Heat and water recovery from wastewater in a passive house – scaling up from building to district level

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Abstract: Centralized water management is energy intensive. Therefore, energy savings and higher efficiencies are major drivers for system transformation towards innovative infrastructure solutions. Herein, heat recovery from domestic wastewater and water reuse of treated greywater are attractive system alternatives. This was analysed within the feasibility study for a passive house construction (66 apartments) and on district level (5,000 people).

On building level hot water generation accounts for 56% of the total heat requirements. 30% of heat needed for hot water generation could be retrieved from domestic wastewater, covering 19% of the basic heat load in the building. However, heat recovery is economically not self-sustaining and should be combined with decentralised greywater treatment and reuse to become economically feasible. Similar result account on district level where a separation into greywater and blackwater seems only attractive when next to heat recovery reuse of treated greywater is involved.

The paper present discusses in addition stakeholder constellations and presents business models to run such an implementation on building and district level. In order to capture the opportunities of new system solutions, new organisation models and structures need to be developed on the local level - both at the municipal administration and (municipal) local utility companies.

Keywords: energy recovery; in-house solution; water reuse; water management; stakeholder constellation, business models;

Introduction

Water management with its centralised infrastructure is energy intensive, water supply and wastewater treatment account for 0.6 kWh m^{-3} to 5.3 kWh m^{-3} (Cornel et al. 2011). Within municipalities wastewater treatment plants are known to be the largest municipal energy consumers with a share of 20% of the overall energy consumed. In addition, hot water generation is with 21 kWh m^{-3} the second largest energy consumer in households after heating (Federal Environmental Agency 2008).

Therefore, energy savings and higher energy efficiencies can be seen as major drivers for transformation towards semi- and decentralized systems (Larsen at el. 2013) when discussing innovative water infrastructure systems. From a technical perspective transformation is possible. From an economic view point it can be attractive as well to reuse water, energy and nutrients as Felmeden et al. (2011) have shown exemplarily. From an organisational and regulatory view point the usual stakeholders will have to take over new roles and responsibilities according to the specific new settings in different spatial dimensions (building level: decentral; district level: semicentral; whole city: central) and services provided.

Therefore, next step forward was to validate those theoretical calculations within a real case. This became possible in form of a feasibility study within a passive house (construction starting in July 2014) in Frankfurt am Main, Germany, containing 66 apartments for approx. 145 persons and a day-care centre for approx. 70 children.

Heat recovery from different wastewater streams and reuse of treated greywater for toilet flushing will be installed.

Additionally, it became interesting to analyse how such a technical installation would perform and be organised when upscaled on disctrict level for approx. 5,000 people as a next step assuming a whole “passive house district”. Various aspects such as material flows, organisational structures and business models were investigated.

Material and Methods

Two different concepts will be installed in the building constructed in Frankfurt:

- Left side: heat recovery from domestic wastewater
- Right side: heat recovery from blackwater incl. wastewater from kitchen and washing machines; heat recovery from greywater; treatment of greywater and use as service water for toilet flushing and irrigation purposes.

Additionally, both technical solutions were assumed to be implemented on district level for 5,000 people. This would mean a transformation of a whole district from connection to the central wastewater treatment system towards a semicentral unit for heat recovery and service water provision. A semicentral operation unit would be installed within this disctrict where heat recovery from the respective wastewater streams takes place as well as greywater treatment and provision of service water in case of the second technical option (see description for “right side” on building level).

Due to the fact of several passive house constructions in Frankfurt and the overall activities in this field, most parameters relevant for a feasibility study in a passive house were available (ABGnova, 2013). Those parameters included the specific heating energy demand with 15 kWh m^{-2} a^{-1} and the specific demand for hot water generation with 20 kWh m^{-2} a^{-1}.

Regarding the heat recovery from the wastewater following assumptions were considered:

- specific wastewater volume in households: 90 l $pers^{-1}$ d^{-1} (due to water saving devices; composed of 30 l $pers^{-1}$ d^{-1} of lightly polluted greywater and 60 l $pers^{-1}$ d^{-1} of blackwater; empirical values by Nolde (2013));
- wastewater by the day-care facility: 5 l $pers^{-1}$ d^{-1} lightly polluted greywater, and 10 l $pers^{-1}$ d^{-1} of blackwater
- heat reduction: 5K for domestic wastewater; 10K for greywater; 2K for blackwater
- coefficient of performance of the heat pump (COP): 4.0.

