1. Introduction

Space heating (SH) still represents around 70% of the energy used in the European building stock [1]. Building professionals have thus, logically, focused on reducing energy demand for SH – with tremendous success, both for the renovation of existing buildings [2] and for new buildings. In Switzerland, for instance, single-family homes built in the last decade consume up to 80% less primary energy for space heating than the oldest buildings of the Swiss stock [3], inducing a 30% drop in specific SH loads in the 2000–2017 period [4]. The improvement of domestic hot water (DHW) systems was less significant: from 2000 to 2017, the energy consumption per capita for DHW dropped only by 15% [4]. As a consequence of this general trend, DHW systems are now often responsible for 50% of the total energy consumption in new multi-apartment buildings, and up to 32% in new single-family homes [5,6]. As we will see later, this is not only an obvious opportunity for a further decrease of domestic energy demand, but also a source of increasing uncertainty for energy planning, because hot water demand is difficult to predict.

Among urban water management professionals, hot water is increasingly considered as a critical aspect of the water-energy nexus – the intimate inter-relationship between water and energy along the urban water cycle. The production of hot water for domestic uses in buildings accounts for the vast majority of the energy consumed across the water cycle, from water supply to treated wastewater disposal [5,7,8–11]. However, most efforts related to the water-energy nexus still typically focus on water treatment and transport, thereby disregarding DHW as it lies outside the typical scope of urban water studies. We see that, regardless of the perspective – building sector or urban water management – we need a fresh look at the opportunities of optimizing DHW systems in buildings, transgressing conventional system boundaries of professional communities.

Urban water as well as building energy professionals have important, but different competences for optimizing the water-energy nexus in buildings. The objective of this short communication is to show that only by integrating the competences and perspectives of both groups – and others – will truly sustainable solutions be achieved, which do not lead to problematic trade-offs. We first show that the optimization of DHW systems must be seen as a complex multi-scale and multi-disciplinary challenge. We then present detailed examples of knowledge integration attempts that have produced important insights regarding water...
demand models for building simulations and wastewater heat recovery. Finally, we highlight how these attempts must be expanded towards other disciplines to generate systemically good solutions.

2. Optimizing DHW systems as a multi-scale, multi-disciplinary challenge

From hot water production to wastewater treatment, energy-related and water-related issues coexist and interact; be it in the household or in the area of urban water management. We selected here four foci of interest to illustrate the necessity of integrating different perspectives: (i) hot water production, (ii) hot water distribution, (iii) hot water use, and (iv) heat recovery.

2.1. Hot water production

Within a household, the same technology often supplies heat for both DHW and SH. Optimizing strategies typically target a reduction of the primary energy consumption (energy efficiency) and/or a reduction of greenhouse gas emissions – for instance for fuel substitutions. Over the last decades, the efficiency of widely used oil or gas boilers has increased significantly, with modulating and condensing boilers as flagship examples [12]. The trend, however, is to avoid fossil fuels through the use of air-, water- or ground-sourced electric heat pumps [13,14], the integration of renewables like solar, wind or biomass [15], the development of district heating networks [16,17], and perhaps most importantly an increased hybridization of all of the above [18]. Integrating DHW and SH may be challenging for some of these systems due to large differences in the required water temperature for DHW and SH as well as uncertainties regarding hot water demand. From an energy point of view, it is attractive to select the lowest possible DHW temperature [19], but as we discuss in more detail in Section 2.2, this generates risks from a hygienic point of view.

2.2. Hot water distribution

Only little literature is available on heat loss from hot water distribution systems (i.e. plumbing layouts) although thermal losses from stagnating hot water in the pipes are significant [20]. Cholewa et al. [21] estimate heat losses to range from 20 % of the DHW energy loads for typical single family homes (SFH) to 70 % for multi-apartment buildings with a circulation system. Recently, Marini et al. [22] have estimated heat losses from dwellings in the UK between 4 % of the DHW energy loads – for a combi-boiler system – and 31 % – for a regular boiler with storage tank –, showing that short tap draw-offs were responsible for most of the wasted heat. Our own modeling efforts [23] confirm this mechanism. Many assume that heat losses are recovered naturally for space heating. This may be partially true during the heating season, but even then Bøhm [24] found that only about 30–40 % of the losses were recovered for SH. We still lack a complete understanding of the dynamics of heat losses within hot water distribution systems, but the evidence suggests a large potential for energy savings, especially in multi-apartment buildings.

