Sustainability Assessment of Urban Water Infrastructure Systems with Special Focus on the Urban Water-Energy Nexus

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1 ABSTRACT

The growing population in cities (United Nations 2011) increases the pressure on water and energy resources. Additionally, water and energy uses are interrelated in manifold ways: for example, water is used in the energy sector for cooling purposes and energy is used for wastewater treatment (Jägerskog et al. 2014). The pressure on resources and their interlinkages are calling not only for a more efficient use of resources but for integrated and more sustainable solutions making, in some cases, reuse indispensable. Facing those challenges, various innovative infrastructure systems have been developed. The appropriate solutions strongly depend on the particular context and must be chosen carefully to shape the respective urban water-energy nexus in a more sustainable way. When implementing new systems the following questions should be considered: What is their particular effect on resource efficiency? Which further impacts on the sustainability performance of the urban water system do they cause? Further research especially on methodological approaches is needed to get answers to those questions.

Therefore, in this study a methodology for sustainability assessment of new alternative water and sanitation systems (NASS) was developed with a special focus on the urban water-energy nexus using as a case study a city district in Chillán, Chile. The technologies for new alternative water and sanitation systems to be compared were chosen in close interaction with the local stakeholders. Moreover, regionally adapted sustainability indicators were developed on the basis of the Integrative Concept of Sustainable Development (ICoS) of the German Helmholtz Association (Kopfmüller et al. 2001). In a first step, a preliminary set of indicators was developed from a scientific perspective based on crucial aspects with regard to the sustainability performance of different water infrastructure systems. In a second step, the indicators were further developed together with local and regional stakeholders.

Keywords: water-energy nexus, sustainability assessment, reuse, water infrastructures, urban planning

2 INTRODUCTION

More than half of the world's population is currently living in cities. Due to UN prognosis this figure will raise by 2.6 billion up to 2050 and cities will have to absorb all the occurring population growth in the coming decades (United Nations 2011). The high population concentration in cities, especially in big cities, leads to a strong pressure on resources to assure among others water and energy supply. Water management systems worldwide have to meet important requirements related to challenges as demographic change, climate change, rising resource prices and increasing situations of water scarcity. Especially more flexibility and reuse options are required compared to the traditional linear water/urban drainage systems.

Therefore, new alternative water and sanitation systems (NASS) have been developed working on a decentralized (household level) or semi-centralized (city district level) scale treating the often separated sectors stormwater, drinking water supply and wastewater disposal in an integrative way. Those resource oriented infrastructure systems are based on separated collection and selective treatment of different flows. They aim at reuse of energy, material and water flows within the catchment and at providing a cost efficient alternative or supplement to existing systems. Another important objective is high flexibility to cope with both rapidly growing population in cities and shrinking population (mostly in rural areas) (see DWA 2008 for more information). Those new sanitation systems have been implemented in several pilot projects at different scales mostly in central and northern Europe but also in other parts of the world, e.g. in China (Albold 2014, Nolde 2013, Bieker et al. 2010).

Water and energy are closely interrelated. Urban water services cause high energy consumption as e.g. conventional wastewater treatment but also water uses at household level, especially warm water production are very energy intensive. In the last ten years the scientific debate about the water-energy nexus has intensified and various assessment approaches have been developed. From the 'energy for water' perspective looking at the energy demand related with water services the focus of most assessment approaches is on resource efficiency, mainly on energy intensities, and on environmental impacts (Nair et al. 2014; Kenway et al. 2011). This is also the fact in optimisation approaches to find the best feasible solution for planning, design and operation of water systems where according to Vakilifard et al. (2018) the importance of spatial aspects is mostly not taken into account. Even more striking is, however, that social and cultural aspects are mostly not included in assessment approaches in the water-energy nexus field, although the term "sustainability" is often used.

There are, however, also approaches for a comprehensive sustainability assessment of water systems. Nevertheless, the very common separation into economic, ecological and social assessment criteria (Dehoust et al. 2015; Ma et al. 2015) has serious shortcomings: Multiple social primary goods that are essential for sustainability assessment are overlapping these criteria and cannot be addressed with a pillar approach. Therefore, an integrative sustainability concept was developed by the Helmholtz Association (Kopfmüller et al. 2001) - the Integrative Concept of Sustainable Development (ICoS). This concept is based on three constitutive elements: 1) inter- and intragenerational justice, 2) a global perspective regarding goals and strategies and 3) an enlightened anthropocentric approach (for more details about the structure of the concept see Kopfmüller et al. 2001). For the operationalization, these three elements were transferred into three general sustainability goals. Based on these, substantial sustainability rules were established defining minimum requirements for sustainable development as shown in table 1.

