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The potential of wastewater heat and exergy: Decentralized high-temperature recovery with a heat pump

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ABSTRACT

There is a large potential in the heat losses from the wastewater leaving a building. We present a novel concept for recovering this heat. Instead of recovering it in a mixed state, the recovery immediately after use is evaluated. This allows the exploitation of the higher temperatures found at the points of warm water usage. By integrating a heat pump to utilize this heat, we can produce a higher temperature heat supply while maintaining a low temperature-lift requirement. This leads to the possibility of directly regenerating the hot water supply through wastewater heat recovery. The concept is a result of research into low exergy building systems, and is part of the IEA ECBCS Annex 49. We have modeled the annual performance of two different system scenarios, which result in a potential average annual coefficient of performance (COP) of over 6. The first scenario supplies up to 4400 kWh of heat for all hot water events with only 790 kWh of electricity, while the second scenario regenerated directly the hot water supply just for bathroom fixtures at 2400 kWh with just 410 kWh of energy. This is a significant reduction in the demand for hot water supply of a building compared to most modern installations.

1. Introduction and background

There is a great impetus to change the way buildings are designed and built. At present, the building sector is directly or indirectly responsible for around half of global greenhouse gas emissions when considering the construction, maintenance and operation of buildings [1]. Buildings are responsible for the consumption of two-thirds of all electricity produced and one-third of global waste production [2]. This impact can be reduced by either increasing the sustainability of the energy supplied through increased renewable supply, or by decreasing the demand through improved building performance. There have been significant strides in reduction of demand through increased efficiency in recent years, but the primary focus has only been on heating and cooling systems. Hot water supply is often overlooked. It is becoming common for high performance buildings to be extremely airtight and well insulated, and to have systems such as exhaust ventilation heat recovery. These buildings, such as Passivhaus designs with less than 15 kWh/m^{2}a of heat demand [3], have very low space heating demand, but there remains a significant hot water demand in the range of 50 kWh/m^{2}a [4]. In this study, we present a new method to potentially reduce energy demand by reducing the energy required to supply hot water.

When we observe the ratio of hot water energy demand compared to space heating and other sources as shown on the left of Fig. 1, it is usually only 10–20% for typical house from the late 20th century [4]. But as we move to more high performance buildings, we see that the hot water heat demand is rarely impacted by improvements in performance, and it becomes a significant, if not a major, fraction of the demand [3].

Not only is hot water a significant demand, but also the wastewater flow has a exergetic value as shown on the right in Fig. 1 [5–7]. Water has a high heat capacity and density, so wastewater provides a concentrated source of heat. Also, hot water usage is at a high temperature, in the range of 40–50 °C. By using exergy analysis, the appropriate value can be given to heat sources like wastewater, which considers the value and potential of their temperature and not just their relative quantity of energy [8]. This leads us to the development of integrated systems that minimize temperature gradients and temperature losses, and thus exergy and not just energy losses, which facilitates the minimization of the building system primary energy demand [5,6]. A comprehensive review of such systems is available [9], and methods for application of exergy analysis for building systems have been reviewed [10], and presented in case studies [11], including exergy analysis of hot water production with heat pumps [12].

In this study we demonstrate the potential of integrating a heat pump directly into the heat recovery from wastewater.

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Nomenclature

Symbols

IEA	Intenational Energy Agency
ECBCS	Energy Conservation in Buildings and Community Systems
COP	coefficient of performance
DHW	domestic hot water
En	energy (J)
Ex	exergy (J)
Q	heat (J)
W	work (J)
t	time (s)
T	temperature (K)
V	volume (m^3)
UA	overall heat transfer coefficient (W/m^2 K)
cp	specific heat capacity (kJ/kg K)
rho	density (kg/m^3)

Indexes

empty	signifies a point where the recovery tank empties
old	signifies a value from a previous event
new	signifies a value from a new event
add	signifies an input value
in	signifies a value for inside
out	signifies a value for outside
hx	heat exchange value
0	value for the dead state
h	signifies the hot value
c	signifies the cold value
ave	average value
demand	demanded by the system and must be supplied
supply	the value supplied by the system
mains	value for the input from the municipal water

Past studies have shown a significant potential for grey water heat recovery [7], and also how a significant amount of energy and exergy can be recovered from wastewater [13,14]. This high temperature recovery integrated with heat pump operation has the potential for increased performance that can be missed in large-scale centralized systems that are based on energy analysis alone [15,16], because the exergetic value of the source temperature is recognized. For example, large-scale installations of heat recovery from municipal sewers [15] may capture the same energy flux leaving buildings, but it does so at a much lower temperature than the hot water usage temperature. Instead of just recovering waste energy, we exploit the waste exergy, which incorporates the value of higher temperatures, and we can maximize the potential of this exergy with a heat pump.

