3Eflow system from the Swedish startup 3Eflow – and a novel experimental technology – a heat exchanger connected to an on-site decentralized treatment membrane bioreactor for greywater treatment. Starting from a reference system validated against experimental data, we test the technologies alone and in combination with each other. We compare the energetic performance of each scenario, i.e., how they contribute to reducing the energy footprint of the modeled system via a mitigation of heat losses from hot water pipes or a decrease in total heat demand. We note that the objective of this study is not to perform detailed analyses of each technology, but rather to explore thermodynamic processes at the core of interactions appearing when technologies are combined. Additionally, we aim at showing how the proposed methodology may be used to test innovative ideas before allocating more resources for in-depth (experimental) investigations. Finally, our results allow us to recommend where more in-depth analyses of additional aspects outside the scope of this study should be performed, like hygiene and economics.

2. Materials & methods

We used the WaterHub modeling framework throughout this work (Hadengue et al., 2019, 2020). In the present work, we selected a reference system – shown in Fig. 1 – already validated against real-world data in previous studies (Hadengue et al., 2020; Kenway et al., 2012). We refer to these studies for details on the modeling, parametrization and validation of the reference model. Compared to the model from Hadengue et al. (2020), three notable differences were introduced: (i) we adapted the shower appliance to account for heat losses during showering according to an empirical model developed by Wong et al. (2010), (ii) We lowered the temperature of the city mains water to 10 °C to better represent typical temperatures in Switzerland (Agudelo-Vera et al., 2020), (iii) Air temperature inside the building – thus surrounding hot water pipes and tanks – is set to a constant 20 °C.

The plumbing layout of the reference model is similar to our previous study: 5 m long, ½ inch (12.7 mm) outside diameter copper pipes (Hadengue et al., 2020). However, we improved the pipe model – a longitudinally-discretized model with five nodes – to include the thermal inertia induced by pipe walls. In addition, it is now possible to model multi-layered pipes and thus account for potential insulation. In this regard, we performed a new validation study of the pipe model by comparing it to experimental data from the literature for two pipe diameters (½ inch, ¼ inch) and three insulation layouts (no insulation, ½ inch, ¼ inch). The water pipe model used in this study is a longitudinally-discretized model of ideally-mixed nodes, inspired by Hanby et al. (2002). Thermal dynamics are governed by the overall heat transfer coefficient UA:

$$ U_A^{-1} = \frac{1}{h_a A_i} + \frac{1}{2\pi L} \ln \left( \frac{r_o}{r_i} \right) + \frac{1}{h_i A_i} $$

(1)

where $h_{a,i}$ are the convection heat transfer coefficient of water and air, $r_o,i$ the outer and inner pipe radii, $A_o,i$ the outer and inner contact surface area, $L$ the pipe length and $k$ the thermal conductivity of the pipe material. For copper, $k$ was set to 400 W K⁻¹ m⁻¹.

Contrary to the original model from a previous study (Hadengue et al., 2020), $h_a$ is separated into a value during flowing conditions $h_a^{flow}$ and a value during static conditions $h_a^{static}$. Using the Reynolds analogy, we can estimate $h_a^{static}$ from the flow and temperature of the water during flowing conditions. The Reynolds analogy links the Nusselt number $Nu$ to the Reynolds and Prandtl number $Re$ and $Pr$, respectively:

![Fig. 1. Reference system – described in full details in previous publications (Hadengue et al., 2020; Kenway et al., 2012).](image-url)
Nu = 0.0396 Re^{0.75}Pr^{1/3} \tag{2}

Here, Nu can be expressed as Nu = \frac{h_{\text{conv}}}{k} with D the pipe diameter. We can therefore write:

\[ h_{\text{conv}}(V, T) = \text{Nu}(V, T) \cdot \frac{k(T)}{D} = 0.0396 \left( \frac{\rho V k(T)}{\mu(T)} \right)^{0.75} \text{Pr}(T)^{1/3} \tag{3} \]

With V the water flow, A the cross-sectional area, \( \rho \) the density of water and \( \mu(T) \) the dynamic viscosity of water as a function of temperature (obtained with a polynomial interpolation of experimental data). With \( h_{\text{conv}} \) out of the way, we only had to calibrate \( h_{\text{static}} \) and \( h_{\text{a}} \) manually. The full results are available in the supplementary information (SI) in Fig. S1. The close match between simulated and experimental values indicate that our model adequately simulates water temperature inside the hot water pipes of our reference system.

