

## Sanitation systems: Are hybrid systems sustainable or does winner takes all?

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### Abstract

Hybrid wastewater systems can be defined as the co-existence of centralized and modular systems in the same catchment. Currently, we have no explicit knowledge if such hybrid systems can be long-term stable or if modular systems always will be a stopgap solution.

The current evidence indicates that depending on the settlement structure, centralized systems can have diseconomies of scale and modelling studies show that there are conditions where hybrid systems are cost-effective. Decisive factors are the costs of modular systems and the heterogeneity of urban areas. Overall, there are good reasons to believe that fortifying centralized systems with modular systems enables overcoming some of the critical weaknesses of the one fits all centralized systems approach.

However, centralized systems show strong path dependencies. Besides a wide range of institutional and organizational barriers, the current engineering economic and planning methodologies also need to be improved and adapted. From a purely engineering perspective, the following research needs can be identified: (i) Long-term transition planning tools that are spatially explicit and can consider a wide range of modular technologies; (ii) Cross-sectoral integration methodologies; (iii) Better methods to integrate multi-criteria decision analysis (MCDA) to consider the broader range of benefits hybrid systems can provide; and (iv) Improved engineering economic methodologies considering uncertainties, unused capacity and the value of adaptability.

### Introduction

The quest for the optimal system configuration to provide an inherently distributed service is not new but still very present in the academic literature. Services, such as wastewater treatment, electricity, heat provision, and many more, can be produced locally with short distribution paths or centrally by relying on an extensive distribution network. Recent examples in the literature are electricity, hydrogen distribution, building heating, manure treatment, computing, chlorine production and biomass gasification (see also overviews in Eggimann et al. (2015) and Dahlgren et al. (2013)).

Wastewater management as a service has some particularities that distinguish it from other services. In terms of mass, it constitutes more than 90 % of a city's waste flux (Brands 2014) and requires considerable efforts to be transported around. Due to wastewater's rapid and unpleasant degradation, the preferred transport mechanism is in underground gravity sewers. This means that – different to water supply or electricity networks – the local topography strongly impacts the network. Both characteristics make it difficult to compare it directly with approaches for electricity or heating.

For wastewater management, the centralized versus decentralized debate can be found in the literature of the 1970s as a consequence of the US-Clean Water Act (EPA 2000). The main goal was to

identify decision criteria for the optimal degree of connectivity mainly based on economic criteria (Downing 1969) (Dajani and Gemmell 1971) (Adams et al. 1972). More recent work was done by Wang (2014), Tchobanoglous and Leverenz (2013), Maurer (2009), and Fane and Fane (2005). Much of these approaches focus strongly on finding a financial optimum for the treatment plant(s) only. The only exception is Roefs et al. (2017), who tries to model simplified but entire wastewater systems to draw some basic conclusions. All this work assume that treatment performance is more or less independent of plant size.

From a technical point of view, the size-independent performance is well documented. Ignoring the large body of literature for low-income countries (e.g. Gutterer et al. (2009); Sasse (1998)), the literature on high-end systems show nicely that small plants can achieve very similar treatment performances as large facilities ((Geenens and Thoeve 2000), (Abegglen et al. 2008), (Barca et al. 2014), (Mažeikienė and Grubliauskas 2020)). Also, in terms of organic micropollutant elimination, they show similar behaviour (Abegglen et al. 2009, Hube and Wu 2021), indicating that the biological processes are more or less size independent. However, empirical evidence shows that the overall system performance is not what one would expect from the technical performance achievable. (Kaminsky and Javernick-Will 2013) attributes this not to the technical hardware but "*software is more likely to be the root cause of system failure*" – defining software as institutional factors ("e.g., knowledge, institutions, education").