The ability of a heat pump to operate with high performance is illustrated in Fig. 2. The coefficient of performance (COP), which is the ratio of heat delivered to energy demand (usually electricity input for residential heat pumps), is dependent on the difference between the temperature of the heat source from which the heat pump acquires heat and the temperature at which the heat pump supplies heat to the building, otherwise known as the temperature-lift. As the temperature-lift drops below 20 K the COP increases rapidly as discussed in [5,6], reducing the energy demand.

Fig. 2 demonstrates how low exergy building systems strive to reach performance levels that result in temperature-lifts for the heat pump below 20 K and a COP above 8 [5,6]. For space heat and cooling, this can be achieved with properly designed low temperature heating and high temperature cooling systems as described in the IEA ECBCS Annex 37 [18]. The higher temperatures needed for hot water supply make achieving a low temperature-lift more difficult. Existing systems utilize exhaust air as higher temperature source for domestic hot water heat pumps [19], but this is limited in power and the temperature-lift is still between 20 and 40 K. As part of our contribution to the IEA ECBCS Annex 49 [20] we developed this concept to minimize the temperature-lift for heat production at a temperature capable of producing hot water.

2. Methods and analysis

2.1. System overview

The system we have devised is a simple heat recovery tank that accepts the outgoing warm wastewater. This could be connected, for example, to the shower/bath and clothes washer in a typical home. It could also be easily incorporated into a grey-water recycle system that accepts all warm waste flows in a high performance building as shown on the right of Fig. 1. In any case, we want to include the potential separation of warm sources from the cold source of toilets so we can observe the highest potential performance.

The recovery tank accepts the wastewater and a heat exchanger supplies the heat to the heat pump. The heat pump lifts the temperature of the recovered heat to a sufficient level to generate new hot water. The heat pump performance is dependant on this temperature-lift, and at lifts below 15 K, more than 10 units of heat can be moved with one unit of energy input [17], thus operating with a coefficient of performance (COP) of more than 10.

2.2. Input data sources

The modeling of wastewater heat recovery presents several obstacles. First, appropriate input data has to be generated or acquired based on highly variable water usage statistics. Because wastewater heat is almost never considered, there are no statistics available for temperature and output of the wastewater itself. Therefore, the model must depend on data for hot water usage, and then calculate a subsequent wastewater output.

The hot water usage statistics often lack the resolution or characteristics necessary to properly evaluate the potential to recover the wastewater. For the recovery, it is necessary to accurately produce an event time and duration so that the recovery can be accurately modeled for multiple events throughout the year. This requires data for the sources of water usage and their temperature, duration, and flow rate. Most of this type of data is available for solar hot water system design and modeling [21]. There is some niche software available for producing hot water event schedules, which was used in some previous work [22]. The input for our model used a dataset that was generated by the National Renewable Energy Laboratory (NREL) [23].

The input data were available for the annual use of baths, showers, sinks, clothes washers and dishwashers for a typical 2-bedroom, 3-bedroom, or 4-bedroom home. The data accounts for typical annual load profiles of the events as well as statistical probabilities of clustered events, such as showers in the morning. This is important to consider for the heat recovery during higher usage periods like the morning.

This model is a new version, which unlike previous versions [13,14], is not based on a dataset with fixed time-steps. Instead of having a continuous time variable on the order of a few minutes for the entire year, the events are modeled with a time stamp, duration, flow-rate and fixture-type. This smaller dataset allows each event to be modeled in a single iteration and allows events for various fixtures to be more easily filtered out.