Additionally, the results from building level where included into a material flow analysis for receiving results on water and energy flows on district level. It was assumed on district level that no water infiltration or exfiltration of the pipes take place as they would be newly constructed. Data for modelling was included in addition tot he data available on building level from Augustin and Koch (2012), Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e. V. (2010), SEF Stadtentwässerung Frankfurt am Main (2011, 2008) and Wiechmann et al. (2011).

Aiming to reveal current obstacles and to develop a transformation management strategy, qualitative approaches like stakeholder mapping, expert interviews and a constellation analysis were chosen firstly to identify key players within the transformation process and secondly to explore and identify new business models.

Stakeholder workshops - applying scenario techniques - for representatives of municipal utilities as well as other public and private actors are scheduled.

Results and Conclusions

Water and energy flows in the passive house

The feasibility study showed that the heat requirements are 15 kWh m^{-2} a^{-1} for the day-care centre and the flats. The heat requirements for the warm water preparation are 9 kWh m^{-2} a^{-1} for the day-care centre and 20 kWh m^{-2} a^{-1} in the flats. The overall heat requirements for the building are 235 MWh a^{-1}. More than half of the required heat, 131 MWh a^{-1} is needed for the generation of hot water. This first result was an encouraging indicator to look further into heat recovery from wastewater.

Further calculations showed that by means of heat exchangers and a heat pump a total of about 30% of the heat needed for hot water generation can be recovered from the various domestic wastewater streams when an average of 90 l $pers^{-1}$ d^{-1} is assumed. In the left side of the building 17% can be recovered from the domestic wastewater and in the right side 9% from greywater and 4% from blackwater. This covers 19% of the basic heat load of the building over the course of one year.

When looking into the economic aspect it became clear that the chosen technology is more expensive than the conventional alternative for such buildings consisting of gas as energy source. The additional annual costs are 3,000 EUR a^{-1}.

However, these calculations do not yet include the potential savings from the reuse of treated greywater. In a similar setup in Berlin (Nolde, 2013) it could be shown that savings from water reuse were five times higher than those from heat recovery. Due to the fact that details on investment costs for greywater treatment and reuse are not available as planning is on-going, this aspect of the feasibility study could not be completed yet. But the authors expect an additional alleviation as in the Berlin case although water and wastewater fees are lower in Frankfurt am Main.

Water and energy flows for a whole district

When assuming that the system described above is implemented for a whole district, an approximate provision of 164,000 m^3 a^{-1} of water is required, out of which 110,000 m^3 a^{-1} have to have drinking water quality in the setting chosen. The 54,000 m^3 a^{-1} of greywater generated and treated for service water provision is assumed to fulfil the required water needs for toilet flushing of 30 l pers d^{-1} determined by Nolde (2013). Additionally, 110,000 m^3 a^{-1} of blackwater is discharged towards the municipal wastewater treatment plant.

When having a look at the energy flow, 98.2 MWh a^{-1} are required for blackwater discharge and treatment (68.2 MWh a^{-1}) as well as sewage sludge incineration (30 MWh a^{-1}). On the other hand, thermal (50 MWh a^{-1}) and electrical (43 MWh a^{-1}) energy is produced within the sludge incineration which can/could be used internally or externally. Regarding the greywater, 86 MWh a^{-1} electrical energy are required for greywater transport and treatment. The potential heat recovery amounts up to 837 MWh a^{-1}. For blackwater, additional 341 MWh a^{-1} could be recovered. This is less then the theoretically expected amount of heat (1271 MWh a^{-1}) which can be recovered from domestic wastewater as such.

Stakeholder constellations in a building context

System innovations such as heat recovery in passive houses are usually characterised by the fact that several players initiate and realise them in joint action. Appropriate constellations as well as the coordination requirements of the innovation during implementation and operation are dependent of the socio-technical system as well as of the spatial context (referring to the specific local conditions as well as dimension of the implementation). Moreover the dominating institutional design (including norms, laws as well as informal regulation systems), which are also embedded in the spatial context, determines the leeways of the actors involved.

Key players are real estate or house owners, who belong to the group of (municipal) housing societies, investors as well as private persons. They create the framework via their decisions on investments and operation & maintenance for a decentralised greywater treatment and heat recovery in a real estate. However, very often they are lacking the knowledge to take over the lead as a prime mover (system leadership) promoting the innovation process by implementing new technical solutions on housing level.