Consequently, decentralized systems are generally viewed as a stopgap solution where sewers cannot be built or are too expensive. This is surprising as from a global perspective sewers network also have some substantial disadvantages, such as very long lead and construction times, large spare capacity due to long planning horizons, high up-front investment costs, low flexibility to adapt to unforeseen changes, high water demand, or great efforts for resource recovery ((Roefs et al. 2017), (Larsen et al. 2016), (Brands 2014)). These disadvantages could be overcome or at least softened by adding decentralized systems to the engineering portfolio and utilising both systems' approaches to provide wastewater services. However, such hybrid solutions seem not to be very common around the world.

In the following, we would like to go to the bottom of why hybrid wastewater systems – as one potential example of a complementary system alternative - are not more common and which barriers and research gaps might play a crucial role. This chapter will have a very technical view on this issue and will focus on wastewater management only. Many relevant aspects (governance, organizational aspects, institutional, socio-economic setting, ...) will be ignored or only hinted at, trusting that other authors will complement these gaps with more authority.

### **Centralized, modular and hybrid sanitation systems (definitions)**

The literature is plagued with many terminology to distinguish sanitation system alternatives from the 'traditional' centralized system. This ranges from distributed and on-site to non-sewered systems, primarily relying on an intuitive understanding of the proposed underlying system layout. In the following, we present some definitions that we find helpful for discussing the main concepts in this article:

*Degree of centralization* (DC) or *connection rate* is defined as one minus the ratio of sinks to sources in a given catchment, weighted by the amount of wastewater per sink and source. A DC = 0 indicates that every source has its own sink, and a DC = 1 means that the sink is outside the catchment area

(Eggimann et al. 2015). We generally equate a source with a single building and a sink as a wastewater treatment plant.

*Centralized sanitation systems* have a high DC. Consequently, these are network and transport dominated systems where the wastewater is transported to a few large wastewater treatment facilities.

*Modular sanitation systems* have a very low DC and therefore shorter and fragmented sewer networks. Compared with the number of sources, they have a relatively large number of treatment plants. This definition does not make a statement about the size of the treatment plants. However, it can be expected that in a modular system, the units are substantially smaller than in a comparable centralized system. The term modular is probably closest related to the term 'distributed'. We deliberately chose this term to distinguish it from a) 'on-site', which is equal to a DC of zero and b) from the term decentralized wastewater treatment system or DEWATS, which is frequently associated with wastewater management in low-income environments (e.g. Gutterer et al. (2009), Sasse (1998)) or then in the US predominantly with septic tanks or any small treatment plants with less than a few thousand population equivalents but still a high DC, e.g. US-EPA (2005) or McCray et al. (2009).

*Hybrid sanitation systems* are a combination of centralized and modular systems. Part of the catchment has a very high DC, and part of the system has a very low DC. The overall DC of the catchment might be anywhere larger than 0 but smaller than 1.

### **Economies of scale of wastewater systems**

Empirical evidence shows that sewer networks show strong path dependencies ((Fam et al. 2009), (Wolf and Störmer 2010)). Besides the arguments of the institutional regime and high sunk costs, there is also a strong element of (apparent) economies of scale leading to a natural monopoly situation. This means that the benefits of adapting the existing centralized regime are not trivial nor obvious. The case for treatment plants is quite well documented over a wide range of capacities, e.g. see compilation in (Maurer 2009). A doubling of the capacity corresponds roughly to a 20 % decrease in investments per population equivalent and about 15 % in operating expenses.

The evidence for economies of scale in sewer networks is much shakier. Although the investments into the network far dominate the installation costs (Maurer 2013), little is known about their cost behavior in terms of size and spatial extent. Nauges and Van den Berg (2013) for example, concluded from the analysis of national data that "[...] *the cost structure of the water and wastewater sector varies significantly between countries and within countries, and over time, [...]*", finding evidence for economies of scale in some but not in other countries.

