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Lighthouse Initiatives in the Urban Water & Sanitation Sector

An Integrative Assessment of Lighthouse Initiatives for Decentralised Wastewater Treatment and Reuse Systems (DUWTRS)

Synthesis Report

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Results

All project results and outputs are accessible open source on www.sandec.ch/lighthouse.

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Abstract

Climate change, rapid urbanization and other grand challenges increasingly show that urban water and wastewater management needs to be deeply rethought. A transformative shift is needed away from linear end-of-pipe to more circular system designs. Actors around the world have thus started developing decentralised urban wastewater treatment and reuse systems (DUWTRS). DUWTRS improve the flexibility, resilience and circularity of water and sanitation infrastructure and can thus play a key role in developing more sustainable cities. Yet, despite their high potential in solving multiple urban development challenges at once, only a few cities worldwide have successfully implemented them at scale. We thus lack well-documented templates and best practices of successful DUWTRS implementation. The Lighthouse Project aimed at filling this gap by assessing promising examples from around the world. To generate practice-oriented lessons, we compared six projects at different scales (city-wide vs. neighbourhood), in different contexts (high-income vs. low-/middle-income) and using different technological set-ups. We selected four neighbourhood-scale and two city-scale projects, equally distributed across high- and middle-income contexts. Data was collected between November 2021 and August 2022 through an extensive literature review and more than 100 semi-structured expert interviews. An integrative assessment framework was developed and used to derive key success conditions for DUWTRS implementation.

Our results show that Innovative DUWTRS solutions are a complex and systemic innovation that not only challenges established infrastructure solutions but also the manner in which they are currently planned, operated and maintained. Our case studies exposed three generic models of DUWTRS implementation. First, policy-induced city-wide implementation as exemplified by San Francisco and Bengaluru, which arguably represents the most transformative model. With city-wide implementation of small-scale DUWTRS, responsibilities for design, implementation and operation and maintenance largely shifts from public service providers (utilities) to private entities (developers, firms, owners, residents). In this model, the role of the utility thus shifts from full-fledged top-down control to permitting, more indirect quality assurance, as well as network facilitation and system intermediation. A second model are neighbourhood-scale solutions with advanced resource recovery systems as exemplified by Hamburg and Helsingborg. They follow a more conventional utility-based model, where a public utility still largely covers water and sanitation services, occasionally complemented with private sector involvement. This model typically also applies advanced source separation and resource recovery solutions, which transcend the traditional institutional and regulatory boundaries between the waste, water and energy sectors, as well as between public and private spheres. Third, the case of Gurugram in India illustrates that manifold models in-between these two ideal-types may exist, in which a DUWTRS solution is e.g. installed at a district scale, but still mostly managed by private actors and the local residents.

Cross-comparing between our in-depth case studies allowed distilling 10 key generic ingredients for successful DUWTRS implementation that are valid across these three models, as well as in high, middle and low-income contexts alike. Key success conditions comprise (1) a dedicated system integrator that coordinates and aligns a large number of stakeholders with varying interests. (2) A dense and transdisciplinary stakeholder network that participatively creates solutions that transcend boundaries between sectors (water, sanitation, energy,…) and between public and private spheres. (3) Given long implementation timeframes, DUWTRS need stable political and policy support including allocation of adequate human and financial resources. (4) Legal and regulatory arrangements that reflect DUWTRS' particular management challenges and which clearly outline the roles and responsibilities of all involved stakeholders are needed. Closely related, (5) well-defined permitting pathways, water quality monitoring and enforcement systems are indispensable. Since DUWTRS offer a unique opportunity to turn sanitation from a 'waste management' problem into a business opportunity, (6) attractive business models and markets for generated products have to be developed. To support market formation, (7) industry-internal standardisation, certified trainings and information sharing are key. Given the 'yuck factor' connected to wastewater, creating legitimacy for DUWTRS is not an easy task. Therefore, (8) developing an active communication and public outreach strategy is very important. (9) publicly accessible pilot- and demonstration projects play a key role in creating legitimacy with local stakeholders and supporting technology development. Lastly, DUWTRS' high costs are a key challenge, especially when compared to conventional (and often subsidised) centralised solutions. Thus, (10) finding financially and economically viable system designs (in a full system and lifecycle perspective) is a key task for any city implementing DUWTRS.

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Abbreviations

BOD	Biochemical Oxygen Demand
BMBF	Bundesministerium für Bildung und Forschung (Federal Ministry of Education and Research)
BMWi	Bundesministerium für Wirtschaft und Technologie (Federal Ministry of Economics and Technology)
CAPEX	Capital Expenditures
CEO	Chief Executive Officer
CHP	Combined Heat and Power Generation Plant
COD	Chemical Oxygen Demand
DBO	Design-Build-Operate Business Model
DIN	Deutsches Institut für Normung e.V (German Institute for Standardisation)
DUWTRS	Decentralised Urban Water Treatment and Reuse Systems
DWA	Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall (German Association for Water, Wastewater and Waste)
ENG	Eawag Process Engineering Department
ESS	Eawag Environmental Social Sciences Department
EU	European Union
EVAA	Energi-Vatten-Avlopp-Avfall (Energy-Water-Wastewater-Waste)
FAQ	Frequently Asked Questions
GMDA	Gurugram Metro Development Authority
HmbAbwG	Hamburg Wastewater Act
HSPCB	Haryana State Pollution Control Board
HWC	Hamburg Water Cycle
KREIS	Kopplung von Regenerativer Energiegewinnung mit Innovativer Stadtentwässerung (Coupling Regenerative Energy Generation with Innovative Urban Drainage)
KSPCB	Karnataka State Pollution Control Board
LCA	Life-Cycle Assessment
LEED	Leadership in Energy and Environmental Design
LH	Lighthouse
LRT	Log_{10} Reduction Targets
MF	Microfiltration
MBBR	Moving Bed Biofilm Reactor
MoEFFC	Indian Ministry of Environment, Forests and Climate Change
MoHUA	Indian Ministry of Housing and Urban Affairs

MoU	Memorandum of Understanding
NBRC	National Blue Ribbon Commission
NGO	Non-Governmental Organisation
NOC	No Objection Certificates
NSR	Nordvästra Skånes Renhållnings (Northwestern Skåne Waste Management)
NSVA	Nordvästra Skånes vatten och avlopp (Northwest Skåne Water and Wastewater)
OC	Occupancy Certificate
ONWS	On-Site Wastewater Treatment and Reuse Systems
OPEX	Operational Expenditures
O&M	Operation & Maintenance
PDP	Pilot and Demonstration Projects
RO	Reverse Osmosis
RWA	Resident Welfare Association
Sandec	Eawag Department Sanitation, Water and Solid Waste for Development
SBR	Sequencing Batch Reactors
SEK	Swedish Krona (currency)
SEPA	Swedish Environmental Protection Agency
SF	San Francisco
SFPUC	San Francisco Public Utilities Commission
SSTP	Small-Scale Sewage Treatment Plants
STP	On-Site Sewage Treatment Plants
SWW	Eawag Department Urban Water Management
TCS	The Close South
TSS	Total Suspended Solids
UASB	Upflow Anaerobic Sludge Blanket Reactor
UF	Ultrafiltration
UV	Ultraviolet Light
UWM	Urban Water Management
WWTP	Wastewater Treatment Plant
ZLD	Zero Liquid Discharge

1. Introduction

The ways in which water and wastewater are managed in cities (i.e. urban water management, UWM) needs to be deeply transformed. Climate change, rapid urbanisation and intensifying competition for limited freshwater resources increasingly expose the inherent limits of conventional, centralised water and sanitation infrastructures. These systems were developed at the beginning of the 20th century, when hygiene and economic efficiency were the main design criteria for UWM infrastructure build-up. The resulting large-scale, end-of-pipe solutions were a great success (at least in high-income countries) in eradicating diseases and giving urban populations access to affordable water and sanitation services. Yet, they also created a deeply locked-in infrastructure system, with high sunk investments, system components with very long life spans (80-100 years for pipes, and 50 years for treatment plants) and several inherent design limitations, e.g. in relation to the system's high water use, limited options for resource recovery, or deficiencies in serving the urban poor.

Over the past decades, cities around the world have increasingly been challenged to reach ambitious sustainable development goals, ranging from combating climate change, eradicating hunger and poverty, to creating neighbourhoods that are adapted to climate change. Recent commitments to reach NetZero greenhouse gas emission goals by 2050 have made it very clear that urban infrastructure sectors need to be fundamentally rethought and re-designed, away from end-of-pipe to circular or regenerative designs. This implies that a transformation of the ways in which UWM infrastructures are planned, operated and maintained is unavoidable. UWM cannot focus on solving urban water (and hygiene) problems in isolation anymore. It rather has to take additional design criteria on board and develop integrative, cross-sectoral solutions that combine solving urban water and sanitation problems with, e.g. reducing energy use, recovering nutrients for regional agriculture or using reused water for local greenery, which mitigates heat waves and enhances biodiversity.

Rather than optimising the incumbent gold standard in UWM, entrepreneurs around the world have thus started exploring and developing a broad variety of alternative onsite, small-scale, distributed, modular, de- or semi-centralised UWM approaches [6]. These systems aim at tackling today's urban sustainability challenges not with end-of-pipe systems, but by treating and recycling water and the resources contained in it (heat, energy, and nutrients) near their source in closed-loop systems. The design philosophy also increasingly includes source-separation, i.e. dividing various 'waste' flows, such as greywater, blackwater, rainwater or kitchen waste, directly at the source and conveying them to separate treatment processes. This approach offers simplified and efficient treatment and allows for recovering resources in a targeted way. In this report, the highly diverse approaches that are quickly emerging in this field will be summarised as 'decentralised urban water treatment and reuse systems' (DUWTRS).

Today, DUWTRS's potential to enabling sustainability transitions in the water/sanitation and related urban infrastructure sectors are widely acknowledged [7, 8]. Among others, DUWTRS can close water loops locally, recover valuable resources, yield marketable products, reduce UWM's energy demand, get adapted quickly to changing context conditions and induce various social co-benefits for local communities. Yet, in solving multiple challenges at once, they also typically transcend traditional institutional and regulative boundaries between the waste, water and energy sectors, as well as between the public and private sphere [9, 10]. Their implementation and diffusion is thus confronted with variegated technical and non-technical (e.g. institutional) barriers that can only be overcome in long-term systemic and collective innovation processes. As a result, despite their potential benefits, only a few cities worldwide have successfully implemented innovative DUWTRS approaches at scale. Well-documented templates and best practices that could inspire and inform policy makers, firms and planners in how to apply DUWTRS are lacking [2, 11]. Thus, the Lighthouse Project at Eawag aimed at identifying and assessing key case studies, which could serve as 'templates' that inform and inspire other cities around the world.

Characterising such templates is by no means an easy task. Evidence of the technological, regulative, economic and institutional approaches that have turned projects and/or cities into Lighthouse Initiatives (LH) for DUWTRS is still largely anecdotal. [2, 11]. There is thus a need to more systematically cross-compare and disentangle the context-specific and generic factors that are backstopping a successful implementation and operation of DUWTRS in different contexts, in particular between high-, middle- and low-income countries. Synthesising insights from prior research projects at Eawag and elsewhere, drawing generic lessons from successful LH initiatives and circulating them through dedicated workshops, conferences and publications is a crucial next step to inform policy and practice and support the global mainstreaming of DUWTRS. In support of this, the Lighthouse Project conceptualised, identified, assessed and synthesised international best practices of selected LHs.

This report summarises the Lighthouse Project's targets, activities and key results. Chapter 2 illustrates the project's research strategy (cf. p. 9). Chapter 3 outlines the results generated for each case study according to the developed integrative assessment framework laid out in chapter 2 (cf. Figure 4). This includes a brief historical summary from project ideation to actual realisation. Following this rather descriptive approach, each DUWTRS project was analysed along six 'spheres'. First, the technical sphere depicts the technical system set-up. The subsequent five chapters are structured along five 'institutional' dimensions of our integrative assessment framework for LHs (cf. p. 11). These include legal and regulatory frameworks, contractual and financial arrangements, industry and market structures, knowledge, skills and capacity, and, lastly, recognition and legitimacy. Finally, each case report closes with a synthesis outlining identified context-specific drivers and barriers. Chapter 4 discusses the results from the individual LHs in summary and compares them against their particular backgrounds. The report closes with chapter 5, which synthesises key interventions and lessons learnt from the individual case study results, as well as the discussion section, and derives key recommendations that can enable successful implementation and sustainable operation of upcoming DUWTRS initiatives in cities not covered in this report.

2. Research Strategy

Given that we systematic evidence on how LHs can be best implemented is still lacking [2, 11], the Lighthouse Project aimed to systematically cross-compare and disentangle context-specific factors from generic ones that are backstopping a successful implementation and sustainable operation of DUWTRS. In support of this, the Lighthouse Project conceptualised, identified, assessed and synthesised international best practices of selected LHs. The objectives of the research strategy were to:

1) define distinctive characteristics of LHs,
2) develop an integrative assessment framework that focuses on the co-evolution of technical and social elements,
3) identify cities and neighbourhoods that have established LHs and assess technological and institutional best practices,
4) apply the developed integrative assessment framework for analysing the planning, implementation and operation processes of each case study, and
5) synthesise the results and produce templates for the diffusion of DUWTRS in cities located in high-, low- and middle-income contexts.

2.1 Defining Lighthouse Initiatives

Recent literature on transitions in urban water management increasingly mention the need for large-scale 'lighthouse' or 'flagship' initiatives that experiment with radically new infrastructure designs [7, 12, 13]. However, a general concept and a definition of 'lighthouse initiatives' is still missing within scientific literature. Only a handful of papers have used this term in the past 10 years in a substantive way (e.g. [7, 13]). In fact, the notion of a lighthouse initiative is used more extensively outside academia, for example by the Swiss FOEN for their energy transition pilot and demonstration programme[1] or the EU Horizon 2020 programme on 'smart cities and communities lighthouse projects'[2].

To-date, most academic literature analysing transitions in infrastructure sectors focus on pilot and demonstration projects (PDP) [14, 15]. Pilot projects are typically implemented in early lifecycle phases; right after basic research has developed a new technological approach at lab-scale, it is tested first in practical applications (e.g. a new treatment reactor in a research project [16]). Demonstration projects, in turn, aim at learning from real-world application of a technology on the trajectory to scaling up. This usually reveals key challenges, including market, economic and regulative hurdles, as well as user acceptability issues (e.g. installing and testing a treatment reactor in a real-world context, like a single building [17, 18]). LHs, in contrast, happen at scale and a stage when technologically mature solutions are available, but still lack a clear governance arrangement, mass-market and widespread legitimacy with the public and in key expert circles (i.e. San Francisco's 2015 mandate to install onsite water reuse systems in all major new real estate developments).

While current literature mostly covers PDPs, LHs are seen here as key (and under-researched) vehicles for mainstreaming and legitimising transformative innovations like DUWTRS [7]. For the scope of the Lighthouse project, we define LHs as "*applications of DUWTRS solutions at a scale that is large enough (e.g. city district, large settlement, onsite plants distributed throughout the city, etc.) to showcase the full value chain of the alternative technology, creating technical, as well as institutional/governance/regulatory templates, that can be diffused to other places*." The crucial function of LHs is providing a protective space for real-world experimentation with novel solutions, which however extends beyond piloting or demonstrating the potential of new technologies toward inducing practical uptake of innovation at a scale comparable to existing (conventional) systems and technologies. In effect, LHs incentivise outcomes (e.g. amended legal/regulatory conditions, improved investment, business and O&M models, broad user acceptance, etc.) that increase DUWTRS competitiveness and market penetration, which ultimately establish a new successful infrastructure paradigm that is legitimised beyond early adopters.

[1] https://www.bfe.admin.ch/bfe/en/home/research-and-cleantech/pilot-and-demonstration-programme.html
[2] https://ec.europa.eu/inea/en/horizon-2020/smart-cities-communities

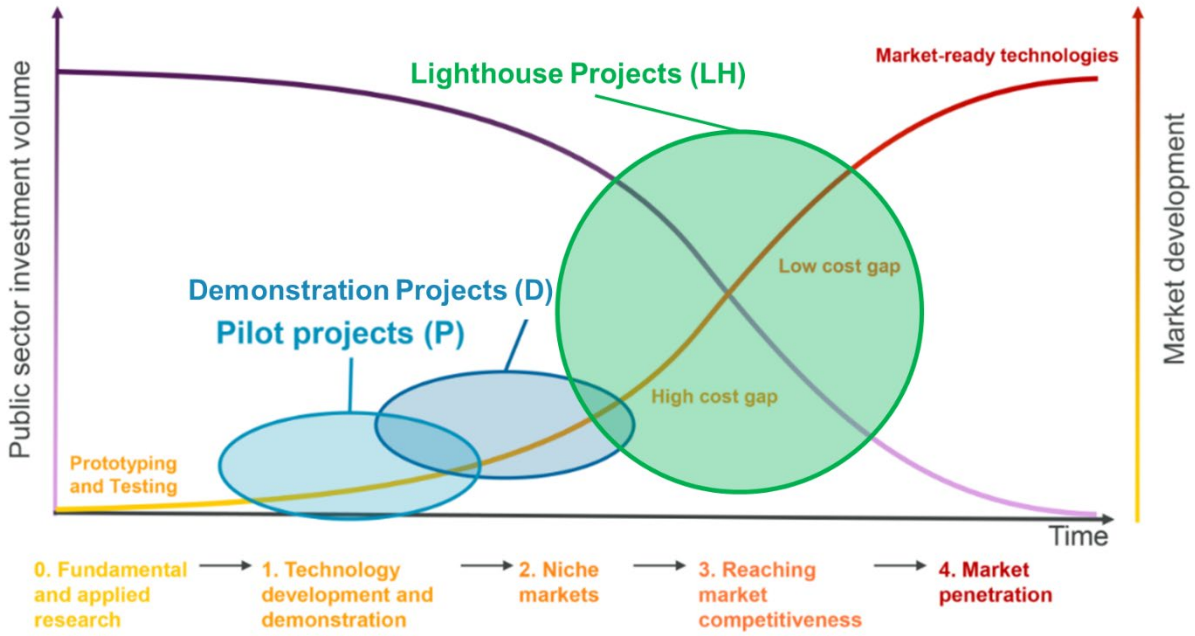


Figure 1: Distinguishing between pilot, demonstration and lighthouse initiatives as a function of market development and public sector investment volume. (Source: Adapted from Swiss Federal Office of Energy (FOEN)).

Especially in infrastructure sectors, such as water, energy or transport, having successful 'lighthouse cases' is arguably a necessary condition for the diffusion of both novel technologies and for developing effective coordination mechanisms and financial and/or regulatory frameworks [15, 19, 20]. Such exemplary developments are foundational for technology diffusion. They legitimise the novel infrastructure design and help aggregate required knowledge, skills and capacities with the involved stakeholders. Thus, assessing and evaluating LHs and their impact(s) on other cities is critical for understanding sustainability transitions and equips practitioners with relevant knowledge on how to best induce and navigate them.

To further conceptualise the notion of LHs, Figure 1 distinguishes them from the PDP concept. A key distinguishing feature is the maturity of the proposed solutions or the phase of the technology/industry lifecycle. In comparison to pilot projects, which tend to emphasise the important role of traditional technological innovation and learning processes, LHs emphasise a 'full value chain' perspective and operate at scale. They thus often depend on inducing regulative change, active market formation or wider social and cultural transformations (Figure 1; [15]). Another key distinguishing feature of LHs is that – given their scale, cost and objectives – they cannot be planned as a single project in a closed-off way, but require widely distributed stakeholder engagement, strategic leadership, interactive learning and long-term backing by policy makers and the general public.

Given our first target and the lack of a widely accepted concept for LHs [7], departing from the definition outlined above, we characterise LHs as comprising the following four key elements:

- Comprehensive socio-technical arrangement: Integrating new technologies into a matching socio-economic and institutional context;
- Long-term perspective: Stable policy support and economic/social incentives that ensure project continuity, available funding and enable 'adaptive learning';
- Broad-scale adoption: Fully developed value chain from collection to end-use/disposal at neighbourhood/city district level comparable to centralised approach;
- Visibility and impact beyond immediate context: Examples that can inspire/guide other initiatives to replicate its core features.

2.2 Developing an Integrative Assessment Framework for LHs

As mentioned above, developing a new paradigm for UWM that embraces circular, cross-sectoral solutions is a complex, systemic innovation problem. This relates not only to developing novel technologies and treatment systems, but also to embedding them in supportive regulative frameworks, industry and market structures or governance arrangements [7, 8, 21]. To assess the success conditions for innovative DUWTRS solutions, technological and social factors and their interplay and alignment over time thus have to be assessed in a structured way. In light of this, the Lighthouse project developed an integrative assessment framework for analysing the relevant technical and social innovation processes in the selected LH initiatives and to systematically cross-compare and disentangle the context-specific and generic factors that are back-stopping a successful implementation and operation of DUWTRS in different contexts.

The integrative assessment framework covers key variables from engineering and social science perspectives, the establishment of DUWTRS over time from ideation to realisation, as well as the full sanitation value chain from waste generation to resource reuse. It synthesized results from prior Eawag projects (4S and BARRIERS) [2, 4, 22, 23], and also generally acknowledged dimensions of technological innovation system studies [2, 24], the literature on enabling environments for UWM planning [4, 22, 23] and adopts (technical) parameters from sustainability assessment approaches for water infrastructure systems [5]. Findings of the 4S and BARRIERS projects were instrumental in the development of the framework. 4S assessed small-scale sewage treatment and reuse systems in South Asia [4, 22, 25]. While technical system performance was the main focus of this project, it also identified social factors that are necessary for sound technical performance (14 critical success factors, see Figure 2). The critical success factors are inter alia organised along temporal phases and based on technical field evaluations of more than 300 sanitation units, and an in-depth governance and financial analysis. The BARRIERS project, in turn, developed a comprehensive framework for analysing enabling innovation system structures for the implementation of DUWTRS that was based on innovation studies and the social sciences (see Figure 3) [2].

Figure 2: Critical Success Factors from 4S for a successful performance of small-scale sewage treatment and reuse systems (Source: [4]).

The Lighthouse Project built on both approaches when synthesizing key aspects of 4S' and BARRIERS' conceptual frameworks into an overarching heuristic, which guided data collection and analysis, especially to take into account and identify key social elements (Table 1).

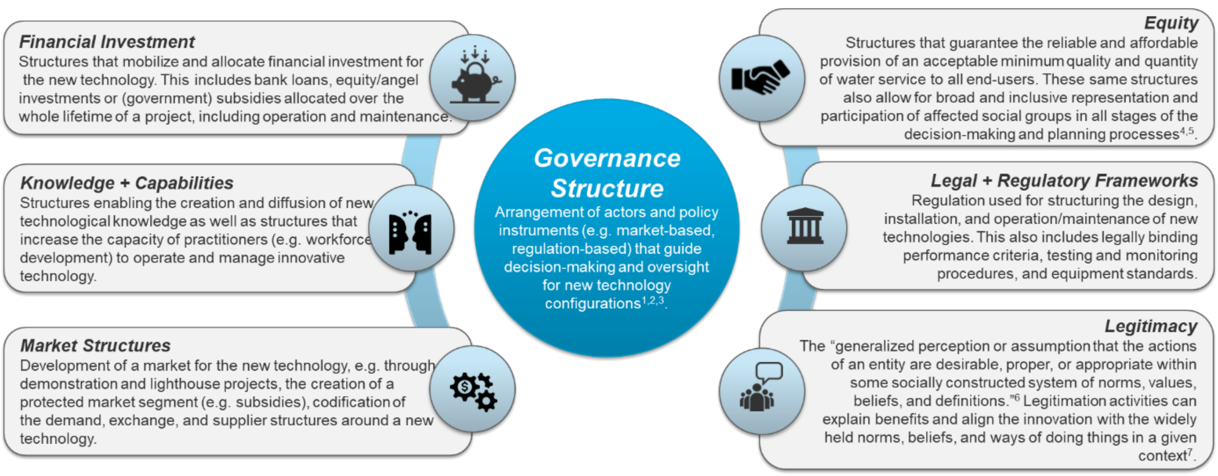


Figure 3: Key institutional dimensions for urban water management innovation (Own illustration adopted from [2]).

Governance & Institutional Arrangements	*Rules that define the roles, responsibilities and relations among and between public and private actors. Functional governance arrangements typically depend on strong buy-in from government actors, utilities, private firms and civil society. Strategically coordinated national sector policies are often key to receive the support of and create synergies among key stakeholders.*
Legal & Regulatory Arrangements	*Incentivising, enabling and supporting legal and regulatory arrangements are key to operate DUWTRS on a legal basis, establish administrative support and create market structures, business models and standardised products.*
Financial & Contractual Arrangements	*Financial arrangements cover allocation and organisation of funds and funding mechanisms needed to establish capital expenditures (CAPEX) and operational expenditure (OPEX). They are essential to project ignition and long-term continuation.*
Industry & Market Structures	*Industry and market structures are essential for developing mature and standardised technologies, to establish reliable operation and maintenance models, as well as for creating business models that enable innovation diffusion and scale up.*
Knowledge, Skills & Capacities	*Broadly and continually established knowledge, skills and capacities among various stakeholders are key for project and system management from planning to implementation, operation and maintenance.*
Recognition & Legitimacy	*Recognition and legitimacy capture key stakeholder's assumption that the innovation is installed and run in line with widely held social beliefs. Those beliefs comprise governance structures, regulatory and legal frameworks, cultural norms, etc. and are of crucial importance for creating widespread (user) acceptance.*

Table 1: Key social factors for analysing lighthouse initiatives (Source: Own elaboration from [2, 4, 22, 23]).

Each of the elements in Table 1 denotes a necessary condition for the successful implementation (and diffusion) of DUWTRS. For example, if a local initiative lacks financial incentives or legitimacy with the relevant decision-makers and end users, DUWTRS solutions will have a hard time in scaling up and influencing other cities opting for the same idea. While analytical clarity required that the different elements of our framework be investigated in an isolated fashion, they can be reciprocally influential and are often mutually dependent.

In addition to the social elements outlined above, key technological elements also deserve focused attention. However, defining generic technical performance criteria that can be evaluated without conducting resource-intensive life-cycle assessments and/or spot-checks is difficult. Thus, we oriented our criteria along DWA's guideline on sustainability assessment of water infrastructure systems [5] and discussed potential indicators in interdisciplinary exchanges with Eawag experts from the Sandec, ESS, ENG, and SWW departments. In doing so, key proxy indicators for different technological elements were defined, that enable an indicative assessment of technical performance (see Table 2).

User satisfaction/Acceptability	*Comfort for end users (ease of use, manageability), Acceptability/Complaints*
Operational safety/Robustness	*Process stability and reliability; Effects in case of failure*
Adaptability/Scalability	*Flexibility with regard to changing boundary conditions*
Integratability/Independence	*Independence from other infrastructures (external energy/water supply); space requirement; synergy potential (e.g. with biowaste disposal)*
Treatment efficiency	*Required (national/local) standards, resource recovery (nutrients, energy, water)*
Resource efficiency	*Financial costs, energy use, environmental impacts (greenhouse gas emissions)*

Table 2: Selected technical performance criteria adapted from Hillenbrand, Bieker [5] and including expert knowledge.

As outlined above, understanding the success or failure of a given DUWTRS system ultimately does not depend on the performance of certain technological or social elements alone, but rather on whether and how well they are aligned to each other. A high-quality DUWTRS technology that lacks legitimacy with the end users will not find broad uptake. And regulative frameworks that are not adapted to DUWTRS might hinder the development of effective industry and market structures. Within the Lighthouse Project, we thus traced key changes in the increasing interplay of technical and social elements in each case study as socio-technical alignments that get spurred by targeted 'socio-technical interventions' [7, 21]. Socio-technical interventions refer to coordinated and strategic actions by several key stakeholders, which significantly improve the technology design, implementation, and/or management of novel DUWTRS solutions. Examples comprise the development of new business models, regulative frameworks or guidance materials / educational resources around innovative DUWTRS. Our hypothesis was that several socio-technical interventions are typically required to turn a given DUWTRS program into a success and to establish a socio-technical configuration 'that works'.