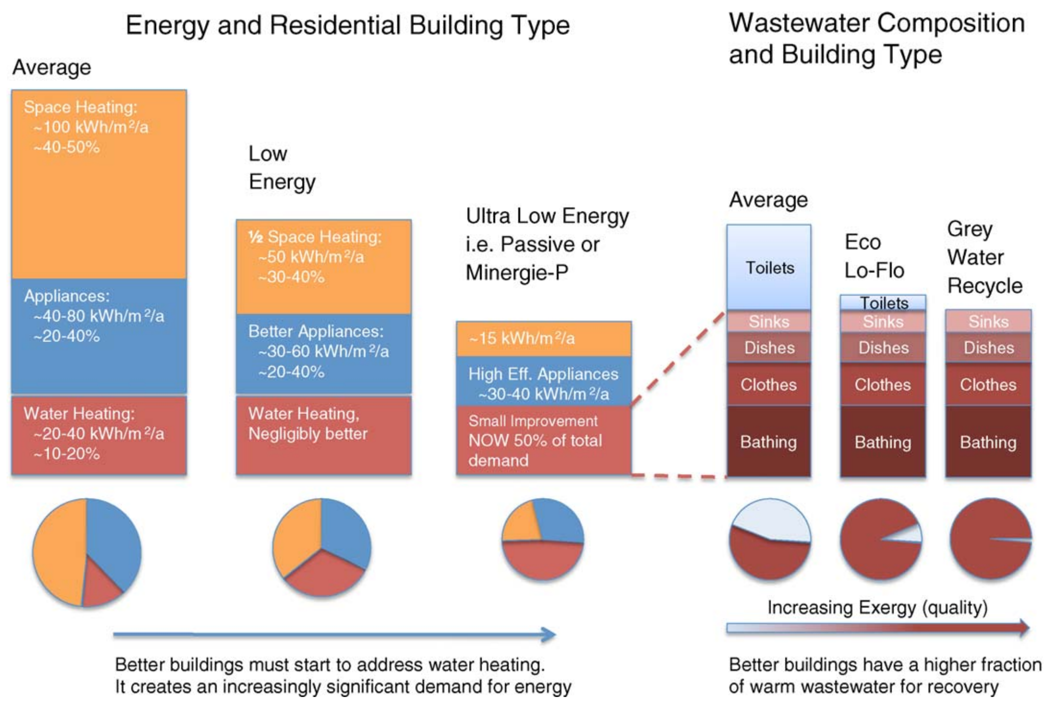

Fig. 1. Hot water energy demand and exergy potential. Illustration of the significant increase in the hot water fraction of total energy demand for buildings as building performance increases (left) [3,4], as well as the increasing quality of wastewater as improved sanitary installation are used (right) [5–7].

2.3. Heat recovery model

The setup for the heat recovery system has been upgraded from previous work [13,14] to use a tank with the heat exchanger installed in the walls. This was selected rather than the spiral heat exchanger immersed in the fluid due to the potential problems with bio-film buildup, and the goal of facilitating a cleaning function. The heat capacity and density, *cp* and *rho*, respectively, are assumed to be standard values for water, 4.2 kJ/kg K and 1 kg/L, respectively. This tank design required a range of heat transfer coefficients for water in a cylindrical tank to be considered. These were determined using standard free convection models for the range temperatures used in the model [24]. These ranged from about 50 to 200 W/m^2 K.

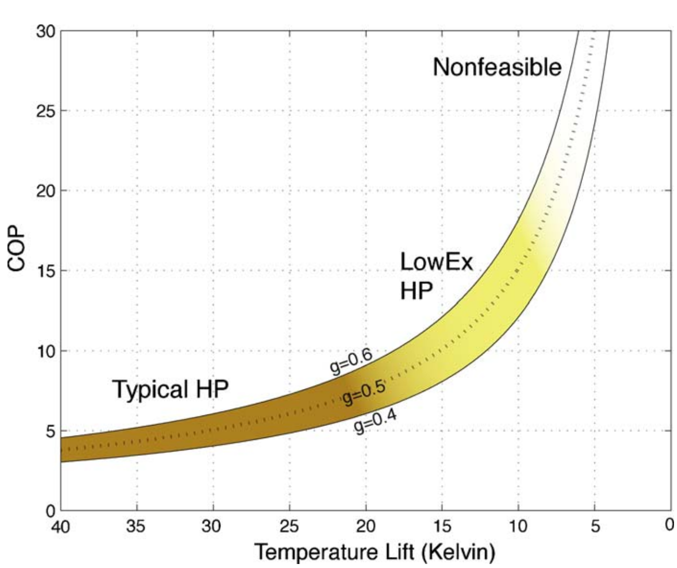

Fig. 2. COP versus temperature-lift. Plot showing the change in COP of a heat pump as the temperature-lift is decreased. A range of Carnot efficiencies from 0.4 to 0.6 are plotted, and the area of desired low exergy performance is highlighted [5,6].

The heat extraction from the tank is done using a new model for heat pump operation. Two versions of this model have been studied: one that recovers heat simply based on the temperature of the wastewater and one that recovers heat to directly regenerate the hot water supply system. For both versions we take a heat pump and fix its condenser temperature for the supply of hot water back to the domestic hot water storage tank. This was fixed at 55 °C, but could be varied. The evaporator temperature is set to follow the tank temperature with a temperature difference of 5 K. This type of heat pump control would be possible with an electronic expansion valve and a variable speed compressor. This allows the temperature-lift of the heap pump to vary with the tank temperature and maximize the potential COP. It also simplifies the calculation for heat extraction, as the tank temperature will fall linearly assuming a constant temperature difference between the wastewater source and the heat recovery fluid as well as a constant heat exchange surface area and heat transfer coefficient for each new event. The heat pump is assumed to operate with a Carnot factor, *g*, of 0.5, shown to be possible for heat pumps down to a temperature-lift of 10 K and a COP of 14, [17].