Own work found a not surprising impact of settlement structure on the scale economies (Maurer et al. 2010). Larger cities have more expensive networks due to larger pipes, but higher population densities might distribute these higher costs over more users. Looking at data from Switzerland, cost and settlement structure hint at very small economies of scale for combined systems (Maurer et al. 2013). A doubling in inhabitants corresponded to a decrease in 9 % in replacement value for the entire network. However, the analysis was averaged over whole cities and towns and ignored heterogeneity within the settlement structure. This averaging is also the case in other investigations in the literature, e.g. Nauges and Van den Berg (2013). We see in Figure 1 that heterogeneity can have a significant

impact on local costs and, therefore, economies of scale. Thus, a more 'individual' approach for specific catchments provides better insights into the viability of hybrid systems.

### **Connect or not to connect – the optimal degree of centralization**

A key challenge for a given wastewater management catchment is which houses should be connected to a sewer network and how extended these networks should be. This spatial explicit problem needs to consider topography – as most sewer networks are gravity-driven. In Eggimann et al. (2015) we developed such a model to explore the cost for different connection rates utilizing a heuristic routing algorithm. As a first step, this tries to connect a house with its neighbors and compares the resulting cost with the option of having a local treatment plant. If the difference exceeds a threshold, then the houses are connected. In the next step, it moves on to the next house and the algorithm is repeated. If there are no cost-effective connections anymore, then a treatment plant is positioned at the lowest point of the sewer network. Changes of the threshold can be used to favor or disadvantage connections over treatment, which allows exploring all the possible degrees of connections. The algorithm also provides freedom to align sewers with the street network or other relevant features.

The approach assumes that the treatment performance is independent of plant size (e.g. biological active, not septic tanks). The cost functions are based on realistic data on sewer construction costs (depending on depth, diameter and if it is under a street or not) and investment costs for treatment plants (depending on their capacity). The operation and maintenance costs also includes spatial explicit travel and transport costs for inspection and sludge removal. Details can be found in Eggimann et al. (2015). Although the absolute costs are based on Swiss data and most probably change substantially from country to country, we still assume that the impact of the relative costs between sewers and treatment plants are still providing generic answers.

(Eggimann et al. 2016) used the model to explore the total costs for the entire range of DC - from purely modular systems (a DC of zero) to fully centralized systems (a DC of one) – for 25 real and mostly rural catchments. From the results, three types of cost behavior emerged, summarized in Figure 1.

