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ORIGINAL PAPER

Eco-efficiency of system alternatives of the urban water-energy-waste nexus

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Abstract

Wastewater systems in developed cities contribute significantly to public health. The related systems are energy and resource intensive and do not recover nutrients in an efficient and effective way. Separating wastewater to greywater and blackwater at the source and exploiting organic municipal solid waste as an additional feed to an adjunct biogas plant could support efforts to make use of the potentials to reduce the environmental impacts, to increase the energy efficiency of winning nutrients, and to implement an additional, locally available energy source. However, the implementation of such systems is seen as expensive.

The overarching aim of the paper is to analyze the eco-efficiency of transforming the current separately organized wastewater-energy-waste systems to an integrated one. The study differs between three system alternatives. The least invasive system change assumes a separation of wastewater at the source without a complete overhaul of the current system; the most elaborated one takes the current wastewater system fully out of operation. The reference for the current system is the existing system of a German medium-sized urban neighborhood. The analysis considers the eco-efficiency of two resource-related (fossil and metal depletion) and three emissions-related (climate change, photochemical oxidant formation and terrestrial acidification) impacts.

Under the conditions of the settlement investigated, a transformation to the system alternatives will generate in all cases a weak eco-efficiency, i.e. the higher costs of implementing a new system counteracts with the noteworthy environmental improvement. Of the three options, the most elaborated one sees the best performance.

Keywords Water-energy-waste nexus · Urban wastewater system · Organic municipal solid waste · Life cycle assessment · Life cycle costing · Eco-efficiency

Availability of data and material (data transparency): Data are available on request due to broad distribution restrictions

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Die Ökoeffizienz von Systemalternativen im Wasser-Energie-Abfall Nexus

Zusammenfassung
Abwassersysteme in entwickelten Städten tragen erheblich zur öffentlichen Gesundheit bei. Diese Systeme sind aber energie- und ressourcenintensiv. Weiterhin werden Nährstoffe ineffizient und wenig effektiv rückgewonnen. Die Trennung des Abwassers in Grau- und Schwarzwasser an der Quelle und die Nutzung von organischen Siedlungsabfällen als zusätzlichen Input für eine angeschlossene Biogasanlage könnte die Bemühungen unterstützen, bestehende Potenziale zur Reduzierung der Umweltauswirkungen zu nutzen, die Energieeffizienz der Nährstoffrückgewinnung zu erhöhen und eine zusätzliche, lokal verfügbare Energiequelle zu implementieren. Allerdings wird die Implementierung solcher Systeme als teuer angesehen.
Das übergeordnete Ziel der Arbeit ist es, die Ökoeffizienz einer Transformation des derzeitigen, separat organisierten Abwasser-Energie-Abfall-Systems in ein integriertes System zu analysieren. Die Studie unterscheidet zwischen drei Systemalternativen. Die Option mit dem geringsten Eingriff in das bestehende System sieht nur eine Trennung des Abwassers vor, ohne dass das derzeitige System komplett beseitigt wird; die Option mit dem stärksten Eingriff würde das derzeitige System vollständig außer Betrieb nehmen. Die Referenz für die untersuchten Systemalternativen ist das bestehende System einer deutschen, mittelgroßen Siedlung. Die Analyse betrachtet die Ökoeffizienz von zwei ressourcenbezogenen (fossiler und metallischer Abbau) und drei emissionsbezogenen (Klimawandel, photochemische Oxidantienbildung und terrestrische Versauerung) Auswirkungen.
Unter den Bedingungen der untersuchten Siedlung führt eine Transformation hin zu den Systemalternativen in allen Fällen zu einer schwachen Ökoeffizienz, d. h. die höheren Kosten für die Implementierung eines neuen Systems stehen einer nennenswerten Umweltverbesserung gegenüber. Von den drei Optionen schneidet jedoch eine „kanalisationslose Gesellschaft“ am besten ab.

Schlüsselwörter Wasser-Energy-Abfall Nexus · Urbanes Abwassersystem · Organische Siedlungsabfälle · Ökobilanzierung · Lebenszykluskosten · Ökoeffizienz

1 Introduction

The water-wastewater system available in developed cities contributes heavily to public health (Daigger 2007). However, the operation of such systems is connected to a noteworthy energy consumption, whereas construction results in material-intensive infrastructures with a long use phase of up to 100 years (Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall 2018; U.S. Department of Energy 2013). Such systems lack of an effective and efficient recovery of nutrients (Arcadis 2016). Although nutrients in the wastewater are collected, in the European Union, for example, only 53% (2015) of the nutrient-rich sewage sludge is distributed to agriculture or to compost facilities (Gutjahr and Müller-Schaper 2018).

Finding technical options to reduce the demand for materials and energies while not worsening the quality of services offered by the systems are widely investigated (Otterpohl and Oldenburg 2002; Lehn 2002; Hiessl et al. 2010; Remy 2010). Key to all propositions is separating wastewater at the source into greywater and blackwater (United Nations World Water Assessment Programme 2017). Greywater, mostly from showers and dishwashers, is generally warm and lightly polluted; the contained thermal energy can be recovered while recycled greywater can be reused for mainly non-hygienic uses, like irrigation. Blackwater, coming from toilets, is nutrient-rich. Complementing it with organic municipal solid waste (MSW) could result into a comparable high caloric feed for biogas plants, providing an additional locally available energy source, as well as an organic fertilizer (Winker and Schramm 2015; Hiessl et al. 2010; Lehn 2002).

These ideas are implemented in first pilot plants, which differ in their scales, reaching from home solutions for single buildings (e.g. Arminplatz, Berlin) (Nolde 2013) to larger neighborhoods (e.g. Jenfelder Au, Hamburg) (Stadt Hamburg 2017). In most cases, these projects are realized in new or completely restructured buildings or new settlements. Existing buildings or settlements are seldom considered as the restructuring is seen as too expensive, without providing publicly accessible cost data. However, recent studies have shown that separating wastewater at its source in building stocks could significantly decrease the resource demand and environmental impacts (Friedrich et al. 2020; Winker and Schramm 2015). This request for an in-depth analysis of the costs of transforming the system considering the environmental performance; i.e. to discuss the eco-efficiency of possible alternatives to the current system of treating wastewater and wastes as well as providing energy.