Within a building or bloc the plant operator (this can be a public or private contractor, for further details see subchapter on business models below) is the key personality guaranteeing the functioning of the heat recovery and greywater treatment units. Especially the plant operator, with technical knowledge beyond the state of the art and the interest in new solution, can be the system leader of the innovation. Many times the distribution of service water and heat through the hot water distribution system is a task of the operator as well. In such a case it has to be decided, if he is operating the further water and wastewater networks in the real estate as well.

Already during the construction of such passive houses well trained craftsmen and plumbers who are aware of the new requirements and have competence beyond the state of the art are a key asset. They are obliged to maintain the treatment plants and networks next to the installation of the technique. Their competences within a new line of technology are influencing significantly the acceptance and by this success. Insufficient or inadequately trained plumbers might risk faulty connections or the inability to fulfil service contracts.

German fiscal policy has created willy-nilly (*nolens volens*) a field of tension between drinking and service water as different tax rates exist for the different types of water: 7% value-added tax (VAT) for drinking water; 19% VAT for service and process water. Therefore, the sale of service water might sometimes be less attractive. Real estate owners, who (let) treat greywater in a decentralised manner and provide it for free to their tenants, do not only undergo this hindrance. Besides, within this institutional arrangement they can also advertise lower incidental costs respectively the proportion between rent and incidental costs shifts towards their benefit.

The local health authorities who are responsible for the hygienic safety of drinking and service water might become active in cases of larger real estates. Where the service water is only used for flushing toilets or watering the garden, fewer reasons for interventions will exist as in cases where washing machines and dish washers are connected. Therefore, it can be expected that the system leader will make sure that the sensible points of connection (white goods) will be excluded.

The inhabitants, meaning the users of the products hot and service water have few contact points with the installations. Behaviour changes are not or barely required.

Therefore, their basic acceptance of such a system can be expected and they only play a side role in the stakeholder constellation. However, when it comes to technical complications, their acceptance eventually goes down.

Stakeholder constellation for a district setting

When such a system alternative of passive houses in combination with heat and water recovery is not only installed in one or a couple of buildings/blocs but on district level (see also Material and method section), some additional coordinative actions are required. Moreover, the existing and above described (see subchapter "Stakeholder constellations in a building context") stakeholder constellation will change.

Most likely in such a setting the greywater will be treated and distributed as service water on semicentral (merging a couple of buildings) or on district level. This comprises legal-political consequences. Decisions and framing by local politics, such as urban planning, are central and already very important aspects in the preparative steps. The municipality after clearance with the key players (based on locally specific governance procedures) should lead and conduct the coordination related to tasks, duties, agreements, time tables, technical norms and systems, etc. by enacting a by-law for the implementation of such innovations on district level. This by-law regulates amongst others the time frame within the real estates will be connected to separate greywater and blackwater sewers and what is counted as blackwater (see also Meinecke and Vack, 1997). Conflicts might arise, as the optimum on the level of a single real estate (e.g. inclusion of wastewater from washing machines into the blackwater due to pragmatic reasons) can differentiate from interests on district level (laundry wastewater goes into greywater to optimise treatment efficiency).

Via the provision of service water as "new resource" a field of tension can be generated with the sales area drinking water. Depending on the different departments gathered in a utility, the delivery of service water could lead to an (internal) competition between the different types of water. It might also be possible to create new products and business models.

New business models and opportunities for water supply and wastewater companies

The key stakeholder in such a constellation on district level might be the municipal holding/multi-utility company (in German often called "Stadtwerke") operating different supply services like heat, electricity, natural gas and (waste)water. Some municipalities run the water and wastewater services in separate water supply and wastewater treatment companies/utilities. Other municipalities opt for public-private-partnerships or intermunicipal associations. Though, there is a wide range of models to organise the provision of local services in German municipalities (Wollmann, 2002).

Traditional water supply and wastewater systems are usually designed as centralised infrastructures operated by one company/organisation in charge. Thus, the centralised logic on the technical dimension of water infrastructures corresponds with a centralised organisation and management model. In the case of wastewater (similar to drinking water supply) in Germany the local (often municipal) wastewater company traditionally operates the entire value chain of collection, transport and treatment of wastewater. Sometimes, the operation of the wastewater treatment plant and of the sewer network infrastructure is managed by two different companies. Nevertheless, there is still a highly centralised organisation of the wastewater system in German municipalities.