Figure 5 outlines the holistic and integrative assessment framework developed in the project that covers technical and social elements, as well as key interventions that improved their alignment over time (see below). Creating a comprehensive overview of social and technical elements, as well as key socio-technical interventions allowed us to distil generic success conditions of LHs and generate practice-oriented recommendations for cities or utilities in other places that are opting for innovative decentralised and resource-oriented UWM approaches.

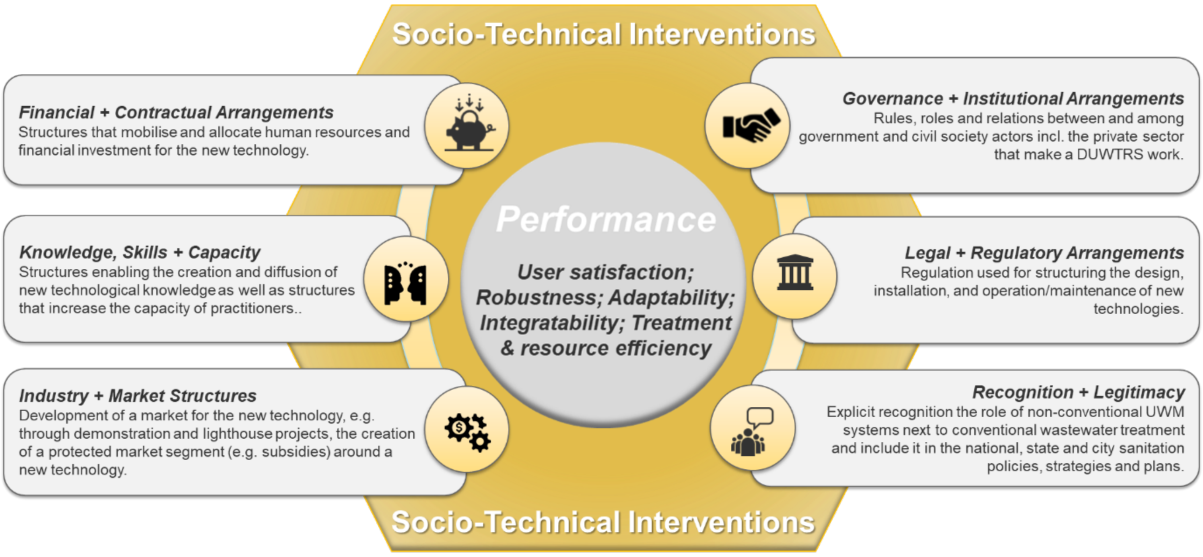


Figure 4: Integrative assessment framework for DUWTRS lighthouse initiatives (Own illustration, adapted from *Hacker and Binz [2]*, *Klinger, Ulrich [4]* and *Hillenbrand, Bieker [5]*.

2.3 Sampling: Identifying Potential Lighthouse Candidates

The above-outlined conceptualisation guided the case study sampling process. To generate practice-oriented and broadly generalisable lessons, we aimed at identifying, assessing and comparing six projects at different scales (city-wide vs. neighbourhood scale), in different contexts (high-income vs. low-/middle-income) and using different technological set-ups. We defined five sample criteria for potential LH initiatives:

1. Must reflect all four LH characteristics defined in section 2.1;
2. Operate a DUWTRS including some form of resource recovery (e.g. water, energy, heat, nutrients,…);
3. Dispose of a fully developed service chain from collection to disposal/reuse;
4. Serve a minimum of 300 residential units;
5. Be in operation for a minimum of 2 years.

Potential LH initiatives were identified through desk-based research, as well as through personal communication and networks. The search turned out to be more difficult than initially expected. Potential candidates were categorised in a characterisation matrix, and the main characteristics were the project location ('context'), the technical system set-up, the scope of reuse/application, as well as their size (residential units served) and duration. For efficiency and budgetary reasons, for the low-and middle income context, we decided to focus on India. A locally hired research assistant scanned the 4S database and used his personal network to identify suitable candidates. When starting data collection in early 2022, three initiatives from different Indian states were selected ('Vasant Vihar', New Delhi (NCT Delhi); 'ATS Pristine', Noida (Uttar Pradesh); Nirvana Country, Gurugram (Haryana)). However, several issues made data collection difficult or even impossible, which is why 'Vasant Vihar' and 'ATS Pristine' had to be replaced with 'M3M Merlin' (Gurugram, (Haryana) halfway through the project. Candidates from the high-income context were identified through literature, online searches and personal networks. Based on the sampling criteria and given the above adjustments, we finally selected four neighbourhood-scale and two city-scale projects, equally distributed across high- and middle income contexts (see Figure 5).

	High-Income Context	Low-/Middle Income Context
City-wide Scale	**Case 1: San Francisco, California, USA** Since 2015, mandatory requirement for new developments above 23,225m^2 (250,000ft^2) gross floor area to install and operate an onsite water reuse system.	**Case 4: Bengaluru, Karnataka, India** Since 2004, buildings with 50+ residential units/5000+ m^2 in unsewered areas must install onsite treatment plants and reuse 100% of the treated water.
Neighbourhood Scale	**Case 2: Jenfelder Au, Hamburg, Germany** Blackwater, greywater and rainwater separation. Vacuum collection system, biogas & heat production. Serves 630 (up to 835) residential units, in operation since 2017.	**Case 5: Nirvana Country, Gurugram, India** Treated water from small-scale treatment plant is used for horticulture. Serves 400 residential units, in operation since 2016/2020.
	Case 3: H+, Helsingborg, Sweden Blackwater, greywater and organic waste separation. Vacuum collection system, biogas & fertilizer production. Serves 320 residential units, in operation since 2020.	**Case 6: M3M Merlin, Gurugram, India** Treated water is used for horticulture and toilet flushing. Serves 760 residential units, in operation since 2018.

Figure 5: Overview of selected and assessed lighthouse initiatives during the Lighthouse project.

2.4 Data Collection

Data was collected between November 2021 and August 2022. For each LH initiative, relevant data was first synthesised from prior research projects, then collected through an extensive and explorative literature review and collated in respective draft reports for each case study. This was then followed by semi-structured guided key-informant interviews. Interviewees were identified through literature reviews and snowball sampling, covering representatives from all relevant stakeholder groups and the full project duration. On average, 20 interviews were conducted per case, which resulted in more than 100 interviews that informed the data analysis. The interview guideline can be found in the Annex (cf. p. 57).

2.5 Data Analysis

Audio recordings of the interviews were transcribed and interview data was analysed through directed and inductive content analysis (Mayring [26]) using MAXQDA 12 software. Directed content analysis requires a predefined set of codes, i.e. labelling statements capturing a certain theme with a descriptive code. This allows for validation and comparison with previous topic-related research findings. For the directed content analysis, we used the holistic assessment framework as outlined in section 2.2 (see Figure 4). As a starting point, interview transcriptions were coded with the key dimensions of our analytical framework and sorted across time, to be able to reconstruct how the social and technical dynamics evolved over time in each case and to identify the key collective interventions that led to successful implementation. In inductive content analysis, first, narrow codes representing the statement's content were assigned and through refinement, themes inductively captured. Labelling statements with codes that thematically capture their contents or message allows sorting and structuring a large number of various statements into meaningful and comparable storylines or data clusters in a logical way. The number of codes inductively increased throughout the coding exercise.

Statements can be labelled with one or more codes. In the first round, we used the collated list of codes (= directed approach). If no existing code from the list could be assigned, these were complemented with a new code. In the second round, all transcripts were checked, and emerging codes refined, merged or deleted. For example, 'Openness to Experimentation' and 'Innovative Attitude' were merged into the sub-code 'Innovation'. Throughout the third round of coding, codes and sub-codes were subsumed into code groups. For example, when participants referred to the intentional generation of 'Common Benefits/Win-Win' among different stakeholders, which were essential for successful project implementation, the code 'Common Benefits/Win-Win' became a sub-code of 'Strategic Driver'. Likewise, 'Innovation' became a sub-code of 'Contextual Driver'. In turn, 'Strategic Driver' and 'Contextual Driver' became part of the code-group 'Drivers'. With this approach, an overarching narrative and key socio-technical interventions in each case could be derived. In a last step, the draft reports from the literature review were then complemented with interview data to generate a description and analysis of each individual case. The individual case studies then served to generate this synthesis report.

2.6 Project Outputs & Limitations

The initial aim of the Lighthouse Project was to sketch an applied framing document that provides stakeholders with a 'toolbox' for setting up local LH initiatives. The produced project outputs are a first step towards developing this 'toolbox' as it documents pathways and synthesises core features leading to successful implementation of LHs. Against this background, this final project report can serve as the basis for producing templates for the diffusion of DUWTRS in cities in high-, middle- and low-income contexts.

Apart from a synthesis report and an academic paper, two types of reports per case were envisaged; full project reports of each individual case, including a detailed outline of the respective LH initiatives for interested researchers and sector experts, and more digestible short reports targeting a broader audience. The short reports are collected in the result section of this document, while the full project reports are available open access on the project homepage.[3] The short reports concisely summarise the respective initiatives, including a brief historical synopsis, followed by a systematic compilation of the results, according to our assessment framework, and close with a concise synthesis of key interventions and lessons learnt. A first scientific research article analysing LH's role in sustainability transitions is at an advanced draft stage ('*How socio-technical configurations travel. Tracing the emergence and diffusion of a configurational template for vacuum-based sanitation systems in Europe).* A second journal article is planned to be submitted; this will summarise the generic lessons of the Lighthouse Project and is geared towards practitioners and sector experts.

Moreover, an international roadmapping workshop is planned that shall create a platform for exchanging best practices between LHs and ultimately to mainstream DUWTRS among leading researchers, firms, cities, and NGOs active in UWM. It aims at fostering discussions on the technical and non-technical challenges in implementing DUWTRS and identifying plausible trajectories for their further mainstreaming. The workshop provides an opportunity for showcasing best practices from different cities around the world, networking with peers pursuing similar solutions elsewhere, and learning from each other's successes and failures. Moreover, it will facilitate a structured roadmapping exercise on how DUWTRS could diffuse and scale-up in the mid-term future.

Some limitations have been imposed on the objectives and thus affect the outputs of the project. First and foremost, the small number of assessed cases coupled with focussing on success cases affect the generalisability of the presented findings. More data and more cases – most importantly a comparison of successful and failed initiatives – are needed to be able to make more reliable statements about which factors are necessary conditions and which combination thereof generates sufficiency for the success of a LH initiative in a given context. This is needed to provide strategic and more detailed guidance for districts and cities on setting up LHs. Second, a detailed governance and institutional analysis for all contexts has not been produced due to a lack of resources. Third, given that the quality and quantity of data collected from M3M Merlin and Nirvana Country did not meet expectations, these case studies were not developed into full project reports, but remained at an advanced draft level. The results presented in the remainder should thus be seen as the first step in a broader and more comprehensive assessment of the success and failure conditions of transformative UWM solutions.

[3] www.sandec.ch/lighthouse. Given that the quality and quantity of data collected did not meet expectations, the M3M Merlin and Nirvana Country cases studies were not developed into full project reports, but remained at an advanced draft level.

3. Results

The results summarise key information for the five Lighthouse Initiatives with sufficient data availability. The summary reports of each LH are also available online. Each summary includes the project developments from a historical perspective, i.e. its background, project genesis and development from ideation to realisation. Following our analytical approach, each project is being analysed along six 'spheres'. First, the technical sphere depicts the technical system set-up. The subsequent five chapters are structured along the above-outlined dimensions of the analytical framework for LHs (cf. section 2.2), excluding a detailed governance and institutional analysis as explained in section 2.6. Finally, each case report closes with a synthesis outlining key interventions and lessons learnt.

3.1 Case 1: On-site Water Reuse Systems in San Francisco, USA

Introduction

San Francisco (SF) is a densely populated major economic hub in Northern California with high economic dynamism and fast population growth [27]. SF used to have a non-diversified water supply system, which heavily relied on the long-distance transfer of surface freshwater [28]. Since the end of the 20th century, increasing water consumption [29] and repeated droughts have resulted in water stress, forcing local authorities to explore alternative water sources [30]. From the 1990s onwards, recycled wastewater increasingly became a potential alternative water source. San Francisco's Public Work Code (Article 22) was amended to define recycled water use areas within the city and as part of the preparations for a 'Recycled Water Master Plan'. In response, the Public Utilities Commission (SFPUC) started exploring the potential of centralised non-potable water reuse [28].

Until the mid-2000s, centralised water reuse was seen as the most viable solution to increase local water resilience. However, this solution proved hard to implement as SF's hilly topography, coupled with long distances between treatment plants and users, required pumping reclaimed water, increasing energy and distribution costs [31, 32]. Many buildings that had installed purple pipes never received recycled water and the city adapted its strategy to supplying large irrigated areas like parks and golf courses with centrally recycled wastewater [31]. In the early 2000s, onsite water reuse systems (ONWS) were increasingly discussed as an alternative [32, 33]. At the same time, several real estate developers approached the local utility (SFPUC), and expressed interest in implementing ONWS in their buildings in order to obtain the highest possible building sustainability certification from the LEED programme [34].[4]

SFPUC thus became interested in promoting the concept of ONWS and established an ONWS demonstrations plant in its new headquarters' building. In September 2012, the city adopted the Onsite Water Reuse Program and added Article 12C to the SF Health Code. The amendment allowed for the collection, treatment and use of alternative onsite water sources for defined non-potable uses. Initially, the ONWS program was implemented on a voluntary basis, which enabled SFPUC to determine the feasibility of mandating such a program. In 2015, Article 12C became mandatory for new construction projects with more than 23,225m^2 (250,000 ft^2) of gross floor area. The article has since undergone further amendments. Since 2021, all new commercial, mixed-use and residential buildings with a gross floor area larger than 9290 m^2 (100,000 ft^2) have to install and operate an ONWS at the building or district scale.

On-site systems can capture, treat and reuse blackwater (wastewater from toilets), greywater (wastewater from the laundry, kitchen/bath sink, and shower), rainwater, stormwater, air conditioning condensate and foundation drainage. There is no one-size-fits-all solution for designing ONWS, and technological solutions differ substantively between different building types and sizes. Yet, they all must adhere to the water quality requirements set by the city's regulative framework. After treatment, the recycled water can be used for indoor non-potable uses (toilet flushing, irrigation, laundry, or cooling towers), as well as for outdoor uses (irrigation, decorative fountains, dust control, or cooling. By Nov 2022, 48 ONWS systems were operational in the city and a total of 119 projects had submitted water budget calculations[5] [35]. SF has

[4] LEED (Leadership in Energy and Environmental Design) is a globally used green building rating system. Its certificates are a recognized symbol of a building's sustainability achievement.

[5] Submitting a water budget to SFPUC indicates that the project is in the pipeline for eventually installing an ONWS and will be counted as such in SFPUC's tracking and reporting systems.

thrived as a leader in using ONWS, receiving several awards for its innovative approaches to water recycling. The city has also become a national and global reference point for other cities looking to adopt ONWS systems. In addition to its own efforts, SFPUC chairs the National Blue Ribbon Commission (NBRC) that works to promote the use of ONWS across North America.

The city's success in becoming a leader in ONWS adoption is rooted in a long-term, iterative and distributed learning process. In this brief, we will examine the key drivers and challenges the city has encountered on the way to implementing ONWS. This discussion will be structured around the five key analytical dimensions of the Lighthouse project's analytical framework. By examining these dimensions, we hope to gain a better understanding of the key factors that have led to the successful implementation of ONWS in SF, and to identify recomendations for other cities that seek to adopt similar urban water management solutions.

System-Set Up: Technology Description

As outlined above, a wide variety of ONWS designs have been implemented in the city. At a generic level, the typical ONWS solution includes: a collection system for different types of source water, an equalisation tank, a treatment system, a treated water storage tank, and a non-potable water distribution system [36]. Treated water is redistributed within the buildings through separate purple pipes with specific signage. Connection to the city's water supply network is required, as is a connection to the sewer network. This way, onsite treatment plants can automatically divert into bypass mode in the case of a system failure [37].

The choice of the exact treatment steps depends on the water sources and reuse purposes ("fit-for-purpose"). Treatment of blackwater and greywater typically comprises a specific combination of primary pre-treatment, secondary biological treatment (activated sludge processes, often membrane bioreactors), and various tertiary treatment steps, such as micro-filtration (MF), ultrafiltration (UF), ultraviolet light (UV) disinfection, ozone disinfection, and/or chlorination (Figure 1) [36]. In response to the local regulatory framework, treatment must comply with mandated $\log_{10}$ reduction targets (LRTs), which represent the minimum inactivation requirements of pathogens (viruses, protozoa, and bacteria). Technology providers increasingly develop standardised self-contained treatment systems with most of the plumbing and electrical work already completed. These turnkey solutions reduce installation timelines, saving time and money [38]. Lastly, developers have to install remote monitoring systems to ensure reliable and safe operation of their ONWS. This includes remote control units, automated alarms and diversion systems, backflow prevention devices, and air gaps [36, 39].

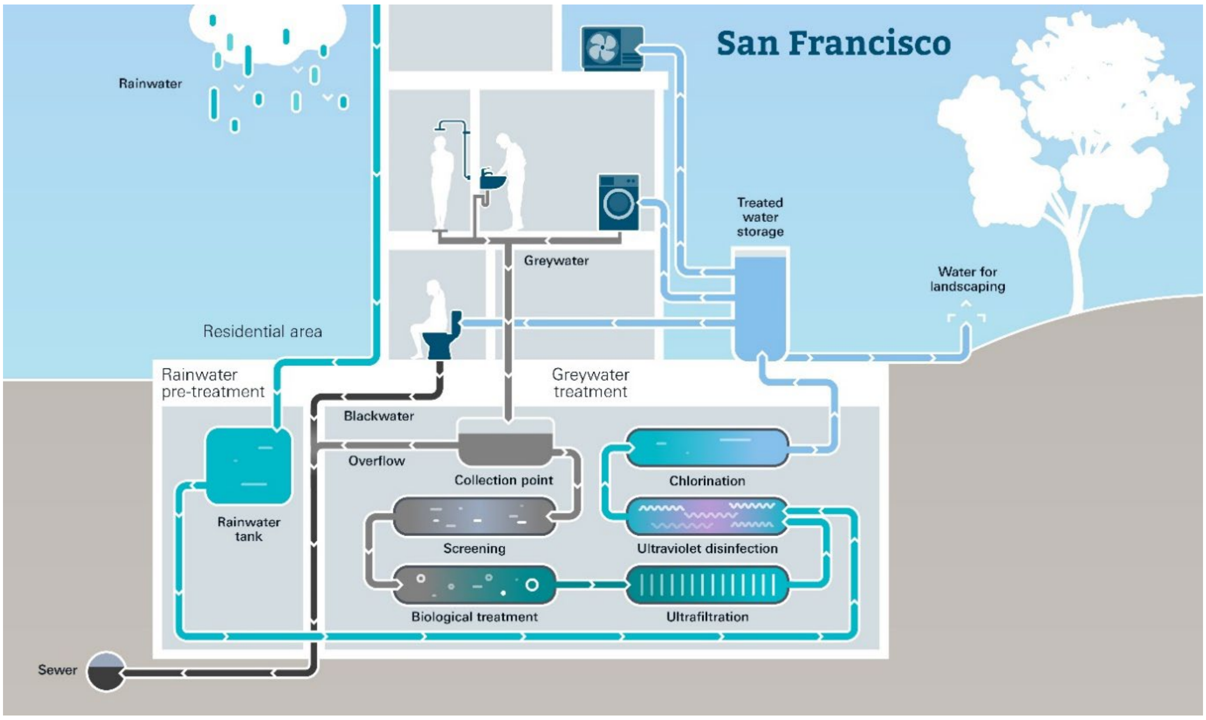


Figure 6: Schematic overview of a typical onsite treatment system in San Francisco (Own illustration based on [15, p. 55]).

Institutional Framework Conditions

Legal & Regulatory Conditions

When SF started installing its first ONWS systems, onsite water reuse was not common practice in US cities nor globally. Templates for effective regulations and governance arrangements were thus widely lacking. To develop a local programme and permitting process for decentralised water reuse systems, SFPUC had to coordinate among different city departments[6] in an experimental, bottom-up process 'from scratch'. In a series of intense exchanges, SFPUC, regulators, and several city departments iteratively drafted a novel city ordinance introducing a regulatory framework for installing and permitting ONWS [34]. They added Article 12C to the city's health code (the Non-Potable Water Ordinance) and established SF's Onsite Water Reuse System Program that outlines a ten-step process to review, permit and monitor ONWS systems (Figure 7). For each step, it defines the key actors, their roles and responsibilities, the information required from developers and the necessary operation & maintenance (O&M) [36].

This work made SF a global pioneer in defining a comprehensive governance arrangement for ONWS that covered the full project cycle, from planning to installation and O&M [36]. However, the initial version of Article 12C and the ONWS program contained many open issues. Specifically, the need for regular effluent water quality testing in onsite plants [40] made ONWS prohibitively expensive. Accordingly, the National Water Research Institute (NWRI) and SFPUC jointly organised an expert panel, including regulators, technology firms, academics, and consultants, which was tasked to develop a regulatory water quality framework tailor-made for ONWS systems. The goal was to ensure public health while simplifying ONWS's design, installation and O&M processes and reducing water quality monitoring costs [30]. This key innovation, the 'Risk-Based Framework', listed LRTs for different water sources and end uses [41]. Its basic idea follows Australian regulatory approaches: instead of focusing on continuously measuring the effluent quality, it defines critical control points in ONWS systems that indicate whether each treatment step is adequately operating. If each step works as expected, the reuse water quality can be assumed to meet the defined quality criteria [41]. If online monitoring systems identify issues with a treatment step, the system automatically switches into bypass mode until they are resolved.

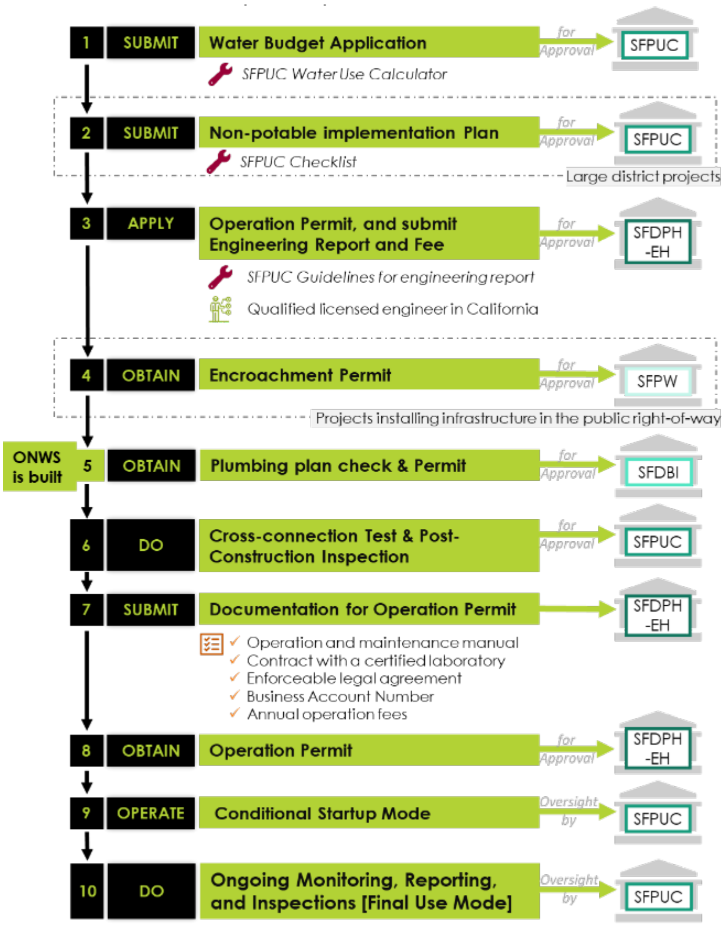


Figure 7: Ten step process for successful implementation of ONWS (Source: own elaboration, based on [38]).

Once the Risk-Based Framework was established, local actors, led by the SFPUC, worked towards a state regulation amendment to mainstream these water quality standards across the state [30]. Approved in September 2018, it is anticipated that the state water board will amend the California Water Code to adopt ONWS quality standards in line with the Framework by late 2023. Additionally, several other states (Colorado, Hawaii, Washington, and Minnesota) have developed legislation and/or policies to advance ONWS based on the Risk-Based Framework [42]. This novel Framework, thus, has played a key role in diffusing ONWS not only within SF, but also across California and the US.

[6] Public Health (SFDPH), Public Works (SFPW), and Building Inspection (SFDBI)

Contractual & Financial Arrangements

In general, the capital expenditures for installing ONWS plants and the OPEX for running them are covered by building owners, developers and/or the building tenants. The capital expenditures for the installation (CAPEX) and the operation (OPEX) of ONWS were initially rather high. Therefore, in 2012, SFPUC developed a grant programme to compensate for some of the CAPEX costs for buildings that voluntarily implement ONWS. These grants are up to $1,000,000 [37] and are still being offered. Their application has however been limited to voluntary applications of ONWS.

Another (small) economic incentive for installing ONWS was created in February 2017, when SFPUC adjusted the procedure for calculating water capacity charges. SFPUC calculates this capacity charge before a site permit is issued for new developments. Buildings with ONWS now have to pay a decreased capacity charge, as they typically put a lower strain on the centralized freshwater and sewer systems. Buildings with ONWS furthermore also use less fresh water, which lowers their average water and sewer bills. In addition, also the increasing technical maturation and standardisation of ONWS products, firms and market structures are likely to further increase ONWS's economic viability through economies of scale. Although these interventions taken together can significantly reduce the payback period for ONWS systems, whether and how quickly a financial return on investment can be achieved by ONWS remains a key discussion point especially among building owners and developers. SFPUC and other local stakeholders keep streamlining and amending the ONWS program to address this point.

Industry & Market Structures

Initially, the lack of local suppliers for high-quality on-site treatment plants and related services made designing and installing ONWS cumbersome and expensive [43]. Since real estate developers had difficulties in finding specialised planners and suppliers, many consulted external national or international firms. Only when the ONWS market started booming, did local start-ups emerge and start supplying innovative ONWS systems.

A critical development in improving the (niche) market for ONWS was the emergence of design-build-operate business models (DBO). In DBOs, the same company designs, plans, implements, and operates the ONWS for a set period. This is beneficial for three reasons. First, the complex ONWS permitting process requires specialised knowledge at different stages. Getting a permit involves a combined effort of owners, architects, and structural, mechanical and electrical engineers, technology suppliers and operator firms. Having one firm responsible for the entire permitting process can be very conducive as it simplifies communication and coordination among all the parties involved in this complex process. Second, regulations define that an ONWS which treats blackwater has to be operated by a licensed "Class Two Wastewater Operator". Since finding certified wastewater operators for ONWS was (and still is) challenging, having the same firm design, plan and implement an ONWS and also operate it strongly improved O&M quality. This arrangement is also conducive to interactive learning, since the operators can directly exchange experiences with the design team on certain technologies' performances and operational challenges in the field. Third, adopting a DBO model enhances the creation of a reliable, long-term income stream for the involved firms compared with directly handing over the projects to a third party after completion. DBOs, thus, entail strong incentives to design a system that is well-adapted to a building's performance needs, as well as increasing regulatory compliance, robustness, longevity, and, ultimately, economic viability [34].