2.1. Scenarios

We simulate a total of fifteen scenarios made of five distinct technologies and their combinations. The five technologies are: (i) pipe insulation, (ii) low-flow appliances, (iii) a shower drain heat exchanger (iv) 3Eflow, self-emptying pipes from the Swedish start-up 3Eflow, and (v) a heat exchanger integrated in a membrane bioreactor. We describe each technology and its associated WaterHub model in the sections below.

To account for the stochastic nature of water demand profiles, each scenario is simulated at least 2000 times (found to guarantee convergence of the daily average results). To increase the generalization of our results, we run all scenarios with two different boiler set-point temperatures: 60 °C and 50 °C. Each step simulates two consecutive days: one day to allow the system to reach a steady state followed by the day-long simulation for which results are recorded. At every step, we record (i) the daily total energy required by the boiler tank, (ii) the daily total volume of hot and cold water flowing to each appliance, (iii) the amount of heat flowing daily through each appliance and (iv) the amount of heat lost daily through the water pipes. Averaging over the 2000 steps (days), we then compute the daily average total energy losses in the plumbing system as well as the daily average energy requirement from the boiler.

In addition, with the aim of exploring temperature dynamics in the system, we record the temperature curves at all locations and for all scenarios.

2.1.1. Pipe insulation

The pipe insulation scenario is built using the insulation parameter of the pipe insulation layers with D the pipe diameter. We refer to the model description at the beginning of Section 2 and to the SI (Fig. S1) for a complete description of the validation process of the insulation layer performance.

2.1.2. Low-flow appliances

We simulated low-flow faucets thanks to a modification of the appliance model in the WaterHub Modelica library: a flow factor limits the flow required by the stochastic water demand profile. In this study, we used a flow factor of 0.5, thereby limiting the incoming flow to 50% of the reference flow. On average, this represents a flow of 6 L/min (instead of 12 L/min) for the shower and all three taps in the household.

2.1.3. Shower HEX

The shower drain heat exchanger (shower HEX) is similar to the one used in a previous study (Hadengue et al., 2020). It is a counter-flow heat exchanger modeled as two longitudinally-discretized water pipes in thermal contact. For the heat exchanger used in this study, we used a discretization of ten nodes and an inner pipe volume of 0.2 L. The heat exchanger is in thermal contact with the surrounding environment (set to 20 °C), losing heat over time during stagnation phases from the contained water volume and the pipe materials. The performance of the heat exchanger is controlled by the overall conductance UA across the two counter-flow pipes, defined as

\[ UA = \frac{Q_{\text{flow}}}{\Delta T_{\text{nominal}}} = \frac{Q_{\text{flow}}}{\Delta T_{\text{in}} - \Delta T_{\text{out}}} = \frac{\ln \left( \frac{\Delta T_{\text{nominal}}}{\Delta T_{\text{in}} - \Delta T_{\text{out}}} \right)}{LMTD_{\text{nominal}}} \tag{4} \]

where \( Q_{\text{flow}} \) is the targeted heat flow at nominal conditions – here set to 7.5 kW to represent a typical commercial shower drain heat exchanger – and \( LMTD_{\text{nominal}} \) the logarithmic mean temperature difference (see Section 4.2). In the present study, we use 3Eflow as a replacement of single hot water pipes, although the system only plays its strengths in considerably larger systems, especially when replacing entire circulation systems in multi-family buildings.

In this study, we model the 3Eflow system as an adaptation of the existing pipe model in the WaterHub library (see Section 2). In order to avoid the complexity of a multi-media water/air model, we artificially lower the overall thermal conductance UA of the hot water pipe whenever the appliance is not in use down to a tenth of its value, thereby dramatically reducing heat losses to the surrounding environment. This method, although not rigorously simulating the underlying physical processes, provides a good emulation of a 3Eflow pipe, as shown by a validation study comparing our results with experimental data from the manufacturer (see SI).