The aim of the concept of eco-efficiency, as defined by the World Business Council for Sustainable Development (2000a), is to promote the delivery of competitive goods and services while securing an improved use of the environment as a source as well as a sink and thus, advancing the well-being of humankind (Lorenzo-Toja et al. 2015). To achieve this eco-efficiency connects the environmental issue of a product or service with the economic one (Wursthorn et al. 2011).

Typically, eco-efficiency assessment refers to a specific product or service (ISO 14045 2012). For example, the service provided by the conventional wastewater system is to transport wastewater and the connected pathogens and harmful substances out of the settlement. In contrast, the system alternatives reviewed in this study shall not only fulfill the goal of the conventional wastewater system, but shall also deliver resources. Thus, the system alternatives have no more a single or dominant output, as they shall provide recycled wastewater, nutrients as well as energy. Therefore, to overcome the impediments of selecting one output as a reference in this study all services offered by the system are treated equally. Thus, the study conducts a multi-functional eco-efficiency analysis (Zhao et al. 2011).

The overarching aim of the contribution is to analyze the dynamic behavior of eco-efficiency due to the transformation of the current system of treating wastewater, organic municipal solid waste (MSW) and providing energy to an integrated water-energy-waste system. Using the multi-functional eco-efficiency approach the study compares three different system alternatives with the status quo. Key to all system alternatives is the separation of wastewater at its source into blackwater and greywater, recognizing organic MSW as an additional feed to a biogas plant. The system alternatives differ in the technological shape of treating separated wastewater flows. The least invasive system change assumes a separation of wastewater at the source without a complete overhaul of the current system; the most elaborated one takes the current wastewater system fully out of operation.

To the knowledge of the authors, no studies are publicly accessible which analyzes the eco-efficiency of a water-energy-waste system as sketched above. The small number of studies related to eco-efficiency of water-wastewater systems concentrates on analyzing single components, with wastewater treatment plants as the most prominent one (Lorenzo-Toja et al. 2015). Hiessl et al. (2010) and Remy (2010) provide a more comprehensive analysis of water-wastewater systems. Hiessl et al. (2010) also offer cost figures for their system under review, whereas Remy (2010) refers to other studies without going into details. Both do not carry out a comprehensive eco-efficiency analysis. Furthermore, they are not considering heat recovering from greywater, the possible recycling of greywater and the inclusion of organic MSW to increase the yield of an adjunct biogas plant (Friedrich et al. 2020).

The rest of the contribution is organized as follows: Chap. 2 discusses the underlying theory of the study. Chap. 3 describes the system under review, whereas Chap. 4 presents the method used. Main findings are shown in Chap. 5 while in Chap. 6 the findings are discussed. Concluding remarks offers Chap. 7.

2 Theory

The original aim of eco-efficiency was to allow for a simultaneous sustainability assessment of two of the three pillars of sustainable development, i.e. environment and economy (Wursthorn et al. 2011; Lorenzo-Toja et al. 2015). To achieve a mostly comprehensive assessment, the use of the environment as a source and as a sink for anthropogenic activities over the entire life cycle of the affected materials is recommended (United Nations and United Nations Conference on Trade and Development 2004; World Business Council for Sustainable Development 2000a). The most comprehensive method to capture environmental impacts is Life Cycle Assessment (LCA), which is used in this contribution. The aim of an LCA is to quantify all by a product induced environmental relevant elementary and product flows over the entire life cycle (ISO 14040 2006).

Comparable with the environmental dimension, the economic one should be included comprehensively, i.e. all economic activities necessary to produce goods and services have to be considered into the analysis. The common suggestion is the estimation of the value added (World Business Council for Sustainable Development 2000b; Lorenzo-Toja et al. 2015; Saling 2016). In highly regulated markets, like grid-bound services, costs could be used as a good proxy to assess economic activities.

The cost analysis shall consider the entire costs of implementing, maintaining and operating of the system, which provides the services under consideration, irrespective of the cost bearer. A most comprehensive method to capture the entire costs is Life Cycle Costing (LCC) (Steen 2005), which is used in this contribution as a proxy to value the economic activities emerged by the system.

Using LCA and LCC as the elements of calculating the eco-efficiency, the underlying approach follows the principles set out in ISO 14045 (2012) (Saling 2016). The core of a life-cycle based analysis of eco-efficiency is a decision regarding the functional unit, the functional value and the systems boundaries. The functional unit defines the "quantified benefit of a product system" (ISO 14040 2006, p. 10). When the functions of product systems are rather clear, a unidimensional functional unit can be defined easily, as m^3 wastewater delivered (Weidema et al. 2004). The primary function of a conventional wastewater system is to transport wastewater and the connected pathogens and harmful substances in a reliable and secure way out of a settlement. Linked with this function is the treatment of wastewater to close the water cycle minimizing the potential impacts on human health. However, the discussed system alternatives have an additional function as a resource pool. Thus, the system alternatives shall be organized in a way that both functions, disposal of wastewater and provision of resources, are equally achieved. Hereby the integrated water, energy, and waste management of the system alternatives has to address the protection of human health as well as the security, reliability and comfort of the services offered. To allow a comparison of the system alternatives with the status quo taking into account the primary functions of all systems demands a necessity to emerge a multi-functional definition of the functional unit: "The treatment of wastewater and organic wastes as well as the provision of energy and nutrients *caused by the user of the wastewater and waste systems in the analysed neighbourhood* within one year."

The calculation of the eco-efficiency differs between the more resource-related impacts, i.e. fossil and metal depletion, and the more emission-related, i.e. climate change, photochemical oxidant formation and terrestrial acidification. The current system is highly dependent on fossil energy and nonrenewable materials. Reducing the demand for primary resources would relieve the anthropogenic burden on the ecological system. The high relevance of energy for operating and constructing the systems could have a noteworthy impact on climate change. The formation of photochemical oxidant, like nitrogen oxides, and terrestrial acidification, with sulfur dioxide as a main component, could disturb the acid-based balance of terrestrial eco systems (Umweltbundesamt 2018). Photochemical oxidants promotes ground-level ozone, fostering irritation of airways and mucous membranes as well as damages to flora and fauna (Bundesministerium für Umwelt, Naturschutz und Nukleare Sicherheit 2013).