As an additional measure to support local industry and market formation, SFPUC published guidebooks and a list of validated and accepted technologies, treatment processes and technology/service suppliers that provide state-of-the-art ONWS solutions [44-46]. Additionally, many ONWS suppliers actively shared general information on treatment technologies and how to effectively implement them on their websites and at specialist conferences and workshops.

Knowledge, Skills & Capacities

SFPUC in many ways champions knowledge, skill and capacity development around ONWS in SF. It organises public outreach activities, expert meetings, workshops and conferences to discuss onsite water reuse with local communities. Publicly accessible guidelines complement these activities, such as SFPUC's Onsite Water Reuse Program Guidebook [36]. This – and many similar - publications aim at improving local stakeholder's capacity to assess alternative water sources and estimate non-potable water demand. They also provide practitioners with examples of how to design treatment systems that meet the LRTs required by the Risk-Based Framework. Furthermore, the technological skills of project planners and suppliers are continuously increased through learning-by-doing processes. More and more firms with strong technological capabilities have entered the ONWS market both within and beyond California, as they sense an increasing demand for these novel solutions.

While SFPUC led its development, the ONWS program is the collaborative result of a broad transdisciplinary stakeholder network [47]. This included key contributions from local sustainability consultants, technology suppliers, universities, NGOs and operator firms. Sustainability consultants and NGOs in particular have made continual efforts to increase the technological knowledge and capacity of local planners, developers, and property owners. For example, the WJW Foundation issued the "Non-potable Water Reuse Practice Guide", which offers straightforward explanations of why and when to consider ONWS in a user-friendly way [48]. Local universities have also published key technical and scientific knowledge around ONWS (cf. e.g. [32, 49-51]).

To further increase technical capacity, especially of operators, the NBRC is working with the Water Environment Federation, Water Professional International, and WateReuse Association to develop tailor-made education and training. Ultimately, the target is to establish a comprehensive training and certificate programme for ONWS operators, which is expected to become available in 2023.

Recognition & Legitimacy

The ONWS program profited both from conducive context conditions in SF and strategic activities by local actors that increased its legitimacy. Droughts, climate change and economic expansion have intensified the city's search for feasible and resilient solutions to water shortages, thus, boosting the ONWS programme's legitimacy. With SFPUC, a local champion furthermore existed, that played a key role in coordinating stakeholders and different city departments, in developing the ONWS permitting process and issuing the novel city ordinance. SFPUC was in a unique position to do so because it manages water, wastewater and energy under one roof. The innovative attitude and openness for collaboration among city departments, regulators and other key stakeholders arguably have been another key factor in the city's success story concerning ONWS.

The strategic activities of local stakeholders were also critical for legitimising ONWS. For instance, installing the Living Machine project at SFPUC's headquarter helped create the credibility of ONWS within the utility and among key stakeholders and the wider public. The Living Machine™ is a constructed wetland system, consisting of primary treatment, tidal and vertical flow wetlands, and disinfection stages. It was designed to treat about 18,927 litres (5,000 gallons) per day of (combined) wastewater for toilet and urinal flushing, reducing SFPUC's potable water demand by 65% [36]. The project's scale proved the water-saving potential of ONWS [52]. Its nature-based treatment steps were furthermore installed at a publicly accessible location. This was instrumental in building public acceptance and normalising the idea of onsite water reuse. Guided tours for the public increased education and awareness of ONWS among city residents [30]. The system is now being updated to get in sync with current LRT standards and includes an advanced treatment system that produces almost potable water quality for educational and outreach activities. The installation of ONWS in iconic high-rise buildings, such as 181 Fremont and the Salesforce tower, also improved the innovation's local recognition and legitimacy.

In addition, SFPUC strategically fostered the development of a dense network of key stakeholders involved in designing, permitting, implementing and managing ONWS systems [53]. This network became instrumental in resolving development barriers, identifying opportunities and defining critical research needs [53]. Recognising the importance of iterative learning in programme development, SFPUC actively sought and incorporated feedback from a broad set of stakeholders as the ONWS program progressed. This interactive and reflexive approach helped to distribute ownership across different stakeholders, thus, increasing the ONWS program's legitimacy. SFPUC was also one of the main actors behind establishing the NBRC, which played a crucial role in diffusing ONWS beyond SF through lobbying of State and National governments, creating legitimacy for it beyond the local level [53].

As the recognition and legitimacy of ONWS grew and the number of successful projects increased in the mid-2010s, large tech companies in Silicon Valley, including Google, Facebook (Meta), and Microsoft, decided to adopt ONWS voluntarily in their new building projects. Mentioned often by interviewees, this development provided an additional boost of legitimacy for the ONWS program. At the same time, some legitimacy challenges remain. For instance, regulative frameworks for ONWS still differ from place to place and between States, creating strong diffusion barriers [42]. OPEX costs are also relatively high. While these costs can be borne easily in many new developments in SF, other communities might struggle with raising the money needed to operate and maintain ONWS. The long payback period for ONWS also makes it difficult for investors to recover their initial investments, hindering market diffusion [31]. Some interviewees questioned whether the energy and resources required to operate and maintain ONWS systems outweigh their benefits in all cases. To address these challenges, full lifecycle assessments, including a holistic view of ONWS costs and (economic, social and ecological) benefits, are needed. In this regard, the Environmental Protection Agency (EPA) has taken steps towards developing a comprehensive assessment tool called the Non-Potable Environmental and Economic Water Reuse (NEWR) Calculator[7]. While it does not conduct a full lifecycle analysis, the calculator is a valuable tool for comprehensively assessing onsite water solutions' environmental and economic impacts.

Key Interventions & Lessons Learnt

As described above, ONWS have been successfully diffused and are increasingly taken for granted in SF. Multiple key interventions of local actors over the past decade have enabled this outcome. Particularly, the detailed and comprehensive permitting process and regulative framework developed in the city are globally unique and a key element in qualifying SF as a "lighthouse case". Based on our analysis, four key interventions proved critical in creating this success case.

First, continued political support and SFPUC's long-term strategic commitment and perseverance in developing and adapting the ONWS program were an often mentioned critical success factor. Introducing the first comprehensive regulatory framework for installing, permitting and running ONWS became possible thanks only to a series of intense interdepartmental exchanges between SFPUC, local and state-level regulators, and several city departments. The collaborative, iterative and self-reflexive way in which the ONWS program and the city ordinance and regulative framework were developed and iteratively adapted thereafter proved highly effective. It brought key stakeholders on board, enabled broad knowledge exchange, as well as the development of local industry and market structures.

Second, extensive outreach and knowledge exchange activities were instrumental in establishing and improving the understanding and capacity of stakeholders to work with ONWS. Initially, there was a lack of knowledge about its potential and application options. Outreach activities by SFPUC and other local actors, thus, strategically targeted lay people, developers, planners, practitioners and regulators. SFPUC and local NGOs produced a series of reports and white papers (e.g. [36, 37, 48]) that provided straightforward explanations of why and how to consider ONWS. These activities proved crucial in establishing and maintaining legitimacy.

Third, the Risk-Based Framework is a key innovation developed by various actors in SF's ONWS program that eased and clarified regulative requirements for ONWS. It is increasingly being used as a template by other jurisdictions in the US and beyond because it provides clear guidelines for equipment suppliers, developers and practitioners when designing, constructing, operating, and maintaining these systems [54]. This pioneering regulative Framework, specifically tailored to the needs of ONWS, outlines how to ensure public health, while reducing water quality monitoring costs.

Fourth and finally, the development of DBO-business models among local technology suppliers has proven to be a key success factor. DBO business models enable an efficient permitting process and simplify the installation process for building owners, developers, and regulators. They also create a more long-term and reliable income stream for the technology suppliers and incentivises them to design well-adapted, robust, safe, and efficient onsite treatment systems with low O&M costs. This model in principle could be emulated in other cities opting for ONWS.

While the ONWS program in SF so far has been a success case, key challenges remain. These include the limited number of operators with the required expertise to operate such systems, which has been addressed by the above-mentioned certified training and exam programme for ONWS system operators. Another challenge is the high CAPEX and OPEX costs of ONWS. These limit fast returns on investments and hinder a fast market-based diffusion trajectory. ONWS in SF are furthermore mostly implemented in new, high-end real estate developments that can afford the high OPEX costs [31]. In many other communities, CAPEX and OPEX are likely to pose more significant barriers for diffusion. Finally, further economies of scale and learning curves both in the (mass-) manufacturing of treatment systems and O&M models (as well as innovative business models) are still needed to make ONWS a global solution to urban water challenges.

[7] https://www.epa.gov/water-research/non-potable-environmental-and-economic-water-reuse-newr-calculator

3.2 Case 2: HWC in the Jenfelder Au, Hamburg, Germany

Introduction

The Jenfelder Au is a sustainable urban development project in Jenfeld (district of Wandsbek), situated in the federal state of Hamburg, Germany. Between 1970 and 1990, Jenfeld increasingly developed into a low-income social structure, with many families depending on welfare measures and financial support [55]. Against this background, local politicians decided to upgrade the Jenfeld district by building a major urban development project on the grounds of the Lettow-Vorbeck barracks, later called Jenfelder Au [56]. Former military grounds owned by the State Government, the area was sold to the federal state of Hamburg. In April 2005, the Senate of Hamburg approved an urban development model for the site [57, 58]. From 2005 to 2011, a development plan was established, which stipulated that the project should serve as a role model for future-oriented and energy-efficient urban development. Innovative energy- and resource-saving approaches were to be implemented at neighbourhood scale [59].

HAMBURG WASSER, Hamburg's publicly owned utility for water supply and wastewater management, has a dedicated innovation department. In 2000, this department was tasked to analyse its existing water management systems and look for alternatives that increase sustainability [60]. As a result, together with the Fraunhofer Institute for Systems and Innovation Research (ISI) in Karlsruhe, the innovation department developed the Hamburg Water Cycle (HWC). The HWC is a concept for circular wastewater disposal and energy supply in urban areas. Its essential feature is the separate collection and treatment of different wastewater flows. In contrast to conventional systems, the HWC treats partial streams within the neighbourhood. It ferments blackwater (wastewater from toilets) for biogas production, treats greywater (domestic wastewater without faecal contamination) for possible water reuse, and uses nature-based solutions for rainwater management. In 2005/06, the innovation group started looking for a suitable implementation area. In 2007, HAMBURG WASSER successfully approached the district of Wandsbek with the idea to realise the HWC in the Jenfelder Au. Because climate change mitigation and adaptation are key topics since 2007/08 at EU, national and the federal state levels, and at HAMBURG WASSER, this created a supportive political framework for realising the HWC, which has been developed at scale since 2012. With 630 residential units connected to the HWC to date (and eventually 835 units), the Jenfelder Au is currently the largest residential neighbourhood in Europe to use a decentralised urban wastewater treatment and reuse system (DUWTRS). The commissioning of the HWC system took place in fall 2016. In spring 2017, the first residents moved into the Jenfelder Au and blackwater treatment has been operational since May 2019. The initial plan envisaged redirecting the treated greywater into the rainwater collection pond ('Kuehnbach pond'). However, since the required effluent standards are not (yet) met, a part of the greywater is upgraded to service water for industry and sold, the rest is discharged into the main sewer as quality standards are not (yet) met to release it to receiving waters. Adequate and efficient greywater treatment methods are still being tested, and in late 2019/early 2020, two experimental greywater treatment plants were constructed for this purpose.

The HWC is considered a lighthouse initiative with international recognition and has won several awards.[8] Delegations from around the world have visited the site and use it as inspiration for developing their own sustainable DUWTRS. In this brief, we examine the key drivers that have contributed to the successful implementation of the HWC and the challenges. This report is structured around the five main analytical dimensions of the Lighthouse project. By examining these dimensions, we hope to gain a better understanding of the key factors that have led to its success, and to identify recomendations for other cities that seek to adopt similar decentralised urban water solutions.

System Set-Up: Technology Description

The HWC is based on a circular approach: wastewater is used to generate energy, the greywater cycle can be closed locally and rainwater retained in the immediate residential environment. The most important component of HWC is the separate treatment of different water flows. Rainwater, blackwater (wastewater from toilets) and greywater (wastewater from kitchens, bath sinks & showers and laundry), are separately collected and treated differently. A vacuum-based sewer system transports the blackwater; and conventional technology transports greywater. By sorting blackwater at source and using low-flush vacuum toilets, water consumption decreases, while blackwater concentration and, thus, the potential for biogas recovery increases. Greywater separation allows for efficient water reuse. At the service yard, the contents of the blackwater

[8] 'Gold Award' of the 'International Urban Landscape awards' (2009), VKU Innovation Prize (2013), Winner of BMBF's 'Excellent Landmarks in the Land of Ideas' (2013).

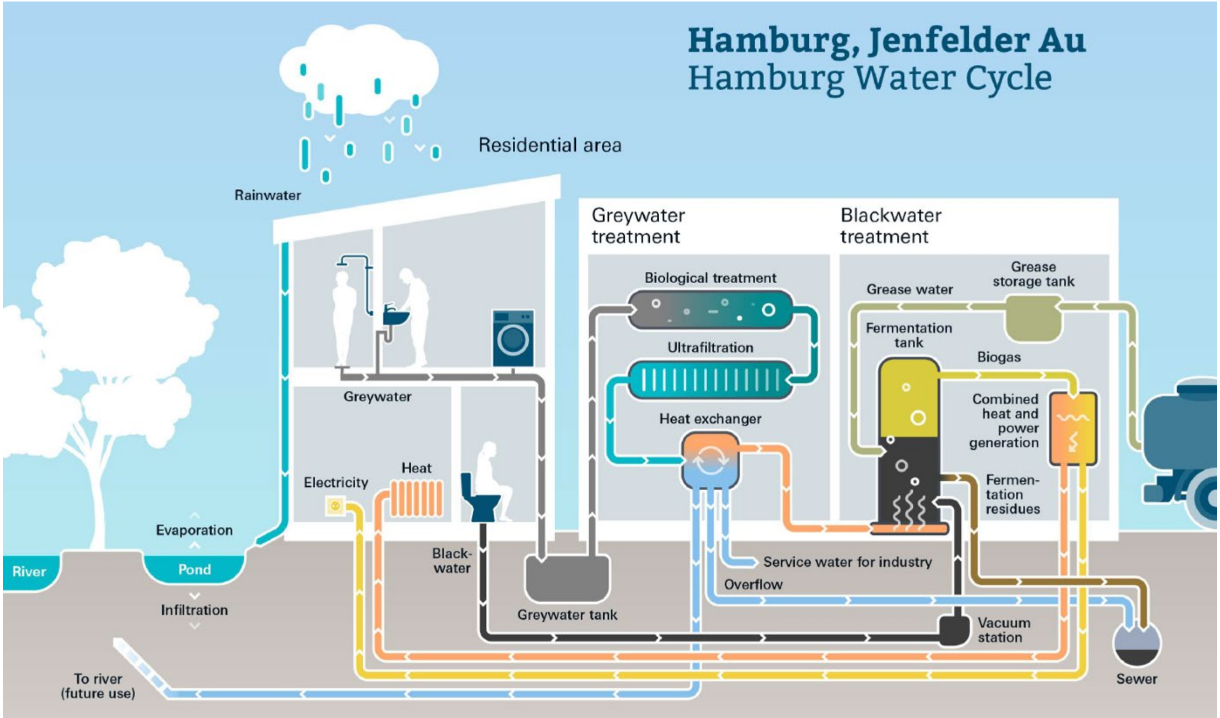


Figure 8: Schematic overview on the HWC, based on interviews and the HW [1].

are fermented in a biogas plant and connected to a cogeneration plant for heat and energy production. Rainwater is retained on green areas, where it percolates and evaporates. Some of it is pumped into the Kuehnbach pond, where it creates co-benefits in the neighbourhood, i.e. increasing liveability and resilience to extreme storm events or heat waves.

The blackwater vacuum network of the HWC consists of the vacuum toilets and pipes in the private area, and the vacuum pipes and network facilities (including shut-off devices, and inspection openings) in the public area. The blackwater accumulating in the neighbourhood is fed via three main lines to the blackwater pumping station in the service yard. There, the vacuum for the entire vacuum network is generated.

Two vacuum tanks collect the blackwater, which is mixed with co-substrate (grease water sourced from local restaurants and reflux from the fermenter), heated and pumped into the fermenter. In the fermenter, the production of biogas takes place. The purified biogas is burnt with air in a combustion engine, which drives a generator that converts the mechanical energy into electricity. The waste heat of the engine, i.e. the thermal energy of the cooling water and the exhaust gas, is transferred via heat exchangers to a water circuit. From this water circuit, heat is extracted for the residential area's heating supply (Power: Electrical power: 60 kW_{el}; Thermal power: 92 kW_{th}). Because the settlement is still under construction, the cogeneration plant does not yet run at capacity and relies too much on co-substrate.

The HWC in theory also enables non-potable water reuse from greywater treatment and nutrient recovery from the fermentation residues. However, while a part is upgraded to service water and sold, given that strict water quality standards are not (yet) met, most of the greywater is discharged into the main sewer. Fermentation residues could in principle be used to produce fertiliser or a soil amendment. This option was investigated during the 'KREIS' research project, and the findings were inconclusive [61]. KREIS analysed design parameters for the discharge and treatment of the black- and greywater flows and was key for the HWC's technical adaptation. Although it is still intended to utilise the fermentation residues and create nutrient products, there are currently no activities planned or ongoing in this respect.

Institutional Framework Conditions

Legal & Regulatory Conditions

In the last decade, the 'sponge-city' concept has received increased recognition in various German cities (e.g. Berlin, and Hamburg). 'Sponge-cities' focus on rain-/stormwater management and aim to retain as much water as possible through nature-based solutions. DUWTRS are neither prohibited nor explicitly promoted in Germany; however, there are key barriers to implementing DUWTRS due to unclear and/or a lack of regulations [9, 62-64].[9] It is legal to treat and dispose of wastewater in (semi-)decentralised systems [63] and the municipalities are responsible for public drinking water supply and wastewater disposal under the supervision of the federal states. Responsibilities can be delegated to municipal companies, private companies or public-private partnerships [65]. The federalist reform from 2006 has created a legal and regulative patchwork; it allows federal states to adopt their own regulations in the field of water law [66].

In Hamburg, originally, parts of the HWC were prohibited by law. While decentralised nature-based rainwater management has been allowed in Hamburg's water management guidelines since 1984 [67], the Hamburg Wastewater Act (HmbAbwG) prohibited vacuum-based systems [68].[10] To start initial planning and implementation, the HWC project team, therefore, had to apply for an exemption permit. Long-term operation and eventual follow-up projects required an amendment to the HmbAbwG. Thus, in 2010, the project team from HAMBURG WASSER initiated an amendment process [69-71], which was successfully concluded in 2018 [9, 69]. Today, §11a Art. 5 of the HmbAbwG contains the term "partial wastewater flows", which allows for separation of black- and greywater, and permits the wastewater disposal authority to set specific requirements for each stream's discharge. According to our interviewees, it helped that the city-owned utility applied for the legal amendment rather than a profit-seeking private company. In addition, in Germany, public drinking water supply and wastewater disposal is regulated at the federal state level. Because Hamburg is a federal city-state and owns the utility, this facilitated the communication between HAMBURG WASSER and the administrative entities necessary to do the HmbAbwG amendment.

Contractual & Financial Arrangements

Existing planning regulations and land ownership structures largely defined the roles and responsibilities of the different stakeholders involved in developing the HWC. The city of Hamburg led the functional planning and marketed and sold the plots through its respective administrative entity (State Department for Real Estate Management and Land Assets (LIG)), while the district of Wandsbek lead the development planning. In addition to the regular planning departments, a dedicated project manager position was created for the real estate development project. A public mandate to provide water and wastewater services to all residents obliged HAMBURG WASSER to establish the HWC up to the property boundaries. A key contractual challenge consisted in mandating that private developers connect to the innovative waste regime, the HWC. Developers – or future owners – could choose, however, to opt out and connect to the centralised system instead. Special contracts were, thus, needed to create a stable arrangement for realising DUWTRS [63]. Because the city was the land owner of the Jenfelder Au, it could mandate that all real estate developers (including all future owners) connect to the HWC. When plots were sold in 2011, the contracts accordingly included a compulsory clause to connect to the HWC.

Concerning costs, the capital expenditures (CAPEX) for installing the HWC were estimated to be 30% higher than a conventional system. The main cost drivers were the installation of additional pipes, the service yard and – based on a precautionary approach since available standards were rare – additional security measures. For example, to date, the emergency solution if the fermenter fails, is direct discharge into the city's wastewater sewer. Because no special public funds could be provided to develop the HWC, given existing regulations[11] [65],, the HWC team tapped EU and national research funds to cover the 30% CAPEX increase. HAMBURG WASSER covered 'the regular' costs, i.e. connecting to the existing centralised system. The EU funds covered the additional equipment costs and national funds (BMBF, BMWi) covered research and development activities. According to interviewees, these grants were indispensable for the project's realisation. Additional infrastructure costs within the buildings had to be paid by the developers/owners (reportedly ca. 1% increase in the total building costs). Concerning human resources for project management, HAMBURG WASSER's innovation department was financed with regular funds. The Wandsbek district administration used internal funds and applied for external grant money to fund the dedicated project manager position. The HWC's operational costs (OPEX) are covered without any special tariffs or financial incentives. The neighbourhood's residents pay regular water and wastewater tariffs, as in other parts of the city. The reduced water consumption of households connected to the HWC (mostly caused by the water-

[9] Although in principle legal requirements exist for greywater reuse (e.g. for toilet flushing and irrigation) or energy generation from blackwater [63], it is unclear whether wastewater or waste legislation applies to the recycling of blackwater [9]. In terms of recovered resources (waste/products), currently, secondary raw materials are hardly covered by existing legal regulations [64].

[10] Sewage transport was legally limited to gravity flow sewers and pressure sewers, but not "negative pressure" (= vacuum).

[11] Financial arrangements must follow the principles of public financial conduct [65].

saving vacuum toilets) mean that a four member household saves around €170/year (prices from 2017[12]) compared to households connected to centralised infrastructure [72].

Industry & Market Structures

Given the federalist reform from 2006 [66], Germany lacks uniform regulations for innovative water systems, such as the HWC. The regulative patchwork results in a lack of standardised (and compatible) treatment technologies, products, planners and suppliers [64]. When planning and implementing the HWC, specialised planners and equipment suppliers were, thus, missing and the existing standards and technical guidelines could not provide detailed guidance. For example, while there is a DIN-standard for vacuum piping in buildings, it is tailored to conventional wastewater systems, not to the low-flush blackwater systems used in the HWC [73]. Likewise, standards for greywater treatment and reuse were not available in the project planning stage. For instance, DIN did not publish minimum quality requirements for greywater reuse until 2021 [74]. This lack of industry standards challenged the vetting process done by the relevant authorities [68].

Many technical solutions and contextual adaptations had to be identified through research (see below). For example, the HWC project team in the KREIS research project evaluated potential vacuum toilet models from three available suppliers (Roediger, VacuSaTec and Jets) [75] and their noise levels. In the end, most of the buildings were equipped with toilets from Roediger. The required system's scale and the residential context in the Jenfelder Au also increased the challenge of finding technical suppliers. This included the lack of people with the expertise to plan, operate and maintain vacuum-based systems. Given this shortage, HAMBURG WASSER during the construction supported the vacuum specialists and trained them together with Roediger. This guaranteed proper installation of system components within the buildings, which is essential for the system's functionality, and to guarantee acceptable sound volumes when flushing vacuum toilets. Furthermore, Roediger invested more time and money than contractually required because of the chance it had to gain a competitive advantage in an emerging niche market.

Overall, there are very few suppliers of vacuum-based systems, such as the HWC, and they still operate mostly in niche markets.[13] However, because heat/energy recovery from biogas is well-regulated and mature suppliers and market structures exist in Germany, technical suppliers for this part of the HWC were readily available (GETEC AG as the contractor).

Knowledge, Skills & Capacity

The knowledge, skills and capacities on how to plan, construct, connect, operate and maintain the HWC system were mostly established through learning-by-doing. Initial practical insights on source-separation and vacuum-based systems were collected through exchanges with other pilot projects, particularly Flintenbreite (Lübeck, Germany), which became *the* initial reference point. In Flintenbreite, a small-scale source-separation concept (rain-, black- and greywater) using a vacuum-based system was implemented in 1999 [76]. Analysis of a similar project in Sneek (Netherlands, since 2005) showed that adequate technology choices and management are conducive to user-acceptance [61]. To increase its understanding and collect practical experience on stakeholder management, in 2011, the HWC team established a demonstration plant close to the Jenfelder Au (Gut Karlshöhe) [75], where various research activities were undertaken from 2011 to 2017. The lessons learnt from such projects as Flintenbreite supported technology selection and the fine-tuning of system components [61, 68, 75, 77]. The evaluations carried out at the demonstration plant during the KREIS research project (2011-2015) [61] were also vital to define the final technical system set-up. Activities at the demonstration plant and exchanges with other projects also helped the establishment of a common vision and mutual trust among all the involved stakeholders, and the movement from the conceptual to the detailed planning stage.

In the construction phase, detailed design and construction guidelines were established to ease knowledge transfer among the involved actors [78, 79]. The construction process was accompanied by advising building owners on the installation of vacuum technology in buildings. In addition, together with Roediger, the HWC team offered trainings for maintenance

[12] As of 2017: water price 1.85€/m^3 and wastewater fee 2.11€/m^3.

[13] Regarding greywater: while technically greywater treatment is doable and effluent standards can be reached using membranes, it is not economically viable since drinking water is simply too cheap. Regarding sludge application: currently, in Germany, treated sewage sludge can be used as fertiliser on agricultural soils or in landscaping measures, provided they meet the standards (low pollutant loads). However, today, in practice, the vast majority of the sludge dry matter is incinerated. While in 2012 more than 45 % of sewage sludge was applied, in 2016 it was about 35 %, and in 2019 around 20%. This can be attributed to, among other things, increasing quality requirements and spreading restrictions (fertiliser legislation).

companies. When people moved in, the HWC development team of HAMBURG WASSER welcomed the new residents and distributed a FAQ-infosheet on the HWC, including do's and don'ts [72].

Despite the above, there are still several knowledge- and capability-related challenges. For example, existing institutional norms jeopardise effective operation. Since the HWC is a closed system, smooth operation requires a dedicated supervisor/operator. After the internal hand-over from HAMBURG WASSER, the 'Netzbetriebe' manages the pipe network and the 'Klärwerke' the treatment plant, creating the challenge of seamless coordination and knowledge transfer between the two entities. Another difficulty is that ideally there would be a caretaker on-site responsible for operation and recurring and on-demand maintenance. However, for HAMBURG WASSER, the HWC is small, not high on its priority list, and seen as a burden by the utility's operational staff. Finally, the lack of follow-up projects within Hamburg and Germany means that the unique knowledge, skills and capacity acquired during HWC's development might be lost again. Without further diffusion, it will be difficult for planners, technology experts, firms and service personnel to specialise in these kinds of systems. This could also diminish user acceptability, if adequate support for end users gets increasingly expensive and/or not timely available.

Recognition & Legitimacy

To foster recognition and legitimacy among the relevant stakeholder groups, the HWC team early on systematically identified and addressed key actors and developed a strategic communication concept [61]. The overriding goal was to establish a positive image by marketing the HWC as a sustainable, high-quality infrastructure solution [61]. The communication dealt with the HWC's technical, ecological and social benefits (e.g. low noise, odour and costs). In addition, the HWC demonstration plant had a dual legitimising function. Through interdisciplinary research, vital technology and system knowledge was generated, which increased trust within the utility and among city officials that the HWC could really work. Simultaneously, it served as a 'proof of concept', and, thus, as a legitimising object for the general public, future developers, owners and residents. Likewise, from 2013 to 2017, the 'Jenfelder Au Urban Neighbourhood' exhibition took place [80]. Trained guides provided tours through the demonstration plant, answered questions and collected feedback [81]. During the construction stage, from 2016 on, a client consultation was organised at 'Gut Karlshöhe' to explain the concept to real estate developers and future owners so as to reduce stakeholders' concerns [82]. Finally, the legal amendment process (HmbAbwG §11a Art. 5) and the development of targeted outreach materials for different stakeholder groups, including design and construction guidelines [78, 79] and a FAQ-infosheet on the HWC [72], served additionally to foster legitimacy.