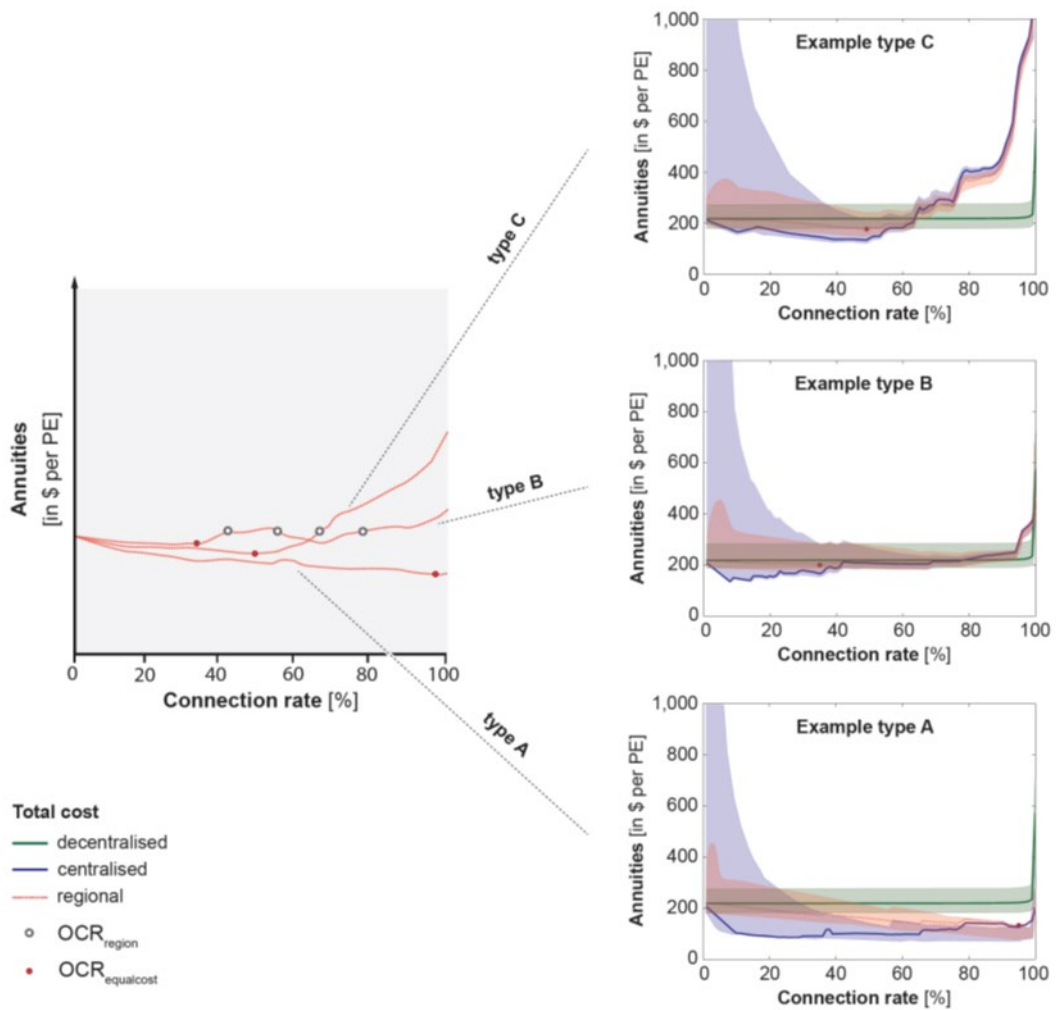


Figure 1: Cost curve configuration typology with examples. For each example type, standard parameter runs (thick line) and scenario uncertainties are provided. The 'Annuities' are annualized OPEX and CAPEX (Eggimann et al., 2016) and used with permission by the creator (Eggimann, 2020).

Catchment type A shows clear economies of scale, where a fully centralized approach constitutes a natural monopoly. The other clear case is catchment type C, where the costs show a pronounced global minimum. The settlement structure and the topography strongly impact this result (e.g. a compact town center with more loosely settled surroundings or houses in a hilly or mountainous area). It is also worth to note that for very high connection rates the costs for the decentralized part of the system is increasing strongly, due to the high transportation costs for the low density of the remaining small-scale treatment plants.

Type C is closest to the idea of a hybrid system and the analysis shows that there are circumstances where from a purely economic point of view, hybrid systems are a viable end-point. Changes in the cost structure might affect at what DC the minimum might be, but the fundamental characteristics of a hybrid system remain. A second interesting result was that the global minima did not coincide with the point of equal costs, where an individual house could connect or then go modular at cost parity. This means that the incentive structure matters. Letting the homeowner decide (and assuming a 'homo economicus') will produce a DC that is not necessarily the overall cost optimum for the entire catchment.

Catchment type B shows a very flat cost curve over a large range of DC. This indicates that small changes in costs can influence the optimal DC substantially. An alternative interpretation is that there

is no clear optimal DC for such type B catchments and that hybrid systems are a cost-effective solution.

The following conclusion can be drawn from these results:

- Under the investigated (Swiss-)cost structure for operating modular systems, hybrid systems can be cost-effective.
- The internal heterogeneity of a settlement structure plays a substantial role in favouring hybrid systems.
- The mix within the hybrid system (optimal DC) depends on the institutional framing. The catchment-wide cost minimum might be at a different point than the individual cost optimum. Therefore, it matters if a catchment-wide entity (benevolent dictator) or the homeowner decides if a house should be connected to the grid or not.
- Many total cost curves turned out to be very flat over wide ranges of DC, with substantial uncertainties. Small changes in the cost structure can have drastic impacts on DC.
- It is very likely that with the increased production of units, the costs for modular systems will go down. For example (Mayor 2020) identified a plant size-independent learning effect of 12 % to 30 % for desalination technologies, depending on the technology. This will most likely substantially affect the extent of modular systems that become cost-effective but most likely will not change the fundamental cost curve behaviour.