The functional value "reflects a tangible and measurable benefit to the user and other stakeholder" (Saling 2016, p. 120). It has to refer to the functional unit, as set out by the LCA. As discussed above, for calculating the functional value LCC is used, which comprises the investment and operating costs required to install and run the entire systems.

Systems boundaries could influence the potential functions of a product and thus the relevant functional unit and functional value. Thus, the functional boundaries should set the systems boundaries (Baumann and Tillmann 2004). The system of water and wastewater management, energy provision and organic waste collection and treatment in a neighborhood in the city of Heidelberg, Germany, set the functional and geographical system boundaries.

3 System under review

The analysis refer to a neighborhood in the city of Heidelberg, Germany, with around 5081 inhabitants. Residential buildings of different sizes and a school with about 1692 students characterizes the neighborhood (Friedrich et al. 2020).

The following description of the current system and of the system alternatives draws heavily on Friedrich (2020) and Friedrich et al. (2020).

Characteristic for the current water-energy-waste system (Fig. 1) is

a) a centralized provision of drinking water;
b) the treatment of wastewater (together with rainwater) in a centralized wastewater treatment plant with the removement of nutrients;
c) a centralized supply of energy for space and water heating; and
d) a separated collection of wastes and treatment of organic MSW in a compost plant.

The treated wastewater is discharged to the local river; sewage sludge is used as a feed for generating sewage gas; the rest is co-fired in a coal power plant. The main feed for the heat plant is with 75% coal.

All system alternatives recognizes elements of a circular treatment of the resources. Due to the way the alternatives are shaped, they could reflect different stages of a transformation of the entire system. While SYstem ALternative 1 (SYAL1) is the least invasive intervention in the current system (Fig. 2), SYstem ALternative 3 (SYAL3) promotes the idea of a "sewerless society" with a complete overhaul of the current system (Fig. 4). SYstem ALternative 2 (SYAL2) is in between (Fig. 3).

Key to all system alternatives is (Peter-Fröhlich et al. 2006; Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall 2006; Zech et al. 2009; Otterpohl 2011)

a) separating wastewater into blackwater and greywater;
b) mixing blackwater with organic MSW;
c) recovering heat of greywater; and
d) reducing of the run-off of rainwater.

Blackwater—coming from toilets—is rich of nutrients. For a less water-demanding transport of blackwater and thus, less energy-intensive treatment vacuum toilets are installed (Staben 2008). Mixing blackwater with organic MSW increases the energy yield of a biogas plant as well as the provision of nutrients by the entire system under review (Han et al. 2016). Greywater—mainly coming from showers and kitchen—is warm and low contaminated. This allows for the recovery of heat and for recycling of wastewater, which could be re-used for non-hygienic purposes

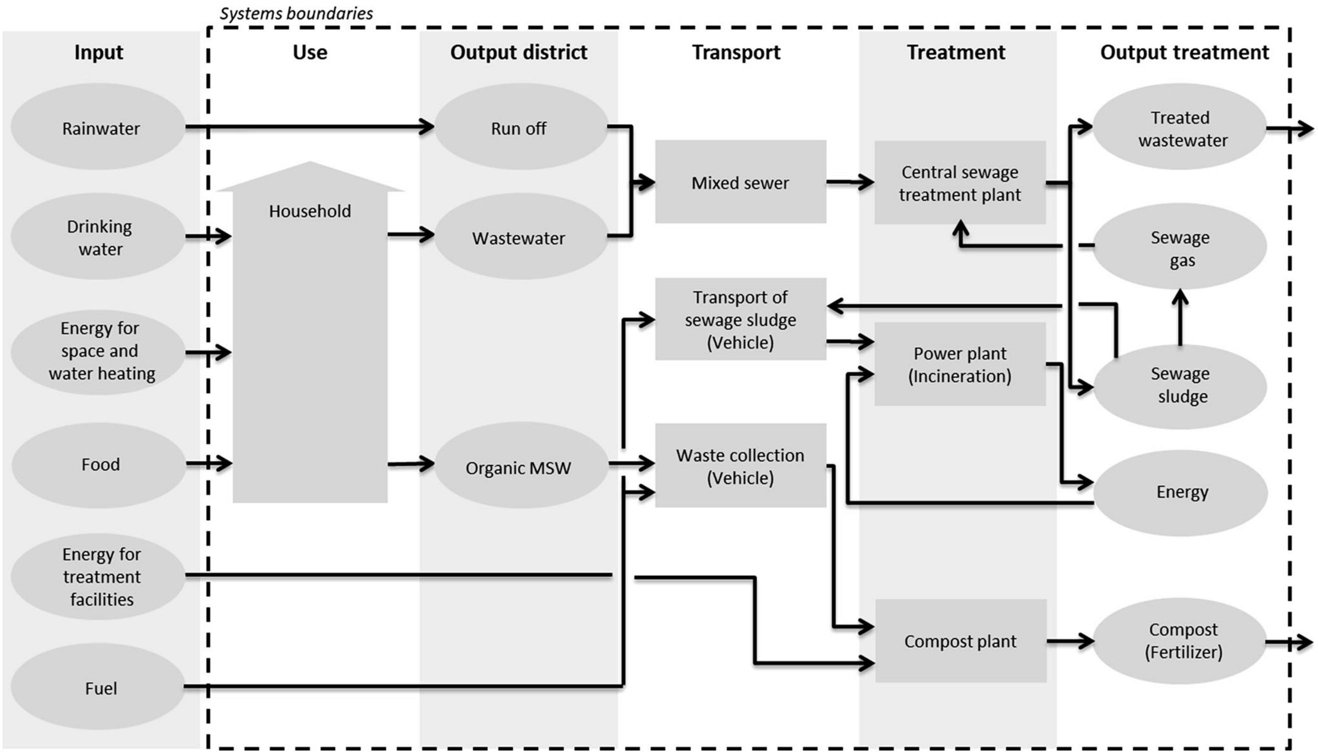

Fig. 1 Status quo (Source: Friedrich et al. (2020))