Heat losses from hot water pipes increase with the hot water temperature. Besides important design choices regarding the plumbing layout [25], a reduction of the DHW temperature would thus be an intuitive solution to save energy. However, growth of *Legionella pneumophila*, bacteria causing the Legionnaires disease, is a major issue in low-temperature setups – and of rising concern in recent years [26,27]. The reason is that 25 – 55 °C is the optimal temperature for the growth of *Legionella*. In the standard proposed by BRE/ASHRAE [28], the temperature of water should be above 60 °C at the hot water heater outlet, above 51 °C at the coldest point across the entire hot water distribution system, and should not exceed 25 °C in any cold water pipe. Another obvious measure, the better insulation of pipes, equally leads to hygienic risks, because it increases the time the temperature in the cooling pipes is kept in the critical temperature range [29]. In multi-apartment buildings, recirculation systems prevent cooling, with the dual purpose of securing hygiene and providing hot water to the consumer within the time span prescribed by the authorities (roughly 10–12 s). This leads to a high energy-demand, from heat losses but also for pumping. A Swedish start-up company, 3EFlow1, proposes to replace (part of) recirculation systems by emptying the DHW pipes during times of no-use. This is an interesting technology with a high potential for energy reduction, but to the best of our knowledge, the hygienic implications are not yet fully understood.

2.3. Hot water use

Reducing warm water demand is arguably the most effective way to reduce the energy consumption of DHW systems [30]. With changes in consumer behavior or through the installation of low-flow appliances, energy savings in the range of 9 % to 63 % are assumed possible [31–34]. In the U.S., energy and water efficiency regulations on clothes washers, dishwashers, showerheads, and faucets have reduced annual water withdrawals from the public supply by approximately 13 % in 2020 [35]. However, the importance of user behavior makes predictions difficult. This is highly important for energy planners and often result in a performance gap between predicted and observed effects of optimization measures. In the literature, we find many examples of mismatching predicted and observed energy consumption patterns, especially for the retrofitting of existing buildings – see, e.g., Branco et al., [36] for a review. The performance of energy efficiency upgrades is the result of an interaction between the technical potential of a building and the behavioral potential of the occupants [37]. Although this interaction is rather well studied in the literature, the performance gap issue is proof that standard methods for the modeling of occupants behavior in a building can still be improved [38]. Among other factors, the rebound effect – a behavioral response offsetting some of the benefits of an implemented technology or measure – plays an important role [39]. In practice, the rebound effect could significantly limit the performance of water-saving strategies in households. For instance, users tend to take longer showers upon implementation of a low-flow faucet, thereby reducing the theoretical energy-saving potential by 15 % [31]. To help reduce energy demand in buildings, many authors have suggested in-home displays (IHDS), informing users about their energy demand. In a recent intervention study, Canale et al., [40] showed that an IHD could counteract the rebound effect for showers.

2.4. Wastewater heat recovery

Heat recovery strategies expand the spatial context of DHW system optimization by making use of waste heat contained in the wastewater at multiple locations along the urban water cycle, from water appliances in the household to receiving waters at the outflow of the wastewater treatment plant (WWTP) (Fig. 1). Wastewater heat is a stable, year-round resource [5] and was recently acknowledged by the European parliament as a renewable energy source, highlighting the importance of wastewater heat recovery as part of the general energy transition [41].

In-sewer wastewater heat recovery benefits from large wastewater volumes. A mature field, many full-scale projects have been

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1 https://www.3eflow.com (accessed 04.05.2022).
implemented around the world since the 1980s [42–48]. However, sewer heat recovery suffers from several drawbacks. First, the wastewater temperature is affected by cold groundwater infiltration as well as rain events [49], thereby reducing the attractiveness of wastewater for heat recovery as its exergy – the “available” energy – is often low. Second, sewer-level heat recovery affects the performance of nitrification and, indirectly, denitrification processes at the WWTP downstream [50]. Authorities regulate the heat extraction to keep the wastewater temperature at the treatment plant at or above the design temperature, often 10 °C [51]. This reduces the recovery potential from wastewater – especially in winter, i.e., when needed the most.

Heat recovery from the effluent of wastewater treatment plants mitigates risks related to low wastewater temperature. In fact, reducing the temperature of the treated wastewater before discharging it into receiving waters (e.g., lakes or rivers) is beneficial for the ecosystems [51]. Similarly to in-sewer heat recovery, heat recovery from the outflow of WWTPs is widely implemented. However, effluents of treatment plants are often rather far from potential heat consumers, thereby inducing large heat losses during transport and additional costs [52]. Additionally, as for energy recovery at sewer level, Spriet et al., [53] highlighted potentially large temporal mismatches between heat recovery and heat demand in the vicinities of the WWTP – i.e., the heat recovery potential is largest in summer, when heat demand is small.