2.1.4. 3Eflow

The 3Eflow technology is an innovative hot water distribution developed by the Swedish company of the same name. After a water consumption tap or shower event, water is pumped back to the boiler tank (or circulation system), leaving the pipe empty. When a consumption event starts, hot water flows quickly through the empty pipe to the point of use. As no water stagnates in the pipes in-between events, the system reduces heat losses from hot water pipes and may limit the growth of harmful bacteria like Legionella pneumophila (see Section 4.2).

In the present system, we use 3Eflow as a replacement of single hot water pipes, although the system only plays its strengths in considerably larger systems, especially when replacing entire circulation systems in multi-family buildings.

In this study, we model the 3Eflow system as an adaptation of the existing pipe model in the WaterHub library (see Section 2). In order to avoid the complexity of a multi-media water/air model, we artificially lower the overall thermal conductance UA of the hot water pipe whenever the appliance is not in use down to a tenth of its value, thereby dramatically reducing heat losses to the surrounding environment. This method, although not rigorously simulating the underlying physical processes, provides a good emulation of a 3Eflow pipe, as shown by a validation study comparing our results with experimental data from the manufacturer (see SI).

2.1.5. MBR HEX

All scenarios above use commercially available technologies. In order to expand the discussion on household-scale heat recovery, we developed the membrane bioreactor heat exchanger (MBR HEX) scenario. The technology, to the best of our knowledge, does not exist nor is it researched in the decentralized water treatment community. Building-scale MBR technologies combine membrane micro- or ultrafiltration with typical biological treatment processes for the treatment of greywater. We propose to combine a MBR tank – typically installed in the basement of a building – with a heat exchanger to pre-heat cold water from the city mains flowing to the building boiler tank or space heating buffer tank. With this scenario, we want to demonstrate how tools like the WaterHub modeling framework may provide initial assessments of novel technologies or ideas before the planning of more complex, resource-intensive analyses.

In this study, we have modeled the MBR HEX similarly to the setup found in the experimental building NEST in Switzerland (Hess et al., 2020). The NEST setup is a modified Aquacell® 800 system with two tanks of 800 L each. The first tank is an aerated buffer tank and the second is for biological treatment and contains the membrane. In our study, we model the buffer tank as an ideally-mixed open tank with an integrated heat exchanger. Because the volume of the tank is always much larger (around 400 L) than the volume of water contained within

1 www.3eflow.com (accessed 13.05.2022).
the heat exchanger pipes, we model an ideal heat exchange: the outlet of the heat exchanger is set as equal to the temperature of the tank volume. The water volume is in thermal contact with the surrounding air (20 °C) and loses heat over time. Based on the real setup in the NEST building, the tank is operated as follows: greywater coming from the appliances accumulates in the tank. When the volume exceeds 520 L, the greywater is discharged into the second tank at a rate of 2 L/s until a minimum volume of 273 L is reached. We refer to the SI (Fig. S2) and to the publication by Hess et al. (2020) for full details on the parametrization of the tank.

3. Results

All figures presented in this section relate to simulations with a boiler set point temperature of 60 °C. We also describe important results of the 50 °C boiler set point, although the related figures are shown only in the SI (Fig. S3). We discuss the influence of boiler temperatures in Section 4.2.