General sustainability goals		
Securing human existence	Maintaining society's productive potential	Preserving society's options for development and action
Substantial sustainability rules		
Protection of human health	Sustainable use of renewable resources	Equal access of all people to information education and occupation
Ensuring satisfaction of basic needs	Sustainable use of non-renewable resources	Participation in societal decision-making processes
Autonomous subsistence based on income from own work	Sustainable use of the environment as a sink for waste and emissions	Conservation of cultural heritage and cultural diversity
Just distribution of chances for using natural resources	Avoiding technical risks with potentially catastrophic impacts	Conservation of the cultural function of nature
Reduction of extreme income or wealth inequalities	Sustainable development of man-made, human and knowledge capital	Conservation of social resources (e.g. tolerance or solidarity)

Table 1: Structure of the Integrative Concept of Sustainable Development (ICoS), general goals and minimum sustainability requirements.

ICoS also defines instrumental sustainability rules concerning the transformation process. Those are, however, not included in the core assessment in this study as they mostly refer to regions or nations as evaluation object and not to technologies. The substantial as well as the instrumental sustainability rules are defined in a very general way and have to be contextualized in every case. Thus, according to ICoS sustainability indicators are developed specifically for every application case combining on one hand a scientific normative perspective and on the other hand a problem oriented approach involving stakeholders. In this study, a methodology for holistic sustainability assessment is developed based on ICoS. It is applied for the comparison of a conventional centralized water system with an innovative semi-centralized water system using a city district of Chillán, Chile, as a case study. The first step is the development of sustainability indicators, discussed in section 3. As in literature about new alternative water and sanitation systems, they are often compared to the conventional centralized system without explaining the reasons for the technological choice of the innovative systems, special regard was given to transparent technology choice in this study as presented in section 4.

3 DEVELOPMENT OF SUSTAINABILITY INDICATORS

The development of sustainability indicators was realized in several steps as described in section 3.1. Detailed explanation of the single indicators and the results obtained from the expert interviews are presented in section 3.2.

3.1 Methodological approach

As a first step in the development of sustainability indicators, a thorough literature analysis including research on new alternative water and sanitation systems (Remy 2010; Hillenbrand 2009; Bieker et al. 2010; Makropoulos et al. 2008; Sapkota et al. 2016 etc.), research on the urban water-energy nexus (Jägerskog et al. 2013; Perrone et al. 2011; Kenway 2013 etc.) as well as studies focussing on sustainability assessment of water services in the Latin American context (Lehn et al. 2012; Kosow et al. 2013) was realized. Well-established sustainability indicators were collected but also key parameters used in different assessment approaches were included. The whole process of developing sustainability indicators is shown in figure 1.

Fig. 1: Development of sustainability indicators including scientific perspective and local expert knowledge in several steps.

As the assessment methodology is intended to serve as basis for decision support, assessment and comparison of different water infrastructure systems shall be possible without implementation of pilot projects within the same region. Hence, the aim is to allow for a prospective assessment without having real experiences and performance data under the framework conditions in which the decision shall be taken. This was taken into account in the development of the sustainability indicator set. As far as possible such indicators were chosen to which performance data can be obtained through modelling of material and energy flows occurring in the different infrastructure systems (or directly from literature on pilot projects in other parts of the world in which case the different framework conditions have to be taken into account when transferring information). This was fairly easy to realize for some rules or topics of ICoS and more difficult for others. As the methodology for sustainability assessment is developed using case studies in Latin America, this was also the regional framework for the first indicator development.

According to Kopfmüller et al. (2001) sustainability indicators have to fulfil numerous scientific, functional, practical and stakeholder driven requirements that were considered in this study. In order to assure that indicators adequately represent the problems and challenges perceived in the society, cooperation with local and regional experts and citizens in the development of indicators is necessary. This was realized in several steps as shown in figure 1. First, explorative semi-structured interviews were conducted. Based on the exploration of perspectives on sustainability challenges regarding the urban water-energy nexus and the perceived potential of innovative water infrastructure systems with reuse options the first literature based set of indicators was modified to obtain a case specific indicator set.

In a second step, systematizing expert interviews as categorized by Bogner and Menz (2009) based on the case specific indicator set as a detailed interview structure followed. In all interviews the position of the interviewer as well from a professional perspective but also the cognitive interest were revealed in order to provide the interviewees with an information basis to allow for opinion making about the interviewer as postulated by Bogner and Menz (2009). In the systematizing interviews, the case specific set was discussed in detail with regional experts in order to get their estimation of the single indicators. The sustainability rules of ICoS were presented as topics as the term is easier to handle. Many criteria play a role to evaluate the suitability and quality of indicators (see Kopfmüller et al. 2001). In this study, relevance was identified as one important criterion for the evaluation of the indicators by stakeholders as it indicates to what degree the proposed indicator represents the sustainability challenges perceived in the society. Besides that, indicators have to fulfil practical requirements. Among those the applicability was identified as most important addressing data availability, periodic updating and reasonable effort for data acquisition.