Key Interventions & Lessons Learnt

The interplay of multiple favourable conditions and constructive interventions by the actors involved were key to the HWC's successful implementation and in qualifying the Jenfelder Au as a "lighthouse case" for DUWTRS at neighbourhood scale. Four key interventions stand out.

First, the strong lead of HAMBURG WASSER and stable political support were key success conditions. The main impetus for the development project was the political decision to change the Jenfeld district's social structure [56]. HAMBURG WASSER's proposal to integrate the HWC into the district's development plan fell on fruitful ground as the HWC was perceived as a key selling point to attract higher-income residents. It complemented state-level climate change mitigation and adaptation strategies, as well as the project's ambitions, in serving as a role model for an energy-efficient and future-oriented urban development [59]. A wide range of local stakeholders supported this vision. With the area being largely undeveloped former military grounds, infrastructure was to be established anyway. Overall, thus there was hardly any opposition during the planning and implementation stages.

Second, several research and outreach activities were key in coordinating the implementation of the innovative technological approach and establishing favourable institutional conditions and public acceptability. This consisted largely of proactive and expansive networking, as well as knowledge acquisition and targeted dissemination. Learning from other projects and research activities, including the establishment of a demonstration plant, were key to developing and contextualising the HWC's final design. Furthermore, the knowledge and capacity gaps of stakeholders were strategically identified and addressed. Targeted activities and materials were developed, respectively, for planners, architects, developers, builders, service companies, researchers, practitioners and residents [61, 68, 72, 78, 79, 83]. To analyse user acceptability, HAMBURG WASSER conducted surveys with residents in 2018 and 2019 [84]. It plans to conduct the survey on a recurring basis over a period of 5 years, the next in 2024.

Third, amending the HmbAbwG was key. HAMBURG WASSER took the lead on this and the result is an amendment to the Hamburg Wastewater Act in 2018, which now includes 'partial wastewater flows', thus, explicitly allowing for DUWTRS [9].

Fourth, continuous networking created a collaborative and cooperative culture around the HWC. Collaboration took place between various public departments, the utility, research institutes and the private sector. The district of Wandsbek created a dedicated project management position, which was key to consistent development planning. This dedicated position increased the district planning department's capacity to coordinate and participate in stakeholder meetings related to the HWC. At HAMBURG WASSER, individuals who were strongly committed and identified with the project were involved across the entire process. This was conducive to knowledge exchange with the private sector, especially with the main technical supplier (Roediger). It also helped to create a collaborative and cooperative atmosphere, which was considered by the interviewees as one of the critical success factors.

3.3 Case 3: Tre-Rör-Ut in Oceanhamnen (H+), Helsingborg, Sweden

Introduction

Since 2006, the city of Helsingborg (Sweden) has developed 100 hectares of land into a modern urban area, First in the staged process of the H+ project is the Oceanhamnen district, comprising 340 apartments and 32’000m^2 of office space. Work on the H+ Master Plan started in 2007, accompanied by the vision-shaping ‘Imagine Helsingborg’ competition in 2008/09. At the same time, in 2009, the city adopted a new Energy Strategy [85] that outlined Helsingborg’s ambition to use 100% renewable energy by 2035, emphasising its strategic prioritisation within municipal planning activities. In this spirit, the ‘Imagine Helsingborg’ competition report presented the area’s lighthouse character: “*[…] to serve as a role model for the concept of ‘the sustainable city’ […]* [86].” The competition-winning proposal ‘The Tolerant City’ conceptualised how to achieve CO_2-neutrality via a circular resource-recovery (and source-separation) approach [86]. Against this background, the strategic guiding document ‘Environmental Profile H+’ from 2010 defined the high environmental goals for the H+ area [85, 87-89]. Among others, it envisaged a CO_2-neutral area served by innovative recycling technologies [87].

In 2011, the H+ management started the ‘EVAA’-project (Energi-Vatten-Avlopp-Avfall, Swedish for Energy-Water-Wastewater-Waste) to maximise sustainable synergies between the energy, water, wastewater and waste sectors [90]. A mixed group with representatives from the city and the three utilities for water & wastewater (NSVA), waste (NSR) and energy (Öresundskraft) led the work. In its first stage during 2011, EVAA generated a common objective, located potential synergies and created strategic guidance on how to contribute to the city's overall sustainability objectives [91]. In the second stage from 2012 to 2013, EVAA investigated a palette of technical options for an integrated energy, water, wastewater and solid waste system [92]. These established the conditions to start detailed planning of an integrated system and, in about two years, EVAA grew from a loose concept into a thriving entity. Initially, given Helsingborg's ambition to be energy neutral by 2035, the H+ project was energy focused and it was planned that it could provide an energy surplus by using innovative recycling infrastructure. The target was a so-called plus-energy area, which is where the ‘+’ in ‘H+’ originates. However, given the technical options available, the respective energy sub-study concluded that the resources in the area would not be sufficient to reach the envisaged target – even in the most extreme efficiency scenarios [93]. With this finding, the energy component within the overall H+ infrastructure strategy moved into the background and the energy utility Öresundskraft became increasingly less involved in the project. The city commissioned NSVA and NSR, the water, wastewater and waste utilities, to lead the planning and implementation of the innovative decentralised urban water treatment and reuse system (DUWTRS) [90]. In 2014, the most suitable system options were identified through a Multi Criteria Decision Analysis [94]. These were further analysed on and in 2015, via the ‘Blackwater & Food Waste Challenge’, with the participation of technology expert teams from around the world, the final system set-up was defined.

Today, three pipes separately collect and transport three waste streams to a local treatment plant ‘RecoLab’: one for blackwater (wastewater from toilets), one for greywater (domestic wastewater without faecal contamination) and one for food waste (via a waste grinder). The goal is to digest blackwater for biogas production, treat greywater for water reuse, and produce fertiliser. Construction started on the ‘Tre-Rör-Ut’ (Three-Pipes-Out) system in 2017 and the first residents moved in during 2020. On 16 June 2021, RecoLab officially opened [95]. To date, the vacuum and the greywater treatment systems are in full operation. Calibration and fine-tuning of the biogas and nutrient recovery components are not yet finished. However, no major performance incidents or user acceptability issues have been reported.

The project has increasingly developed into an internationally recognised lighthouse initiative. It has won several national and international awards[14] and is attracting water experts and urban planners from around the world. Discussions are taking place whether to implement a similar concept in Östra Ramlösa. Given that this is a new development area located outside Helsingborg, it is potentially cheaper to implement a DUWTRS there than to construct a connection to the centralised system. Similar projects in Sweden are already underway in Visby (without organic waste separation) and – potentially – in Stockholm (Stockholm Royal Seaport). In this brief, we examine the key drivers that have contributed to the successful implementation of Tre-Rör-Ut and the challenges. This report is structured around the five main analytical dimensions of the Lighthouse project. By examining these dimensions, we hope to gain a better understanding of the key

[14] ‘Sewage and Circularity’ prize (2018), ‘Sustainable Future’ prize (2019), ‘Smart City Implementation Award’ (2020), ‘Wastewater Project of the year’ (2022) [96, 97].

factors that have led to its success, and to identify recomendations for other cities that seek to adopt similar decentralised urban water solutions.

System-Set Up: Technology Description

Tre-Rör-Ut is a world-unique source-separation and resource-recovery system for water, wastewater and food waste [97]. Its main benefits entail energy recovery, increased nutrient recycling for agriculture, and reduced air pollution and nutrient discharges into the sea [90].

A vacuum-based sewer system transports the blackwater and food waste streams, while greywater is transported with conventional gravity-based technology. By sorting blackwater and food waste at source and using low-flush vacuum toilets and pipes, the blackwater concentration and, thus, the potential for biogas and nutrient recovery increases. Greywater separation enables efficient removal of micropollutants and water reuse.

At RecoLab, the organic kitchen waste and concentrated blackwater are treated in separate Upflow Anaerobic Sludge Blanket (UASB) reactors for anaerobic digestion [98]. In the upper part of the UASB reactor, the liquid effluent and biogas are separated. The biogas is upgraded to vehicle gas (e.g. fuel for buses) in the city's centralised wastewater treatment plant (WWTP) [99]. The UASB effluent contains most of the nitrogen and phosphorous compounds that are essential fertiliser components. Thus, the effluent is suitable for nutrient recovery. Sludge from both digesters (food waste and blackwater) is dewatered and returned to farmland as fertilizer sludge [99]. The liquid effluents are combined to recover struvite (a phosphate fertiliser) and ammonium sulphate (a nitrogen fertiliser) via struvite precipitation and ammonium stripping [100, 101]. These are mixed in specific ratios with potassium chloride and dewatered sludge from both digesters to produce pelletised NPK fertilisers. This process is enabled by existing Swedish national fertiliser certifications for sludge-based 'products' and fits in to the EU end-of-waste process[15].

Greywater is treated with a biological process and passes through nanofiltration membranes to produce very high water quality. Because recirculation still faces legal barriers, the effluent is sent to the Helsingborg sewage treatment plant. Options for reuse are currently being explored, e.g. for the municipal indoor swimming pool. In addition, a heat exchanger retracts heat from greywater to heat the digestion chambers to 35°C [3].

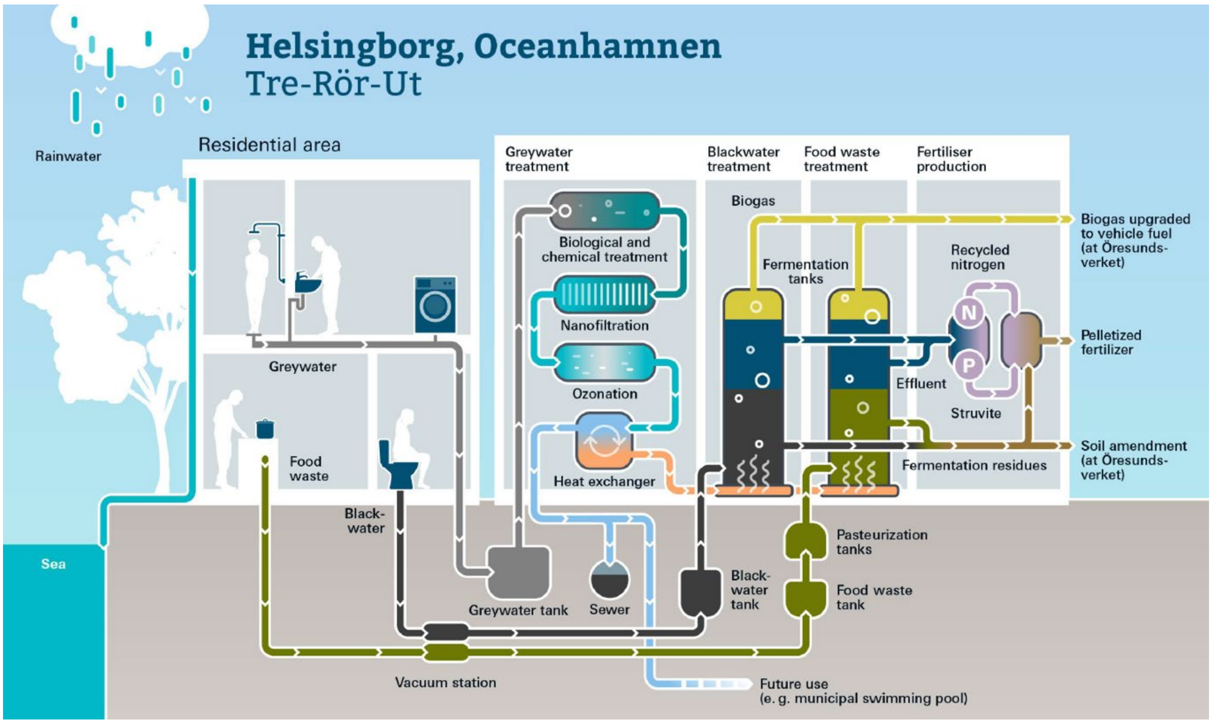


Figure 9: Schematic overview of the Tre-Rör-Ut System and RecoLab (Own illustration based on [3].

[15] End-of-waste criteria specify when waste ceases to be "waste" and takes on the status of a product (or a secondary raw material).

Institutional Framework Conditions

Legal & Regulatory Conditions

In Sweden, the legal framework does not encourage, nor prohibit implementing DUWTRS. The municipalities, which are responsible for providing water supply, sewerage and wastewater treatment [102], basically have the freedom to decide on technologies. However, resource-oriented systems (at scale) lack explicit incentivising regulations. When compared internationally, Sweden's regulative framework for wastewater treatment and resource recovery can be considered progressive. At the end of the 1990s, Sweden developed 16 national environmental quality objectives [103], several of which were linked to (food) waste and wastewater systems [104]. The Swedish Environmental Code (MB), introduced in 1999, already included the objective to create closed loops [105]. In 2006, the Swedish Environmental Protection Agency (SEPA) published new advice on interpreting the MB and made nutrient recycling a priority for on-site sanitation systems [105]. In 2008, the SEPA pushed municipalities to find new solutions for resource-recovery from (small-scale) wastewater systems and urged them to develop a strategy for dealing with different wastewater fractions [90, 105-107].

At the local level, Helsingborg responded to this advice by establishing the 'Environmental Profile H+' [87, 94], which set ambitious environmental targets for the H+ area. Among others, it stated that *"new technical solutions will be tested and introduced in the areas of energy, waste and water to maximise environmental benefits […]"* [87]. Transforming Helsingborg into a 'sustainable city' that would be an example for other cities to follow was a key guiding principle. In general, the idea of being a 'sustainable city', particularly in regard to environmental issues, became increasingly pertinent within Helsingborg's vision. Already in 1983, the aim of the city's first environmental programme was to "*strengthen the city's long-term environmental work and to work towards making Helsingborg an environmentally sustainable city*" [103]. And since 2006, the city adopts a 'Sustainable Development Plan' every year [108]. The formulated sustainability targets and environmental programme led Helsingborg to adopt an Energy Strategy and an Energy Plan in 2009 and 2010, respectively [85]. The Energy Strategy stated that the city should be energy neutral by 2035. H+ would be the one of the areas that generated 'the energy surplus' to compensate for other city districts. In general, the entire H+ framing documents and follow-up activities manifest Helsingborg's ambitions to be at the forefront of innovation and to be an inspiring example. Thus, after completing EVAA in late 2012, it was the city itself that commissioned NSVA and NSR to drive the planning of the source-separating system [90].

Contractual & Financial Arrangements

NSVA is the municipally owned water utility of eight municipalities and the city has ownership and responsibility for it [90], while the waste management company NSR is owned by six northwest Skåne municipalities [90]. Delineating responsibilities between them for (waste)water and waste has been a challenge, particularly regarding legal aspects, such as connection points, areas of operation and costs/tariffs [90].

Concerning costs, within the public spaces owned by the city, not by private real estate developers (subsequently referred to as 'developers'), taxes covered the capital expenditures (CAPEX) for installations. The building owners are responsible for all costs incurred in the private areas. Because the municipality owns NSVA, it paid for (and owns) most of Tre-Rör-Ut's infrastructure, i.e. the vacuum sewer network and treatment plants. The costs for establishing the RecoLab were mostly covered by municipal funds available for upgrading the centralised WWTP. In addition, the team acquired national and international research funds, which were used to pay CAPEX, but were not essential for the project's realisation. Concerning the total costs for 'Tre-Rör-Ut', no detailed numbers are available. However, two cost analyses were carried out in 2012 and 2017 [90, 109]. The 2017 study estimated that there would be a moderate cost increase of around 940 SEK (€ 90) per capita/year compared to a conventional centralised system (including total annual CAPEX and OPEX).

In terms of management, an operational project group with representatives from NSVA and NSR and an associated strategic steering group were established (including relevant city departments and utilities' CEOs) [90]. This organisational set-up was more or less copy-pasted from the EVAA project. It was agreed that RecoLab would be jointly operated by the City of Helsingborg, NSVA and NSR together with a number of partners. When the final system set-up was agreed upon in 2016, ownership and operational responsibilities were regulated in a new agreement [90] that established NSVA as the managing entity and is valid for five years. It also defined that the ownership of Tre-Rör-Ut remains with the City and NSR [90]. The operational responsibility for the three pipelines and the treatment plant lies with NSVA, which in turn invoices NSR and Öresundskraft for parts of the operational and maintenance costs [90]. The tariffs are set just as they are for city customers; there are no financial incentives [90].

Because the city owned the Oceanhamnen area, it was able to mandate all new developments to connect to Tre-Rör-Ut via contracts when selling the first plots in 2014.

Industry & Market Structures

According to the literature review and expert interviews, weak industry and market structures were key challenges to the project's realisation. There is no big pool of planners, technology suppliers and operators of source-separating and resource-recovery technologies to draw from. Tre-Rör-Ut was, thus, established with the expertise of small and medium enterprises distributed across (Northern) Europe.

On the supply side, the scale of the planned system and the fact that it is a residential project made finding adequate technical partners difficult. For example, most suppliers of vacuum-based technologies originate from the transport sector (airplane, train and ferry toilets). Residential areas have different requirements, for which adapted technologies need(ed) to be developed. This particularly concerned reducing the sound emissions from flushing vacuum toilets and developing novel maintenance options as the pipes are built into walls. The above-mentioned 'Blackwater & Food Waste Challenge' helped to identify business partners and technical suppliers. Given the lack of a general contractor, different technical suppliers provided specialised technological components. The technical partner for the vacuum technology is Jets. RecoLab's treatment facility was designed by DeSah, which also installed the systems for heat recovery, blackwater and food waste, and greywater and sludge treatment [96]. At RecoLab, NSVA partnered and worked with technologies from EkoBalans Fenix AB (fertiliser), Landustrie BV and DeSah (grey- and blackwater, and food waste), as well as Jotem, Primozone and NX Filtration (greywater) [3, 96].

To date, business models exist only for Tre-Rör-Ut's biogas and fertiliser production.[16] Biogas is upgraded to biomethane at the centralised WWTP [99]. It is primarily used as vehicle fuel in Sweden as it is not taxed, whereas petrol is heavily taxed [112]. Since 2005, biomethane is being produced in increasing amounts and private companies have moved into this market. Several investment support programmes have developed to facilitate this [112]. For fertiliser, it works as follows: EkoBalans delivers the 'turnkey' fertiliser production plant. NSVA operates the plant and produces ammonium sulphate and struvite that is then sold to EkoBalans, which sells it to farmers / private customers. The product can be tailored to fit the needs of both domestic garden and agricultural applications. In addition, the recently introduced EU Fertiliser Regulation from 2019 (2019/1009) has opened new marketing opportunities [113]. It allows for CE marking of manure products and selling struvite (a phosphate fertiliser) across the EU since July 2022.

To date, the demand for the products generated at H+ remains limited. Both the fertilisers (at least before the current war in Ukraine) and treated greywater cannot compete with the low (and subsidised) prices of mineral fertiliser and drinking water. In addition, greywater reuse faces legislative barriers, although options for reuse are being explored – e.g. for the municipal indoor swimming pool.

Knowledge, Skills & Capacity

The knowledge on how to plan, build, connect, operate and maintain Tre-Rör-Ut and RecoLab was developed in a learning-by-doing way during the project. While the listed activities suggest strategic capacity development, at times they were developed in an ad-hoc manner.

Basic knowledge, skills and capacities were established from 2011 to 2016 through technical feasibility studies, an innovation competition (Blackwater & Foodwaste Challenge), and excursions (incl. developers) to similar projects in Europe. These were key in establishing technical know-how and trust among the utilities, the city (planners) and developers and moving the project from a conceptual to a detailed planning stage.

To enable knowledge transfer, the city and NSVA organised regular (voluntary) meetings for developers and builders, respectively, and brought in external experts to share experiences. Yet, the information did not trickle down to those responsible for construction. Therefore, together with the developers, design guidelines that included norms and standard procedures were established [114]. Also, the Tre-Rör-Ut team regularly reviewed the detailed installation plans. Moreover,

[16]Initially, the Swedish national sludge certification system incentivised the production of fertiliser from sludge [94]. Sludge-based fertiliser certificates are available for biogas digestate (SPCR 120, launched in 1999), hygienised sludge from large-scale WWTP (SPCR 167, "REVAQ", established 2008) and from onsite/small-scale WWTP (SPCR 178, established 2012). Whether sludge is safe enough for agricultural application remains a controversial topic [110, 111].

together with Jets, they offered trainings for maintenance companies; these also served as a key feedback mechanism for the identification of technical issues.

When the residents moved-in, they received an information brochure on how to operate the kitchen grinder and vacuum toilets (see below) [115]. Since then, to consolidate and expand understanding of operational issues, the Tre-Rör-Ut project team regularly organises bi-monthly meetings. To improve technical understanding of the vacuum system (e.g. pipe incrustations), NSVA began a monitoring project together with Jets in summer 2022. In addition, NSVA participated in national exchanges on circular systems, co-published a Swedish guidebook for planning source-separating UWM systems in urban areas [116] and provided inputs to installation guidelines on vacuum installations in buildings [114, 117]. Given its importance, the project team intends to keep these training and information campaigns running in upcoming H+ development stages.

Recognition & Legitimacy

Resource-recovery and source-separating sanitation systems have received increased recognition by national policy makers in Sweden. However, many of the implemented small-scale systems generated mixed results on user-acceptability [105]. In view of this and to develop a user-friendly system for H+, in 2014, a transdisciplinary workshop was organised by NSVA and NSR [94]. In the workshop, participants identified the main requirements, success factors and pitfalls of source-separating systems. The results helped the stakeholders to identify issues and to address them.

In parallel, during the conceptualisation and planning stages, the project team organised several excursions to similar projects in Germany (Jenfelder Au) and the Netherlands (Sneek). These had a vital trust- and team-building effect and created a shared understanding and vision among project team members, utilities, and developers. Interviewees reported that the hands-on experience of flushing a vacuum toilet and the opportunity to exchange with actual users was invaluable to establish trust in the envisioned technical solutions.

To foster awareness and acceptability among end users, the project team organised meetings for future residents and distributed information sheets. After moving-in, unexpected user behaviour by the residents caused technical malfunctions (clogging). Apart from an information brochure [115], there was only one person responsible to instruct new residents on how (not) to use the vacuum toilets and kitchen grinders. This proved insufficient and required additional investments in active user support. Nonetheless, no major acceptability issues among end users were reported.

Key Interventions & Lessons Learnt

Although specific technical components still need adaptation, the absence of major incidents and successful operation qualifies Tre-Rör-Ut and RecoLab as a lighthouse case for neighbourhood-scale DUWTRS. The interplay of several favourable conditions and constructive interventions were key for turning the project into today’s success story. Five key coordination mechanisms stand out.

First, consistent political support and the buy-in and strong lead of local utilities were key for realising Tre-Rör-Ut. Helsingborg’s established a long-term vision that included concrete and ambitious targets to be a spearheading, innovative city. Its goal was to be energy neutral by 2035, and the project's energy efficiency and environmental co-benefits, helped to convince decision-makers to choose this environmentally friendly option rather than the cheapest / conventional one. Furthermore, it resonated with SEPA’s national call for municipalities to find innovative wastewater solutions that enable nutrient recycling in agriculture [90, 94, 107]. A supporting factor was that the site was a largely undeveloped former harbour area. Residential infrastructure was planned for this area already. The city as the land owner could mandate Tre-Rör-Ut to all developers and future owners. Individuals in key positions were present and exercised strong leadership across all project phases, which guaranteed continuity. These included in particular the mayor of Helsingborg, the H+ project manager, as well as the CEO’s of NSVA and NSR. Their positive attitudes, openness to experimentation and change and personal commitment resulted in a high degree of project-identification among the involved stakeholders.

A second key success factor was the strong vision developed in Helsingborg. This pushed the three utilities and the public and private actors to define a holistic sustainability solution that strongly deviated from the status quo. The project team strategically addressed planners, developers, builders, residents and farmers when developing the project and made them engage in networking and joint problem solving activities. Technical feasibility studies, excursions to similar projects in other European countries and an innovation competition played a key role in enabling this alignment. These generated a shared understanding among the city (planners), the utilities and developers, played a key role in establishing trust and technical know-how and made different actors increasingly converge around a shared vision.

Third, and closely related, a collaborative and cooperative culture among utilities, city leaders and the private sector emerged. The city hired a dedicated H+ project manager and requested that the utilities and the administrative city departments provide human resources and support. This was key for project coordination and enabled meaningful interdepartmental and transdisciplinary exchanges.

Fourth, continuous and structured outreach to the system's users was critically important. The user-friendliness and demonstrations of Tre-Rör-Ut's sustainability and socio-economic benefits were emphasised early and continuously [94, 118]. RecoLab also worked to legitimise the project by developing a test facility for research and development, a visitor centre and meeting areas. In effect, there was never any opposition during planning and implementation.

Fifth and finally, knowledge transfer between the project management, technology suppliers and builders was strategically fostered during the construction stage. This included meetings with developers and builders, and with external technical experts, making participatorily developed technical guidelines, offering assistance in reviewing the detailed construction plans, as well as trainings with Jets for construction and maintenance companies. Users received instructions on how (not) to use the vacuum toilets and kitchen grinders. Taken together, these interventions were of key importance to make the final system work and created a common technical and applied understanding among all involved parties.

3.4 Case 4: Small-Scale Water Reuse Systems in Bengaluru, India

Introduction

Bengaluru is a major economic hub in south India that is experiencing rapid population growth. As in many megacities, growth outpaces infrastructure expansion and neither piped water nor sewerage networks serve the entire city. The water supply system relies on the long-distance transfer of water from the Cauvery River, and largely unregulated private bore wells that tap into groundwater resources as do tanker trucks delivering water. This has resulted in severe water stress and price hikes during drought periods. Moreover, a significant portion of the population disposes wastewater directly into stormwater drains that feed into local rivers and lakes. Coupled with poorly performing large-scale wastewater treatment plants, this has led to widespread environmental pollution and health risks.

Until the late 1990s, urban water management largely followed the conventional template of a state-led expansion of *centralised* pipe-networks. Yet, given the city's explosive growth, the relative share of households served by centralised water and sanitation infrastructure has been constantly shrinking. Over the last two decades, in an attempt to address issues of environmental pollution and water security, Bengaluru has adopted ambitious policies promoting *on-site* wastewater treatment and reuse systems (ONWS), in addition to expanding the centralised pipe networks [119].

In 2004, local authorities started mandating the installation of *small-scale sewage treatment plants* (SSTPs) in all new apartment buildings larger than 20 apartments or 2000 m^2 [120]. This mandate reflected a monumental shift in the underlying logic of urban water management in Bengaluru. Instead of a public utility, private firms and resident welfare associations (RWAs) became responsible for building, operating, and maintaining SSTPs and ensuring adequate treatment quality. This was followed by mandates to reuse treated water for non-potable onsite purposes, such as gardening and toilet flushing, and later for off-site reuse, e.g. in the construction industry. In India, RWAs are the entities responsible for managing residential apartment complexes on behalf of their members, who are the homeowners.

To date, estimates suggest that more than 2500 SSTPs have been installed in the city [121]. The mandate has induced a quickly growing market for ONWS, with many new and established wastewater treatment firms entering the field. This fast and uncontrolled market growth did not, however, come without challenges. Many installations have been made by firms without proper technological expertise, sometimes with the blessing of cost-cutting builders and plumbing consultants. In addition, once construction is finalised, RWAs are typically responsible for operating the plants. Yet, even well-designed systems require expert knowledge and skills for proper operation and maintenance (O&M), which is often lacking. There is also a lack of monitoring and enforcement activities by the local authorities. As a result, it is estimated that up to 80% of the systems perform poorly [121].