These modelling exercises, illustrative as they are, have some substantial restrictions in answering the question of whether hybrid systems are sustainable. First, they assume green-field conditions and ignore existing infrastructure. Second, it is a very static snapshot of the situation and does not consider changes in population, costs or technology. Thirdly, it only considers (average) costs as the main deciding factor and ignores any environmental, institutional and organizational aspects. In the following sections, we would like to address these issues in more detail.

### **Path dependency of centralized systems**

The next critical question worth focussing on is the dynamic stability of existing systems over time. Empirical evidence indicates that sewer networks show strong path dependencies ((Fam et al. 2009), (Wolf and Störmer 2010)). Therefore, introducing or maintaining hybrid systems might not be viable, even if they would be the best and cheapest option. Here we will focus exemplary on two regime stabilizing aspects: the perceived synergies between stormwater and wastewater drainage and cost calculation methods. We will ignore all the other relevant institutional and governance aspects, as this would go beyond the scope of this article. However, it is essential to acknowledge that these - from an engineering point of view - 'soft' aspects play a crucial role in stabilising the path dependency of a dominant socio-technical system.

#### *Stormwater and wastewater*

The option of using combined sewers makes things more complicated. They promise the alluring prospect of combining two essential urban water services with one single infrastructure and therefore utilizing synergies. As with any hydrological catchment, a city must provide ways for stormwater to drain. The transport capacity of a corresponding pipe network is proportional to the drained area and typical rain intensities. In many 'wet' climate zones, the capacities needed to drain stormwater dwarf the wastewater flow – typically by two or more orders of magnitude. Consequently, wastewater can be easily added to the drainage infrastructure often without needing any additional capacity.

Such combined sewer systems create a path dependency of their own. Compared with stormwater drainage, combined systems have very particular technical requirements. They are generally closed conduits (compared with the option of open stormwater drains), with higher demand for water tightness (to prevent wastewater leaking) and deeper construction depths to accommodate sufficient flow velocities and minimise pumping needs. Moreover, for water pollution protection the combined sewers cannot just drain into the next surface water body but need to lead to a treatment plant. In this respect, they are more similar to foul sewers but with substantially more transport capacity. However, not all stormwater can be treated in the wastewater treatment plant, and wastewater is discharged from the system during rain events – also known as combined sewer overflows. These require substantial additional efforts and infrastructures (e.g. overflow tanks) to minimize their environmental impact.

Although this is a simplified view of the two fundamental urban drainage design approaches, these examples highlight an important point. Combined sewer systems are not just stormwater systems with wastewater but distinct technological systems with specific adaption needs. Correspondingly, combined sewer systems have their own lock-in logic and breaking the path dependency has most likely its particular challenges compared to separate systems. To our knowledge, this aspect is not explored in sufficient detail in the literature.

In terms of hybrid systems, stormwater management is a significant step ahead of sewage. Science and practice provide many more decentralized engineering alternatives to mitigate the challenges and opportunities stormwater management has for cities. We will touch on this in the next section about transition management.

#### *Cost calculation methodology*

A crucial element stabilizing the strong path dependency of sewer networks are the economic methods used to assess the cost-effectiveness of system adaptation. Current costing and financing approaches are suited for evaluating incremental system adaptation but not for fundamental system changes and therefore tend to stabilize the path dependency of the current system. Here we would like to mention two key points: Insufficient life costing methodologies and the cross-subsidizing effect of tariffs.