The central criteria relevance and applicability allowed for a guided and structured discussion of the proposed indicators. This was realized in bilateral meetings with academic or research oriented experts. These were chosen as interview partners after a first test discussion within an expert workshop showed the difficulty to discuss sustainability indicators (being very far from the daily work life) with professionals from local and regional administration without comprehensive preparation of the topic. The workshop results were also included in the interpretation of the results but show a lower information level than the results from the bilateral meetings.

A detailed joint discussion of the sustainability indicators with experts from local and regional key institutions has to be conducted with more profound preparation which was not possible in the framework of the conducted field work. This will be realized in a second research stay. First, bilateral meetings to exchange on sustainability indicators and second a round table to discuss jointly will take place. Furthermore, the inclusion of affected citizens is very important. In this case, instead of detailed sustainability indicators more general sustainability challenges (based on the ICoS rules) would have to be used as a basis for the discussion. The results can then be included in order to identify up to which degree the developed sustainability indicator set overlaps with the sustainability problems perceived by the citizens and where no overlap exists which means that indicators address challenges that are not perceived as problems in the society or which problems exist that are not sufficiently covered by the sustainability indicators. In the ideal approach, those deficits have to be addressed again in a circular way by developing additional indicators and modifying the existing ones.

3.2 Resulting sustainability indicator set

The expert interviews showed that stakeholders evaluated relevance and applicability quite heterogenously. In table 1-3 a detailed explanation of the regionally developed indicators and the reasons for their development based on literature and explorative expert interviews is given. The results from the systematizing interviews concerning the relevance of the indicator and the applicability are presented in the last four columns. Relevance and applicability are listed in the table as tendency shown in the interview results. The range of the corresponding answers is indicated by the colour (green in case of quite similar answers; yellow in case of more differing answers; red in case of very diverging answers). Additional information gained from the systematizing expert interviews is presented in additional columns.

Table 2 shows the indicators developed on the individual level concerning the general sustainability goal “Securing human existence”. The first indicator concerning the first topic “protection of human health” is the *concentration of faecal coliforms [MPN/100 ml] in the receiving water bodies upstream and downstream of the discharge points of the corresponding treatment plants*. This indicator was developed based on considerations about the direct link between waterborne diseases and missing or insufficient sanitation systems (WWAP and UNESCO 2015). According to the interviews this indicator seems to be quite relevant as it was stated that this path presents the principal contact to human beings as many illegal connections exist to use the river water for irrigation or filling of swimming pools. The answers were quite similar regarding relevance as indicated by the green colour. It was however also pointed out that in the application the productive activities in the area have to be taken into account to consider their contribution to possible contaminations and especially to distinguish different contamination sources. Moreover, it was commented that the distance upstream and downstream to the discharge point have to be defined very carefully based on available data. The applicability was estimated with a tendency towards medium but the answers differed within a wide range between low and high applicability as indicated by the red colour.

SECURING HUMAN EXISTENCE						
Topic	**Indicator**	**Reason for development of indicator**	**Rele-vance**	**Additional information on relevance**	**Applica-bility**	**Comment regarding application**
Protection of human health	Concentration of faecal coliforms [MPN/100 ml] in receiving water bodies upstream and downstream of discharge points of the corresponding treatment plants	Many severe waterborne diseases are directly linked to insufficient sanitation systems	high	Presents an important exposure pathway for human beings as there are many illegal connections for irrigation and swimming pools;	medium	Productive activities (potential contamination sources) to be considered; lack of data probable (no upstream control is prescribed)
	Concentration of faecal coliforms [MPN/100 ml] in effluents of the specific treatment plants	Additionally to first indicator because easier to apply	high		high	Is measured according to the regulation (DS 90)
	Concentration of faecal coliforms [MPN/100ml] in shallow aquifers possibly influenced by wastewater influence (sewage leakage etc.)	Groundwater often influenced by sewer leakage; high number of private dug wells used for garden irrigation	high	In some sectors pit latrines exist contaminating groundwater but groundwater is not widely used but through scattered private dug wells	medium	Lack of data because no monitoring of faecal coliforms in groundwater takes place;
	Average temperature difference between urban zone and rural environment in summer months (day and night temperatures) [°C]	Given the climatic conditions in the region heat stress can present a health problem	Low	No high density of houses but wide streets and a lot of urban green; heat is not perceived as a problem as people are used to it;	medium	
Ensuring satisfaction of basic needs	Interruptions of the respective supply systems (hours per year)	Constant stable water supply is essential for good sustainability performance	High	Supply interruptions seldom in current centralized system but possibly more frequent in the future; innovative systems might be prone to frequent interruptions;	High	No data on innovative semi-centralized systems in Chile
	Interruptions of the respective discharge and disposal systems (hours per year)	Non-reliable functioning of the disposal system can provoke health issues	High	Unlikely to happen in centralized system; higher risk (less control) in semi-centralized system;	High	No data on NASS in Chile, differences (level of maintenance…) to be considered when transferring information from European pilot projects