Over time, firms started experimenting with new technologies and business models, and they developed new skills and capabilities related to ONWS design, implementation and operation. In parallel, policymakers introduced new regulations and mandates, and local NGOs and research institutes started to engage in broader system building activities. This included targeting the lack of quality labelling and technology standardisation in the ONWS market. The importance of proper SSTP installation and O&M is increasingly emphasised by local authorities.

Despite these challenges, Bengaluru spearheaded the implementation of a city-wide mandate aiming for 100% reuse of wastewater treated on-site. Approximately 20% of the city's wastewater is now treated in SSTPs, which is globally unique. Bengaluru has developed into a potential lighthouse initiative that could serve as a template for developing an ONWS program in other rapidly urbanising areas in middle-income countries – if certain problems with the current technologies, business models and governance arrangements are resolved. In this brief, we will examine the key drivers that have contributed to the successful implementation of ONWS in Bengaluru and challenges. This discussion will be structured around the five key analytical dimensions of the Lighthouse project. By examining these dimensions, we hope to gain a better understanding of the key factors that have led to the success, and to identify recomendations for other cities that seek to adopt similar decentralised urban water solutions.

System Set-Up: Technology Description

The typical ONWS in Bengaluru is based on an on-site treatment plant (SSTP) set up on the premises of a single apartment complex, consisting of 20 to 1000 apartment units. Most complexes are not connected to the central sewerage network, or to the piped municipal water supply. Instead they rely on bore wells and/or tanker water supplies. Most SSTPs installed in the city use conventional aerobic treatment technologies. Vendors also offer anaerobic treatment plants, emphasising such benefits as low energy use and maintenance costs, or hybrid variants combining aerobic and anaerobic processes.

For safe non-potable water reuse, SSTPs are (increasingly) complemented with tertiary treatment. This typically includes such processes as microfiltration (MF), ultrafiltration (UF), ultraviolet light (UV) disinfection, ozone disinfection, and/or chlorination. In many apartment complexes, however, the wastewater treated in the SSTP is used directly for gardening, car washing and toilet flushing without tertiary treatment apart from water softener and chlorination. In rare cases, the water is additionally treated in a central reverse osmosis (RO) system. Most individual apartments are also equipped with point-of-use RO appliances, e.g. at the kitchen tap. These are used for drinking water and cooking purposes.

For toilet flushing, apartment buildings are equipped with dual plumbing, i.e. with a separate pipe supplying treated wastewater to the toilets. After the flush, the water is brought back to the treatment plant in the ordinary sewerage pipe. For other reuse purposes, such as gardening, car washing and off-site reuse, water is typically accessed directly from the treatment plant.

To date, no 'turnkey' ONWS solutions exist on the market. Treatment technology choices are shaped by the quality standards introduced by state authorities [120], which call for a consistent treatment quality regardless of wastewater source and reuse purpose [122]. Most technologies on the market can meet these standards if operated properly. Only a few standards or guidelines are available to assist builders in selecting a technology that suits the particularities of the apartment complex, different water sources or the reuse purpose. Technology selection is often made at the whim of sometimes inexperienced, technology consultants and vendors. This has led to the installation of systems that are difficult and costly to operate and prone to malfunction.

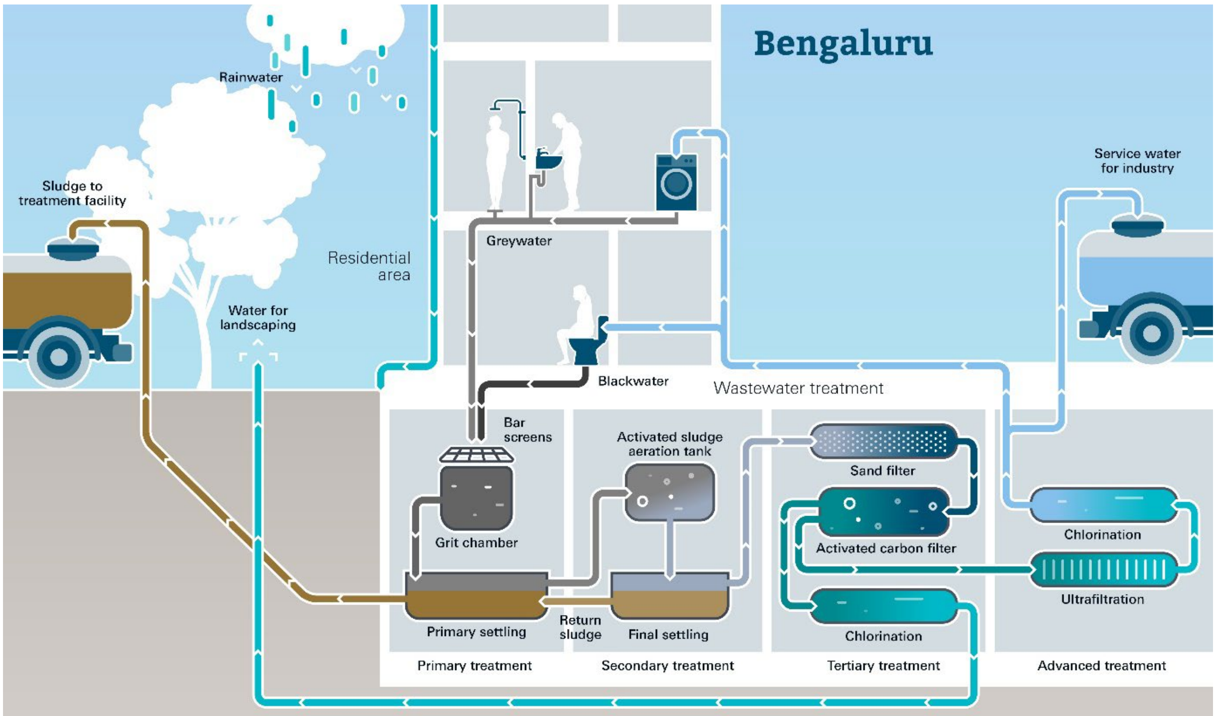


Figure 10: Exemplary schematic overview of a typical ONWS in Bengaluru.

Institutional Framework Conditions

Legal & Regulatory Conditions

In India, government actors at the national, state, and city levels are responsible for urban water management. At the national level, the Ministry of Housing and Urban Affairs (MoHUA) and the Ministry of Environment, Forests and Climate Change (MoEFFC) are the ones primarily shaping developments in water management [119]. At the State level, State Pollution Control Boards are responsible for implementing pollution legislation. In Bengaluru, the Karnataka State Pollution Control Board (KSPCB) has the authority to set effluent standards and is responsible for monitoring the performance of all wastewater-discharging entities [120].

A series of government mandates, targeting environmental pollution and water security issues, have been developed to facilitate on-site wastewater treatment and reuse in Bengaluru. The first mandates targeted environmental issues resulting from the release of untreated wastewater into Bengaluru's lakes and streams. In 2004, the KSPCB mandated the installation of SSTPs in new residential buildings (larger than 20 apartments or 2000m^2) and commercial establishments (larger than 2000m^2) [120]. In parallel, KSPCB also established a permitting process that developers and construction companies must adhere to. This included a Consent for Establishment (CFE) based on a review of the SSTP design proposed by the builder, and a Consent For Operation (CFO) based on an on-site review of the constructed plant by KSPCB officials. In response to public complaints about lake pollution, in 2014 the KSPCB announced a Zero Liquid Discharge (ZLD) requirement [123]. This meant that no wastewater (untreated or treated) can be discharged into storm drains, lakes and rivers. This mandate primarily targeted environmental pollution issues, but also complemented previous calls about not using potable water for non-potable uses, such as landscaping or construction [124]. It created strong incentives for on-site reuse, as this became the only legal way to dispose of treated wastewater. This was followed by an explicit mandate in 2016 to reuse treated wastewater in all larger residential, commercial and educational buildings, as well as in construction projects [125], and to retrofit existing buildings over a certain size with an SSTP.

To date, the regulatory framework specifies: 1) when an SSTP should be installed in new and existing buildings, 2) quality standards of the treated wastewater, 3) that no treated wastewater can be discharged in storm drains and local water bodies, and 4) that treated wastewater should be used for non-potable purposes i.e. toilet flushing, gardening, car washing and construction. It also specifies a permitting pathway for ONWS managed by the KSPCB. In addition, state authorities have mandated the installation of sensors to measure the quality of the treatment process. This complements the manual sampling and monitoring procedures currently in place; the owners of plants (e.g. RWAs) are supposed to take grab samples of the effluent and send them to third-party labs. However, this is often not done [121], and it remains to be seen if such sensors will actually be installed.

Beyond these rather general mandates, the regulatory framework does not specify in much detail how to fulfil the water quality requirements. For example, there is no guidance on selecting approved technologies or defining actor responsibilities beyond those of RWAs and real estate developers. The design and implementation of reuse systems has largely been left to the private sector and residents; the regulators provide very limited guidance, oversight and/or enforcement. The regulatory environment, especially for water reuse, is characterised by widespread non-compliance and enforcement deficits.

Contractual & Financial Arrangements

Most SSTPs in Bengaluru are privately constructed, owned and operated with minimal public sector involvement. The SSTP and reuse mandates, thus, essentially shift the financial burden for sanitation from public service providers to residents. No financial support (e.g. tax reliefs or subsidies) is provided by the government to builders or residents. The building owners are responsible for the capital expenditures for the installation (CAPEX) and the costs of O&M (OPEX) of ONWS.

In the early phase after the 2004 mandate, homebuyers generally lacked awareness of the importance of well-designed SSTPs. Builders tried to minimise CAPEX, which led to low quality components being used and mediocre system designs. This increased the OPEX for the RWAs, which usually have the responsibility for operating the plants. This tempted the RWAs to cut OPEX, e.g. by hiring low-cost (and low-quality) operator firms or turning aeration pumps off during the night, thus, risking the operational quality of the plants [126]. As a general rule, RWAs with a high water demand have more incentives to invest in proper O&M of their ONWS and proper tertiary treatment to fully reap the potential of reusing water instead of relying on tanker supplies.

There are only a few funding sources that support innovation activities among smaller local ONWS suppliers, hampering innovation in the sector. In recent years, firms experimenting with alternative treatment technologies have started to apply for funding from the start-up field, technology incubators and smart city funds. For example, a "property technology" incubator initiated by a major real estate developer funded innovation activities among SSTP start-ups. Some industrial actors have also started to direct funds earmarked for corporate social responsibility or carbon offsetting to investments in SSTPs. And because the business models of firms focusing on high-quality water reuse often include promises of rather quick returns on investments, this may give them access to the vast ecosystem of venture capital and private investors in Bengaluru and beyond in the future.

Industry and Market Structures

One key feature of the Bengaluru case is the speed at which the initial mandates led to the emergence of a mass-market for SSTPs. The exploding market induced an industry capable of designing and constructing a variety of systems. In many respects, market-driven implementation was, however, 'running ahead' of local capability formation, standardisation and market governance, thus, leading to quality issues along the value chain.

Acting upon the sudden demand for SSTPs coming from real estate developers, a wide range of predominantly local firms began providing services, such as consulting, design, technology delivery, and O&M. While some had solid expertise in large-scale treatment plants and SSTPs, many had been plumbing consultants or came from unrelated fields. Reportedly, market entry was easy and based on personal relationships and price-based competition, rather than on technologies or product quality. Over time, the challenges of this laissez-faire, market-driven approach became increasingly visible. A lack of standards, labels, certificates, etc., made it hard for buyers to make informed decisions about the quality of ONWS products and services. The 2016 mandate asking for zero liquid discharge proved a critical pivot point in increasing the awareness of O&M issues among home buyers and residents, as treated wastewater now had to be reused within their apartment complexes (for gardening) and inside their apartments (for toilet flushing). Firms, thus, started offering products and services that: 1) addressed malfunctioning SSTPs, 2) made the relationship between CAPEX and OPEX explicit, and 3) emphasized the benefits of substituting expensive tanker water with a more reliable (and cheaper) local water source.

Some market segments have, therefore, experienced a recent shift from price- to quality-based competition, incentivising innovation among technology- and service providers. Firms started to offer new business models, i.e. rehabilitating malfunctioning ONWS and operating them over a set period of time for a fee. Some of the most innovative business models are found among firms seeking to harness the potential value of treated wastewater. These companies offer 'turnkey' tertiary treatment modules as an add-on to existing SSTPs. They then sell the treated water back to on-site or off-site customers at a price lower than the average cost of tanker water, but high enough to achieve decent returns on investment. Firms with a 'platform' business model also started to match the supply of wastewater from the plants they operate with demand for treated wastewater in local industries, particularly the construction sector.

Knowledge, Skills & Capacities

The rapid growth of the ONWS market and the high number of newly implemented SSTPs also outpaced knowledge and capacity development. Consequently, the first decade after the 2004 mandate was characterised by learning-by-doing and catching up processes. These included efforts to develop the technical capabilities of local ONWS suppliers along the full value chain, particularly among real-estate developers and RWAs.

Today, 'best practice' ONWS examples are usually supplied by firms with strong technological capabilities gained through experience in the SSTP field. These are often based on the extensive learning done by individuals at the RWA level who use the internet and exchange with people at other RWAs to learn about various ONWS technologies. However, the complexity and 'tacitness' of O&M has prevented the formalisation of knowledge and knowledge transfer from technology vendors to RWAs. Developing standardised manuals or instructions is challenging given the vast variation in SSTP designs and technologies.

Efforts are currently underway to more strategically build-up knowledge, skills and capacities around ONWS. At the public administrative level, the KSPCB began training SSTP operators in 2019 with the help of the Environment Management Policy & Research Institute. Engaged RWAs are using the Bangalore Apartment Federation (BAF) and local research institutes as platforms for knowledge exchange. For example, RWAs organise tours of best-practice apartment complexes through the BAF.

At the level of ONWS suppliers, the basic knowledge of treatment processes has increased in all but the lowest market segment. There are now a number of firms profiling themselves as aware of the problems in the ONWS field and as competent to solve them. There are also companies fostering innovation to minimise the O&M skills required for operators. This includes the introduction of standardised designs and modular plants. Recently, some operators have started to provide technology-specific training for their staff, established trainee systems and built up technological expertise by rotating personnel between different plants. The slowly increasing competence of certain operators has substantially reduced the pressure on RWAs to internalise the knowledge required to successfully operate their ONWS.

Recognition & Legitimacy

The legitimacy of ONWS has developed in several ways over the past decade. Real estate developers and RWAs initially did not support the mandates, as these burdened them with additional responsibilities, e.g. installing and managing wastewater treatment facilities. However, the determination of local governments to introduce the mandates meant that decentralised SSTPs quickly spread and became a taken-for-granted feature in mid- and upper-tier apartment complexes. High-profile pollution problems in the local lakes, the SSTP mandates' alignment with national policies, and the local framing of SSTPs as a solution to environmental problems supported legitimation processes. Only in 2016, when a revision required existing apartment buildings to be retrofitted with SSTPs and dual plumbing, did organised opposition pop up. Due to public protests, this mandate was relaxed in terms of the size of buildings included in the retrofitting requirement.

When the government's focus shifted from wastewater treatment to onsite wastewater reuse around 2016, additional legitimacy challenges emerged. In addition to the universal 'yuck factor' connected to recycled wastewater, many residents did not trust the treatment quality of their SSTPs due to recurring problems with the odour and colour of the treated water used for toilet flushing. Using treated wastewater, therefore, still has legitimacy and acceptability issues, even for basic reuse applications, such as gardening and toilet flushing [127]. Nevertheless, there has been no substantial pushback from the public when it comes to the reuse mandate. Similar to the SSTP mandate, water reuse is increasingly becoming taken-for-granted and even an aspirational solution for some RWAs that depend on unreliable and expensive tanker water supplies.

Important sources of legitimacy are water self-sufficiency and additional income streams. Reusing as much water on the premises and within the building (even up to potable uses in some visionary RWAs) can make buildings 'water independent'. Also, economic arguments are increasingly at play due to increasing tanker water supply costs from higher fuel costs, which increases the price of freshwater, particularly during droughts. Selling excess treated wastewater to local construction sites, laundries or parks (which have all become increasingly relevant) can provide additional income streams to cross-subsidise some of the OPEX.

Key Interventions & Lessons Learnt

Despite the prevailing challenges, the globally unique scale of diffusion and legitimacy of ONWS as an alternative to centralised water and sanitation systems qualifies Bengaluru as a lighthouse case for ONWS implementation. Four key features stand out as enablers of the diffusion and legitimation of ONWS achieved so far in this city.

First, the 'top-down', policy-induced and largely technology-neutral approach used by regional and local regulators has proven very effective in establishing a large market and supplier structure for ONWS and positioning it as a promising solution to the city's pressing sanitation and water scarcity problems. In contrast to other Indian cities, the national push for (onsite) water reuse has been transposed very consistently and consequentially into local mandates and regulations. This long-term policy programme has de facto established a new infrastructure paradigm in the city that is now legitimised beyond early adopters.

Second, the local mandates have induced a unique local entrepreneurial ecosystem around ONWS, with firms capable of designing and constructing a variety of systems. The average technological capabilities have increased substantially among SSTP providers and O&M firms since the first mandate two decades ago. This technological and industrial variety could be a powerful breeding ground for radical innovation. Innovative firms are increasingly experimenting with globally unique business models and advanced ONWS technology suitable for local contexts. Specifically, business models based on selling treated wastewater to off-site customers with specialised demands, such as laundries, public parks or construction sites, have great potential. Emerging connections to the IT start-up and venture capital scene in Bengaluru, as well as the strong involvement of returnee entrepreneurs, could further leverage innovation activities in the field.

Third, Bengaluru’s market-based (and laissez-faire) implementation logic has stimulated considerable demand-side dynamics and the emergence of innovative ‘lead users’. RWAs with highly visionary and engaged board members, real estate developers with sustainability profiles, and industrial actors with high water needs, have especially taken on the role of lead-users. RWAs are demanding better ONWS technologies and ‘turnkey’ solutions, affordable and efficient O&M services, and business models around water reuse that create economic benefits. This emerging demand has already started to trigger innovation dynamics in the field of on-site and off-site water reuse. Examples include ‘rehabilitate-operate-sell’ business models that sell treated wastewater in booming off-site markets (construction, public parks or laundries). Another example are RWAs that opt for achieving (almost) potable water quality in their ONWS systems.

Finally, despite some contestation over the years it is striking how end-users and other key stakeholders increasingly take ONWS for granted. Albeit often considered a nuisance among RWAs, most accept the current provisions and many do their best to try to exploit the potential of wastewater reuse and fulfil the mandates. Also, at the government level, ONWS are increasingly discussed as a potential solution to local water problems, despite the centralising of infrastructure that results.

Despite the (still fragile) successes outlined above, many challenges remain in Bengaluru. Its transition to ONWS cannot yet be declared a template for other cities. The public authorities grossly underestimated the need to provide measures accompanying the mandates. These include the lack of (adjusted) governance structures and complementary regulations, standards and labels, as well as market governance mechanisms that ensure accountability along the service chain. The regulatory environment, especially for water reuse, is still patchy and many ONWS do not yet meet required effluent standards. Finally, concerns about the health and safety of low-paid workers operating SSTPs or handling treated wastewater, such as gardeners and construction workers, have also been raised by advocacy groups and experts.

3.5 Case 5: Water Reuse in Nirvana Country, Gurugram, India

Introduction

Nirvana Country Township is part of a rapidly expanding urban development in Sector 50 of Gurugram[17], located 30km south-west of New Delhi, in Haryana State, India. New Delhi today has 32 million inhabitants and is India's most populous metropolitan area. In India, progressive water reuse legislation is increasing. The most important reasons for this are the combined effects of droughts, heat waves and sinking groundwater tables, which have led to growing water stress and over-extraction of groundwater resources. As a case in point, the average groundwater level in Gurugram has dropped from 6.6 metres in 1974 to under 22 metres in 2014 [128]. The State of Haryana has, therefore, introduced major policy changes that promote decentralised urban wastewater treatment and reuse systems (DUWTRS) for non-potable uses. In 2018, a new Haryana state policy mandated that new developments withdrawing more than 50m^3 of groundwater per day had to install on-site sewage treatment plants (STPs) and reuse the treated effluent for non-potable uses.

The Nirvana residential area was built in two phases – the first phase in 2006 to 2009 and the second phase between 2016 and 2019. Until 2016, the high-end real estate development consisted of five residential societies (named A, B, C, D, and E). To date, it has increased to eight, which all have their own Resident's Welfare Association (RWA). The latest additions were the Fresco and The Close South (TCS) residential areas, built in 2016 and 2019, respectively. Today, the Nirvana Country development serves 4000 units in eight residential societies with a population of almost 12'000 residents. Unlike other residential colonies, Nirvana houses an expansive amount of greenery. With the increase in green spaces, the water demand for horticultural purposes grew. Until 2017, the residential areas A, B, C, D and E met their non-potable water demand through water tankers.

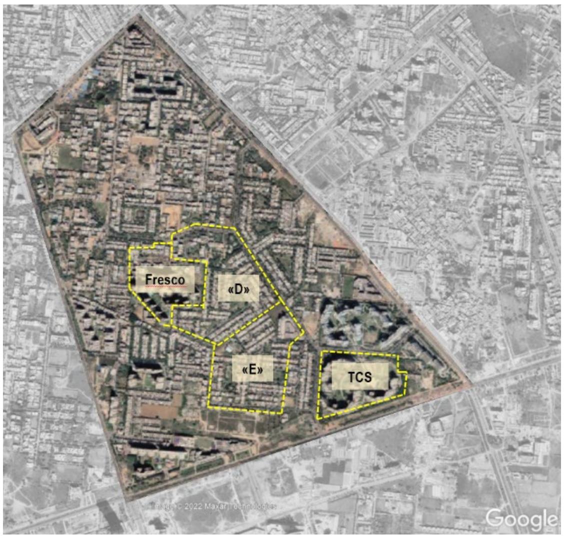


Figure 11: Sector 50 in Gurugram, which is in the Nirvana Country residential colony.

In 2017, Fresco constructed an on-site STP because public authorities denied its request to connect to the centralised sewer system. With the commissioning of the STP, Fresco reused around 20% of the treated water for irrigation, whereas tanker trucks illegally disposed of the treated excess water at night. Meanwhile, residents from A, B, C, D and E started voicing their discomfort at the high tariffs for procuring water tankers for fresh water for urban gardening. The costs of getting fresh water from sources across India had been increasing due to higher fuel costs. They began exploring alternative options and, consequently, their RWAs decided to use Fresco's treated excess water for irrigation and signed a Memorandum of Understanding (MoU) in late 2018. Since early 2019, a small pipeline for treated effluent connects Fresco with the neighbouring residential areas. Through this synergistic move, Fresco could avoid any further legal issues caused by the dumping of their excess treated wastewater and the neighbouring residential societies could meet their irrigation water demands.

However, due to the poor quality of such parameters as BOD, TSS, COD, odour and colour, which exceeded twice the permissible limits, as well as the low-pressure of the delivered treated wastewater, in April 2020, the RWAs of settlements D and E again jointly explored alternative water sources. They found a new partner in TCS. Built in 2019, TCS was subjected to the newly introduced state policy and, thus, had a more modern on-site STP producing treated excess water. D and E were able to negotiate a new MoU, this time with TCS. Since January 2021, a new water pipeline connects the treated effluent of the TCS high-rise development to the neighbouring D and E estates in Nirvana. Today, the treated effluent is used for urban greening without any complaints or quality issues. Effluent water quality testing is done every six months.

Nirvana Country Township is an example of a successful bottom-up initiative of an eco-conscious RWA interested in reusing treated wastewater for urban greening. The MoU and the installed 'mini-grid' for water transport could be a promising template for high-density settlements. The successfully established micro-water market qualifies the Nirvana case as a

[17] Formerly known as Gurgaon.

lighthouse example for DUWTRS at neighbourhood scale. In this brief, we examine the key drivers that have contributed to the successful implementation of the pipeline in Nirvana Country and the challenges. This report is structured around the five main analytical dimensions of the Lighthouse project. By examining these dimensions, we hope to gain a better understanding of the key factors that have led to its success, and to identify recomendations for other cities that seek to adopt similar decentralised urban water solutions.

System Set-Up and Technology Description

Constructed in 2019, the TCS apartment complex was equipped with cistern flush toilets, which are common in new Indian high-end developments. The wastewater is transported with conventional gravity-based technology to the small-scale treatment plant situated in the basement of each high-rise apartment complex.

The treatment plant is equipped with a state-of-the-art on-site Moving Bed Biofilm Reactor (MBBR) wastewater treatment process. The MBBR technology has only a small spatial footprint in comparison to other biological treatment processes. If operated and maintained adequately, it ensures reliable and high quality treatment. Currently, between 300'000 to 400'000 litres of effluent is treated at TCS per day. According to our interviewees, the Haryana State Pollution Control Board (HSPBC) conducts half-yearly quality controls of the effluent. Since its commissioning, TCS's treatment plant meets its internal targets, as well as the water standards prescribed by the Government of Haryana.

Learning from the poor implementation of the PVC piping network installed for the Fresco project, E and D decided to install HDPE pipes to transport treated water for reuse. HDPE pipes are more durable, leak free, and can handle higher water pressure. However, they are more costly and require trained personnel for installation and energy intensive installation equipment. The agreed limit of treated water received at D and E is 100,000 l/d. This was calculated based on previous peak water consumption data (Fresco) of 70,000 l/d and a 30,000 l/d safety margin.

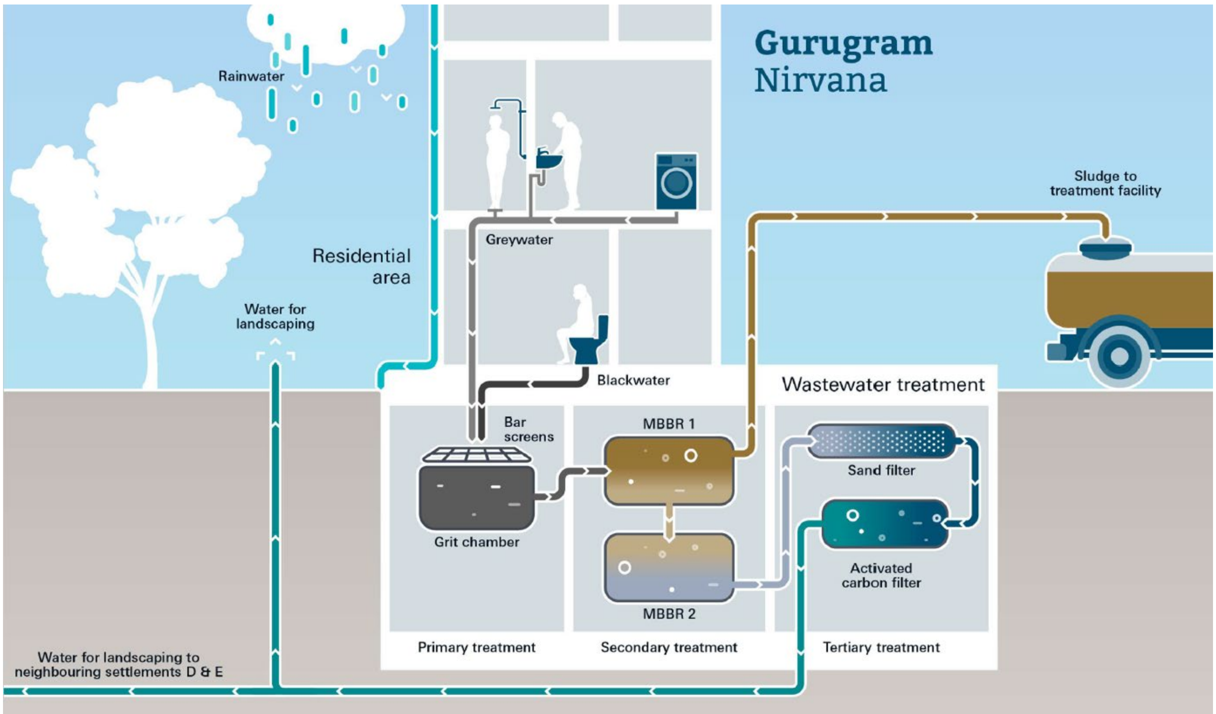


Figure 12: Schematic overview of the wastewater treatment and reuse process of The Close South high-rise settlement.