The extremely long lifespan of pipe networks (typically in the range of 30 – 100 years) and the corresponding long planning horizon pose a 'wicked problem' ((Rittel and Webber 1973)) for proper life cycle costing methodologies mainly because of four reasons:

- i. Long-term discount rates are highly sensitive for life cycling costing, but unfortunately very subjective. E.g. (Weitzman 2007) points out that we are a lot less sure about what interest rate should be used for very long-term discounting than is commonly acknowledged. High discount rates favour delayed investments, while low discount rates enable much more present spending.
- ii. Even small population changes over the long planning horizon lead to substantial overcapacities as typically these infrastructures are designed to deal with peak demand. Consequently, cost methodologies focus on the cost of providing peak demand. Examples in Maurer (2009) show that the so created unused capacities lead to substantially higher per capita costs compared with no growth situation or more flexible alternatives. For example, modular or hybrid systems could be built as needed and the overall investment pattern would adapt more closely to the actual future demand and therefore could be cheaper - especially

under high discount rate regimes. It should be noted that this is also true for negative growth rates, where modular systems have the distinct benefit of shorter life spans.

- iii. Prognosis uncertainty over several decades of planning is horrendous and therefore usually not considered systematically in cost calculations. The effect of this is nicely shown in de Neufville and Scholtes (2011) for different engineering fields. For wastewater systems, it can be demonstrated that uncertainties increase the probability of much higher specific costs over the lifetime of the considered infrastructure (Hug et al. 2010). Again, the flexibility of hybrid solutions could provide a cost advantage due to the demand-driven investment pattern. This is especially relevant in areas with very high growth rates, where two factors – population change and high uncertainties – come together. Ignoring uncertainties generally favours static approaches.
- iv. Decisions are generally made for one specific project or measure and without consideration of the long-term lock-in effects. This favours distinctively incremental changes and, therefore, path dependency, as they can rely on the already existing sunk cost infrastructure. Compared to this, options that aim for more radical changes will fare worse as they often require a higher initial investment, not just in infrastructure but also governance and organizational structures. See also the call for long-term planning instrument in the section 'Transition planning' to help to overcome this specific disadvantage.

Another stabilizing factor for the centralized regime is the financing of the system over tariffs. Most tariff schemes apply the same rules to everybody in a catchment and do not distinguish the specific costs needed to connect an individual house. This leads to the situation that the connection of unfavourable neighbourhoods to the grid is subsidized by the rest of the catchment. This averaging effect of tariff schemes decreases the incentive to find cheaper alternative solutions and stabilizes the path dependency of the current system.

## Transition planning

Interestingly, in stormwater management, hybrid systems are widely accepted and actively implemented in practice. Several key concepts were developed since in the 1990s, such as SUDS, LID, WSUD or Sponge City (see for a good overview Fletcher et al. (2015)) that rely heavily on modular systems to strengthen the resilience and performance of urban stormwater drainage. This offers an opportunity to learn from the successes and failures to establish hybrid systems and transfer some lessons learnt to wastewater.

In a detailed investigation of the modular stormwater systems in Melbourne (Kuller et al. 2018a), the authors concluded that "*opportunistic WSUD (water sensitive urban design considering stormwater hybrid systems) planning leads to unintentional outcomes that fail to capitalize on the full potential of WSUD benefits. [...] integrated planning for WSUD are encouraging and have the potential to significantly improve the outcomes of water quality, flood safety and amenity for urban communities.*" This exemplary highlights the need for suitable planning tools that are capable to transcend the complexity of technological options and to capitalize on the additional benefits a hybrid system can provide over a centralized approach.

This emphasis on planning is also one of the main conclusions of an investigation of the feasibility of modular systems (Särkilähti et al. 2017). The authors identified a series of drivers, barriers and enablers for system change, and they concluded: "*The results indicate that sustainability transition can*



*be facilitated through impartial urban planning that allows the early participation of actors and improved communications. Additionally, studying the impact of alternative solutions and city guidance according to environmental policy may enhance transition".*

This highlights the importance of urban water infrastructure planning as a key element for transition management. From the evidence presented above, we can conclude that a suitable planning approach should minimally fulfil the following four key requirements: (i) representing very long planning horizons, (ii) need to be spatially explicit, (iii) consideration of a wide range of technological development options that includes modular systems, and (iv) the need to consider a sufficiently broad range of goals and benefits (Kuller et al. 2018b), (Brands 2014).