Table 2: Sustainability indicators regarding the general sustainability goal “Securing human existence”.

MAINTAINING SOCIETY'S PRODUCTIVE POTENTIAL						
Topic	**Indicator**	**Reason for development of indicator**	**Rele-vance**	**Additional information on relevance**	**Applica-bility**	**Comment regarding application**
Sustainable use of renewable resources	Ratio of total water demand to renewable water resources in the basin of the Rio Chillán	Well-established indicator (water exploitation index, WEI); aim: scale up effects of NASS to basin level to see impact of residential savings on general water situation (vs. e.g. agriculture)	High	Might become more important in the future due to rising water demand and declining water resource availability	Medium	Data on groundwater resources and also on updated water demand might be difficult to obtain
	Ratio of water extracted from Rio Chillán to flows in Rio Chillán	Greater level of detail in the assessment like the specific impact of residential uses on superficial water resources and information on seasonal fluctuations	High		Medium	Water rights no suitable information basis for water demand but actual extraction not measured, only extraction point is monitored;
Sustainable use of non-renewable resources	Energy demand for operation of urban water system based on non-renewable resources per supplied inhabitant	Urban water infrastructure systems have a high energy demand especially on the household level which is also included here;	High	Indicator has educational bearing as it shows the benefits of the innovative systems	High	Seasons of the year and corresponding water sources have to be taken into account in the analysis;
	Possible coverage of nutrient demand in subcuenca of the Rio Chillán by use of WW residues as fertilizer (%)	NASS might present higher potential to use sanitation residues as fertilizer to substitute mineral fertilizer due to the higher quality of the sludge that can be achieved in semi-centralized systems.	Medium	Presents new business case, small farmers to be prioritized; use of sludge restricted to forestry, fruit growing, floriculture;	Medium	Data on the sludge from ESSBIO is necessary as use potential depends on quality; data on use of fertilizers available
Sustainable use of the environment as a sink for waste and emissions	Conc. of parameters defined in Chilean regulation *Decreto 90* at corresp. discharge points into environment	Bunch of parameters as starting point to be further narrowed down; parameters regularly monitored; discharge points defined in broad way to include all discharge points in the different systems	High		Medium	Groundwater should be included in assessment; greywater should comply with regulation for irrigation uses (under development)
	Anthropogenic pollutants from sanitation residues (sewage sludge, blackwater digestate) per specific quantity of nutrients	Sludges with different qualities; possible pollution referred to nutrients which should control amount of sludge applied;	Medium	Currently, sludge deposition only allowed in forests	Low	Emerging pollutants probably not measured, only data on heavy metals available

Table 3: Sustainability indicators regarding the general sustainability goal "Maintaining society's productive potential".

With regard to the topic "Sustainable use of the environment as a sink for waste and emissions" (see table 3) the assessment presents some challenges. On the one hand, the first indicator is rather a bunch of indicators: it was discussed as *concentrations of parameters defined in the Chilean regulation 'Decreto 90' at the corresponding discharge points into the environment (WWTP effluent or greywater used for irrigation…)*. The reason to choose those parameters defined in the regulation for waste water treatment plants as a starting point was the fact that those parameters are regularly monitored and well-established as quality criteria. However, the high number of parameters has to be narrowed down in the course of the project. On the other hand, the discharge points were defined in a very broad way in order to include all different discharge points where emissions into the environment might occur in different water systems. In innovative semi-centralized systems these might include green areas where contaminated irrigation water is applied or leakage from the blackwater treatment. Therefore, in the comparison of different infrastructure systems the different impacts linked to the different contamination paths (soil, aquatic environment, direct human contact etc.) have to be taken into account. Thus, it is not possible to define one single threshold value or sustainability target value for the different paths that occur in the different systems. This makes a simple comparison of the performance of the systems in this topic difficult.