Institutional Framework Conditions

Legal & Regulatory Conditions

In India, water governance and management has received steady recognition at the national level since 1974. Regulatory agencies and both national and state governments have to abide by the Water Act. Urban wastewater management is mainly driven by the Ministry of Housing and Urban Affairs (MoHUA), the Ministry of Environment, Forest and Climate

Change (MoEFCC) and their line agencies [25]. Regulatory agencies ('Pollution Control Boards') are responsible for monitoring water quality by monitoring groundwater, surface water and wastewater. While 'reuse or recycle' were mentioned for the first time in a government policy in 1992[18], the *National Environment Policy* developed in 2006 (8) emphasised recycling sewage and used water. The *National Urban Sanitation Policy* 2008 (7) soon followed and recommended water recycling and reuse. Subsequently, the *National Water Policy* 2012 (6) focussed on reducing water pollution, while embracing the imperatives of recycling and reuse. While the vision is set by the national departments, the responsibility for policies and regulations lie with the State Governments.

In Haryana, the key policy document regarding the reuse of treated wastewater, the *Draft Policy on Reuse of Wastewater* [129], was published in 2018 ("2018 Mandate") and ratified in 2019 [130]. It provided ambitious goals for the reuse of treated wastewater for non-potable use in residential, commercial and industrial contexts. By 2025, the goals aim at: (i) achieving a minimum sewer connection coverage of 80% in all of Haryana's towns and cities (ii) attaining 100% treatment of wastewater arriving at treatment facilities, and (iii) increasing reuse of treated wastewater from 25% to 50% (and from 50% to 80% by 2030). The minimum percentage of wastewater reuse for all towns and cities is stipulated at 25% and includes domestic indoor and outdoor uses of non-potable water. These include urban greening/irrigation, water for extinguishing fires, toilet flushing and other non-potable uses defined by municipalities. In late 2018, the Gurugram Metro Development Authority (GMDA) issued notices to all residential societies and developers to install on-site STPs and gradually increase the amount of water reuse by 2030. All new real estate developments built after 2018, therefore, feature state-of-the-art STPs, most of which are MBBRs or SBRs (Sequencing Batch Reactors).

The 2018 Mandate introduced 'No Objection Certificates' (NOC) for developers installing non-potable water systems. A NOC is an essential legal document, in this case issued by the GMDA, stating no objection to the covenants mentioned in the certificate. In other words, it makes the pipeline structure a legal construction as attested by the GMDA. In addition, the (previously existing) 'Occupancy Certificate' (OC) confirmed that a building adheres to national building codes and is suitable for occupancy. Theoretically, in case of non-compliance of water quality standards after spot checks, based on how much the quality varies from the prescribed standards, the officials can charge a fine (up to Rs.50,000 / US$ 625), which may be extended up to Rs.2,00,000 / US$ 2500). In cases of repeated non-compliance, the NOC of the plant and the OC of the residential site can be annulled. However, in reality, control and enforcement are unreliable and insufficient. For example, as mentioned above, the SPCBs are responsible for monitoring wastewater quality in all Indian States. Interviewees reported that the Haryana SPCB (HSPCB) is understaffed and struggling to keep pace with the growing number of DUWTRS in urban areas. A main reason is that the 2018 Mandate has allocated additional tasks to HSPCB, without providing it with additional funds. Thus, regulators had to work on more STP sites with the same resources. In addition, as interviewees report, the HSPCB is insufficiently and unreliably enforcing corrective measures in regards to non-compliance to water quality standards. However, reportedly, within Nirvana's residential societies D and E, water quality reports are shared with the operators and residents every six months to maintain transparency of the system performance for the received treated water.

Contractual & Financial Arrangements

In Haryana, the 2018 Mandate shifted the financial burden for sanitation from public service providers to residents. No financial support (e.g. tax reliefs or subsidies) is provided by the government to builders or residents. Building owners and residents are responsible for both capital expenditures for the installation (CAPEX) and operational expenditures (OPEX) for DUWTRS. In addition, while it is mandated to reuse water, treated wastewater cannot yet be sold for a price. Therefore, transferring excess treated wastewater to local users does not generate an income for the society or offset any costs. Consequently, the 2018 Mandate was not well received by developers and property owners. However, with implemented prices to be set in the foreseeable future, (see next section), new financing (and business) models will likely emerge. This, in turn, should increase DUWTRS legitimacy among developers and building owners, respectively.

In India, private real estate companies or developers plan and construct new townships and residential developments, which are then sold on the market. The Indian Real Estate Act (2016) states that these developers are responsible for providing and maintaining the essential services of a building/residential development until a formal RWA is formed [131]. Hence, the developers also have initial responsibility for operation and maintenance (O&M) of the wastewater treatment plants. The Real Estate Act also includes a five-year warranty clause on "*structural defect or any other defect in workmanship,*

[18] 'Policy statement for Abatement of Pollution (PSAP), 1992' (15) which presented pollution prevention methods through the promotion of "treatment technologies, reuse or recycle".

quality or provision of services" [131]. It additionally states that a housing society must establish a RWA within three months after a majority of the houses have been reserved. As the name suggests, a RWA's primary intention is to work towards their residents' overall welfare. At some point, the RWA has to take over responsibility, e.g. for the wastewater treatment plant. This can be several years after the commissioning, but typically happens after one to two years. The RWAs ensure that monthly or annual payments (maintenance charge) are made to a residential welfare fund to guarantee O&M and any necessary extension or repair work. In Gurugram, most RWAs outsource O&M of onsite STPs to private companies, as is also the case with TCS.

In the case of Nirvana Township, the RWAs played an essential role in the drive to use treated wastewater for horticultural needs. The initial connection to Fresco's STP, as well as the extension of the pipeline with water pumps from TCS to D and E, was initiated by and covered with RWA funds. In the case of TCS, a MBBR unit in each basement cost US$ 25'000 (2018) and monthly OPEX is around US$ 640, both paid by TCS. D and E covered pipeline installation costs (US$ 3800) and monthly OPEX (US$ 250). Since treated water cannot currently be sold for a price, only pumping charges are levied to D and E to cover electricity costs. The MoU fixed a small monthly fee of 0.01 INR/litre, which is much cheaper compared to 1.5 INR/litre for receiving treated wastewater from a centralised STP. It is a pay per use model, where D and E only pay for the volume of water they use, not for the maximum of 100,000 l/d. Overall, assuming maximum use, D and E would today have total monthly costs of 30,000 INR (ca. US$ 365) to cover irrigation demands. Conversely, the monthly bill for trucks previously amounted to approximately 100'000 INR (ca. US$ 1220) and fluctuated throughout the year. Considering that societies D and E each have 300 houses, today a household pays a monthly maximum of 50 INR (ca. US$ 0.60). This is approximately three times less compared to the previous 166 INR (ca. US$ 2) per month/household (250 INR during May and June).

Industry & Market Structures

The recent legislative changes at national and state levels have spearheaded the creation of an expanding market for private companies. The State of Haryana is neighboured by Delhi and Punjab. Both of these states introduced their respective state wide water reuse policy in 2018, which was soon joined by the State of Haryana. Thus, in the same year, three neighbouring states rolled out water reuse policies. This led to the emergence of a regional market of DUWTRS designers, suppliers and operators. Most RWAs outsource O&M to private sector companies. However, given Haryana's market-led approach, these suppliers remain largely unregulated. While O&M is usually outsourced, there is no evidence that other business models have developed beyond this.

There is not yet a market for reuse water in Haryana, and no profitable business model for this has been established. New legislation, such as the Haryana Water Resources Act from 2020 [132] and the 2022 Amendment [133], recognise treated wastewater as an economic resource that will in the near future become a tradeable commodity. The 2018 Mandate envisaged to "*[...] promote treated unused water as an economic resource [...]*" and defined that "*[t]he price [...] shall be kept lower than the price of fresh water*" [129, 130]. The 2020/2022 Act allows municipal authorities to decide the tariff for bulk water uses of treated wastewater on the principles of economy, equality and sustainability. This will incentivise future developers and RWAs to ensure high quality treated wastewater, which can be sold to nearby users with a clear market value. However, as the respective price has not yet been set, the sale of treated wastewater still has to be approved. The Nirvana Country Township case presented here, thus, provides an early adopter example of quality effluent of one settlement (TCS) exported for external use (D & E settlements), albeit still (almost) free of charge.

Knowledge, Skills & Capacity

Prior to the 2018 mandate, the city faced a major gap in terms of specialised DUWTRS regulators, technology implementers, and operators. Since then, the number of operators and suppliers for DUWTRS has proliferated in Gurugram. However, four years since the policy release, no state or city level document was found that mentioned or provided any guideline for O&M of these facilities. Thus, the technological capabilities of local service and technology providers are still very limited. The lack of formalised training and skills development in urban water management and onsite solutions have been identified as some of the greatest challenges facing the sector throughout India [2]. As of 2022, there are no certified training or courses required for small-scale wastewater treatment plant operators. Likewise, universities or technical colleges lack courses or electives that focus on this rapidly growing sector. Most of the training happens on the job and is provided by private sector service providers. This leads to operators not receiving formal training before managing STPs. In addition, since the market for local suppliers is highly competitive, there is a general sense of secrecy among operators, hindering knowledge diffusion within the sector.

Legitimacy and Recognition

The Nirvana case is a policy-driven yet market-led example where state legislation (notably the 2018 Mandate and the 2020 Water Resources Act), has boosted official recognition of DUWTRS almost overnight. However, the public authorities grossly underestimated the need to provide accompanying measures. These included a lack of (adjusted) governance structures and complementary regulations, standards and labels, as well as market governance mechanisms that ensure accountability along the service chain. There is also a lack of certified training courses, standard operating procedures and minimum requirements for the O&M of these facilities. This leads to sector-wide underperformance and substandard effluent quality for key parameters (COD, BOD, TSS). Additionally, a 'fix it when it breaks' approach endangers the legitimacy of onsite treatment systems.

Creating legitimacy for non-potable water reuse is not an easy sell in India because it is a faecophobe society. This notwithstanding, in some residential units, such as the Nirvana Township, high levels of social cohesion among the residents and their RWA allowed the development of a shared understanding of eco-friendly approaches to energy, waste segregation and water use. Concomitantly, this led to the promotion of non-potable water reuse for urban greening. To foster legitimacy among the Nirvana stakeholders, the RWA undertook a number of sensitisation events to convince the residents to use treated wastewater for irrigation where children would play. Any doubts were clarified and the RWA agreed to share the water quality test reports with all the residents on a timely basis. In addition, a bidirectional communication channel through Whatsapp (RWA internal) and MyGate (society wide security application) exists. This feedback loop allows users to provide feedback and operators to notify users, e.g. when repair works are carried out.

Key Interventions & Lessons Learnt

The implemented MoU among Nirvana's and TCS's RWAs, the successful installation and continued operation of treatment and a 'mini-grid' for water transport, the availability of adequate quantity and quality of reuse water and residents' satisfaction qualifies the Nirvana case as a lighthouse example for DUWTRS at neighbourhood scale. A specific mix of enabling conditions and constructive interventions were key to success, four of which are worth highlighting.

First, proactive legislation introduced since 2018 provided the basis for this policy-induced, yet market-led example of DUWTRS implementation. The accelerating water stress experienced in (northern) India – and respective emergence of water reuse policies in Haryana and its neighbouring states – led to the formation of a regional market of alternative technologies, suppliers and operators and acts as a catalyst in promoting water reuse. In addition, the absence of sunk infrastructure and costs in the form of conventional sewers for new urban developments and the introduction of robust and compact treatment technologies in the past decade have been instrumental in establishing a rapidly growing ecosystem of DUWTRS providers.

Second, Nirvana Country Township exemplifies a successful bottom-up initiative of an eco-conscious RWA interested in reusing treated wastewater effluent for urban greening. A high level of cohesiveness among the residents (of D and E) enabled planning and implementation of the new pipeline. This was incentivised due to the poor quality of water that had previously been used for this purpose and cost increases for tanker trucks supplying fresh water for urban gardening.

Third, performing regular effluent quality tests and transparently sharing the results among local residents have been important, particularly in establishing and maintaining trust. In addition, The RWA conducted a series of awareness-sensitisation events about the legitimacy of using treated wastewater for irrigation. This resulted in high acceptability of DUWTRS among the residents of D and E. The water quality meets HSPCB standards and the quantity meets the demands of societies D and E. At a city level, however, interviewees report that regulators are not adequately monitoring DUWTRS performance or enforcing sanctions in cases of non-compliance.

Fourth, the MoU signed in 2021 between TCS and the neighbouring residential societies D & E, including the pay per use model, represents a legal document with mutually binding responsibilities. This could be a promising template for making best use of excess non-potable water for high-density settlements. As an early adopter, the RWA of TCS might even have anticipated the emergence of a true 'micro-water-market'. Although a profitable business model for water reuse in Haryana is not yet available, treated wastewater will soon become a tradeable commodity. The fact that the price is lower than the price of fresh water will further promote DUWTRS diffusion and might give rise to interesting new business models that focus on selling excess treated wastewater in local micro-markets. At the least, it will generate revenue that can be used to (partially) offset operating costs.

4. Discussion

This section draws on the individual case studies and synthesizes their main commonalities and differences. It identifies the critical success factors and the backstopping characteristics for successful implementation and sustainable operation of DUWTRS at different scales (city-wide vs. district-scale) and in different contexts (high-, vs. low-/middle-income contexts). The topics discussed below are derived from the synthesis reports and partly augmented with insights from the full project reports.[19] The practical recommendations from the project are discussed in section 5.

The five case studies allow us to discuss three generic models of DUWTRS implementation. The first one relates to policy-induced, city-wide implementation of DUWTRS as exemplified by San Francisco and Bengaluru. With relatively small, building-scale DUWTRS systems implemented across the urban fabric, this model shifts key responsibilities from public service providers (utilities) to other responsible parties that are often private entities (developers, firms, building owners, and residents). The role of the utility thus shifts from full-fledged top-down management and control to more indirect quality control, as well as network facilitation and system intermediation. The second generic model exemplified by Hamburg and Helsingborg can be characterized as utility-based, neighbourhood-scale solutions with advanced resource recovery. In this model, a public utility still largely provides water and sanitation services, with occasional private sector involvement if and where regulations allow. As our case studies in Hamburg and Helsingborg vividly illustrate, a key challenge in this model is that traditional boundaries between the waste, water and energy sectors, as well as between the public and private spheres are clearly transcended. Substantive innovation among the involved utilities and related stakeholder groups are thus needed to make this second DUWTRS implementation model work. The third model illustrated in the case study of Nirvana Country, in Gurugram, India, represents one among many intermediate models between the two 'ideal-types', in which DUWTRS solutions are installed at a district scale, but still mostly managed by private actors such as local resident's welfare associations. Many other system configurations for 'distributed' or 'cluster' solutions exist in this intermediary space, which could however not be fully covered in this study. The discussions below will thus mostly focus on discussing the commonalities and differences, as well as key success conditions of the two 'ideal-type' constellations represented by San Francisco & Bengaluru, resp. Hamburg & Helsingborg and venture into the space between them only selectively.

4.1 Implementing DUWTRS at a City-Wide vs. District Scale

Given the above discussion, a first – and most interesting – distinction can be made between city-wide and district-scale DUWTRS interventions. These two models differ quite fundamentally from each other in several key respects. At a most aggregate level, city-wide implementation needs a full-fledged new infrastructure management approach that strongly diverges from the status quo. Regulative frameworks, actor roles, economic incentive structures, O&M models, etc. need to be thoroughly revised or even developed from scratch to guarantee safe, affordable and sustainable operation of DUWTRS spread across the city. This model thus depends on a 'stretch and transform' trajectory in which existing technologies, policies, actor roles and organizational templates need to be deeply transformed. San Francisco and Bengaluru provide relevant evidence on how a new model 'that works' could look like, but we are still far away from having a clear and standardized template of how this solution could be quickly diffused and scaled to cities around the world.

District-scale DUWTRS, in turn, are arguably closer to the status quo, as existing utilities can maintain a leading role in the design, implementation and O&M of the relevant water and sanitation infrastructure. Rather than developing novel technologies, regulations and actor roles 'from scratch', this model can be implemented by adapting and/or adding layers to existing organizational and regulative frameworks in a more incremental 'fit-and-conform' trajectory. Still, a key challenge in this model is that district-scale source separation and recovery systems create various new synergies between formerly 'siloed' sectors like water, sanitation, energy and waste management. Technology designs, regulative frameworks and actor roles have to be adapted in ways that allow defining solutions that optimize the requirements not just of one, but several closely intertwined sectors at once. A key success condition here is the creation of a strong unifying vision and organizational/regulative reforms that enables key stakeholders to think and act across professional silos.

[19] All project reports are available on www.sandec.ch/lighthouse.

At the same time, commonalities exist between both models. Among others, both of them show a strong need for coordinating different stakeholder groups – from the public, private and civic sectors. The active establishment and continuous nurturing of a dense network of firms, utilities, policy actors and end users is crucially important e.g. to induce knowledge exchange, developing targeted outreach activities and decision support and guidance materials, or enabling lobbying activities and regulative adaptations [53]. Also, developing adequate technical guidance and practical training is essential to guarantee correct installations and to establish an adequate supply of skilled personnel. Also, legitimacy for innovative DUWTRS solutions to be 'actively' created in both models. This can be done e.g. by implementing and showcasing pilot & demonstration projects that make the benefits of DUWTRS - such as increased water self-sufficiency, decreased greenhouse gas emissions (if applicable) or reduced water bills - tangible to end users and decision makers.

In the remainder, the specific character of both implementation models will be teased out in more depth by summarizing and comparing the key insights from the project reports.

4.1.1 City-Wide Implementation of DUWTRS

Both Lighthouse initiatives representing city-wide implementation (Bengaluru and San Francisco) were driven by water scarcity issues coupled with rapid urban development. In the case of Bengaluru, this was further combined with major water pollution issues. Urban expansion coupled with increasing water scarcity forced both cities to explore options for tapping into alternative water sources. In both cases, a local policy mandated DUWTRS implementation for residential and commercial buildings of a certain size. While in San Francisco the policy mandate was continuously and iteratively adapted and improved based on dense exchanges among key stakeholders, Bengaluru implemented its mandate in a more top-down manner and gave local firms, planners and building owners considerable freedom in choosing concrete technologies and O&M models. Both cities successfully promoted the implementation and diffusion of DUWTRS. Yet, they also generated divergent results regarding treatment performance, operational sustainability and affordability of the implemented systems.

A key difference is the speed of diffusion in the two cities. Estimates suggest that to date more than 2'500 systems have been installed in Bengaluru [121]. By 2022, approximately 20% of Bengaluru's wastewater is thus treated in DUWTRS, a globally unique ratio. However, a substantial share of the installed DUWTRS are semi-functional at best. In comparison, in San Francisco, which initiated its DUWTRS program in 2012, by November 2022, only 48 DUWTRS were operational [52]. This much slower implementation of DUWTRS arguably made it easier to gradually develop and adapt the local policy program [9]. Results from Bengaluru suggest that the poor performance of DUWTRS can largely be attributed to the (lack of/limited/inadequate) provision of accompanying measures, such as clearly defining different actors roles and responsibilities, mobilizing enough financial resources for professional O&M, the lack of knowledge, skills and capacity with local engineering consultants and regulators, as well as difficulties in creating a regulative framework that defines water quality reuse criteria in an enforceable manner.

In the remainder, we will characterize the intricacies of the city-wide DUWTRS implementation model in more depth for each of our analytical framework's main dimensions.

Technical System Set-Up

The DUWTRS implemented in both cities follow a similar basic logic, focusing on packaged treatment systems that are installed in the basement or a separate service unit. Bengaluru has adopted a technology-neutral 'laissez-faire' approach, which led to a huge diversity of system designs installed in the city. In San Francisco, technology selection depends on the water source and reuse purposes that have been clearly defined and outlined in the local "risk-based" regulatory framework. Overall, San Francisco has thus installed more sophisticated system designs which include tertiary treatment, whereas in Bengaluru most DUWTRS systems 'only' include secondary treatment processes. Conversely, while in Bengaluru offsite water reuse options (reuse of DUWTRS effluent in local parks, laundries, malls or construction sites) is a viable - and increasingly attractive - option, this possibility does not (yet) exist in San Francisco.

Legal & Regulatory Arrangement

The permitting pathway for DUWTRS follows a similar three-tier structure in both cities. Design and construction require approval by official authorities, whereas, once operational, building owners or a designated responsible managing party have to monitor performance and inform the authorities that the systems are adequately performing. A closer look shows that in San Francisco, the DUWTRS permitting pathway is more complex, but also better supervised. In Bengaluru, the permitting pathway is patchier and there are persistent challenges, especially related to post-implementation water quality monitoring. In Bengaluru, clear and 'fit-for-purpose' water reuse standards are lacking and compliance is weak. Owners have little incentive to comply with regulations and focus on circumventing monitoring rather than investing in improving the performance of their DUWTRS plants [25]. When developing the DUWTRS program, San Francisco exhibited a higher degree of iterative adaptation and contextualisation based on intense stakeholder interaction [4]. Conversely, the adaptations to Bengaluru's DUWTRS policies and permitting pathway were issued in a top-down manner, without stakeholder participation, which may explain the problems with DUWTRS performance in this case.

Knowledge, Skills & Capacities

In San Francisco , the local utility led, supported and fostered the participative development of knowledge, skills and capacities in the local stakeholder network [53]. The private players in Bengaluru were in turn rather left alone in developing their technological knowledge, skills and capacities. SFPUC was furthermore strongly engaged in public outreach activities and explaining the benefits of DUWTRS to all relevant audiences in easily approachable ways (cf. [32, 36-38, 44, 46, 48-51]). In Bengaluru, public authorities did not provide guidance, accompanying measures and support materials, so local NGOs, research institutes and intermediaries mostly took over knowledge dissemination activities. In addition, while in SF technology suppliers openly shared information, in Bengaluru, the highly competitive market hampered knowledge diffusion within the sector. This ultimately prevented the formalisation of knowledge and knowledge transfer from technology vendors to resident welfare associations (RWAs).

Contractual & Financial Arrangements

In both cities, the DUWTRS mandates in essence shifted the financial responsibility for sanitation from public service providers to private actors and RWAs. No – or only very limited - public financial support (e.g. tax reliefs or subsidies) was provided in both cases. Building owners and/or tenants thus remained responsible for both capital expenditures for the installation (CAPEX) and the costs of O&M (OPEX). While in 2012, SFPUC introduced a grant program to partially offset installation costs, it remained reserved for projects that voluntarily implement an onsite system. The financial viability for implementing DUWTRS in both cases thus depends strongly on whether a 'business case' can be developed for the building owners / tenants that install a DUWTRS, which in turn strongly depends on (political) incentives, as well as standardizing industry & market structures.

Industry & Market Structures

In San Francisco, the emergence of a 'DBO-business model' played a key role in establishing a business case for DUWTRS. Having one firm that manages the full implementation process significantly reduced transaction costs and improved O&M quality. Firms operating under this model tend to install reliable technologies with higher initial CAPEX, which can however be recovered through lowered CAPEX, increased regulatory compliance (avoiding fines), longevity of components, etc., which taken together also increase economic viability for building owners [34]. This model also enables learning, since operators can directly exchange experiences with the design team, thus increasing the robustness of installed solutions. In Bengaluru, DBO business models are still the exception. Most firms operate under a highly competitive 'design-build-transfer' DBT business model, in which the entities that build the plants and the once operating them are not the same. The city's market-led approach led to fierce price-based competition that prioritizes low initial CAPEX for the real estate developers at the expense of much higher OPEX for the residents operating the non-functional systems later on. Recently, RWAs have identified this mismatch and started demanding better DUWTRS solutions and affordable O&M models. The quickly increasing demand for DUWTRS effluent from off-site customers (construction sites, public parks, laundries…) may provide additional business incentives for developing more high-quality DUWTRS solutions.

Recognition & Legitimacy

'Actively' creating legitimacy for DUWTRS has proven rather difficult in both cities. In San Francisco, the ONWS program profited from conducive context conditions and local actors' strategic interventions, particularly SFPUC, in actively framing storylines that enhanced the program's legitimacy [53]. In Bengaluru, the legitimacy of DUWTRS was for a long time not actively fostered among key decision makers and the general public. In San Francisco, main narratives legitimizing the idea referred to DUWTRS's inherent sustainability, their contribution to creating resilient local water supplies and to the 'greenness' of the buildings implementing them (and the tenants living or working in them). In Bengaluru, economic arguments are more centre stage, as DUWTRS increasingly provide a cheap and reliable alternative to tanker water supplies, which experience repeated price spikes due to shifts in freshwater and fuel supplies, particularly during recent droughts.

Overall Assessment and Remaining Challenges

Our case studies show that the city-wide implementation of DUWTRS is an attractive strategy option especially for cities dealing with water scarcity and rapid urbanization problems. At the same time, this transformative model still features some key development challenges that need to be overcome before comprehensive templates are available for the quick global diffusion of this solution. First and foremost, well-coordinated regulatory frameworks and governance arrangements need to be developed. Cities opting for this model need to provide accompanying measures to ensure accountability along the full service chain. The regulatory environment, especially for decentralized water reuse is still patchy in most contexts. If coordination between relevant governmental agencies is weak and adequate resources for oversight are missing, this model can result in many DUWTRS inadequately performing and not meeting required effluent standards, with adverse effects on public health and the environment. Also, the limited availability of skilled personnel especially for O&M and the relatively high CAPEX and OPEX challenge the quick diffusion of this model and hinder implementations in low-income neighbourhoods [31]. Novel (DBO) business models, as well as approaches including offsite reuse and 'trading' of treated wastewater between buildings should be developed in the future. Moreover, the high energy demand and limited resource recovery of systems distributed across the city would have to be addressed to further increase their sustainability.

4.1.2 Neighbourhood-scale DUWTRS with Advanced Resource Recovery

The key drivers and challenges for the second DUWTRS implementation model differ from the model discussed above. The LH initiatives of Helsingborg and Hamburg share many similarities, whereas the Nirvana case is rather difficult to compare, as it represents a hybrid case between the city-wide and district-scale implementation models. This section thus mostly focuses on Hamburg and Helsingborg, whereas findings from the Nirvana case are included if and when deemed suitable.

A first defining characteristic of the Hamburg and Helsingborg cases is that the main driver was not water scarcity or rapid urban expansion, but rather a strong policy ambition to develop visionary, sustainable urban development projects [59, 86]. In both cases, responding to wicked global sustainability challenges and becoming a front-runner city in the global sustainability discourse was a key motivation to experiment with radically novel UWM solutions. 'Green Innovation' was thus the key driver, which was pushed from different ends. In Helsingborg, the city commissioned three utilities to collaborate on developing an integrative and circular infrastructure solution for a planned sustainable city district [90]. In Hamburg, HAMBURG WASSER pro-actively asked its internal innovation department to develop a new infrastructure solution that challenges the status quo [60]. In both cases, local decision-makers embraced a storyline that DUWTRS could locally produce energy from waste, reducing the greenhouse gas emissions of these areas when compared to conventional systems [85, 90, 93, 103, 108].