In-building wastewater heat recovery is a relatively new field of study. One of its main advantages is the availability of high-temperature wastewater streams, especially greywater (all domestic sources excluding the toilet). The use of heat exchangers and heat pumps is thus straightforward, oftentimes with a temporal and spatial match: heat is recovered close to the point of use and when the consumer requires it [6,54]. However, in-buildings heat recovery is a decentralized and small-scale process. A generalized deployment of the technology may be slow unless production and adoption are scaled up, because price reductions only occur with mass production. As we will show in Section 3, in-building heat recovery is also a field where water and energy specialists strongly depend on each other.

3. Facilitating knowledge integration for the optimization of DHW systems

We have seen above that conflicts of objectives may arise when attempting to optimize domestic hot water systems. Some of these conflicts can be approached simply by communication and regulation (e.g., temperature requirements for boilers and hot water pipes in households). However, in order to achieve real progress and reduce the energy footprint of DHW systems, there is a need to integrate perspectives from different groups of professionals, primarily from the energy and water sector, but also from other sectors as we will show below. In this context, the new modeling framework WaterHub is an attempt to facilitate the integration of perspectives from different fields [23,55]. The framework, used alone or in combination with specialized modeling tools from various fields, can provide the – for now missing – quantitative basis to assess whether proposed solutions to reduce the energy footprint of DHW systems are systemically reasonable. In the next paragraphs, we give concrete examples of what is meant with knowledge integration and discuss future lines of research that could embody this vision.

Water demand and DHW technologies. Accounting for the inherently stochastic and dynamic nature of water demand in buildings is critical to assess the performance of DHW technologies. Water professionals have experience of coping with the natural variability of water use [56–58], and we have used the WaterHub framework to integrate this knowledge with more traditional building performance simulation (BPS) methods. In Hadengue et al., [59], for instance, we have combined a realistic water demand model with a BPS tool [60] for an in-depth assessment of a greywater heat recovery technology for air-source heat pumps. Where performance assessments of active greywater heat recovery systems using simple water consumption models showed remarkable efficiencies [6], our study using more realistic water usage dynamics and building configurations challenged these conclusions. The realistic description of water usage dynamics also proved critical in [30], where the WaterHub framework was used to assess five different DHW technologies and their combinations under realistic, dynamic water demand profiles. Thanks to insights into the system thermodynamics, we were able to identify and provide a rough quantification of inter-technology interactions, i.e. technologies either competing or working together in synergistic patterns. The study of interactions is critical to optimize the integration of technologies in the system not only at the building level, but also at the catchment level, as researchers have shown that in-building technologies could influence the performance of in-sewer technologies – for instance a wastewater heat pump [61].

The studies described above are first steps towards the closer collaboration between water and building experts we advocate for. However, with individual behavior at the core of the underlying uncertainty in DHW loads, this is not sufficient. To make predictions on the performance of optimizing measures to reduce the energy footprint of DHW systems, notably due to phenomena
like the rebound effect described in Section 2.3, the models must be extended. Behavioral scientists have tested nudging technologies, e.g., in-house displays (IHDs) presented in section 2.3 [40]. Such nudging could be an integral part of energy planning and therefore integrated on platforms like the WaterHub framework, possibly improving the predictability and effective performance of energy-saving technologies like low-flow devices. The necessity to integrate behavioral knowledge is also obvious for on-site heat recovery from wastewater. Although effective, technologies like shower drain heat exchangers, which recover energy from warm shower water to heat up cold influent water, could suffer from behavioral rebound effects, leading to reduced performance and consequently longer pay-back periods.

Heat recovery and wastewater treatment. Wastewater heat recovery is not a neutral process for the urban water cycle, requiring an extension of the sensible system boundaries to the catchment scale. We know that low temperatures may negatively impact nitrification processes at the treatment plant [62]. Reduced nitrification in wastewater treatment does not only lead to increased emissions of ammonia into the receiving waters, but can also be linked to increased emissions of N₂O, a potent greenhouse gas [63,64]. It is currently not possible to predict how a temperature decrease due to heat recovery upstream of the wastewater treatment plant may influence this behavior. The issue of N₂O emissions, still not fully understood, is an additional indication that energy and water professionals should collaborate closely to ensure that climate change mitigation efforts on one side – heat recovery – are not canceled out by new issues on the other – N₂O emissions in the WWTP. In this context, we have used the WaterHub framework as the interface between BPS tools and urban water simulation tools like SWMM-HEAT [65] to simulate the fate of wastewater temperature from the household tap to the WWTP and quantify the influence of in-building heat recovery on wastewater temperature at the plant inflow [66]. Despite a rather conservative approach, we observed that in-building heat recovery led to a close to negligible effect on the temperature at the entrance to the WWTP: the average temperature drops only by 0.3 K in the most extreme scenario. Compared to sewer-level heat recovery, the thermal impact of in-building heat recovery on the treatment plant is only half what it would be if the same amount of heat was recovered in the sewer line just before the WWTP. At the core of this result is the “thermal damping” effect – a thermal disturbance upstream will be “damped” at the other end of the network because of the non-linear thermal processes at stake in the transport of wastewater. Although observable across the entire network, thermal damping is most pronounced in private sewers connecting buildings to the public sewer network, often neglected in urban water management studies because they belong to the house owners and not to the municipality. The damping effect was also observed by Golzar and Silveira [67], who used a data-driven model (without a specific focus on private sewers) to quantify the impact of in-building heat recovery on the available heat budget at the WWTP in the city of Stockholm. Confirming the finding, Saagi et al. [68] showed that in-building heat recovery would have a negligible effect on wastewater temperature at the WWTP in the Swedish city of Linköping.