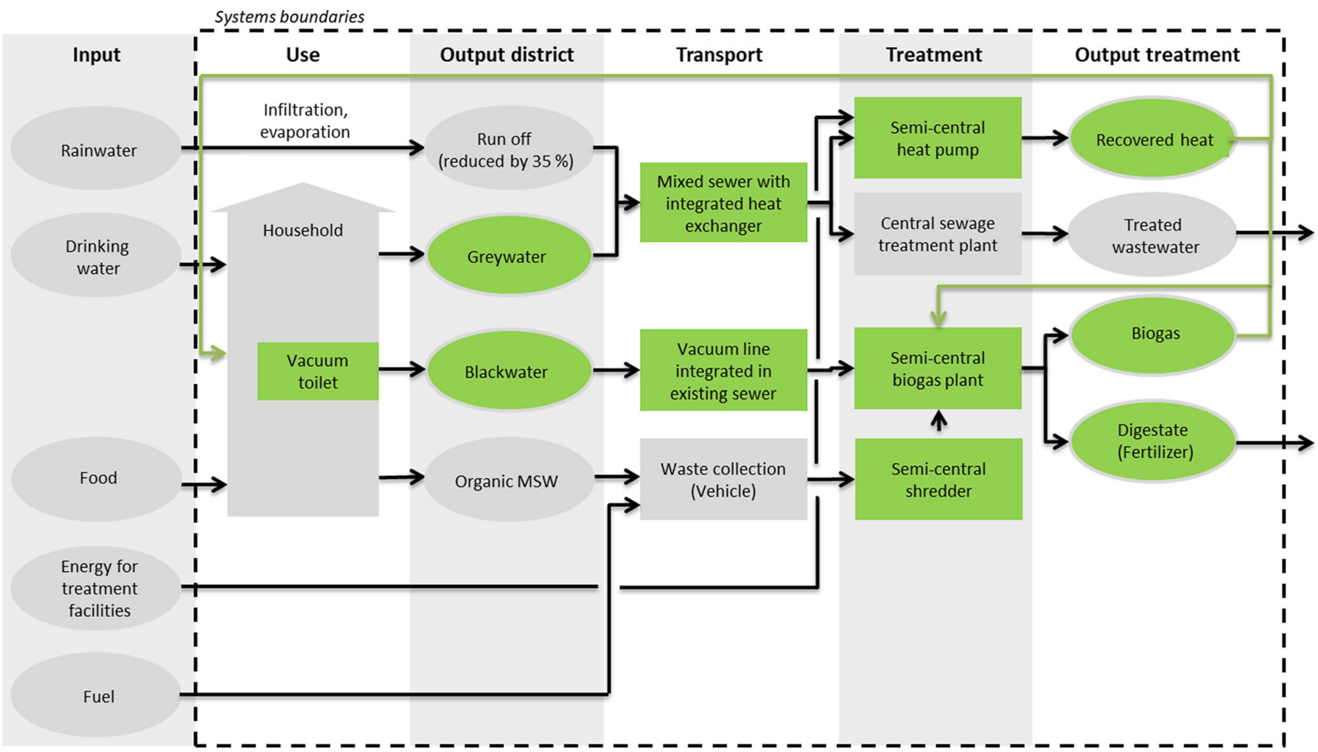

Fig. 2 System Alternative 1; changes against the status quo are marked in *green* (Source: Friedrich et al. (2020))

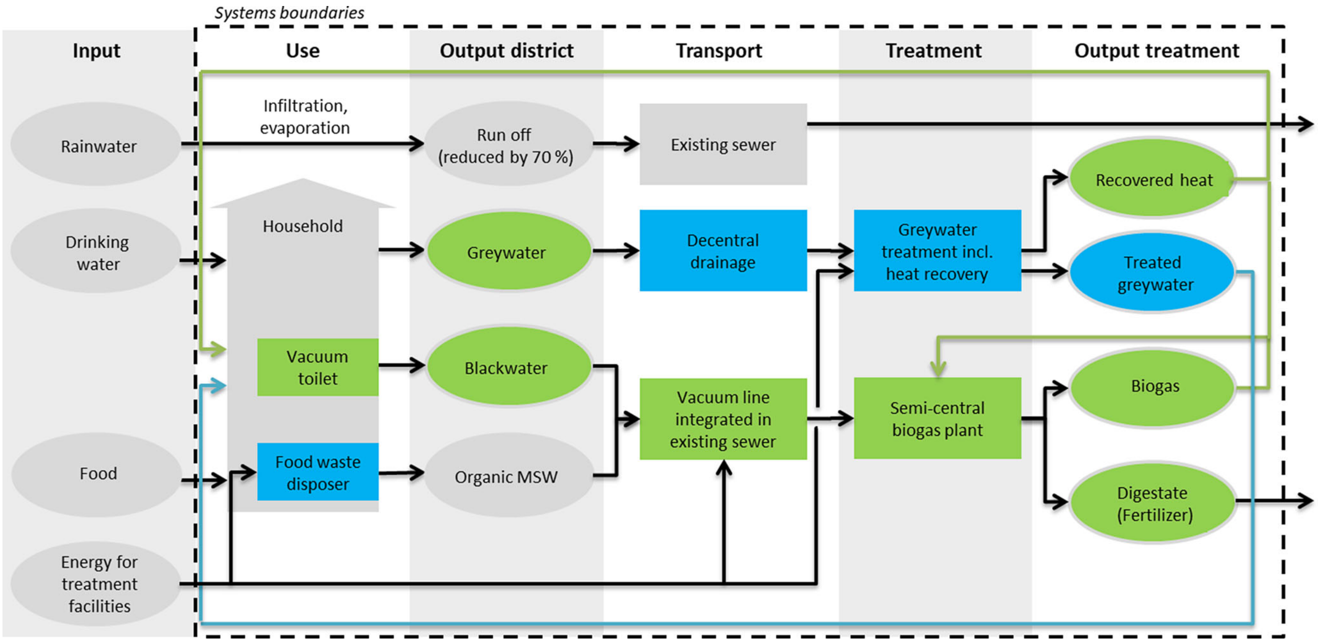

Fig. 3 System Alternative 2; changes against the status quo are marked in *blue* and *green* (Source: Friedrich et al. (2020))

like flushing of blackwater (Menger-Krug et al. 2010; Winker and Schramm 2015; Hiessl et al. 2010).