Political support and/or supportive framing policy programmes are also essential for successful neighbourhood-scale DUWTRS examples, since they increase legitimacy and can facilitate access to the financial and human resources vital for project implementation. Since neighbourhood level examples dispose more of a 'project character', dedicated project management offices or positions were important for the planning and coordination of DUWTRS integration with different public and private stakeholders and to manage the coordination of interdepartmental and transdisciplinary exchanges. Evidence suggests that individuals in key positions should be continuously present and exercise strong leadership so as to guarantee continuity across all project phases. Since at the outset, specialised planners and equipment suppliers are usually rare and technical standards and guidelines most likely absent, the strategic integration of a guided learning-by-doing process is needed to gradually establish the knowledge about the planning, construction, connection, operation and maintenance necessary for the DUWTRS. 'Undeveloped' publicly owned land is most suitable for this type of Lighthouse Initiatives, as infrastructure has to be established 'from scratch' and as the city can mandate all developers and future owners to connect to the DUWTRS.

Also here, a more detailed assessment of the six analytical dimensions reveals the key properties of this DUWTRS implementation model.

Technical System Set-Up

The Helsingborg and Hamburg systems employ a similar basic design philosophy centred on separating black- and greywater, using vacuum pipes for transporting blackwater, recovering heat (and nutrients) and generating biogas. Although they both treat greywater, current regulations hinder its reuse, which is why it is still largely left unused. Helsingborg additionally collects food waste via kitchen grinders and produces pelletized fertilisers. Lastly, in contrast to Helsingborg, the Jenfelder Au in Hamburg also integrates rainwater management. Rainwater is retained in a local pond and on green areas where it percolates and evaporates. In Gurugram, the DUWTRS's treated effluent is used for landscaping, but energy and nutrients are not recovered. All three systems thus create some tangible benefits for their respective neighbourhoods, such as increasing liveability (pond and park in Hamburg and Gurugram), recovering heat and electric energy for local dwellers (Hamburg and Helsingborg), or making the nutrients in waste streams usable in local agriculture (Helsingborg).

Legal & Regulatory Arrangement

All three projects profited from the formulation of supportive policy programmes. In Haryana state, a political mandate required the installation of DUWTRS for residential areas like Gurugram. In Hamburg and Helsingborg, environmental policy goals played an important role. While in Helsingborg, these goals were defined top-down, in Hamburg they were – at least partly – self-imposed by the utility [10, 60, 87, 90, 94, 103, 136, 137]. Because both European projects were realised in 'undeveloped' city-owned areas[20] [56, 86], both used a clause in the land sales contract to force developers and future owners to connect to the DUWTRS. While this was not challenged in either case, solid legal ground for such a mandate exists only in Hamburg. HAMBURG WASSER successfully managed a legal amendment process, which now explicitly vets source-separating DUWTRS as a legitimate infrastructure option [69-71]. Given that Germany is a Federation, and Hamburg a city-state, amending the (waste-)water law was relatively easy. A similar amendment in Sweden would have to be done at the national level. Despite these legal differences and somewhat ironically, follow-up projects are currently only being planned in Sweden, not in Germany. A key success condition in Helsingborg was that the city commissioned the utilities to collaboratively address DUWTRS-related organisational challenges. They thus crafted written agreements that clearly outlined roles and responsibilities. Hamburg experienced similar legal challenges in combining (organic) solid waste and wastewater, but the local utilities did not ultimately collaborate because of persistent regulatory challenges.

Contractual & Financial Arrangements

In Hamburg and Helsingborg, planning regulations and land ownership structures largely defined the roles and responsibilities of the different stakeholders involved in DUWTRS projects. Since in Hamburg only one utility (HAMBURG WASSER) was involved, delineating contractual and financial responsibilities was relatively easy. In Helsingborg, delineating contractual and financial agreements among the three involved utilities was more difficult, but ultimately worked rather well once a common vision had been established. In Helsingborg the city requested that the utilities and involved city departments provide human resources and financial support, whereas in Hamburg, the additional (human) resources had to be (at least partly) financed by external grants. In Gurugram, private real estate developers were responsible for covering all CAPEX and OPEX, while in both European cases, the utilities were forced to fund the DUWTRS treatment plants and connections up to the property boundaries with public funds. Hamburg and Helsingborg also tapped international and national research grants to cover some of the CAPEX. In Helsingborg, these were reportedly a welcome but not essential contribution, conveying a symbolic PR message to decision-makers that they were 'on the right track'. In Hamburg, these were indispensable to the project's realisation. In both cases, the end users pay the same general water and sanitation fees like in other parts of the city. According to our interviewees the OPEX of the district-scale systems are slightly higher than that of centralized systems, but costs can be recovered if profits from selling electricity, biogas and fertilizer are fully factored in.

Industry & Market Structures

Weak industry and market structures were key challenges to the project realisation in all three initiatives. At the outset, specialised planners and equipment suppliers (e.g. for vacuum toilets and sewer systems) were rare and existing standards and technical guidelines provided insufficient guidance for technology implementation and monitoring [68]. In the European cases, the scale of the DUWTRS realised in a residential area made it hard to find adequate technical partners. Vacuum technologies, for instance, had initially been developed for the shipping sector and thus needed adaptation for

[20] In Hamburg, the project was realised on military grounds formerly owned by the State Government and the area was sold to the federal state of Hamburg. In Helsingborg, Oceanhamnen was a largely undeveloped former harbour area, and because activities in the port of Helsingborg had changed, the inner pier was no longer needed.

residential areas. Modified technologies, such as quieter toilets, were needed, which meant that the supply of technologies and skilled personnel had to be developed from scratch. In the case of Gurugram, a regional market of DUWTRS designers, suppliers and operators existed thanks to policy mandates in neighbouring regions, but local firm's technological capabilities remained limited. In Europe, specialised suppliers, business models and demand for end-products existed only for biogas/biofuel and heat/energy recovery, but not for greywater reuse and pelletised fertiliser. Both treated greywater and the pelletised fertiliser currently cannot compete with the (subsidised) low prices of drinking water and synthetic mineral fertiliser. Climate change, the war in the Ukraine and regulative changes like the EU Fertiliser Regulation from 2019 may change this landscape in the mid-term as they all open new marketing opportunities for circular products [113].[21]

Knowledge, Skills & Capacities

All three initiatives developed knowledge on how to plan, build, connect, operate and maintain this DUWTRS type in a learning-by-doing way. In the European initiatives, several targeted R&D projects, as well as exchanges with other projects were key in establishing technical know-how, coordinating project implementation and educating installers about new technologies. Learning from reference projects and research activities elsewhere were key to develop a shared vision on the final technical set-up [61, 75, 76, 93, 109, 139-148]. Both European initiatives had to (voluntarily) support private companies when installing technical components within the buildings. Close cooperation between the respective DUWTRS development team and vacuum system suppliers were of particular importance. Overall, knowledge transfer was strategically fostered during the construction stage by regular meetings with developers and builders and the establishment of (participative) developed guidelines [78, 79, 114, 117], assistance in reviewing the detailed construction plans, and the offering of practical trainings to private companies together with the main technical suppliers. Both projects also disposed of dedicated project management offices which enabled meaningful interdepartmental and transdisciplinary exchanges and they distributed information brochures to new residents to inform them on how (not) to use vacuum toilets [72, 115]. Some interactive and iterative learning was also reported in the Gurugram case, yet at a much lower level.

Recognition & Legitimacy

Achieving recognition and legitimacy for district-scale DUWTRS is easier than for city-wide implementation, as end users and the utilities can largely retain their usual roles and responsibilities. Still, district-scale DUWTRS remain a niche phenomenon. Our results suggest that they are comparatively more legitimised in Sweden [90, 105-107], where an active discourse around DUWTRS exists at a national level [114, 116, 149]. In Germany, rainwater management and the 'sponge-city' concept are widely discussed, while DUWTRS remains more of a niche topic [67, 150]. Yet, in June 2021, the German Ministry of Environment (BMUV) drafted a national water strategy and action plan [151], which encourages linking water, energy and material cycles and removing legal barriers, such as the strict obligation to connect buildings to central infrastructures [151]. In Gurugram, district-scale DUWTRS were legitimized mostly by emphasizing their potential for achieving water self-sufficiency and lower freshwater delivery costs. Another key legitimizing storyline for district-scale DUWTRS in Europe was their increased energy efficiency compared to conventional systems [90]. H+ resonated with a call by national regulators for municipalities to find innovative solutions for nutrient recycling [90, 94, 107]. All three initiatives also actively fostered recognition and legitimacy by interacting with key stakeholders and developing targeted communication strategies [61, 94]. Information and outreach materials were developed for specific audiences like planners & architects, developers, builders, service companies, practitioners and residents, respectively [61, 68, 72, 78-83, 94, 114-118]. Excursions to similar projects and the establishment of demonstration plants further created tangible 'proofs of concept' for decision makers, building owners and tenants and the general public,

Overall Assessment and Remaining Challenges

Overall, district-scale implementation of DUWTRS is a viable strategy option especially for cities aiming to address multiple interrelated sustainable development challenges in new 'greenfield' residential areas. District-scale DUWTRS hold considerable potential in inducing innovative infrastructure solutions at the interface of closely related sectors like water & sanitation, energy and waste management. However, also this model still features some key development challenges. First and foremost, coordinating the diverging interest of different often siloed utilities and developing a joint vision is of crucial importance. Quite often, close coordination is hindered by legal and regulatory hurdles [9, 62-64, 138]. Cities opting for this model thus need to be prepared to harmonise water, wastewater and waste legislation and adapting (national) laws, also to create markets for the 'products' created in advanced resource recovery systems. Providing subsidies and/or tax

[21] It allows for CE marking of manure products and selling struvite (a phosphate fertiliser) across the EU since July 2022.

reliefs are other potential incentives to foster (niche) markets. Lastly, follow-up projects are needed to secure and further diffuse the knowledge, skills and capacities acquired in recent LHs, to further consolidate industry and market structures and to create a steady supply of planners, technology experts, firms and service personnel that are able to diffuse the idea of district-scale DUWTRS for other settings.

4.2 Implementing DUWTRS in High-income vs. Low-/Middle-income Contexts

In addition to the scale of application, clear differences also exist between implementing DUWTRS in high- vs. low-/middle-income contexts. For example, the planners, suppliers and operators of DUWTRS solutions in low-/middle-income contexts (here: India) can be expected to start from a lower overall level of technological capacity. The firms developing DUWTRS in Bengaluru and Gurugram had to largely learn about the intricacies of onsite wastewater treatment from scratch and gradually build up their technological and organisational capabilities over time. In the high-income contexts of SF, Hamburg and Helsingborg, cutting-edge components, treatment technologies, and knowledge about treatment train design and O&M procedures were readily available locally or could be imported from elsewhere. In addition, in high-income contexts, tertiary treatment of wastewater is widespread, while in India, secondary treatment is the minimum standard, with occasional (but not required) add-ons of a tertiary treatment step. Moreover, in the high-income contexts, fit-for-purpose water quality standards are increasingly implemented, whereas in the Indian context, only discharge-specific standards have been defined so far [135, 152].

High-income contexts by definition also have more financial resources available to foster DUWTRS implementation. This in turn enables government agencies and regulators to establish entities that specialise in managing or administering DUWTRS and equipping them with adequate (human) resources to fulfil their compliance monitoring tasks. In our case studies, the roles and responsibilities of the involved public and private actors were better defined in high-income contexts and monitoring, enforcement and sanctions were also more effectively applied. Funds for the assessed LHs could be sourced from various local, national, and even international funding streams, including EU research funds. A comparable breadth of funding options was not available in the low- and middle-income case studies.

Closely related, our findings also suggest that the water and wastewater utilities in high-income contexts were better able to play an active role in DUWTRS planning, installation and management. A utility-driven governance model of DUWTRS implementation thus appears more suitable for high-income contexts, whereas in many low- and middle-income cities, a more distributed governance approach that includes private firms and various intermediary actors like NGOs, research organizations or civil society organizations may be more effective. In this model, understaffed and underfunded government agencies and utilities set the general boundary conditions for DUWTRS implementation (water quality standards, permitting pathways, etc.). The actual planning, installation and O&M activities are then in turn more strongly governed through market incentives and quality standards that are sanctioned through a polycentric web of top-down (state-driven), bottom-up (end-user driven), and industry-internal self-coordination mechanisms.

The key drivers for introducing and fostering DUWTRS also seem to fundamentally differ between high- and low-/middle-income contexts. In our low- and middle-income cases, a lack of infrastructure, as well as pressing water scarcity and/or pollution problems were key drivers. In high-income contexts, more abstract innovation- and sustainability-related objectives were the main push factors. These differences arguably also influenced technology design choices. In Hamburg and Helsingborg, very ambitious sustainability goals related to energy consumption and greenhouse gas emissions led to the development of complex, integrated, and cross-sectoral resource recovery systems. Initiatives in India in contrast focused more narrowly on improved wastewater treatment, water scarcity and water reuse objectives. The resulting solutions were clearly geared toward solving a pressing water scarcity issue, while giving less attention to energy consumption and nutrient pollution problems.

Despite these differences, common challenges also exist across high- and low-/middle-income contexts. First, DUWTRS solutions in both contexts had to deal with the need for increased coordination and communication between a large number of stakeholder groups. Our results indicate that DUWTRS in high-income contexts showed higher institutional density and more structured interactions between public administration, utilities, research institutes and the private sector. They all had some sort of collaborative and cooperative exchange, and – at least to some extent – developed new regulative frameworks, business models and key outreach materials in a participative way [32, 36-38, 44, 46, 48-51, 61, 68, 72, 78-83, 94, 114-118]). In three out of our five case studies, the most obvious actor – the local water and/or wastewater utility

– took over a key coordinating role. In low-/middle-income contexts, utilities were able to perform this system integrator's role to a more limited extent, most likely due to a lack of financial and human resources and the required organizational capabilities. Other types of organisations, such as industry and end user associations, NGOs, or even research institutes gradually took over this coordinating role and played a key role in inducing the needed networking and communication channels, yet in a much more complex and polycentric governance network. How this model could be brought to full fruition for DUWTRS implementation and how to create incentive systems, procedures and toolboxes that enable denser stakeholder coordination and participation in these contexts remain high priority topics for future research.

5. Synthesis – Ingredients for Successful DUWTRS Implementation

This report illustrates that DUWTRS solutions are a systemic, cross-sectoral innovation, which deeply challenges the established paradigm on how urban water and sanitation infrastructure is planned, operated and maintained. As such, no one-size-fits-all approach for implementing and diffusing them exists and interventions will always need contextualisation. This notwithstanding, the project allowed us to distil some key success conditions for LHs that seem to be generally valid, no matter which of the three ideal-type models are followed and/or whether a DUWTRS program is set up in high- or low-/middle income contexts. At this most aggregate level, we identify 10 key ingredients for successful DUWTRS implementation.

1) A dedicated system integrator that coordinates and aligns a large number of stakeholders with varying interests

No matter the DUWTRS type, main drivers, or income levels, coordinating a large number of different stakeholder groups, such as regulators, utilities, planners, architects, developers, builders, service companies, researchers and end-users, is indispensable. Having a 'champion' or system intermediary is key for identifying potential synergies between siloed interests, mitigating conflicting worldviews and creating long-term visions and strategic guidance. As successful DUWTRS implementation usually takes 10 or more years, this actor type must be ready for long-term engagement and a collective learning process that moves through several iterations. All the successful initiatives presented here exhibited at least one actor who kept the DUWTRS implementation process on track based on a long-term vision. Both city-wide and neighbourhood-scale examples suggest that the water and/or wastewater utilities are suitable candidates for this role. In all three initiatives in high-income contexts, the local utility was the key system integrator, occasionally with support from utilities in adjacent sectors (waste and energy). In the case of San Francisco, the local utility also took a leading role, but distributed key governance tasks in a much wider and densely connected network structure. In low/middle-income contexts, system intermediation proved more challenging, as utilities lacked the financial and human resources, as well as organisational means to fully perform this role. Yet, the case of Bengaluru shows that system integration may potentially also be performed by a more polycentric network of policy actors, industry associations, as well as firms, research institutes or civil society organisations.

2) A dense and transdisciplinary stakeholder network, which participatively creates solutions that transcend sectoral boundaries between sectors and between public and private spheres

Given the sheer complexity of DUWTRS solutions, the involved stakeholders need to be pro-actively connected through workshops and events that allow for open, interactive and constructive formal and informal exchanges. Relevant stakeholders need to be actively identified and the networks between them strategically nurtured on a regular basis. Our evidence suggests that sustained networking coupled with a participative planning approach helps create a collaborative atmosphere and establish a common vision, all of which are crucial for stabilising a DUWTRS implementation path. An interactive and reflexive approach furthermore helps to distribute ownership, which increases overall legitimacy.

3) Stable political and policy support including allocation of adequate human and financial resources

Given the long implementation timeframes discussed above, DUWTRS cannot (yet) be implemented without stable support from the relevant policy circles. The city-wide initiatives in SF and Bengaluru exemplify that a long-term policy programme – or at least concise and long-term policy support - drastically increases the chances of successfully establishing a functional DUWTRS configuration, legitimising it beyond early adopters. Most importantly, policy support should go hand in hand with budget allocations that endow the key system integrators with sufficient (financial, organisational and human) resources to effectively perform their leading roles. In high-income contexts, these resources could be successfully mobilised. In middle-income contexts, key resources remained scarcer, even if policy support was stable as in the case of Bengaluru. In the future, (national/local) climate change mitigation and adaptation strategies and NetZero pledges are likely to provide a legitimising framework for allocating financial resources to DUWTRS implementation – at least if their many sustainability-related co-benefits are effectively communicated in policy arenas.

4) Legal and regulatory arrangements that are adapted to DUWTRS's specific requirements

In all of our case studies, DUWTRS implementation was confronted with major legal and regulatory barriers. In the case of SF, Bengaluru and Gurugram, the main issue was that existing regulatory frameworks were adapted to conventional centralised UWM systems, which made water quality monitoring in onsite systems prohibitively expensive and/or not enforceable. The district-scale solutions, in turn, combined previously separated waste streams, which were individually regulated and managed. They also created new 'products', for which either no, unclear or only prohibitive regulations existed. In all cases, local actors had to actively engage in regulative change processes or smartly adapt their technology solutions in ways that made them operate on a sound legal basis. While in the district-scale DUWTRS, regulative barriers were of a rather context-dependent nature, city-wide DUWTRS struggled with a more fundamental problem: developing novel legal & regulative frameworks that are contextualised to the needs of onsite DUWTRS. Onsite DUWTRS typically rely on a broad variety of source waters (rainwater, greywater, blackwater, A/C condensate, etc.), which can be used for many different local indoor and outdoor reuse options (toilet flushing, washing machines, irrigation, cooling, etc.). They thus inherently ask for a 'fit-for-purpose' regulatory approach, which aligns water quality standards and O&M procedures with specific combinations of water sources and reuse purposes. For a long time, no coherent template for such a 'fit-for-purpose' regulative framework existed globally. Among others, San Francisco has now spearheaded such a framework. Although the San Francisco case was developed for the specific local context, it can be iteratively developed in various new contexts. The existence of this regulative template is a potential game changer. If it is applied in more and more contexts, this will create more predictable and standardised market environments, and firms can tailor their solutions to this framework's core technical requests, standardise treatment trains for different reuse purposes, reap economies of scale in manufacturing, increasingly automate O&M and thereby significantly reduce the costs of onsite DUWTRS operations.

5) A well-defined permitting pathway, water quality monitoring and enforcement system

Closely related to the point above, legal and regulatory frameworks only lead to sustainable outcomes if it they are combined with effective permitting pathways, formalised water quality monitoring procedures and enforcement mechanisms. Especially for city-wide onsite solutions, it is important to implement an approval procedure that clearly outlines the roles and responsibilities of all the involved authorities, the effective quality monitoring approaches, and the necessary enforcement and sanction mechanisms. Permitting pathways for onsite DUWTRS are notoriously complex and hard to communicate to the relevant stakeholders. The fit-for-purpose standards discussed above have in turn proven effective in creating cost-efficient quality monitoring procedures and in providing technology decision support. To enforce compliance,, a well-defined vetting process for design and construction quality, remote quality monitoring processes and a lead-authority equipped with adequate human and financial resources to conduct spot-checks are key. Establishing a regularly updated (online) DUWTRS database may facilitate monitoring activities. Making essential water quality data publicly accessible could help increase public trust and legitimacy. In middle-income contexts, creating incentive systems for voluntary and industry-based water quality standards might be another inroad for broad compliance.

6) Attractive business models and markets for the products generated in DUWTRS

Overall, our case studies suggest that DUWTRS offer a unique opportunity for turning sanitation from a conventional 'waste management' problem into a business opportunity in the circular economy. The water, nutrients, and heat contained in different wastewater streams can be effectively turned into marketable products, which create interesting economic, environmental and social co-benefits to local communities, building owners, tenants and the firms involved. Reaping those benefits is only possible if stakeholders work on constructing functional markets for the end products and develop related business models. At a most basic level, in the case of San Francisco, a novel type of design-build-operate business model emerged, which made the same firm responsible for all parts of the DUWTRS implementation cycle. These models entail strong incentives to design well-adapted systems and to increase regulatory compliance, robustness, longevity, and, ultimately, economic viability. In India, 'micro-markets' for the reuse water from onsite plants increasingly emerge. For example, in the Gurugram case, treated wastewater is sold to another compound in the same residential development. RWAs in Bengaluru, in turn, increasingly sell their reclaimed water to local construction sites, laundries or public parks. The district-scale systems in Hamburg and Helsingborg, finally, produce energy/heat, as well as high-quality fertilisers and soil amendments, which can be sold to customers in agriculture. Our case studies illustrate the considerable business and market potential of these solutions, although they are only marginally tapped in the current regulatory and business environment. In essence, new policy/regulative paradigms are needed that shift the focus from treating waste(water) and removing pollutants to the recovery of valuable and marketable resources. In this respect, end-of-waste regulations for recovered resources need to be clarified, and tax reliefs/subsidies awarded for DUWTRS that recovered energy, heat, and water.

7) Industry-internal standards and norms, certified training systems and information materials

Our results suggest that a key success factor for DUWTRS is industry-internal standardisation, training and information sharing. First, the city-wide DUWTRS model is particularly in need of formalised, accessible and understandable industry standards, norms and guidelines. The decentralised market structures of this solution hampers knowledge diffusion and quality monitoring among competitors. For example, the unregulated market in Bengaluru made firm entry relatively easy and quickly increased the supply of system suppliers and service providers. At the same time, insufficient industry standardisation also led to a proliferation of untrustworthy consultants, technology suppliers and after-sales service providers, which decreased the overall quality and trust in the installed DUWTRS systems. Having widely shared quality vetting, standardisation and quality labelling processes in place are thus a key basis for establishing mature markets and an industry that is able to supply the requested technical equipment and expertise for guaranteeing that DUWTRS meet performance (and thus environmental and public health) standards. A formalisation of industry-level standards and norms also enables standardised, compatible system components, and the certification of vendors and suppliers increases transparency, fostering accountability across the service chain.

Second and related, certified training systems have to be developed that allow for establishing and sharing state-of-the-art knowledge, skills and capacities among planners, installers and (especially) the operators of DUWTRS solutions. Certified trainings for planning, construction, and maintenance companies are best delivered in collaboration with the (main) technical suppliers and organised by an industry association. In SF, a new training and certification system for DUWTRS is currently being established by a network of local and national (waste)water industry associations. In Hamburg and Helsingborg, substantive training happened on the job between technology suppliers and builders.

Third, well-designed information and training materials tailored to key target groups are crucial. To guarantee a smooth knowledge transfer and training process, formalised design guidelines, including technical norms and standard procedures have to be developed. In several of our case studies, detailed information was available, but did not trickle down to those responsible, e.g. for DUWTRS planning or construction. Key guidance materials must be known by the respective target groups and be accessible and comprehensible. This requires a knowledge dissemination strategy for which national professional associations could serve as promoters and as a platform. Finally, knowledge also needs to be disseminated to building owners and tenants. Distributing info-sheets, including do's and don'ts is helpful, especially if an unfamiliar technology is being implemented that requires users to adapt their behaviour.

8) An active communication and public outreach strategy that fosters legitimacy

Given the 'yuck factor' connected to wastewater in cultures around the world, creating legitimacy for DUWTRS is not an easy task. Thus, legitimacy for DUWTRS need to be actively and strategically created as it is unlikely to be 'passively' generated (only) through external drivers, such as droughts, climate change or rapid urbanisation. 'Actively' fostering recognition and legitimacy means that institutional changes and core storylines need to be developed that embed DUWTRS in pre-existing societal norms and make its benefits easily understandable to broad audiences. Our case studies show that communication can focus on DUWTRS's manifold ecological, social, economic and/or technical co-benefits. For example, in India, important sources of legitimacy are the increased water resilience and additional income streams that RWAs can generate through implementing DUWTRS. In high-income contexts, (technical) innovation and environmental sustainability are additional and increasingly effective legitimising storylines. Apart from general outreach and communication campaigns, also more targeted interventions can be highly effective. These include guided tours to PDPs; client consultations for real estate developers and future owners; transparently sharing water quality monitoring results, etc.

9) Pilot- and demonstration projects enabling technology development, public outreach and exchange between LHs

For both neighbourhood-scale and city-wide initiatives, publicly accessible pilot and demonstration projects played a key role for technology development and legitimation. On the one hand, the pilot and demonstration projects induced interdisciplinary research, through which vital technology and system knowledge was generated, which in turn increased trust within the utility and with city officials. Simultaneously, they served as an accessible and tangible 'proof of concept', and thus as a legitimising object for developers, owners and (future) residents. The hands-on experience of flushing a vacuum toilet and the opportunity to exchange with users was invaluable to establish trust in the novel technical solutions implemented in Hamburg and Helsingborg. In many cases, actors drew on experiences from PDPs in other places, adopted successful fragments thereof and adapted them to the local context. Ultimately, these technical and organisational templates can assist specialised commercial actors to pro-actively engage in diffusing a given template further and implementing it in cities around the world.

10) Proven long-time economic and financial viability in a full system and infrastructure lifecycle perspective

Two final, yet key challenges for DUWTRS reported in all our case studies are their (still) comparably high CAPEX and OPEX, especially when compared to conventional (and often highly subsidised) centralised UWM solutions. These challenges are most pertinent for onsite city-wide DUWTRS solutions; district-scale solutions can often offset the additional costs by selling recovered resources and with higher overall efficiencies in the used treatment processes. Finding financially and economically viable system designs is thus a key task for any city implementing DUWTRS. At the same time, comparisons with centralised infrastructure should be based on a full system and comprehensive environmental life cycle assessment. For example, district-scale solutions can achieve high sustainability impacts at reasonable additional costs. In middle-income contexts, freshwater prices tend to fluctuate strongly and centralised infrastructure usually performs rather poorly, thus making city-wide DUWTRS economically and environmentally highly attractive. This notwithstanding, it is important that investments into DUWTRS pay-off for investors and end-users, and prove beneficial for the environment in the long term. Significant economies of scale and learning curves can be expected for DUWTRS in the near future, both in the (mass-)manufacturing and automation of treatment systems and O&M models (as well as innovative business models).

6. Outlook

DUWTRS are a radical innovation in UWM and there are only few successful Lighthouse Initiatives worldwide. At the same time, we have arguably moved beyond the stage of basic R&D and pilot/demonstration projects, as cities around the world have successfully implemented Lighthouses with tangible economic, environmental and social benefits. Through these initiatives, innovative technical solutions, organizational best practices and management templates have become available, which can now be mobilised and adapted when diffusing the innovations into new contexts. The technologies, regulative frameworks, business models, communication strategies, etc., described in this report (and related academic and grey literature) arguably provide a fertile ground for fundamentally transforming the dynamics in UWM toward the diffusion and mainstreaming of different types of DUWTRS. We are positive that a global mainstreaming of this novel UWM paradigm is around the corner and that the formidable potential it embodies for creating more sustainable and liveable cities will become increasingly visible in the decade(s) to come. Complementing and showcasing the best practices outlined here with additional examples in various contexts around the world will be indispensable in this venture. We thus invite researchers, policy makers and technology experts to engage in establishing a global database of lighthouse initiatives and the many ways in which they may transform urban water management, sanitation and related sectors.