In the literature, several of these elements can be found for water infrastructure planning in different combinations. To our knowledge, only two modelling approaches can be found in the literature that covers all the factors mentioned above. One is DAnCE4Water (Dynamic Adaptation for enabling City Evolution for Water, (Rauch et al. 2017), (Urich et al. 2013)) and the other is SinOptikom (Baron et al. 2017, Baron et al. 2015). Both simulate in detail the transition of water infrastructures for an entire catchment over long periods considering deep uncertainty and multi-criteria assessment algorithms to evaluate numerous options to meet targets at a variety of spatial scales. Unfortunately, DAnCE4Water is mainly focused on stormwater management, and SinOptikom disappeared into obscurity after the end of the project.

An excellent indication of the importance of a wide range of goals for infrastructure transition can be found in Lienert et al. (2015) and Zheng et al. (2016). The authors present a procedure that combines long-term scenario planning with a sophisticated multi-criteria decision analysis (MCDA) approach. One of the key results was the finding that most stakeholders highly valued performance, resource protection and intergenerational equity while cost and social acceptance were only of minor importance (Zheng and Lienert 2018). This result is only valid for the analyzed Swiss cases. Nevertheless, the authors could show for realistic decision cases that, stakeholders value modular systems as high or higher than centralized approaches (Beutler et al. 2021). However, the presented approach does not support the modelling of the spatial explicit transition of the infrastructure.

## Conclusions

The final verdict of whether hybrid systems for wastewater can be sustainable in urban catchments is still out. The evidence indicates that there are good reasons to believe that, once established, they would improve sustainability under certain circumstances. The main strength of modular systems is the high flexibility in accommodating demand change and planning uncertainty, providing locally adapted solutions in low-density areas and avoid significant upfront investments into sewer networks (Larsen et al. 2016). Fortifying centralized systems with these benefits enables overcoming some of the critical weaknesses of the one fits all centralized systems approach – especially in cities with large heterogeneities.

However, centralized systems show very strong path dependencies that need to be overcome for hybrid systems to be implemented in the first place. Besides a wide range of institutional and organizational barriers (Särkilähti et al. 2017), the current economic and planning tools also need to be improved and adapted. Much of the existing engineering tools for infrastructure management, such as costing or long term planning, work very well for incremental adaptation of the dominant centralized

system but have essential weaknesses in terms of integrating fundamentally novel technological approaches.

From an engineering perspective, the following research and development gaps still need to be closed for hybrid wastewater systems to have widespread dissemination:

- The development of long-term transition planning tools that are spatially explicit and can consider a wide range of modular technologies. The main challenge is identifying the proper degree of model resolution and accuracy as such models can get very demanding very fast (Bach et al. 2014), (Rauch et al. 2017). The goal of such models is not to predict the future in all detail but to facilitate short-term decision making by assessing the long-term consequences of the decisions.
- There is also an urgent need to find ways to consider cross-sectoral integration appropriately - such as energy, stormwater and water supply - to understand the broader synergies hybrid systems can provide (Trapp et al. 2017).
- Stronger integration of multi-criteria decision analysis (MCDA) or any other structured decision making procedure into the planning is essential to consider the broader range of goals and benefits hybrid systems can provide.
- Engineering economic methodologies need to be developed so that they can include planning uncertainties and adaptability. Real option approaches (de Neufville and Scholtes 2011) might be the first step. However, due to the difficulty of quantifying unsatisfying performance in monetary terms, real options are not readily applicable in wastewater.

This is not to say that there is no research need in the realm of engineering 'hardware'. However, compared with the needs to support regime change on a system level, these are relatively minor.

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