Next to the separation of wastewater, another measure to reduce the amount of treated wastewater is to lower the run-off of rainwater by infiltration, retaining and evaporation (Matzinger 2017).

The transformation of the distinct systems of wastewater, energy and waste treatment to an integrated one shall have no impact on the primary functions of the systems, although the way of treating waste and wastewater as well as providing of energy will change.

In SYAL1, after separation of wastewater, greywater as well as the reduced run-off is discharged to the mixed sewer, where the heat from greywater is recovered. A vacuum line integrated in the existent sewer system transports the blackwater to a biogas plant in the neighborhood. Organic MSW

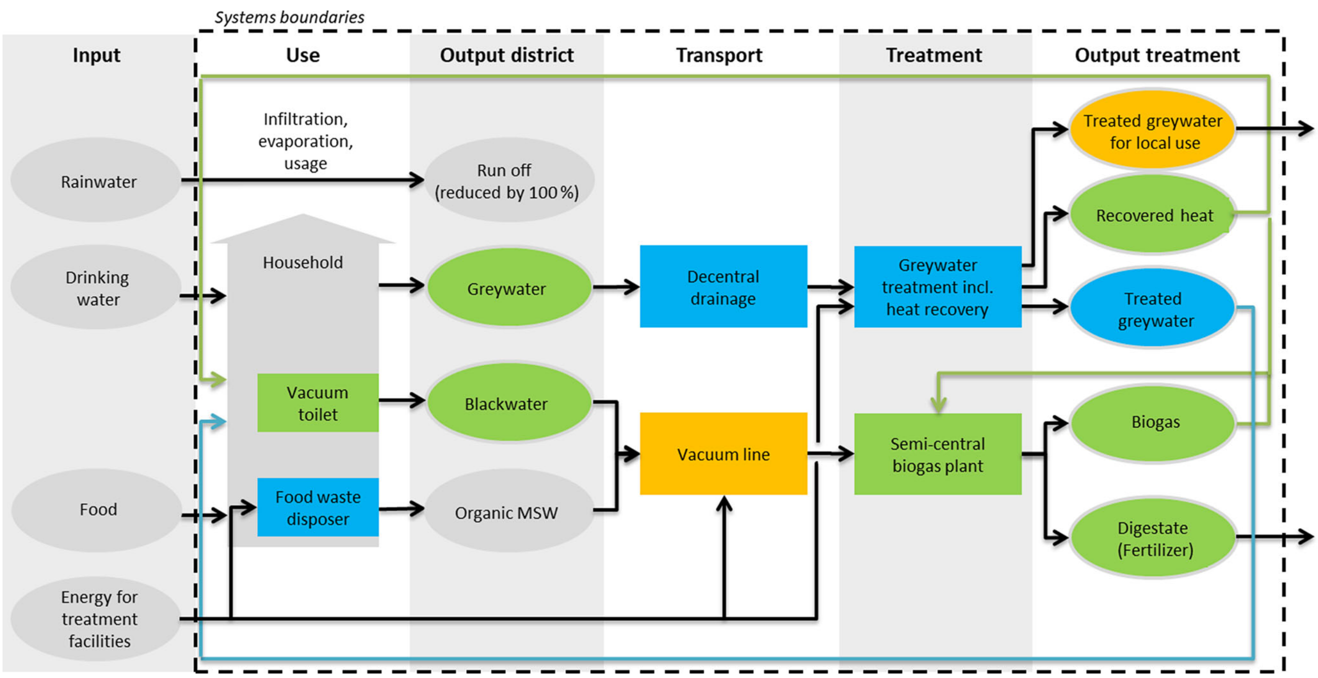

Fig. 4 System Alternative 3; the changes against the status quo are marked in *orange*, *blue* and *green* (Source: Friedrich et al. (2020))

is an additional input for the biogas plant. The residue of the digesting process could be used as a fertilizer (Fig. 2).

In SYAL2, the recovery of the heat of greywater and the recycling happens in a decentralized treatment plant directly in the building. The recycled greywater is partly used for non-hygienic purposes; the rest is disposed to the local river. The general outline of heating blackwater and organic MSW corresponds to SYAL1; only organic MSW adds to the vacuum line right in the households by shredding via a waste disposer in the kitchen sinks (Fig. 3).

In SYAL3, the existing sewer system is set out of service by implementing a vacuum line outside existing sewer and by infiltrating, retaining and evaporating rainwater locally (Fig. 4).

The water and energy flows as well as the recovered nutrients and an overview on the most important used materials for construction of the components are shown in the Supplementary Information (Tables A1 and A2). Friedrich et al. (2020) discuss the underlying model and the main assumptions.

4 Method

The study scrutinizes the change of the eco-efficiency due to transforming the existing system, i.e. status quo (SQ), to the system alternatives 1 (SYAL1), 2 (SYAL2) or 3 (SYAL3). For the analysis environmental productivity, the commonly used approach in eco-efficiency analysis is selected. It defines economic performance per environmental impact (Huppes and Ishikawa 2005).

Commonly eco-efficiency is defined as the relation between economic performance and environmental impact (Kicherer et al. 2007; ISO 14045 2012). For the decision process, the calculated eco-efficiency of each option is compared. This study will follow a slightly different approach, which allows revealing immediately the change of the eco-efficiency between two alternatives (Zhao et al. 2011; Lorenzo-Toja et al. 2015).

Due to methodological reasons, the calculation of eco-efficiency needs a two-step approach. In a first step, all possible alternatives with a joint worsening of the economic and environmental performances compared to the reference needs to be sorted out. In the second step, the variation of the eco-efficiency is calculated, using e.g. Equation 1:

$$\Delta EE_{k,l} = \frac{Co_l - Co_{SQ}}{\left|EI_{k,l} - EI_{k,SQ}\right|} \forall \left|EI_{k,l} - EI_{k,SQ}\right| > 0 \quad (1)$$

with $\Delta EE_{k.l}$ as the changed eco-efficiency of system alternative l = SYAL1, SYAL2, SYAL3, compared to the one of the status quo in respect to the impact category k = FD, MD, CC, POF, TA. FD corresponds to fossil depletion, MD to metal depletion, CC to climate change, POF to photochemical oxidant formation and TA to terrestrial acidification. Co_l complies with the total costs of the system l, Co_{SQ} with the one of the status quo. $EI_{k,l}$ indicates the environmental impact k of the system l; whereas $EI_{k,SQ}$ indicates the environmental impact k of the status quo.