PRESERVING SOCIETY'S OPTIONS FOR DEVELOPMENT AND ACTION						
Topic	**Indicator**	**Reason for development of indicator**	**Rele-vance**	**Additional information on relevance**	**Applic a-bility**	**Comment regarding application**
Participation in societal decision-making processes	Percentage of planning processes including stakeholder participation	Cannot be measured prior to implementation; purely used as background information	High	Stakeholder participation required and requested in such water infrastructure projects especially as residential uses are concerned;	Low/ mediu m	Survey on knowledge of potential users about different water systems necessary (without knowledge no informed decision making possible)
Conservation of the cultural function of nature	Concentration of faecal coliforms [MPN/100 ml] in the receiving water bodies used for bathing upstream and downstream of the discharge points of the corresponding treatment plants	Rivers are used for bathing	High	People use river for bathing despite low water quality due to lack of knowledge	Mediu m	Unclear which areas are used for bathing; monitoring of faecal coliforms only in official bathing zones;
	Days of the year during which the flow in the river Chillán is below the environmental flow	Included as indicator to assess impact of water withdrawals for anthropogenic uses on the river quality (assessed as cultural value for humans)	High	Tourists only care if river falls dry and residents care a little more but not much;	Low	Reduced residential water uses might have only small impact on water with-drawals ("saved" water used for other purposes);

Table 4: Sustainability indicators regarding the general sustainability goal "Preserving society's options for development and action".

The topic "Participation in societal decision-making processes" is also influenced by the water infrastructure systems (see table 4). Depending on the framework conditions the existence of centralized service systems can lead to a poor power position of the individual users towards big institutions or companies. Therefore, in some situations the gain of power is one reason to think of semi-centralized systems as it is assumed that in a semi-centralized system the individual user has more influence on the operation of the system than in centralized systems. Although the gain of power of the individual user is no motivation for innovative semi-centralized systems in the study area Chillán participation is still an important issue to be taken into account as there might be indirect effects of infrastructure systems on participation issues. However, these cannot be measured prior to implementation. Therefore, a simplified indicator being the *Percentage of planning* *processes including stakeholder participation* has been included in order to serve as background information because no information on the different impacts of the compared systems can be obtained without implementation. It was confirmed in the interviews that such water infrastructure projects absolutely required participation especially as residential uses were addressed and that participation was in general highly requested. It was, however, pointed out that a high number of environmental conflicts showed that in decision processes information was taking place instead of participation. Another interesting aspect that was pronounced was the need to do a survey on the level of knowledge of potential users in order to know whether or to which level e.g. people buying a house are aware of different water systems and their implications which would be a prerequisite for informed participation in decision-making processes.

With regard to the topic "Just distribution of chances for using natural resources" no indicators have been developed so far as the precise city district could not be determined by the time of the interviews. City districts with different levels of income might require a different approach in the design of the corresponding indicators. Therefore, although this topic is influenced by the type of water infrastructure system the indicators will be developed later in the study which is still in progress.

The last of the sustainability topics discussed based on ICoS that is influenced by water infrastructure systems is the "Conservation of the cultural function of nature". The first indicator developed to that topic was concretized to bathing zones based on stakeholder feedback. It was then defined as *concentration of faecal coliforms [MPN/100 ml] in the receiving water bodies [used for bathing] upstream and downstream of the discharge points of the corresponding treatment plants*. But it was also mentioned that unofficial bathing zones exist which should be taken into account but where it might be difficult to obtain data.

In summary, 7 of the 15 sustainbility topics were considered important for the implementation of innovative water systems in the respective region. Usually 1-2 indicators were defined for each topic, one exception is 'human health' with 4 indicators. This emphasises the relevance of human health with regard to the water-related technologies.

4 SELECTION OF TECHNOLOGICAL COMPONENTS

In this study, special regard was given to a transparent choice of the technologies which are implemented in the new alternative water and sanitation system (NASS). First, potential technological components were identified from a thorough literature analysis about existing pilot projects which aim at a more sustainable design of the urban water-energy nexus and second, out of that compilation appropriate technological components for the local context were selected based on evaluation of the particular components by local stakeholders as described in section 4.1. The result of the technology choice which is the system design that will be modelled and compared to the conventional centralized system is presented in section 4.2.

4.1 Evaluation process

Special regard is given to the choice of the technology components which are included into the NASS compared to the conventional centralized system. First, components that are implemented within pilot projects (mostly in Europe) have been collected. The semi-centralized innovative system shall guarantee high standards with regard to supply security and professionalism. Decentralized components, however, may represent considerable hygiene risks due to lack of maintenance etc. (Bieker and Cornel 2016). Household based solutions like compost toilets and urine-separation toilets according to some authors (Bieker et al. 2010) present problems in densely populated urban areas due to hygiene, maintenance and disposal of output products. Those components were, therefore, not included in the collection.