3.1. Heat losses from hot water pipes

In the 60 °C configuration, the heat losses from hot water pipes in the reference system amount to 1.8 ± 0.2 kWh/day. Fig. 2 shows the reduction in heat losses for all scenarios. Technologies specifically targeting the piping system (3Eflow and pipe insulation) offer the larger reduction, up to 73.2% decrease in heat losses when pipes are well insulated and 30% when the 3Eflow system is implemented. Low-flow appliances have a significant impact on system losses from the piping system (21%), while heat recovery technologies (shower HEX and MBR HEX) offer only marginal help in reducing the losses. The largest reduction occurs when combining the two technologies targeting the piping system (as much as 95.7%). However, the added benefit of combining pipe insulation with low-flow appliances is less clear: we would expect 94.2% heat loss reduction but we achieve 74.7%, indicating competing dynamics in this configuration. Similarly but not as dramatic, we would expect the combination of 3Eflow and low-flow appliances to reduce heat losses by as much as 51%, but we achieved only 40.8%, highlighting a technological competition. In the 50 °C boiler set point configuration, heat losses from hot water pipes in the reference system drop from 1.8 to 1.4 ± 0.2 kWh/day, but the relative technology performances are very similar to the 60 °C scenario – the largest difference being the low-flow appliances scenario increasing its performance from 21.0% to 21.6% heat loss mitigation, i.e. only 0.6 percentage points (%p) (see SI – Fig. S4).

3.2. Energy consumption of tank boiler

We compared the daily energy demand of the tank boiler compared to the reference system in the 60 °C set point temperature configuration (Fig. 3). With a reference value of 13.0 ± 2.8 kWh/day, the technologies alone and in combination achieved reductions ranging from 3.5% (3Eflow) to 47.2% (MBR HEX with low-flow appliances). The results show that the best performance is reached in scenarios with low-flow appliances, a consequence of the 50% reduction in water consumption for the shower and the three taps. Heat recovery technologies (shower and MBR HEX) follow, with −20.6% and −24.0% respectively. The results for the shower HEX are in line with available data on shower drain water heat recovery studies (Ip et al., 2018; Kenway et al., 2019). MBR HEX is only marginally better, although the system recovers energy from all greywater sources rather than just shower drain water.

In this system, heat losses from hot water pipes represent only 14% of the total energy consumed by the boiler, thus technologies that best reduce heat losses have a lower impact here (3.5–8.6%, 11.7% in combination). However, they do not appear to compete with other technologies and may provide significant performance boosts with heat recovery technologies. For instance, the energy reduction induced by shower HEX jumps from 20.6% to 29.7% when combined with well-insulated pipes, which even indicates a slight synergy between the

![Fig. 2. Percentage reduction of heat losses from hot water pipes against the reference case (boiler temperature: 60 °C, shown with daily standard deviations) for combinations of compatible technologies. The matrix diagonal shows the performance of single technologies.](image-url)
two technologies (i.e. the reduction gain is larger than the linear sum of the single technologies).

When the boiler temperature is 50 °C, the reference energy consumption drops from 13.0 to 12.4 ± 2.8 kWh/day. Although the relative energy consumption reductions, as for heat losses, are very similar to the 60 °C case, we note an interesting difference: scenarios containing the MBR HEX show consistently better performances in the 50 °C scenario. The better performances range from 2.3 % additional performance, up to 4.9 %p. However, all the other scenarios – except for the low-flow appliances as a single technology – perform relatively worse in the

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**Fig. 3.** Percentage reduction in energy input to the boiler tank against the reference case (boiler temperature: 60 °C, shown with daily standard deviations) for combinations of compatible technologies. The matrix diagonal shows the performance of single technologies.

**Fig. 4.** Example temperature time series. Top: Temperature at the outlet of the pipe connecting the tank boiler to “Tap Adults” (see Fig. 1). Bottom: temperature in the MBR tank.
50 °C case (0.3–4.6 %p differences).