Since all analyzed system alternatives show a better environmental performance compared to the status quo (see next section), the denominator is set in absolute terms. By this, a decreasing $\Delta EE_{k,l}$ indicates an improvement of the eco-efficiency. This assumption permits directionally safe results. The calculated numbers indicate immediately a weak improvement of the eco-efficiency occurs or a strong one, in contrast to the conventional approach. There, an increased eco-efficiency could be the result of a weak or strong improvement, a lower number the result of a weak improvement or even a worsening of both, economic and environmental performance. $\Delta EE_{k,l} > 0$ defines a weak improvement of the eco-efficiency, i.e. only the environmental performance improves. $\Delta EE_{k,l} < 0$ indicates a strong improvement of the eco-efficiency, i.e. both components of the eco-efficiency reveal a better performance (Saling 2016).

The cost calculations take into account all investment and operating costs for installing and running the entire water-energy-waste system, irrespective of the cost bearer.

For each system under review, the net present value (NPV) of all costs is estimated using the "Guidelines for the Implementation of Dynamic Cost Comparison Calculations" (KVR Guidelines) of the Federal Government/State Working Group on Water (LAWA) as a reference (Bund/Länder-Arbeitsgemeinschaft Wasser 2012). The investment costs includes reinvestment costs. Reinvestment costs occur as the components differ in their life span, demanding replacements within the life span of the entire system. Each system runs for 80 years, which corresponds to the longest life span of a single component, i.e. of the sewer system (Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall 2015). Since no information on costs of disinvestments of the components is available, these are not taken into account.

The operating costs comprise recurring expenses incurred for the operation incl. maintenance and servicing of the systems.

The entire NPV is the sum of all cost factors:

$$\begin{aligned} Co_p = IC_p &+ \sum_{u}^{v} \left(\mathrm{ICR}_{p,u} * \frac{1}{(1+i)^{xm+1}} \right) \\ &+ \sum_{t}^{n} \left(OC_{p,t} * \frac{(1+i)^n - 1}{i \cdot (1+i)^n} \right) \end{aligned} \quad (2)$$

with p = SQ, SYAL1, SYAL2, SYAL3. IC_p are the investment costs to implement the entire system. $ICR_{p,u}$ are the reinvestment costs of the component u— the entire system consists of v components. The parameter m denotes the life span of each component, x accounts the times a component is substituted, i.e. $x = 1, ..., 4$. The reinvestment happens in the year after demolishing of the component, i.e. in the year $x\,m + 1$. The reinvestment costs are discounted with i as the corresponding interest rate. $OC_{p,t}$ corresponds to the annual operation costs, which are discounted with i. n denotes the life span of the entire system.

The planning costs are set to 10% of the investment costs of each component. The interest rate for financing and discounting equals to 3%; the refinancing period is set to the life span of each component. Each investment takes one year. The Supplementary Information (Tables A3 and A4) gives a detailed breakdown of the investment costs and operating costs. Since not all components are used solely by the neighborhood, the respective costs as well as energy and material flows are downsized to the settlement.

The calculation of the impacts make use of the estimated material and energy flows for operating and construction (Supplementary Information Tables A1 and A2), using ReCiPe method (Goedkoop et al. 2013; Friedrich et al. 2020).

5 Eco-efficiency assessment

All system alternatives show in respect to all discussed impact categories a better environmental performance compared to the status quo (Table 1).

The decline of resource use and emissions ranges between 67.8% (metal depletion; SYAL1) and 96.5% (climate change; SYAL3), compared to the status quo. Looking at the impact categories, on average of all system alternatives the change is lowest in case of metal depletion (–73.3%; range: –67.8% (SYAL1) to –78.8% (SYAL3)); the most pronounced in respect to climate change (–95.7%; range: –94.5% (SYAL1) to –96.5% (SYAL3)). The decline of metal depletion stems from a reduced demand for metals. The system alternatives use more materials that are plastic. The noteworthy drop of fossil fuels and climate change rel-

Table 1 Resource use and emissions. (Source: Friedrich et al. (2020) and own calculations)

Impact category		Unit	SQ	SYAL1	SYAL2	SYAL3
Fossil depletion (FD)	Construction	t Oil_e	64	37	48	43
	Operation	t Oil_e	2162	86	53	53
	Total	t Oil_e	2226	123	101	96
Metal depletion (MD)	Construction	t Fe_e	132	44	35	27
	Operation	t Fe_e	14	3	4	4
	Total	t Fe_e	146	47	39	31
Photochemical oxidant formation (POF)	Construction	t NMVOC	0.9	0.4	0.4	0.3
	Operation	t NMVOC	5.8	0.3	0.2	0.2
	Total	t NMVOC	6.7	0.7	0.6	0.5
Terrestrial acidification (TA)	Construction	t SO_{2e}	8.6	1.2	0.7	0.7
	Operation	t SO_{2e}	1.0	0.4	0.4	0.3
	Total	t SO_{2e}	9.6	1.6	1.1	1.0
Climate change (CC)	Construction	t CO_{2e}	230	114	111	82
	Operation	t CO_{2e}	7693	320	198	198
	Total	t CO_{2e}	7923	434	309	280

Table 2 Total costs (net present value)

Cost items	Unit	SQ	SYAL1	SYAL2	SYAL3
Investment costs	Mio. EUR	14.14	32.97	44.33	41.81
Operating costs	Mio. EUR	28.08	32.40	28.22	22.85
Total costs	*Mio. EUR*	*42.22*	*65.37*	*72.55*	*64.66*
Of which					
Drinking water	%	17.5	8.2	5.3	6.0
Wastewater and greywater treatment	%	63.4	23.8	25.7	18.4
Sludge, blackwater, organic waste treatment	%	0.8	39.5	39.4	44.2
Toilet system	%	4.5	12.4	11.2	12.5
Planning costs	%	2.0	3.4	4.3	4.6
Financing costs	%	11.8	12.6	14.1	14.3