In order to compare water infrastructure systems generally suitable for the case study area, the resulting collection of potentially feasible technologies was then evaluated by local and regional experts. Besides a general evaluation of each possible component the respective incentives and barriers were inquired. Therefore the interviewees were invited not to stick too strictly to currently existing limitations e.g. legal restrictions but also to suggest ideas going beyond that. A visualization of possible technological components and the respective water streams was used to structure the answers and evaluations given by the interviewees as shown in figure 2.

The technology evaluation was first planned for a joint expert workshop in Chillán. Due to a low number of participants the evaluation was then continued in bilateral meetings between the researcher and one or more experts from one institution in the premises of the respective institution in order to make the participation as easy as possible.

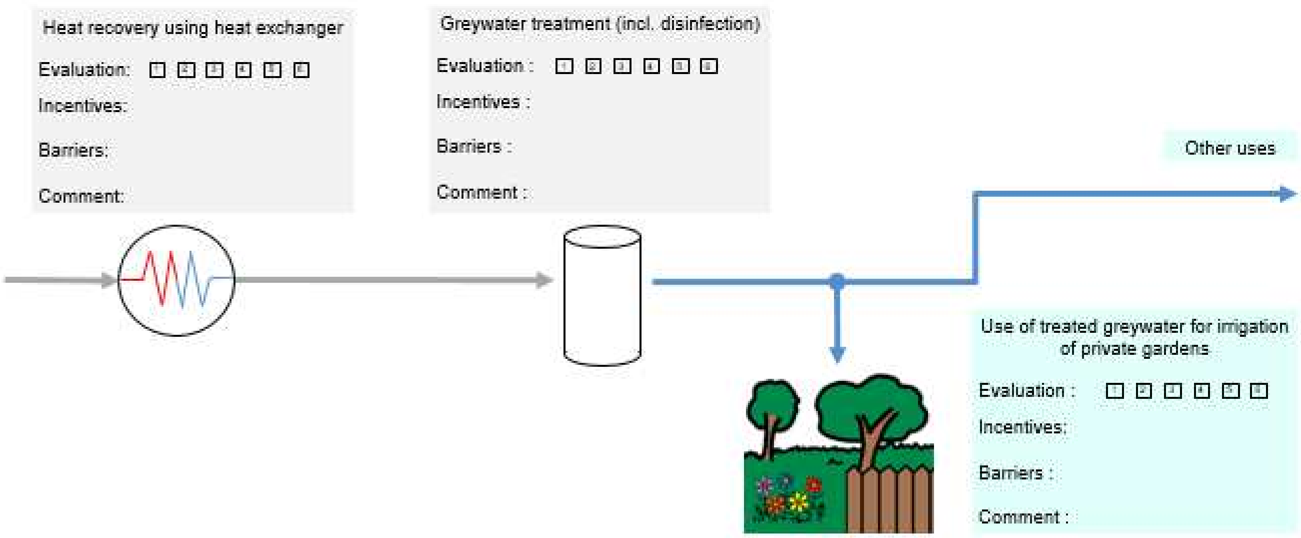

Fig. 2: Section of visualization of system components and possible flows which was used for evaluation with experts.

4.2 Resulting system design

The results of the interviews showed very diverging opinions on different technologies.

Collection of stormwater is already implemented in areas where no stormwater collector exists and is even mandatory in those areas. However it was pointed out that depending on the use of that water the sanitation company would have to treat a higher volume of wastewater compared to the metered supplied drinking water. Furthermore, the seasonal variations have to be taken into account when designing a use concept (as there is almost no precipitation during summer). Based on that, the most favoured use of rainwater is toilet flushing where it is preferred over treated greywater because implementation seemed easier to the respondents. Due to lack of rain in summer, use for irrigation would be restricted to a very short period or huge storage capacities would be required and was therefore evaluated as poorly feasible. The use of rainwater for laundry was also seen as problematic because of seasonal quality fluctuations (smoke contamination in winter and pollen in spring).