### 3.3. Temperature dynamics

The analysis of single temperature curves allows us to gain insights into the temperature dynamics and understand how technology interactions may occur (see Section 4.1). Figs. 4 and 5 show temperature curves of particular interest for selected scenarios and time periods. In Fig. 4 (top), we show the reference temperature curve in a tap as being influenced upon the implementation of a single technology (low-flow appliances) or a combination of technologies (low-flow appliances + pipe insulation). In the low-flow appliance scenario, hot water pipes tend to start stagnation phases (in-between two draw offs) at a lower temperature – about 5 K – than in the reference scenario. On the contrary, the same stagnation phases start at a much higher temperature – about 5 K above the reference curve – when pipes are also insulated, leading to the heat loss mitigation effect of low-flow appliances being canceled out by the effect of pipe insulation. Another technology interaction is visible in Fig. 4 (bottom), showing the average temperature in the MBR tank. The MBR HEX being located downstream of the shower heat exchanger, its temperature drops by around 1–2 K when the two technologies are combined, thereby reducing the performance of the MBR HEX. Lastly, Fig. 5 shows how temperature curves during a shower event are influenced when a shower HEX is implemented alone and in combination with pipe insulation. We note that, when pipes are insulated, hot water reaching the shower head is warmer (0.5–1 K) during the whole shower event, thereby influencing the performance of the shower HEX as the hot/cold water ratio at the mixing valve decreases. The heat transfer flow across the heat exchanger, accordingly, increases by around 45 W during the shower event when hot water pipes upstream are insulated, highlighting the better performance of the device.

### 4. Discussion

Figs. 2 and 3 show which technology and what combinations may best reduce the energetic footprint of a building’s DHW system. However, it is not straightforward to relate the results to underlying dynamic processes within DHW systems and their consequences on technology performance. In the next sections, we identify and describe some important dynamic processes. Further, we investigate in detail the MBR HEX technology as it is the most novel of all tested technologies. Finally, we discuss the generalization of our results and we expand on perspectives invisible to the energy metrics of Section 3: hygiene and economics.

#### 4.1. Performance and interactions

##### 4.1.1. Low-flow appliances and system losses

In the studied system, low-flow appliances reduce heat losses from the hot water pipes by 21% (Fig. 2). This result is surprising as low-flow appliances are not initially designed to optimize the piping system but rather to save energy as less hot water is being consumed. We attribute the mitigation of heat losses to a dynamic phenomenon observable mostly in taps. Tap consumption events are numerous (more than 10 per day per person) and rather intense (about 12 L/min) but generally very short. In our model, a typical hand wash event lasts roughly 5 s and uses less than 1 L of water. During short events, hot water pipes have no time to replace completely the stagnating water in the pipe – here about 2.5 L – with hot water from the boiler (Fig. 4, top). This phenomenon is visible in the reference system and is accentuated when low-flow appliances are implemented because the pipe-filling process is slower. Less hot water enters the pipe; thus less heat is lost to the surroundings during the subsequent stagnation phase.

This effect is less pronounced when low-flow appliances are implemented together with pipe insulation and the 3Eflow technology, indicating a competitive behavior. Tap events are numerous, thus insulated hot water pipes do not cool down much between events, thereby reducing the effect of low-flow appliances described above which depends on the temperature at the start of each stagnation phase (Fig. 4, top).

In our model, however, the water consumption behavior of inhabitants is not influenced by low-flow appliances, although we expect the behavior to change upon the implementation of these technologies. In reality, tap and shower events may become longer as the user is waiting for warm water, thereby mitigating some of the water-saving – and thus energy-saving – performance. This specific issue is intricately linked to the rebound effect, highlighted as an important aspect of the general mismatch between predicted and observed effects of building optimization measures (Brogger et al., 2018). In this context, Ableitner et al. (2016) have analyzed how low-flow showerheads lead to longer shower durations using a dataset of more than 5000 shower events. Their results indicate that the longer shower durations reduce the energy reduction potential of low-flow showerheads by 15%: where in theory 45% of the shower energy could be saved, 38% was effectively achieved. We note that 38% energy reduction is still very significant, larger than what is expected from most other DHW technologies. However, due to their effect on user comfort, low-flow appliances may be most impacted by rebound phenomena compared to all other technologies in this study. This issue must be studied further, for instance through the use of in-house displays, which have been shown effective in reducing warm water consumption (Canale et al., 2021).