2.3.1. Recovery model independent of DHW demand

For each event the volume and temperature of the input to the tank are accounted for. The time since the previous event is checked against the time, t_{empty}, that it would take the tank to empty. This is calculated from Eq. (1) with a selected tank emptying temperature, T_{empty}, by using an energy balance based on the old temperature, T_{old}, the fixed temperature gradient between the wastewater and the recovery fluid, ΔT_{hx}, the overall heat transfer coefficent, UA_{hx}, and the tank volume, V_{old}. If the there is sufficient time since the last event, then the heat extracted and exergy extracted from the last event are calculated using Eqs. (2) and (3) where T_{in} is the intial temperature of the tank and T_{out} is the emptying temperature of the tank, T_{empty}. If the time, t_{empty}, is greater than the time since the last event, t_{event}, then it is still extracting heat from a previous event when the next event occurs. In this case, the new partially cooled temperature, T_{new}, of the previous event is calculated based on the heat extracted since it was added to the tank using Eq. (4). Also the energy, *En*, and exergy, *Ex*, extracted are recorded since the event was added, again from Eqs. (2) and (3). The new temperature, T_{new}, of the old event is then used to determine the new combined temperature of the tank, T_{tank}, using the energy balance in Eq. (5), where V_{add} is the new volume added to the tank and V is the actual volume total for the event, in this case the combined total.

$$t_{empty} = \frac{(T_{old} - T_{empty}) \times cp \times rho \times V_{old}}{(\Delta T_{hx} \times UA_{hx})} \tag{1}$$

$$En = cp \times rho \times V \times (T_{in} - T_{out}) \tag{2}$$

$$Ex = cp \times rho \times V \times (T_{in} - T_{out} - T_0 \times \log(T_{in}/T_{out})) \tag{3}$$

$$T_{new} = \frac{T_{old} - \Delta T_{hx} \times UA_{hx} \times t_{event}}{(cp \times rho \times V_{old})} \tag{4}$$

$$T_{\tan k} = \frac{(T_{in} \times V_{add} + T_{new} \times V_{old})}{V} \tag{5}$$

Once all the iterations have been completed we have a dataset containing the temperature and duration of each event. We have designed our system to minimize the heat pump temperature-lift by having the evaporator temperature follow the tank temperature. We know the amount of heat recovered and its temperature so we can now calculate the COP of the heat pump, and its subsequent potential heat supply and work demand.

The heat recovered, Q_c, calculated in Eq. (6), is constant throughout each event because of the constant recovery tank heat exchange temperature difference, ΔT_{hx} and the constant overall heat transfer coefficient, UA_{hx}, based on the free convection models [24] and surface area from the tank volume and geometry. The total energy recovered, Q_c, is also dependent on the time, t, of recovery, which is either the time it takes to empty the tank, t_{empty}, or the time between events, t_{event}, in the case that there is an overlap. The COP is a ratio of higher temperature heat supplied, Q_h, to work input, W, but also based on the 2nd Law of Thermodynamics can be defined as a function of the Carnot factor, g, and its temperature-lift, ΔT, as in Eq. (7). We have fixed the warm heat pump supply temperature, T_h, so the only time-dependent variable is the cooler evaporator temperature, T_c, for recovery, which can be defined linearly as above in Eq. (4) for T_{new}. Therefore we can integrate the COP function over the duration, time, of each heat recovery event to determine the actual average operational heat pump COP, COP_{ave}, over that time period, Eq. (8).

$$Q_c = \Delta T_{hx} \times UA_{hx} \times t \tag{6}$$

$$COP = \frac{Q_h}{W} = 1 - \frac{Q_c}{W} = g \times \frac{T_h}{(\Delta T)}, \quad \text{where } \Delta T = T_h - T_c \tag{7}$$

$$COP_{ave} = g \times \frac{T_h}{k1} \times \frac{[\log(T_h - T_c + k1 \times t) - \log(T_h - T_c)]}{t} \tag{8}$$

where $k1 = (\Delta T_{hx} \times UA_{hx})/(rho \times V \times cp)$.

From the operational COP we can then take a time-weighted average over the year and determine the annual performance. This also allows us to determine the amount of heat that can be supplied and what amount of work (i.e. electricity) it will take to supply that heat using the heat pump as calculated in Eqs. (9) and (10).

$$W = \frac{1 - Q_c}{COP_{ave}} \tag{9}$$

$$Q_h = COP_{ave} \times W \tag{10}$$

Based on the input data for hot water usage we also know the amount of heat supplied at each event, and thus the amount that needs to be replaced in the hot water storage. This is calculated in Eq. (11). It is based on the volume of hot water supplied and its temperature compared to the temperature of the cold water supply from the municipality mains, which varies over the year and for different locations. We used an arbitrary sinusoidal function for the mains temperature taken from the US DOE data [18]. With this calculation we can then compare the potential recovery of heat using the heat pump to the heat supply, Q_{demand}, that would be demanded for the actual hot water being used based on the volume added at each event, V_{add}, the temperature of each supply event, T_{supply}, and the mains temperature, T_{mains}.

$$Q_{demand} = cp \times rho \times V_{add} \times (T_{supply} - T_{mains}) \tag{11}$$

This first application of the model works for the case when there are flexible heat demands and/or heat storage opportunities within the building, because the heat supply is independent of any specific demand. For example, it could be representative of a full grey water recycling system where all non-toilet flows are captured. The amount of heat recovery is dependent on the set point at which the heat recovery tank is emptied. In this model an emptying temperature, T_{empty}, is chosen as the set point. The higher that temperature, the less heat is going to be extracted, but the higher the average COP because the heat pump will have a higher average source temperature, and thus a lower average temperature-lift.