Table 3 Change of the environmental productivity

Impact category		Unit	SYAL1	SYAL2	SYAL3
Fossil depletion	Construction	EUR/kg Oil_e	711.51	1905.82	1350.88
	Operation	EUR/kg Oil_e	2.08	0.07	–2.48
	Total	EUR/kg Oil_e	11.01	14.27	10.54
Metal depletion	Construction	EUR/kg FE_e	213.24	311.11	263.56
	Operation	EUR/kg FE_e	385.06	13.01	–485.60
	Total	EUR/kg FE_e	232.61	281.33	193.86
Photochemical oxidant formation	Construction	EUR/kg NMVOC	38,144.92	58,543.92	45,583.76
	Operation	EUR/kg NMVOC	795.06	25.29	–943.92
	Total	EUR/kg NMVOC	3904.50	5007.75	3650.08
Terrestrial acidification	Construction	EUR/kg SO_{2e}	34,474.36	50,712.66	40,922.43
	Operation	EUR/kg SO_{2e}	584.63	17.91	–668.51
	Total	EUR/kg SO_{2e}	2916.32	3602.55	2640.10
Climate change	Construction	EUR/kg CO_{2e}	163.07	254.73	187.14
	Operation	EUR/kg CO_{2e}	0.59	0.02	–0.70
	Total	EUR/kg CO_{2e}	3.09	3.98	2.94

The figures reveal the change of the environmental productivity defined in Eq. 1. The figures of construction and operation do not sum up to the total costs, since the denominators differ between construction and operation

evant emissions results in the shift from a coal based heat provision to a renewable energies based.

Contrary to the environmental performance, the costs to install and operate the system alternatives are noteworthy higher: SYAL1 +54.8%; SYAL2 +71.8% and SYAL3 +53.0% compared to the status quo (Table 2). The main reasons are the investments in the biogas plant and toilette systems (Supplementary Information Table A3).

Since the system alternatives show in respect to all discussed impact categories a better environmental performance compared to the status quo, a switch to the system alternatives leads always to an improvement of the environmental productivity (Table 3). From a transformation perspective, the gain is highest in case of SYAL3 followed by SYAL1 and SYAL2, i.e. the cost increase is per environmental improvement lowest in SYAL3 and highest in SYAL2. This is true for all impact categories. SYAL3 shows the best environmental performance of all system alternatives as well as the best cost performance. The environmental benefit generated by SYAL2 is comparable with the one of SYAL3, but the costs are about 12% higher. The cost disadvantage of SYAL2 compared to SYAL1 is larger than the environmental benefit, resulting in the least improvement of the eco-efficiency.

However, for all system alternatives and for all impact categories only a weak eco-efficiency can be observed. That means the total costs of each system alternative are higher, compared to the status quo, while the environmental impacts are in all alternatives lower. The differences between transforming the system from the status quo to SYAL3 compared to SYAL2 is noteworthy, irrespective of the selected impact category. The changed environmental productivity ranges from 26.2% (FD) to 27.1% (POF), with MD as an outlier (31.1%). The large discrepancy is mainly due to the cost difference (s. Tables 2 and 3). The advantage of SYAL3 against SYAL1 is less explicit: the respective figures vary between 4.3% (FD) and 9.5% (TA); once again, MD is an outlier (16.7%). The costs of SYAL1 is comparable with the one of SYAL3; but SYAL1 shows a worse environmental performance, which is lower than the cost difference between SYAL3 and SYAL2.

The system alternatives substitute metal components, which dominate the wastewater and energy system of the status quo, by plastic materials. Since the substitution rate relating to the components in SYAL3 is higher than of the one in SYAL1 and 2, the differences between the system alternatives is quite large.

Considering only the operation of the system a switch to SYAL3 generates in all impact categories a strong eco-efficiency: both factors, costs and environmental impact, are improving compared to the status quo. Transforming the system would re-shape the cost structure. The most dominant cost factor of the status quo is the treatment of wastewater, accounting for two thirds of the entire costs. In SYAL3, the most relevant cost factor is operating the biogas plant, also sharing two thirds of the entire operating costs. However, the latter is 25% less expensive (Supplementary Information Table A3). For the other two system alternatives only a weak eco-efficiency is observable, with SYAL1 always trailing behind SYAL2. Nevertheless, the operation cost differences between status quo and SYAL2 are very small, i.e. less than 0.5%. The cost gap between wastewater treatment and biogas plant is closed by the greywater treatment and the rainwater treatment in SYAL2, which is noteworthy less costly compared to the status quo.

Regarding construction, in all cases a switch to the system alternative will generate a weak eco-efficiency, in case of SYAL3 outperforming the strong eco-efficiency of operating. SYAL1 shows always the best performance, while SYAL2 the worst, compared to the status quo (Table 1). The lower environmental impacts of SYAL2 and 3 do not outperform the low investment costs of SYAL1. The main reason for the higher investment costs in SYAL2 and 3 compared to SYAL1 are the greywater treatment plant and 2nd grid for the transport of blackwater (Supplementary Information Table A4). The difference between SYAL2 and SYAL3 is the installed sewer system in SYAL2, which is not necessary in SYAL3.

The ranking between the system alternatives depends crucially on the chosen interest rate for discounting and financing. As long as the interest rate is below 4.5%, a transformation to SYAL3 shows the best performance in all impact categories. Beyond 4.5%, the transformation to SYAL1 starts to outdo the one to SYAL3: However, the critical interest rate varies between the impact categories (Table 4). If the relevant interest rate is higher than 13.1%, transforming to SYAL1 outperforms the implementation of SYAL3 in all impact categories. An increasing interest rate favors SYAL1 compared to SYAL3, due to the higher impact of increasing interest rates on operating costs. Irrespective of the selected interest rate, SYAL2 shows always the lowest improvement of the eco-efficiency.

The costs of innovative technologies is another crucial aspect regarding the advantageous of a specific transformation pathway. In this study, innovative technologies are those technologies, which substitute in the system alternatives components of the status quo system or are newly installed. Costs of innovative technologies below the assumed one favor all system alternatives; however, SYAL3 with the highest share of innovative technologies will see the greatest improvement. 10% lower costs of innovative technologies increases the eco-efficiency of the transformation to SYAL3 by 12.8%, whereas the one to SYAL1 by 6.1% and to SYAL2 by 9.5%. The changes hold for all impact categories.