Now, by implementing semi- or decentralised innovative wastewater systems, the boundaries of the infrastructure systems and services are changing and new services and business models are coming up. Probably water supply and wastewater services become “closer”, if greywater is treated and commercialised as service water. Wastewater and energy supply merge, when heat is recovered from the wastewater flow in the sewer. Theoretically, the central treatment plant can be partially substituted and complemented by a number of small, de- and semicentralised plants on the building and bloc or district level; analogically, instead of just one central plant additionally many de- and semicentralised plants need to be operated. This includes control, monitoring of (critical) parameters and operational maintenance and surveillance. Also accounting and billing are possibly new services, which (both municipal and private) water companies could offer to their (new) customers, either private single homeowners or housing societies. Probably, existing markets of operator services expand by increasing numbers of decentralised plants.

Local wastewater companies can offer their specific knowhow and resources to plan and to design the de- and semicentralised systems. Of course, knowhow concerning the technical and economical part of these innovative systems has to be established inside the company. Some water companies may specialise in planning de- and semicentralised systems and at the same time offer services to the central sewer network and wastewater treatment plant operator, in order to coordinate and merge the centralised with several de- or semicentralised networks/systems concerning the water and energy flows. Because central networks and plants (wastewater, drinking water supply or heating systems) may suffer under-utilisation, if (too many) de- or semicentralised infrastructures offer competing services and products like, e.g., tap water instead of drinking water. “Smart” coordination between central and de-centralised systems is essential (see subchapters on stakeholder constellations).

In case of the sewage company owning and operating the heat recovery plant, heat could be commercialised either directly to the user/customer or to local energy/heat supply companies. Another option is to sell concessions to energy companies dealing rights to use the sewer and recover the heat of the wastewater flow.

Constraints for the development of new business models by municipal enterprises are in the legal frame of German law concerning local self-government and the legal structure of the water companies. According to the legal-organisational setting of the municipal utilities or companies for example as an owner-operated municipal enterprise (Eigenbetrieb), authority or stock corporation different rights and duties are evolving during the operation of plants and infrastructures and the service provision. The legal-organisational setting influences significantly the leeways of the municipal water supply and wastewater organisations (associations, companies, authorities, etc.) such as the possibility to operate the provision of greywater as service water and thus, to develop new services, products and business models. For instance, in some public legal forms of municipal enterprises the purpose of the organisation has to be defined in a quite concrete and specific way. Thus, entering the energy market by commercialising heat could be forbidden for municipal wastewater companies under specific legal structures of public companies (e.g. law of association). Consequently, in order to capture the opportunities of new system solutions, new organisation models and structures need to be developed on the local level. In some cases it may be adequate to reform the legal structures of municipal companies. In other cases it may be necessary to think of more fundamental adjustments. Some German municipalities establish hybrid companies as a part of holding structures like Frankfurt am Main, where the local energy company (Mainova) and the housing society (ABG) instituted a mixed owned company (ABGnova), which is opening new business models and, in fact, planning and constructing a passive house with heat recovery of wastewater and greywater reuse as reported in this article. Or, private water companies specialised in operator models enlarge their business activities. Nevertheless, also in this case municipal government and administration have to fulfil their legal duties and guarantee the local provision of public services (Libbe et al., 2004). This includes integrated (spatial and urban) planning and the coordination of heterogeneous stakeholder constellations seeking public interests.

Conclusions

It has to be stated that the technical solutions discussed strongly correlate with the choice of low-energy buildings. If such a decision on building level is taken, heat recovery from wastewater can become an option. About 30% of the heat needed for hot water generation in a passive house could be retrieved from the domestic wastewater. This, the remaining energy lack of passive houses caused by disposal of wastewater could be partially closed.

However, in the case of separation of the blackwater and greywater stream, the energetic and due to this economic attractively is strongly connected to the implementation of greywater treatment and provision as service water on building as well as on district level. Separation of greywater only for heat recovery does not seem to be rational.

Various new business models and services become possible by implementing innovative de-/semicentralised water systems, but adjustments in the local structures of municipal holdings and companies may be necessary to capture the opportunities. The constellation of key players is determined by the institutional, spatial and technical setting. Thus by up-scaling passive houses at a district level key stakeholder and logic of action may change. Possible clashing interests have to be taken into account since they may lead to obstacles/blockades. At least a system leader promoting the innovative process is crucial.

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