2.3.2. Recovery model connected to DHW demand

The second version of the model involved an extension to match the heat recovery to the hot water demand. This eliminates the arbitrary emptying temperature, T_{empty}. Instead of selecting an emptying temperature, the system is set to run until hot water supply is regenerated using the recovery system heat pump. Specifically, the wastewater heat recovery supply from the heat pump, Q_h, is matched to the heat demand for hot water supply, Q_{demand}. In order to determine the time needed to extract this amount of heat supply, an iterative solver is employed to find a solution to the non-linear equation setting the demand, Eq. (11), equal to the heat supply, Q_h, Eqs. (8)–(10). This determines the time necessary for the system to run and the subsequent values of the average COP, heat recovery, heat supply, and work input. The extraction time is again checked for overlap with subsequent hot water events, and is combined with potential overlapping events in the energy balance described above. Thereby, we are able to evaluate the performance of a system that is designed to operate to exactly match the heat demand for hot water and replenish the hot water supply storage tank directly.

We can also use the recovery performance to optimize the parameters of the tank design. The design variables that impact the performance are the tank geometry and volume as well as the temperature at which the tank is emptied. The avoidance of overflows in the recovery tank as well as of complete emptying of the hot water supply tank are also considered. The model itself has been run iteratively to explore the impact of varying these parameters on the overall performance.

One of the principle variables to investigate is the sensitivity of the performance of the system to variations in the heat transfer rate, UA_{hx}, of the recovery tank with the heat exchanger in the walls. The heat transfer rate is calculated based on simplified models of cylindrical tanks filled with water experiencing free convection [24], which provide only rough estimates. The heat transfer rate can also easily be influenced by changes in the tank design and shaping. The walls of the tank could be designed to slightly improve the surface area, or the shape of the tank could be modified. These potential changes would all influence the heat transfer coefficient and thus variation in the parameter and the subsequent influence on system performance was evaluated.

3. Results and discussion

3.1. Recovery model independent of DHW demand

The initial model that analyzed the potential for heat recovery, which would be independent of a defined demand, resulted in an annual average COP ranging from 5.5 to 7.5. The COP results were similar across the range of 2, 3, and 4 bedroom residence datasets. The COP range was dependent on the temperature chosen at which the tank emptied, T_{empty}. This temperature was varied from 15 to 30 °C. At lower temperatures, it is possible to recover more heat than is actually used to supply the hot water itself. This is due to the additional input of the work of the heat pump, as shown in Fig. 3, which plots the performance over a range of emptying temperatures. A larger amount of heat can be recovered when the wastewater is cooled to lower temperatures, but the performance, defined by the average COP, is higher if the emptying temperature is higher.

Fig. 3 demonstrates how the higher temperature recovery benefits the average performance of the system. This can be viewed by comparing the energy recovered from the tank to the exergy recovered. In both cases the total amount is reduced as smaller amounts of heat are recovered, but as seen in Fig. 4 the percent of exergy recovery remains higher as the temperature of recovery increases. This difference is caused by the increase in average recovery temperature, which also results in the increase in COP in Fig. 3. The analysis of the exergy recovery from the tank [13,14] allowed us to initially observe the higher potential of decentralized wastewater heat recovery, and to subsequently connect a heat pump to the system to take advantage of this potential.

The heat pump achieves a high level of performance across all emptying temperatures compared to typical values for hot water heat pumps [19]. For example when the tank is emptied around room temperature, at 20 °C, a heating demand of 3300, 3800, 4400 kWh/a was provided with a heat pump demand of only 550, 690, and 790 kWh/a for each residence size, respectively. This is a small amount of energy input compared to the typical energy demands for hot water that are on the order of 5000 kWh/a [4]. These relatively small electricity demands facilitate the combination with other renewable systems, such as photovoltaics, which can more easily supply this amount of electricity. At these COP levels, any PV panel with an efficiency of greater than 18% can supply more than 100% of the solar energy as heat, clearly outperforming any solar thermal system.

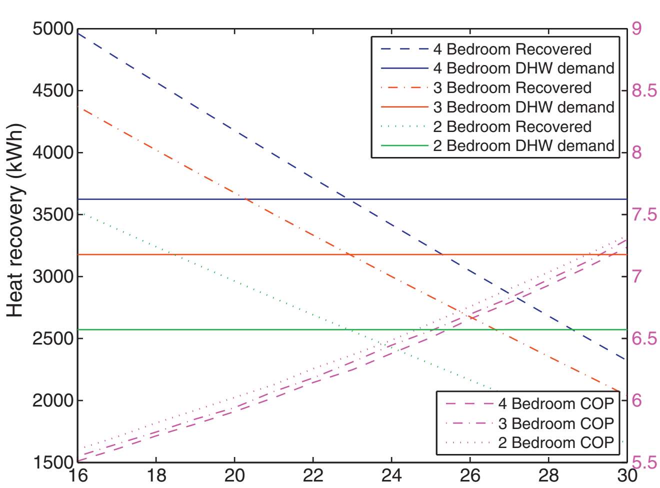

Fig. 3. Performance for varying emptying temperature. The heat recovery and COP are plotted on two axis versus the tank emptying temperature. At lower recovery temperatures, a larger amount of heat can be generated by the heat pump shown by the recovery that can be larger than the actual demand. But the average COP of the operation is lower because the overall temperature is lower.