##### 4.1.2. Heat recovery technologies

Heat recovery technologies – shower and MBR HEX – compete for the same resource: greywater-contained heat. Therefore, combining a shower HEX and a MBR HEX is not equal to the sum of their performance as standalone devices. The temperature in the MBR tank, located downstream of the shower HEX, is reduced by around 2 K upon the implementation of a shower HEX. The MBR HEX thus cannot recover as Fig. 5. Typical temperature dynamics during a shower event for the shower HEX scenario and the shower HEX - Pipe insulation combination. The area shaded in light blue indicates the shower event. The main axis shows hot water temperatures in the shower pipe (red and blue curves). The secondary axis (green curve) shows the difference in heat transfer in the heat exchanger located after the shower, indicating a slightly better performance when upstream pipes are insulated. This difference explains the small synergy identified between the shower HEX and technologies targeting the distribution system (pipe insulation and 3Eflow). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

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much heat for the pre-heating of water from the city mains (Fig. 4, bottom).

In addition, heat recovery technologies show a competitive behavior when combined with low-flow appliances. The MBR HEX used alone recovers on average 3.2 ± 0.8 kWh daily. When combined with low-flow appliances, the daily average drops to 2.0 ± 0.6 kWh, a 33% decrease. Similarly, the absolute performance of the shower HEX decreases by 48% from roughly 2.7 ± 1.2 kWh to 1.4 ± 0.6 kWh, only short of 50% - what the flow reduction would dictate – due to the increased heat exchange performance at low flow. Although not quantified, the competitive interaction was highlighted by Kordana et al. (2014) in their computation of the economic performance of a shower HEX alone and in combination with low-flow appliances. In some scenarios, the net present value of the system decreased upon the implementation of a shower HEX, suggesting that little or no economic benefit can be gained from combining the technologies – at least at the current high prices of this relatively new technology.

Lastly, we mention the synergy between heat recovery technologies and pipe technologies. Pipe technologies reduce heat losses in pipes, thus hot water reaching the shower head is 0.5–1 K warmer than in the reference case (Fig. 5). Consequently, the hot/cold water ratio at the mixing valve decreases, thus increasing the performance of the heat exchanger as more cold water flows through. We note that this effect would not occur in a flow-matching configuration (e.g., if the shower HEX is used to pre-heat all cold water flowing from the city mains, to the shower itself and to the boiler). We expect the synergy to become significant in buildings with larger piping systems – discussed in Section 4.2 –, thereby opening the discussion to exploit the synergy and thus increase the economic efficiency of the technology combination.

4.1.3. MBR HEX

The MBR HEX, in essence, takes advantage of existing MBR technologies. An MBR is designed to recycle greywater streams within the building for further reuse – such as toilet flushing or even showers. Their rise is mostly driven by increasing water scarcity in dense urban areas and arid regions. As we can expect MBR tanks to be located close to the DHW utilities in the basement of a building, it is straightforward to imagine a heat exchanger linking an MBR tank to the tank boiler providing hot water for the whole building. Our results indicate that this technology may save up to 24.0% (28.9% for the 50 °C tank boiler) of the energy required for domestic hot water, which is significant and rather close to the performance of low-flow appliances.

The performance of the MBR HEX system described in this study is a promising first estimate. In order to assess the full potential of the MBR HEX technology, though, two critical points need to be addressed. First, research must investigate various operation strategies for the MBR HEX system, in order to maximize the temperature of the tank at all times. As a further constraint, the operation strategy must integrate well with current research on treatment operation, aiming at keeping the treatment process smooth and efficient under variable loads (Hess et al., 2020, 2021). Second, importantly, research must evaluate the effect of biofilm growth on the efficiency of the MBR heat exchanger as biofilms were shown to reduce heat transfer in sewer heat exchangers (Wanner et al., 2004).

The actual design of an MBR HEX will be critical to its performance. Among other points, the boiler-MBR pipe connection, the maintenance process and the potential for retrofitting existing MBR systems must be addressed carefully to determine whether an MBR HEX would be energetically and economically viable.

4.2. Results generalization

The modeled system represents a family of five in a single building. Although the trends and effects described in the sections above are probably generalizable to many domestic hot water systems in temperate climates, we note that the results are largely system dependent. We explore aspects of results generalization in the next paragraphs.