Table 4 Thresholds where SYAL1 outperforms SYAL3

Impact category	Interest rate %	Cost difference regarding innovative technologies %
Fossil depletion (FD)	4.5	7.0
Metal depletion (MD)	13.1	36.3
Photochemical oxidant formation (POF)	5.5	11.0
Terrestrial acidification (TA)	7.1	17.3
Climate change (CC)	4.8	8.3

If the costs of innovative technologies would be higher than the assumed one, the ranking of the system alternatives could change. 7.0% higher costs would result in the impact category FD in a higher eco-efficiency gain of SYAL1 compared to SYAL3 (Table 4). A transformation to SYAL1 will outdo a transformation to SYAL3 in all impact categories, if the costs of the innovative technologies are 36.3% above the assumed one (Table 4). There is no cost level favoring SYAL2 in a way that this system alternative could succeed.

Varying the environment performance of the innovative technologies has no significant impact on the eco-efficiency of each system; thus, the rankings are not affected.

6 Discussion

No comprehensive eco-efficiency analysis of integrated water-energy-waste systems are known to the authors. However, Hiessl et al. (2010) address in their study environmental impacts as well as costs. Focusing on a technological setting comparable with SYAL1, they estimate negative impacts on climate change and terrestrial acidification, but a better performance regarding photochemical oxidant formation. According to their cost estimation, the analyzed technical setting is 71.9% more expensive than a conventional wastewater system. Thus, the eco-efficiency in respect to climate change and terrestrial acidification would decline, whereas regarding photochemical oxidant formation a weak improvement could be expected. However, Hiessl et al. (2010) stress in their summary that their findings depend crucially on the small size of the reference settlement (about 100 households), forcing to install presumably inefficient components.

Remy (2010) focuses mainly on the environmental impacts. No costs analyses were carried out, but he refers to Oldenburg et al. (2007) and Dockhorn (2007). Oldenburg et al. (2007) identified operating costs' advantages of separated systems, but taken into account investment costs the potential advantages diminish. Dockhorn (2007) sees a general economic benefit of separation systems. Combining Remy (2010) with Dockhorn (2007), even a strong improvement of the eco-efficiency seems to be possible.

A crucial question in the appropriateness of the chosen system boundaries. Looking at the costs, the selected cost approach, i.e. LCC, takes only the costs into account, which investors and users have to consider in their own cost calculations. Environmental costs generated by the system are not included, which comply with the understanding of the World Business Council for Sustainable Development (2000a) and with ISO 14045 (2012).

In addition, potential benefits, which could be created by the system alternatives, but are not recognized by LCA or LCC, are not included in the analysis (Steen 2005). For example, the implementation of SAYL3 would disconnect the direct link between wastewater treatment and surface waterbodies, reducing the potential contamination of these waterbodies and thus, increasing the water quality of these waterbodies. The related benefits of an improved water quality could be relevant, according to a recent study. Börger et al. (2021) estimate a consumer surplus of about 2000 € per year and person on average of 14 EU member states.

The provided eco-efficiency analysis did not included the treatment of micropollutants due to a lack of comprehensive data. Micropollutants, mainly pharmaceuticals and microplastics, are an increasing challenge to the treatment of wastewaters. They consists of harmful substances albeit in smaller quantities (Chavoshani et al. 2020). Conventional wastewater treatment plants cannot eliminate or reduce sufficiently micropollutants, demanding additional purification stages. Nevertheless, none of the currently known technologies will remove micropollutants completely (Chavoshani et al. 2020). Technologies treating greywater and blackwater will face the same challenge, i.e. only a noteworthy purification will be possible, but no complete re-movement of micropollutants (Butkovskyi et al. 2018; Hernandez Leal 2010). In contrast to existing costs estimations in respect to the additional purification stages (Umweltbundesamt 2015), none is available for separated wastewater treatment systems, not allowing a comprehensive eco-efficiency analysis.

The aim of an eco-efficiency analysis is to promote the delivery of competitive goods and services while securing an improved use of the environment as a source as well as a sink and thus, advancing the well-being of humankind (Lorenzo-Toja et al. 2015). Considering this aim, the approach implicitly assumes an equal impact of both the economic and the environment sphere on the human welfare. Although a strong eco-efficiency should be the aim of any transformation process, a trade-off situation, which is indicated by a weak eco-efficiency, is likely, also considering available literature (Pretel et al. 2015).

From the perspective of a decision-maker, the question arises, whether the equal valuing of both spheres, without considering the intensity of the changed impacts on each sphere is reflecting correctly the preference structure of the society. A society could reflect on the intensity of the impact. For example, if the stronger intensity of reduced greenhouse gas emissions (e.g. 96.4% in SYAL3) is valued higher than the cost increase (e.g. 53.2% in SYAL3), a transformation to SYAL3 would be seen as a gain. Additional research is needed, using multi-criteria decision approaches (Zanghelini et al. 2018), like the analytic hierarchical process (AHP), to analyze the boundaries of societally accepted valuing of both spheres recognizing that each sphere should not be treated homogenously, like this analysis differed between different environmental impacts.

7 Conclusions

The overarching aim of this contribution is to discuss whether different system alternatives of urban infrastructures are favorable from an environmental and cost point of view, i.e. whether transforming of the current water-energy-waste system to an integrated one will improve the eco-efficiency. The decision whether and which system alternative should ultimately be realized will depend on how society evaluates both spheres, but also the different environmental impacts. That is, whether the additional costs are worth to achieve the potential environmental gains. The decision process sees different challenges. To name just a few:

a) The decision-maker will typically differ from the user, who will finance (partly or completely) the new systems via fees; the opportunities of a user to avoid the consequences of the decision is generally limited and expensive;
b) Those who are affected by the environmental damages could differ from the beneficiaries of the new system;
c) Finally, even if the beneficiaries of the new system would willingly pay, the ability to pay should not be taken for granted.

The findings of the study refer to the specific situation in a neighborhood of Heidelberg. The actual shape of the current energy, wastewater and waste infrastructures and their management sets the reference for the transformation. The current system determines not only the possible shape of a future system, due to potential path-dependencies, but also influences the potential gain of a transformation. Additional research is needed to falsify the presented findings.

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