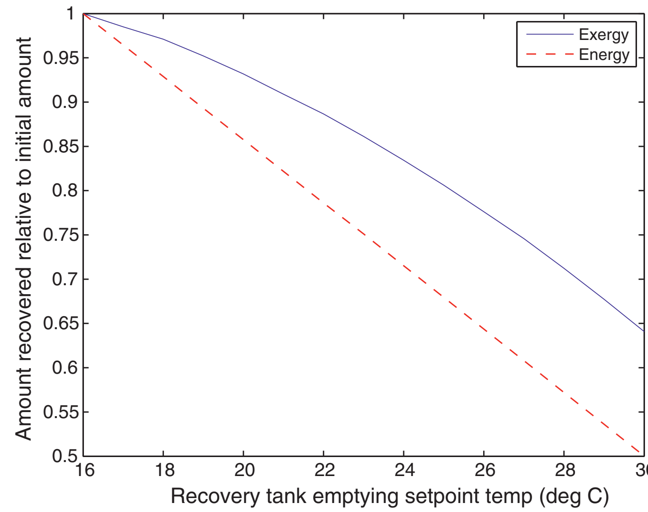

Fig. 4. Energy and exergy comparison. Plot of energy recovered, also depicted in Fig. 3, and the exergy recovered, both normalized to their initial value at a emptying temperature of 16 °C and based on the 4 bedroom dataset. The increase in average temperature of the recovery causes the exergy to retain a higher value than the energy analysis does alone.

This analysis assumes recovery using a heat pump that then supplies the heat at a higher temperature, which would be capable of generating new hot water. As illustrated above, the heat supplied from the system is independent of, and can be greater than, the actual domestic hot water heating demand. Thus, this excess heat would have to be utilized by another system or deposited in a storage system for use on a later day or in a subsequent season [6].

In the periods of many uses, there is the potential that heat is not regenerated quickly enough. This will require adequate sizing of the system hot water supply, as well as wastewater recovery tank. For the 4-bedroom dataset, a cylindrical recovery tank 1.4 m wide by 1 m high eliminates all overflow events. But this result was for a rather conservative value of the recovery tank heat transfer coefficient, which leads to a longer recovery time for each wastewater heat recovery event, increasing likelihood of overflow events and required tank size. As previously mentioned, the heat transfer coefficient is the most difficult variable to predict and depends heavily on the design. It is also influenced by the surface area and geometry of the tank so by observing its influence on the performance we have a proxy into the potential range of performance of the system. Fig. 5 demonstrates that a reasonable performance can be expected across the range of expected heat transfer coefficients for the tank system, in this case for the 4 bedroom dataset.

These results show that there is great potential for very effective recovery of wastewater heat made possible by extracting it at a higher temperature with a heat pump. In operation, the results will vary according to the details of system construction and heat transfer dynamics that cannot be predicted. Still, across the range of realistic overall heat transfer rates, a stable operation with high performance is observed in Fig. 5. More importantly, the realistic datasets and modeled operation demonstrate the potential for a performance not possible from modern hot water production systems.

A realization of this independent system could be envisioned for a centralized installation where the heat pump recovery supply provides heating for multiple demands. In this model, all hot water sources (shower, bath, sink, dish, and clothes) were used as inputs to simulate a larger installation. The heat pump could be part of a

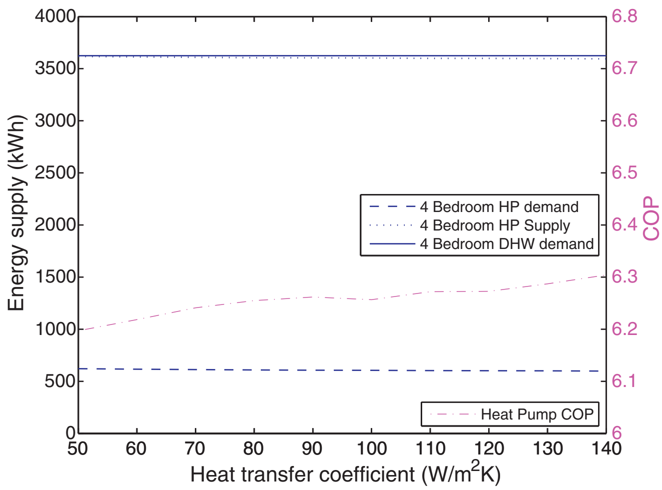

Fig. 5. Heat transfer coefficient influence. Plot showing the change in the heat pump (HP) energy demand and the supplied heat compared to the constant hot water demand for a residence. In this case the 4 bedroom dataset is plotted and an emptying temperature of 23 °C is selected so that a similar heat output to the hot water demand can be observed.