The piping layout (pipe length, diameter, location, as well as alternate systems like circulation pumps) largely influences system losses and thus the relative performance of technologies targeting the piping system like pipe insulation and 3Eflow. In buildings where 50% of the DHW energy consumption is lost through its piping system, as sometimes observed for multi-family buildings with circulation pumps (Bohm, 2013), technologies like pipe insulation may be the most efficient way to save energy. Additionally, the 3Eflow system is the only technology that has potential to replace (part of) the circulation system with a traditional plumbing system due to its unique operation, thereby dramatically reducing its associated heat losses and pumping energy costs.

More generally, the building topology and its surrounding environment surely influences the relative performance of all technologies tested in this study. The number of DHW appliances and the topology of the network, the hot water production system, the temperature of water from the city mains, the relationship to space heating, all these aspects will all have an impact on what technology and what combination will perform best.

As an additional perspective on results generalization, we mention the variability of water consumption profiles among building types. Non-domestic buildings such as office buildings, schools or hospitals may have very tap-focused consumption dynamics: the relative importance of heat losses in the total energy consumption may therefore be large, thus favoring technologies targeting an optimization of the piping system. Similarly, the relative importance of shower-related energy is large in swimming pools or large families, thereby increasing the overall performance of heat recovery technologies at large as they often rely on high-temperature flows from the shower drain.

Each building and each person consuming water differently, the results from Section 3 depend on the actual use case. Nevertheless, the performance dynamics and interactions described in Section 4.1 are easily generalizable to all building types, even though their relative impact may vary. We add that some technologies – low-flow appliances and MBR HEX, notably – are less topology-dependent than others. Low-flow appliances will perform similarly in many situations because the energy savings stem from a decrease in water consumption, regardless of the initial consumption profile. Similarly, an MBR HEX recovers energy from all greywater streams, thereby reducing its dependence on only one heat source as opposed to the shower HEX.

We conclude the discussion on the results generalization by noting that results from Section 3 and the SI are largely insensitive to the boiler set point temperatures (here 50 °C and 60 °C). Three differences are worth mentioning: (i) the lower set point temperature reduces heat losses in the piping system, thus technologies like pipe insulation and 3Eflow perform overall slightly worse. (ii) The lower set point temperature influences the hot/cold water mixing ratio in the shower. Less cold water flows to the shower, thereby reducing the performance of the shower HEX. (iii) The generally larger hot water flows induce a better performance of the MBR HEX: more cold water can be pre-heated in the MBR tank.

4.3. Additional perspectives: hygiene and economics

Recommending specific technologies or combinations requires discussing additional aspects of technology integration. Although not the main focus of this study, hygiene and economic considerations are critical, which we expand in the following paragraphs.

Concerns about hygiene are to a wide extent related to the recent rise in detection of the Legionella bacteria in DHW systems (Bundesamt für Gesundheit, 2019; Centers for Disease Control and Prevention Legionella). Authorities aim at preventing Legionella cases by essentially limiting the time stagnating water spends in the growth-friendly temperature range of the bacteria (roughly between 25 °C and 55 °C) (Van Kenhove et al., 2019). Regulations and guidelines, in addition to various
anti-septic thermal treatments, often impose a minimum temperature at the boiler outlet (around 60 °C) and at the location furthest away from the boiler (around 50 °C) (BRE/ASHRAE, 2011; SVGW, 2020). In this context, hot water pipes cooling down rapidly between consumption events are assumed safer than well-insulated pipes efficiently reducing heat losses from the distribution system. In the example day of Fig. 4 (top), the water contained in the uninsulated pipes of the reference system spends roughly 9.4 h in the Legionella growth range, as compared to 23.7 h in the pipe insulation scenario, i.e. 2.5 times more. The 3Eflow system has potential to decrease heat losses from distribution systems without compromising hygiene because pipes are emptied between consumption events. This unique operation may prove especially interesting in large water distribution systems, traditionally requiring recirculation systems to meet comfort and hygiene requirements. However, additional research should confirm the statements with respect to hygiene.