Greywater treatment including disinfection to allow for reuse of the water is seen mostly as favourable. However, some interviewees are also critical because the price for drinking water is considered to be quiet low compared to the investment needed for the greywater treatment. Furthermore, the maintenance requirements and the legal framework are seen as potential barriers for greywater reuse. One interesting issue can be found when looking at the different answers: The sanitation company is named as potential barrier by one interviewee but the sanitation company's representative himself assumes the operation of a greywater system to be a potential new business case that might be interesting for his company in some new areas. This contradiction can be interpreted as a hint to a mentality or tendency of searching barriers and hindering aspects in the field of responsibility of other stakeholders. But it also underlines that the question, who operates such a system is seen as very important. One important use of treated greywater is toilet flushing in times of insufficient rainwater. Another important use is irrigation. However, there is no consensus on whether a use for the irrigation of the private gardens of the house owners is preferable or whether irrigation of public green areas by the municipality should be preferred. In this context the question of ownership and beneficiary has to be addressed. For example in a case where private house owners pay for the greywater treatment but the municipality benefits through the use for irrigation of public green areas a remuneration would have to be paid. Referring to the existing legal framework it was pointed out that a regulation for greywater reuse is in progress which only allows use for toilet flushing and for irrigation of private gardens. A strong cultural barrier was seen for the use of treated greywater for laundry.

Concerning the use of greywater not only as material but also as an energy resource, heat recovery from warm greywater (using a heat exchanger) was discussed and is clearly seen as promising. However, the costs for the installation are seen as a barrier. Therefore, a cost benefit analysis is required. It is pointed out that use of the recovered thermal energy not only for warm water production but especially an integration with the heating system would be promising as the heat demand in winter is high and is causing considerable air pollution because wood stoves are a widespread technology. Furthermore, a combination with solar thermal systems which are already a well-established technology in Chile is proposed by a majority of the respondents.

Solar thermal heating systems were assessed positively by the interviewed experts. It was commented that they function very well in summer but have a limited potential in winter. Therefore, a combination with heat recovery from warm greywater was proposed. Additionally, it was highlighted that subsidies for solar thermal exists but only for social housing. Therefore, in other houses the costs for the installation are seen as a possible barrier. An interviewed architect pointed out that solar thermal systems were no purchase criterion and were therefore no longer implemented in new houses.

Another technical option to reduce the energy demand that was evaluated together with the experts is technical adiabatic cooling to substitute conventional air conditioning (AC). Although this was seen as interesting to save energy and related costs in general, it was pointed out that, as it is a new technology, lack of knowledge and maintenance might be a problem in the Chilean context and that the use of AC is not very widespread in Chillán anyway. Furthermore, the general level of insulation is not very high and radiators usually don’t exist. Therefore, the conditions for a proper functioning of technical adiabatic cooling systems were doubted. The only use option that was mentioned as possibly promising was the use in buildings, especially in public buildings. In this case the use of treated greywater for technical adiabatic cooling was seen as a good option as rainwater is not available in the summer period and drinking water should not be wasted for cooling purposes. Given the strong barriers assigned to that component and the fact that the case study is a residential district it will not be integrated in the design of the new infrastructure system that is to be compared to the conventional system.

Adiabatic cooling through evaporation from green facades and green roofs was also discussed. It was mostly seen as problematic because strengthening of the roofs and regular maintenance would be required both causing high costs. In addition to that, a cultural barrier was mentioned because people are not familiar with the technology and might fear problems with mould formation. Furthermore, the interviews on sustainability indicators showed consensus that heat island effect is not a problem in Chillán. Therefore, green roofs or green facades will not be part of the new infrastructure system that will be modelled and evaluated in the further course of this project.