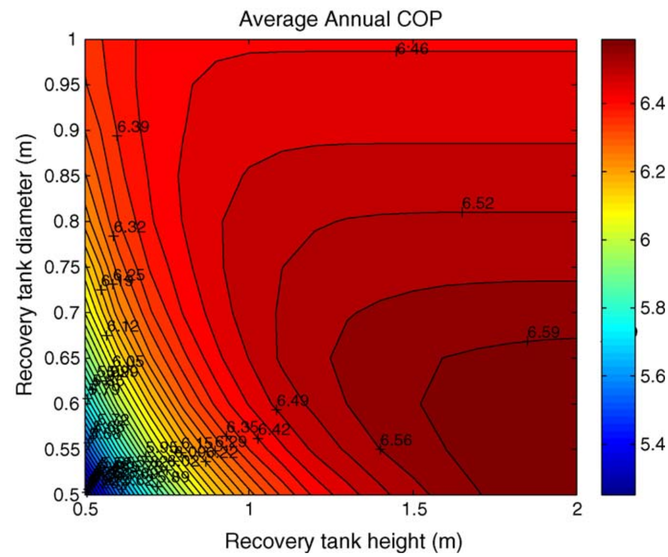

Fig. 6. Contour plot of COP for tank diameter and height. The 4 bedroom dataset is displayed to check the largest total input. The optimal operation is found around 0.6 m in diameter and 1.5 m in height, leading to a tank of about 400 L.

multistage system that also provides the base-level space heating, and if reversible, the cooling as well.

3.2. Recovery model connected to DHW demand

The model for the system that directly supplied the recovered heat to regenerate the hot water supply tank using the integrated heat pump had an average annual COP of 6.7, 6.6, and 6.5 for the 2, 3, and 4 bedroom residence datasets, respectively. The hot water heating demand for the closed system including only the typical bathroom fixtures of showers, baths, and clothes washing was 1700, 2100, and 2400 kWh/a respectively. In this case the heat provided by the heat pump is modeled to match these heating demand numbers. This demand was provided with a heat pump that demanded only 280, 350, and 410 kWh/a, respectively. Even in cloudy Zurich, this demand could be met by less than 1 m^2 of PV, and for the COP values above, if the PV has an efficiency of greater than 15%, more than 100% of the incoming solar energy can again be supplied as heat.

The closed model represents the potential scenario where the recovery tank and heat pump are built as one unit that includes the hot water supply, and they are installed within a single bathroom unit or set of stacked bathroom units in one residence. The recovery system then serves as the principle supply system for the hot water. In the model, the system recovers heat from the wastewater until the hot water supply is regenerated, thus eliminating the arbitrary emptying temperature used in the previous model.

The results were determined by first analyzing the necessary tank sizes for optimal operation. The recovery tank was sized to maximize the performance of the heat pump. This was done assuming a conservative heat transfer coefficient of 70 W/m^2 K. An optimal size of about 400 L was determined with the cylindrical tank diameter of 0.6 m and height of 1.5 m, as shown in Fig. 6.

Next the hot water supply tank was sized to minimize the events when the hot water tank is used up, because in this case we are modeling the system to provide the hot water supply as well. Fig. 7 shows the number of times per year that the supply tank of hot water runs out of water. A tank of about 400–500 L was found adequate to minimize these events to less than 10 per year for 2, 3 and 4 bedroom datasets.

Again, in this case it is interesting to observe the performance across different heat transfer characteristics, so we vary the heat transfer coefficient and observe the performance change. As mentioned, the heat demand and subsequent recovery is fixed for this model, so Fig. 8 shows the dependency of the heat pump work and COP on heat transfer performance. This was done for the optimized tank dimensions.

There is not a significant change in performance for varying heat transfer coefficients. The heat pump work is reduced by about 3–4% as the heat transfer is increased, caused by a slight increase in the average COP, but is generally more variable. Overall, the variation is small and so the expected performance can again be assumed to be possible across the likely variations in heat transfer of a real system in operation.

Another important aspect of the system operation is the relative time frame of operation when supplying hot water. The average time to recover the heat from the wastewater and restore the heat supply tank to a full state is on the order of 1.5–3 h depending on the heat transfer coefficients. This is clearly a limiting factor, and it is also a reason why the tanks need to have relatively large sizes to