The financial return of the tested technologies is largely location- and building-specific. The economic performance, for instance, will vary if part of a retrofitting project or the construction of a new building. Insulating pipes in new buildings is straightforward and inexpensive, but can be expensive as part of a retrofitting project. On the contrary, the implementation of a heat exchanger in a MBR is rather insensitive to the project type – providing that MBR treatment tanks already exist or are planned. Nevertheless, the literature points to interesting economic points in relation with some technologies present in this work. Kordana et al. (2014) have highlighted that low-flow appliances are financially beneficial in all cases and shower HEX mostly in shower-intensive settings like swimming pools and gyms. Spriet and McNabola (2018) reach similar conclusions and advice against the implementation of shower HEX in single family buildings as the economic performance is too poor. Interestingly, Stec and Kordana (2015) have shown that greywater recycling units and shower HEX combined may be financially viable, we can thus expect a hybrid system such as the MBR HEX we propose to be a financially interesting option. We note that economic analyses of new technologies often only provide a snapshot of a technology’s performance. The studies mentioned here thus do not consider future changes – e.g., potential economies of scale – that may influence their financial performance. In this regard, we expect shower heat exchangers to sell at lower prices in the future, potentially challenging the conclusions of some studies stated above.

With the hygiene and economic discussion in mind, we can safely recommend low-flow appliances as the most energy and financially efficient technology, without compromising hygiene in the system. Combining low-flow appliances with other technologies should be considered on a building-specific basis. We highlight heat recovery technologies (shower and MBR HEX) as interesting options providing large energy savings in buildings with intensive (shower) usage – either a large single-family home or a public building. The MBR HEX, specifically, shows potential and should be investigated further. We do not recommend piping-specific technologies such as insulation and the 3Eflow system for SFH with simple piping layouts. However, these technologies may prove essential to reduce the energy footprints of large buildings, notably those with recirculation systems. More generally, we emphasize that the integration of any new technologies has the potential to influence the rest of the urban water cycle (Hadengue et al., 2022). Thus, all relevant stakeholders must be involved: microbiologists, building professionals, water engineers and economists.

5. Conclusions

We used the WaterHub modeling framework to test five technologies and their combination in a single-family home, comparing in total fifteen scenarios with a validated reference system. Low-flow appliances performed best in scenarios with single technologies, with roughly 30% reduction of the energy consumption for domestic water use. They also raise least concerns regarding hygiene or financial performance. However, low-flow appliances generated most competitive interactions when combined with other technologies, notably reducing the performance of devices recovering heat from greywater streams. Despite the competition, the low-flow appliances + membrane bioreactor heat exchanger yielded the best results overall, reducing the energy consumption by close to 50%.

We formulate the following recommendations: low-flow appliances should be used in all building types and domestic hot water systems. Combinations with additional technologies should be building-dependent: (i) heat recovery technologies in buildings with intensive hot water usage. (ii) Technologies aiming at reducing heat losses from hot water pipes for buildings with large or complex distribution systems. We note that combinations of heat recovery and pipe technologies may create synergies in larger buildings, increasing the energetic and economic viability of such combinations. Regardless of the technology, we stress that hygiene concerns must be critically assessed and answered.

Within the selection of technologies analyzed in this work, we highlight the membrane bioreactor heat exchanger, a modification of an on-site greywater treatment device to recover heat from the greywater tanks. We showed the significant energy-saving potential of adding a heat exchanger to an existing MBR, and recommend that the system should be investigated carefully in future research in order to combine the benefits of on-site greywater treatment with energy savings.

Combining technologies together and testing novel ideas like the membrane bioreactor heat exchanger was made possible by the flexibility, modularity, and adaptability of the WaterHub framework. It provides straightforward analyses of technology configurations and complex combinations. Moreover, dynamic simulations allow the identification of subtle interactions in the system, making the framework efficient to assess the rough potential of novel technologies before allocating more resources to in-depth – and experimental – investigations.

CrediT statement

Bruno Hadengue: Methodology, Software, Investigation, Writing - Original Draft. Eberhard Morgenroth: Supervision, Writing - Review and Editing. Tove A. Larsen: Supervision, Writing - Review and 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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2022.115713. The source code and resulting raw data for the analyses presented in this article can be found online at https://doi.org/10.25678/0006QY.

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