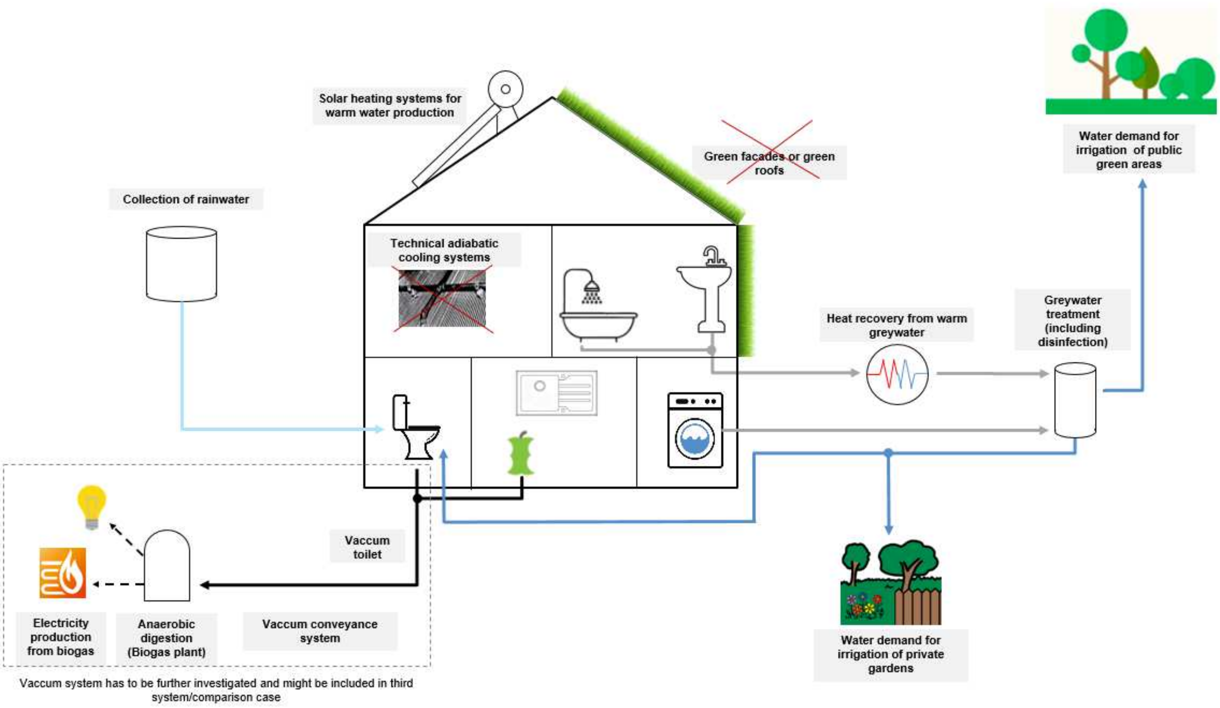

Fig. 3: Resulting system design of the innovative semi-centralized system that will be modelled.

For the disposal of the remaining blackwater stream a vacuum system was evaluated in a discussion with the experts. The experts were asked for their evaluation of a vacuum toilet and a vacuum conveyance system separately in order to get a more detailed image on the existing barriers which might e.g. be technical in case of the vacuum pipe and pump but cultural in case of the vacuum toilet. The other components that were discussed were the anaerobic treatment of the concentrated blackwater and the use of the herewith produced biogas for electricity production. The answers showed two clearly different poles. Some interviewees rated the whole vacuum system as unfeasible mainly due to strong cultural barriers but also due to legal and institutional barriers arguing that the sanitation company had the concession for the wastewater disposal. Other respondents assigned a high potential to the vacuum system. They pointed out that the high water savings would be a strong incentive and that there would be interest from agriculture to use the digestate as fertilizer but commented that lack of knowledge might be problematic. As many and strong barriers were named for the vacuum system it will not be included into the innovative system to be modelled, first. But as some experts on the other hand attributed a high potential to the vacuum system it will have to be further investigated whether it should be included in a third system as additional comparison.

Figure 3 shows the innovative system which will be modelled and compared to the conventional centralized system based on the results of the expert interviews.

5 CONCLUSION AND OUTLOOK

Aim of this study is to compare the sustainability performance of different water infrastructure systems in the respective local context. For this purpose, different water infrastructures to potentially improve the sustainability performance were chosen. Furthermore, sustainability indicators were developed upon which the technology components should be compared. Both steps considered the expertise and judgements of local stakeholders.

Important infrastructure components are among others the reuse of heat from warm grey water using a heat exchanger and the reuse of the greywater itself after treatment and disinfection. Stormwater collection and use for toilet flushing is also seen as very promising. Not considered as a technological option were for example green facades what might be a consequence of the fact that the heat island effect does not play an important role in the regional setting. The most relevant sustainability indicators according to local experts are addressing the fields of human health and of the sustainable use of renewable and non-renewable resources. Stakeholders had very different opinions on relevance and applicability of the indicators. The reasons for the different perspectives will be further analysed in an upcoming workshop.

In a next step, the application of the chosen technologies shall be modelled with the software SIMBA#. The results on the respective sustainability performance of the different systems shall be compared without implementing them in order to allow for prospective sustainability assessment as a contribution to well-informed decision making. Where possible, target values for the resulting indicators will be defined and a distance-to-target analysis for the different water infrastructure systems shall be carried out. The sustainability assessment shall combine the quantitative values received from the modelling with semi-quantitative data on the system performance obtained from local stakeholders. The results from sustainability assessment will finally be interpreted and visualized allowing the use for decision support.

With regard to the development of sustainability indicators, the inclusion of affected citizens is also very important. In this case, the discussion could be based on more general sustainability challenges with regard to the water-energy nexus instead of detailed indicators. By comparing those to the expert's sustainability indicators, additional fields of actions (which are not covered by the indicator set) could be identified.

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