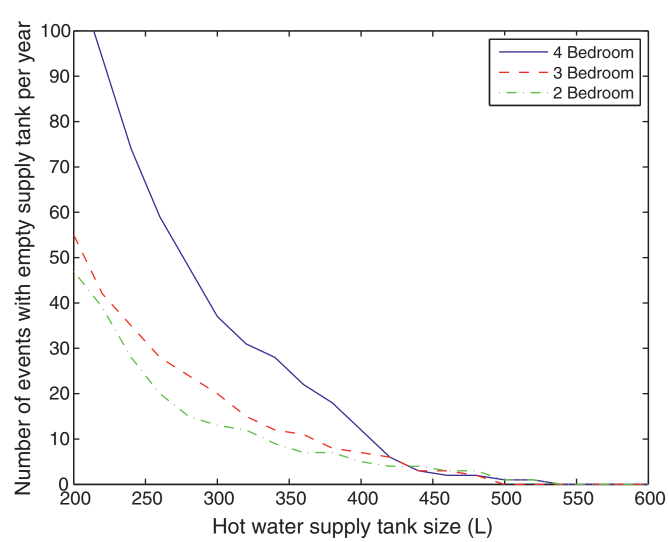

Fig. 7. Adequacy of supply recovery. Plot of the number of times per year that the hot water storage tank runs out of water. At about 400 L the number of empty tank events drops below 10, and at about 500 L there are no more empty events.

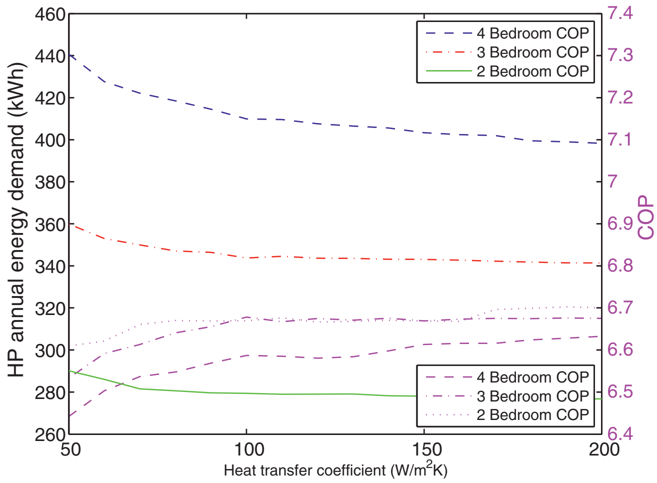

Fig. 8. Heat transfer coefficient dependency for direct recovery. The change in performance of as the heat transfer coefficient is changed for the system. The heat pump annual demand and the annual average COP are plotted.

avoid the scenario of no hot water left in the supply. For this reason, it would probably be necessary to increase the power of the heat pump supply in the case when the demand runs low. This could be achieved by increasing the temperature difference between the evaporator and the recovery supply. Assuming a programmable control is used, this could be easily added to the logic. Nevertheless, although the tank sizes are large, they are not infeasible, and can achieve an acceptable performance.

Finally, we should discuss the potential implementation and the economics of such a system. The system certainly adds complexity as compared to typical hot water heating systems today, and the cost of these new components would be higher. Nevertheless, as previously mentioned, with the integration of our heat pump into other building services where we also minimize the temperature-lift [5,6], the total cost comes down, especially relative to the overall benefits achieved for the entire integrated building operation. In practice, a small system was realized in a zero energy building in Ireland [25] based on the results of a previous study [14], and a public–private partnership supported by the Swiss government was established between one of the largest sanitary firms in Europe and the ETH Zurich to bring the system to market, but was unfortunately stopped in the wake of the financial crisis. Still, further collaboration for future prototypes are under consideration and we hope more building system designers and companies consider the potential of bringing such a concept to market.

4. Conclusion

The use of wastewater heat as a source for heating systems is not often considered. It has been previously studied and implemented, but the value of the higher temperature recovery has not been exploited, and is available only close to the point of use. We have shown that there is great potential in higher temperature extraction when the recovery is combined with a low exergy system that incorporates a high performance, low temperature-lift heat pump.

Two scenarios have been studied. One for the highly integrated case where the total recovery was evaluated for all hot water sources in the building and for an unconstrained potential storage or usage for the heat supplied by the recovery. In this scenario a COP of above 6 can be maintained when the wastewater is cooled to 20 °C. The second scenario matched the heat recovered to the actual demand for hot water heating. In this case a stand-alone system can be imagined where the heat pump and recovery tank are part of an integrated domestic hot water supply system, and a COP of greater than 6.5 was maintained for all residence datasets. In both scenarios the total electrical energy demand for the heat pump operation was well below 200 kWh/a per number of bedrooms in the household. For the 4 bedroom household the, bathroom hot water heating demand of 2400 kWh/a was met with just 400 kWh/a of energy input. These low electrical energy inputs make the integration and supply by photovoltaics more feasible.

The decentralized extraction of wastewater heat on a per residence basis provides a new opportunity to achieve hot water production performance levels above what has previously been possible. Considering the increasing fraction of total building energy demand that hot water now creates as buildings are made more efficient, it is essential that we begin to focus on reducing this demand along with the space heating and cooling demands that are presently the primary focus. By looking at the system as a whole and integrating these new high performance technologies, there is still great potential for increased efficiency, and reduced demand on fossil fuels and CO_2 emissions.

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