7. Annex

7.1 Interview Guideline

Lighthouse Initiatives: Interview Guideline

Overall interest: Temporal perspective on actors, events, processes and mechanisms that have contributed from project development, planning and design to implementation, operation & maintenance.

Acquire consent for recording, information about data handling procedures (Consent Form).

Part I: Introductory questions

Personal (only ask if you can't find out anything about the person through desk research)

- Can you tell me a bit about yourself and your role? Since when have you been involved? During which stages and with what responsibilities?

Project-related

- What was the main reason for engaging with alternative solutions in the sanitation sector to begin with (from your perspective / that of your organisation)?
- Where did the idea "come from"/what triggered the initial interest in this project in your organisation (or the city of *XYZ* in general)?
-

Part II: Process & Institutional Set-Up

Process[22] (Ask participant to be as specific as possible about 2-3 key events, come back to them in the questions below)

- What were the most important events from the initial stage up to the implementation? Which were the most challenging moments?
- Were there any specific events that worked as drivers for project implementation? Was there any direct opposition from local stakeholders?
- Alternatively, were there any specific events where challenges/problems were addressed/resolved? How were these addressed/resolved?
- Regarding the initial "schedule"/timetable, have there been any (process-related) challenges that delayed the planning and/or implementation of the project?
- Have there been process-related challenges that intensify or dissolve due to specific events and/or actors? How were those challenges resolved?

Stakeholders

- Was there a broad interest among different stakeholders in the beginning to do this kind of project? Alternatively, had the interest and motivation yet to be generated among local stakeholders?
- Were there any particularly important individuals or organisations in the early stage that worked as drivers? Were there any specific stakeholders that opposed the project? How was this addressed?

[22] I.e. ask whether they could illustrate some of the problems and ways to overcome them based on examples in these specific events.

Recognition & Legitimacy

- Were there specific challenges that triggered interest or motivated people to think about installing an alternative sanitation system in *XYZ*? Was there "external" pressure to engage with these type of issues – or did interest emerge bottom-up in *XYZ*?
- Were there existing norms, values, cultural beliefs, 'ways-of-doing-things' within the utility, the government and/or end users, etc. that hindered progress with the project? How was this addressed?
- In order to overcome eventual barriers/resistance: Did positive experiences from other places play a role in convincing key stakeholders? Can you elaborate how you collected inspiration?
- In terms of social acceptance: How easy are users with the new technologies? Were there any challenges? Was there organized opposition to the project (i.e. an association, social movement, etc. campaigning against it)? How were these challenges addressed? Alternatively, were there any specific actors/events/circumstances that fostered user acceptability?

Governance, Legal & Regulatory Framework

- In terms of compatibility with (existing) regulations: Were/are there any regulative and/or legal challenges to implementing the new system? Any problems that can be highlighted?
- In case regulations had to be established/modified: What were the drivers, barriers and challenges in establishing/modifying the legislative/regulatory framework? How were barriers and challenges addressed? How was this addressed?
- How were regulatory requirements from different sectors (waste, water and sanitation; construction; public health, pollution control board, etc.) coordinated? Is this generally working well or are there any issues regarding coordination, e.g. among different public authorities/regulative bodies?
- Which particular actors and/or events contributed to addressing these challenges and how?
- Are there clear roles and responsibilities regarding the relevant government departments involved?
- Are the relevant government departments working and coordinating effectively?
- Is the permitting pathway for on-site systems clearly defined and enforced? Who is responsible for which of these tasks?
- Are there dedicated resources in relevant government departments (human, financial/budget) and are these suitable/sufficient according to the performance needs?
- To date, are there any performance targets/standards explicated? If so, are these targets/standards being monitored and sanctioned/enforced?
- Have there been any changes within how things are organised and coordinated in terms of water reuse in the past years/decade? To what extent have project related (or e.g. policy related) experiences/outcomes contributed to this?
- Is there a market for (some of) the recycled products generated by the system? Were there any particular measures (e.g. creation of a legal entity) to (legally) operate within the regulatory/legal boundaries?

Industry, Market Structures & Financial Arrangements

- CAPEX: How has the project funding been established to implement the project? Were there particular funding mechanisms?
- OPEX: How are the funds generated to keep the project running? Were/Are there any subsidies or tax relief measures or are costs recovered? Are there particular investment incentives & pricing schemes?
- How do the costs compare to a conventional centralized system? Can users / the government bear them in the long run? Can a return on investment be achieved in a reasonable timeframe?
- How (and by whom) are these financial arrangements managed/coordinated? How were these arrangements established?
- Have there been measures to develop additional (niche) markets for the solution during your project? Could the same approach/key technologies be sold to another place?
- *The system in XYZ produces ABC: Is this sold to the households? How does this work? How was this process set up*?

- Is there some sort of business model, which creates a regular income/profit for firms/other actors, which incentivizes them to further diffuse and push the idea?
- Is there an ecosystem of competent firms, consultants & operators that can design, install and operate the systems? If not, why? What type of firm is missing/underdeveloped?
- How easily can customers find a local supplier of technologies or services? Are the quality levels of different firms transparent? Is there some quality vetting by the government / other actors?

Part III: Technology & System Choices

Technology Choice

- What motivated the choice of technologies and system components/set-up? I.e. why does the system look like this? *Why was urine separation excluded? Why not grey water reuse? Why is there no fertilizer production?*
- The system that is now implemented: Did this particular set-up already exist somewhere else (i.e. is it copy-pasted from another context)? What adaptations were made and why?
- Where did you find (inspiration for potential) technologies and know-how (*vacuum toilets, piping for vacuum systems, biogas production, heat/energy converter)?* How were these imported to *XYZ* (e.g. hiring consultants, visiting other places, learning from others' experiences)?
- Were there any technical surprises/challenges during the construction stage? How did they influence the final system design (choices)?

Operation & Maintenance

- In terms of the system start-up/handover: Were there any issues? If yes, how were these addressed?
- In your opinion, is the quality of the design adequate to meet the treatment/performance targets? Is the system reliably (and securely) performing?
- How often is effluent water quality checked? By whom? Can the results be (publicly) accessed?
- Are the monitoring costs acceptable? What happens in case of non-compliance?
- Is there any measure to guarantee that skilled personal is available when needed?
- Are maintenance activities reliably performed or easily accessible and available when needed? Is there any supervision of these O&M activities?
- Is there a clear protocol on how to deal with system failures?
- Are spare parts reliably available when needed?

Knowledge, Skills & Capacities

- How competent are local technology suppliers and operators in installing and running the systems?
- How competent are the regulators? Do they have the technical expertise and financial means to effectively oversee system installation & operation?
- Are there any information events or workshops to establish continued adequate "supply" of skilled management and personnel?
- Are there any feedback loops for example regarding user satisfaction or required maintenance/repair works?
- Since the system is running, have there been any changes to how things are done (e.g. in guiding policies, operation or maintenance, but also other related procedures)? In other words, has any kind of "adaptive learning" taken place?
- Is there any form of knowledge documentation, which is shared with involved/concerned people?
- Is there a "network" among experts that has regular/frequent exchanges about experiences?
- Will experiences be communicated/diffused to other places? Is there a target group?

Technical Performance

- Overall, how well is the system performing? Are the (internal) performance targets and (external) standards met? Were/are there any unexpected problems in terms of the technical performance?

Treatment Efficiency (see also questions on "Operation & Maintenance)

- Depending on the reuse purpose: Are treatment processes meeting required (national/local) standards?

System Performance Criteria

- Are users satisfied with the implemented system?
- Are reusable products reused as planned or have there been any acceptability issues?
- Do users have some sort of reporting system in case they have any complaints?
- Are users informed when the system fails? How is this performed?
- Do treated quantities and produced products (*reusable water*, *biogas*, *fertilizer*) match the required quantities required for the reuse purpose? For example, is there enough flush water to flush toilets/biogas to heat up the targeted apartments?
- Is the implemented system cheaper compared to the conventional system?
- Has the implemented system an increased energy efficiency compared to the conventional system? Alternatively, does it use less kW/h per m^3 compared to the conventional system?
- Does the implemented system have less environmental impacts (e.g. greenhouse gas emissions) compared to the conventional system?

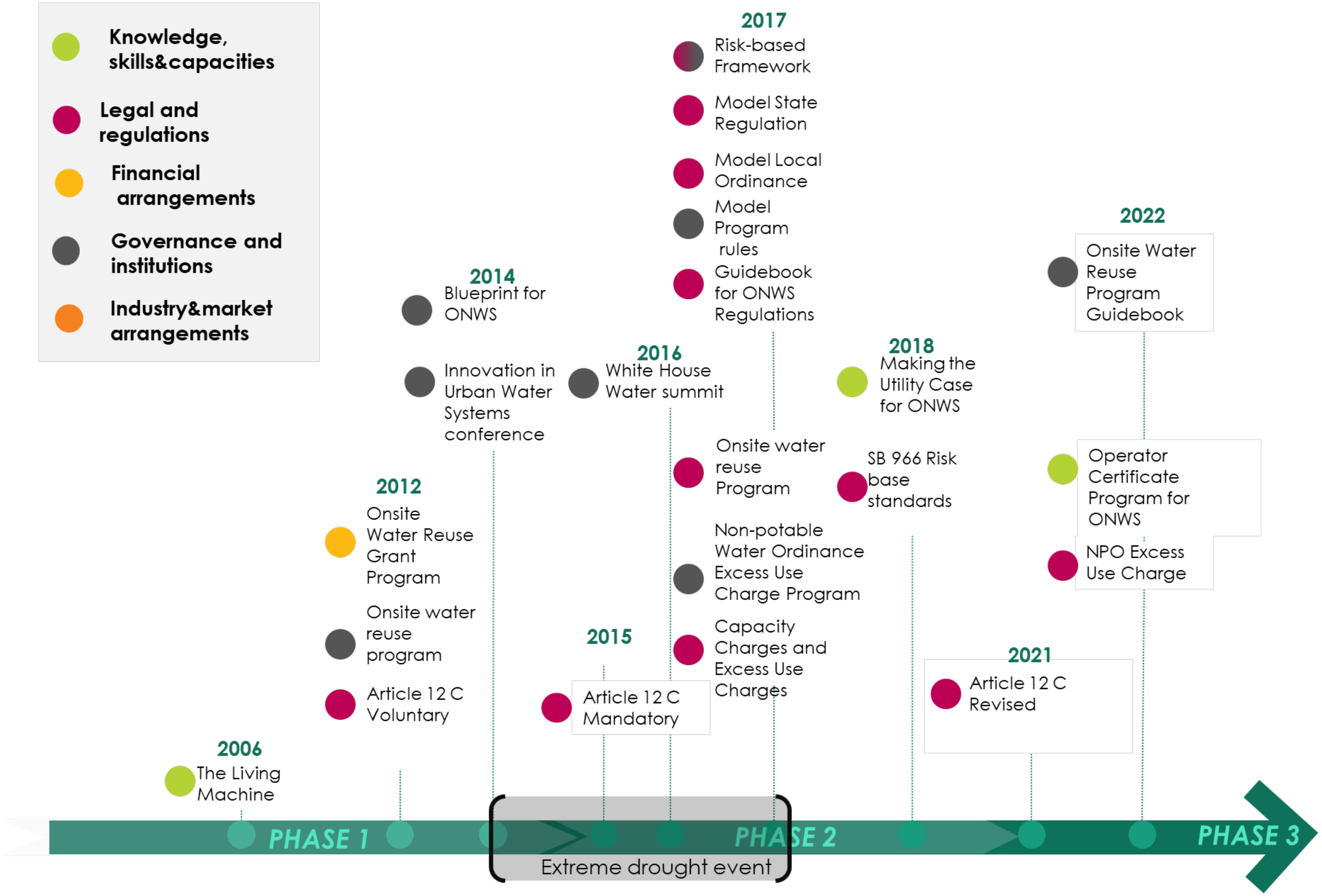
Technical Robustness

- Does the system run on its own or does it need a lot of support? (e.g. external energy/water supply; maintenance works & spare parts)
- Is the system scalable/easily replicable or highly context-sensitive?

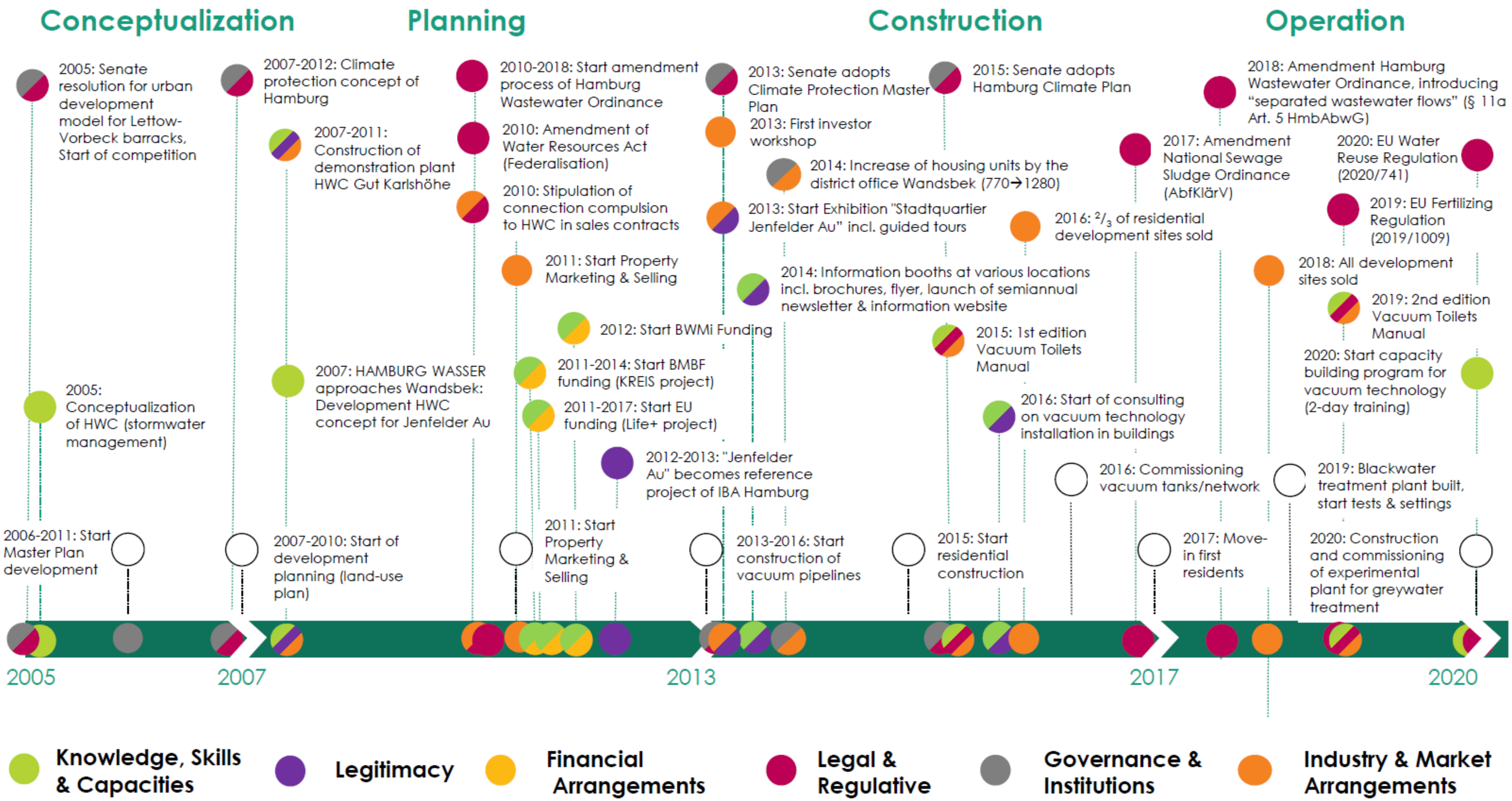
Anything else you would like to share?

7.2 Project Timelines

San Francisco

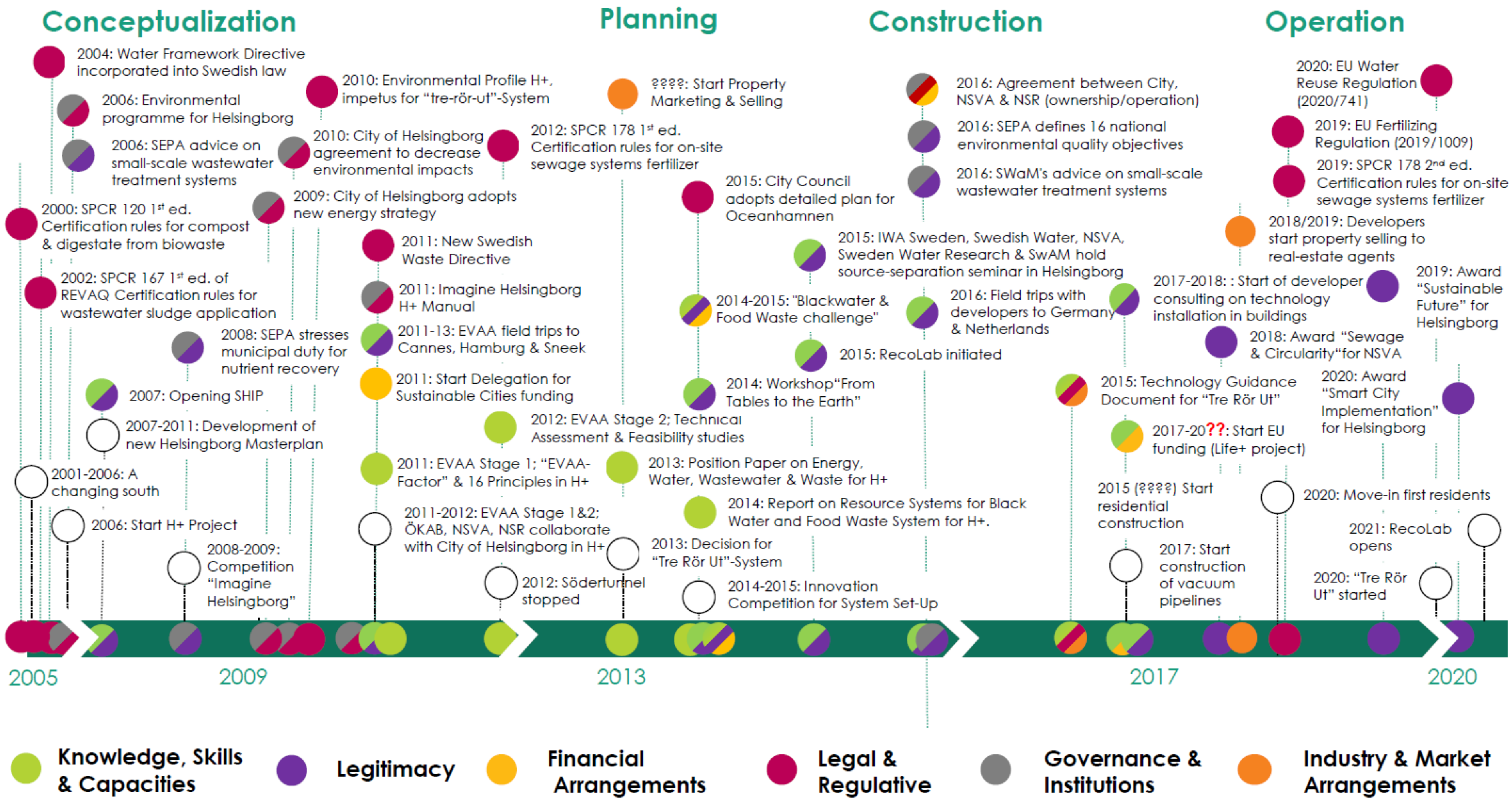


Hamburg

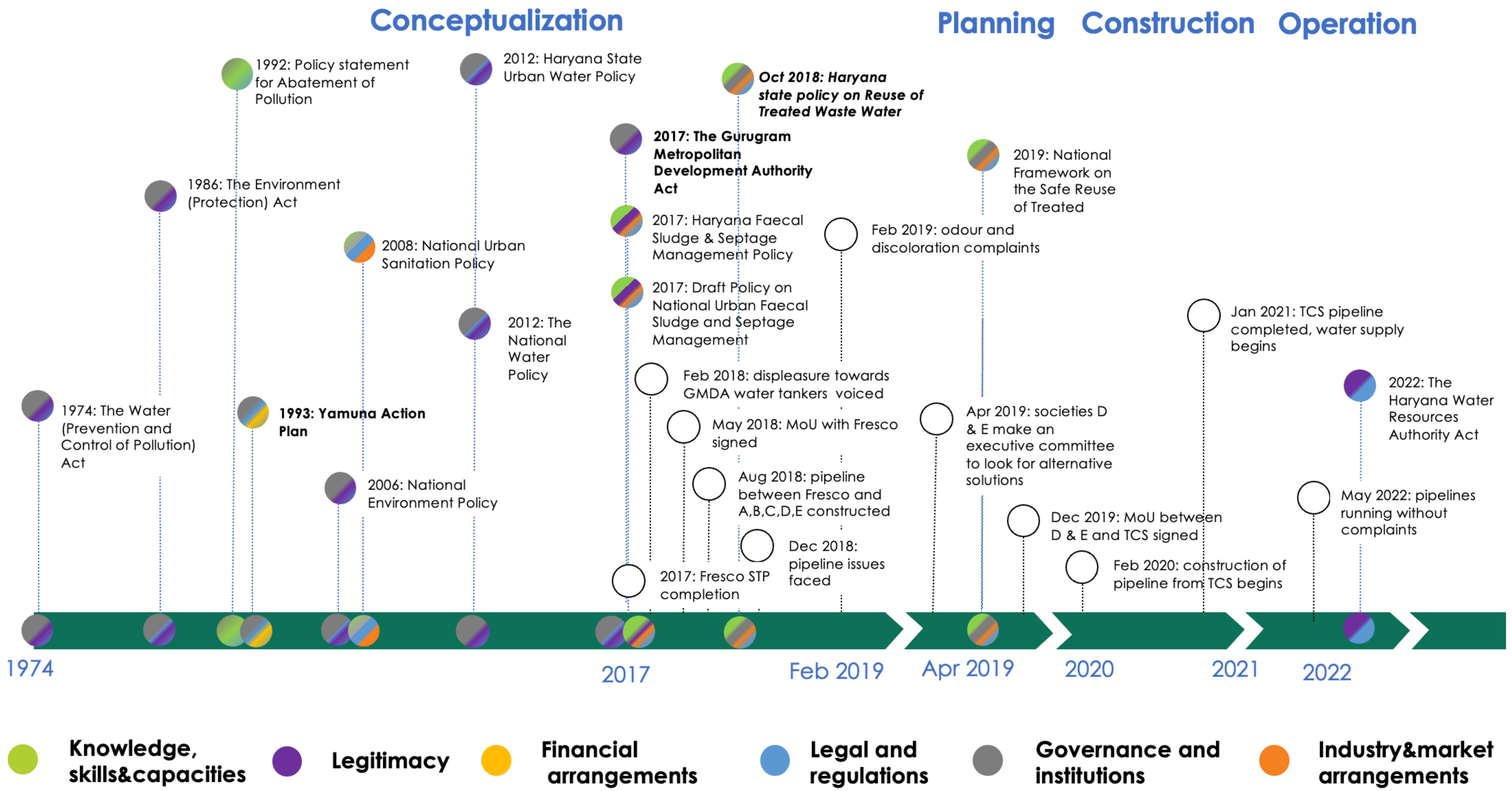


Conceptualization
Planning
Construction
Operation
2005: Senate resolution for urban development model for Lettow-Vorbeck barracks, Start of competition
2007-2012: Climate protection concept of Hamburg
2007-2011: Construction of demonstration plant HWC Gut Karlshöhe
2010-2018: Start amendment process of Hamburg Wastewater Ordinance
2010: Amendment of Water Resources Act (Federalisation)
2010: Stipulation of connection compulsion to HWC in sales contracts
2011: Start Property Marketing & Selling
2013: Senate adopts Climate Protection Master Plan
2013: First investor workshop
2014: Increase of housing units by the district office Wandsbek (770→1280)
2013: Start Exhibition "Stadtquartier Jenfelder Au" incl. guided tours
2015: Senate adopts Hamburg Climate Plan
2016: 2/3 of residential development sites sold
2014: Information booths at various locations incl. brochures, flyer, launch of semiannual newsletter & information website
2018: Amendment Hamburg Wastewater Ordinance, introducing "separated wastewater flows" (§ 11a Art. 5 HmbAbwG)
2017: Amendment National Sewage Sludge Ordinance (AbfKlärV)
2020: EU Water Reuse Regulation (2020/741)
2019: EU Fertilizing Regulation (2019/1009)
2018: All development sites sold
2019: 2nd edition Vacuum Toilets Manual
2020: Start capacity building program for vacuum technology (2-day training)
2012: Start BWMi Funding
2015: 1st edition Vacuum Toilets Manual
2005: Conceptualization of HWC (stormwater management)
2007: HAMBURG WASSER approaches Wandsbek: Development HWC concept for Jenfelder Au
2011-2014: Start BMBF funding (KREIS project)
2011-2017: Start EU funding (Life+ project)
2016: Start of consulting on vacuum technology installation in buildings
2012-2013: "Jenfelder Au" becomes reference project of IBA Hamburg
2016: Commissioning vacuum tanks/network
2019: Blackwater treatment plant built, start tests & settings
2006-2011: Start Master Plan development
2007-2010: Start of development planning (land-use plan)
2011: Start Property Marketing & Selling
2013-2016: Start construction of vacuum pipelines
2015: Start residential construction
2017: Move-in first residents
2020: Construction and commissioning of experimental plant for greywater treatment
2005
2007
2013
2017
2020
Knowledge, Skills & Capacities
Legitimacy
Financial Arrangements
Legal & Regulative
Governance & Institutions
Industry & Market Arrangements

Helsingborg



Nirvana



Conceptualization
Planning
Construction
Operation
1992: Policy statement for Abatement of Pollution
2012: Haryana State Urban Water Policy
Oct 2018: Haryana state policy on Reuse of Treated Waste Water
2017: The Gurugram Metropolitan Development Authority Act
2019: National Framework on the Safe Reuse of Treated
1986: The Environment (Protection) Act
2017: Haryana Faecal Sludge & Septage Management Policy
Feb 2019: odour and discoloration complaints
2008: National Urban Sanitation Policy
2017: Draft Policy on National Urban Faecal Sludge and Septage Management
Jan 2021: TCS pipeline completed, water supply begins
2012: The National Water Policy
Feb 2018: displeasure towards GMDA water tankers voiced
2022: The Haryana Water Resources Authority Act
1974: The Water (Prevention and Control of Pollution) Act
1993: Yamuna Action Plan
May 2018: MoU with Fresco signed
Apr 2019: societies D & E make an executive committee to look for alternative solutions
Aug 2018: pipeline between Fresco and A,B,C,D,E constructed
2006: National Environment Policy
May 2022: pipelines running without complaints
Dec 2019: MoU between D & E and TCS signed
Dec 2018: pipeline issues faced
2017: Fresco STP completion
Feb 2020: construction of pipeline from TCS begins
1974
2017
Feb 2019
Apr 2019
2020
2021
2022
Knowledge, skills&capacities
Legitimacy
Financial arrangements
Legal and regulations
Governance and institutions
Industry&market arrangements

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