Next steps in the building/urban water engineering integration should be the pursuit of optimal locations for in-building and in-sewer recovery of heat along the urban water cycle, maximizing heat recovered upstream of the WWTP without influencing treatment processes. We suggest that it is generally safer to recover heat at the system’s extremes: in households or at the outflow of the WWTP.

The Legionella issue. The WaterHub framework was designed as a platform to facilitate the integration of various knowledge and disciplines towards low-energy DHW systems. As we have seen above, first steps were made, but additional perspectives should be integrated in the future. One of them is hygiene: Legionella pneumophila is of rising concern in many countries, with potentially severe consequences for an ageing society (see Section 2.2). On the one side, energy professionals are looking to different countries in order to find the most favorable regulations for energy savings and develop new technology to adapt to such regulations [19]. On the other, microbiologists are trying to understand whether microbial adaptation has led to more pathogenic strains over the last decades [69,70]. Both approaches have been successful, but their integration – for instance as part of a common modeling platform – could prove a giant leap forward. Energy professionals, with their understanding of building and hot water system topologies, can help microbiologists to analyze specific Legionella strains under relevant DHW topologies and configurations. Microbiologists on their side can provide critical insights, preventing technical developments leading to high-risk situations from a hygiene perspective. We also argue that it may be sensible to integrate knowledge from water experts: the dynamics of Legionella growth may depend on water demand patterns (short draw-offs, infrequent long events, etc.). The inherently stochastic nature of water consumption is thus an additional dimension of the Legionella issue. The WaterHub framework may be a useful platform in this context: we could, for instance, combine existing models simulating the infection risk of Legionella [71,72] with realistic water demand models as well as various DHW technologies and system topologies included in the framework. For example, different control strategies for circulator pumps could be evaluated from both energy and Legionella perspectives.

We hope to have shown from the examples above that resolving these issues is possible if professionals from various sectors collaboratively address these challenges. One obvious challenge of this call for multi-disciplinarity is to find ways to incentivize collaborations and to break “knowledge silos” that limit possible exchanges between disciplines. We think that the modeling platform approach may ease the process by streamlining the integration of people, methods and vocabulary of either field. However, help from the vast research on multi-disciplinarity will be critical for success [73]. We also note that, for the sake of brevity, we have hardly touched upon one critical dimension: economics, which could as well be integrated into existing (modeling) frameworks. Water-related energy challenges in domestic hot water systems are intrinsically multi-disciplinary and multi-scale. The main message of this short communication is that they should be tackled quantitatively and with a holistic mindset. The WaterHub framework, showcased in some of the examples above, is our attempt at designing a platform able to operationalize this mindset.

4. Conclusions

After remarkable efforts made to decarbonize and reduce the energy required for space heating in our building stock, reducing our energy footprint further requires us to tackle challenges of the water-energy nexus – the intricate relationship between water and energy. These challenges are, by essence, multi-scale and multi-disciplinary. We advocate for a greater collaboration and integration between professionals of the relevant fields: urban water experts, appliance and building energy and water professionals, and microbiologists among others. We showed in this short communication that multi-scale and holistic modeling approaches have already proved useful in water-energy investigations: realistic water demand profiles from the water sector challenge conclusions from the field of building engineering, hybrid models combining urban water models with building simulation...
tools inform us on the optimal location for heat recovery along the urban water cycle. To push forward the idea of knowledge integration, we suggest triggering in-depth discussions on the hygienic implications of energy-saving technologies and measures, as well as on their financial relevance. In this context, we envision a common modeling platform able to integrate tools and perspectives from all relevant disciplines.

CRediT authorship contribution statement

Bruno Hadengue: Conceptualization, Investigation, Writing – original draft. Eberhard Morgenroth: Supervision, Writing – review & editing. Tove A. Larsen: Conceptualization, Supervision, Writing – original draft.

Data availability

No data was used for the research described in the article.

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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