



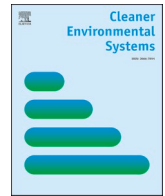
Conceptual decision support framework for sustainable and energy-efficient water supply systems

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Conceptual decision support framework for sustainable and energy-efficient water supply systems

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ABSTRACT

This paper develops a multi-criteria decision support framework to provide a structured process for selecting and assessing sustainable and energy-efficient water supply systems. The research addresses the need for a unified, practical tool that consolidates the diverse factors involved in water sustainability. We developed this conceptual framework by conducting semi-structured interviews and focus groups with 13 diverse stakeholders in Sweden, including representatives from municipalities and water suppliers. This participatory process identified 30 criteria and 39 indicators dimensions of water, energy, health, resilience, and climate. The criteria were organized into national, regional, and project-related categories to ensure seamless adaptability to local conditions. The framework utilizes a modular boundary logic and organize criteria into national, regional, and project level tiers. It was validated through proof of concept for a residential building in Stockholm and sensitivity analysis was conducted to test the robustness of the result. Ultimately, this framework offers a robust and adaptable methodology for assessing water and energy systems in buildings. By translating complex academic research into a practical tool, it serves as a vital bridge between theory and implementation, enabling more informed and sustainable decisions in water resource management.

1. Introduction

Sustainable water supply systems have increasingly become a focal point for policymakers, researchers, and practitioners as urbanization and climate change place mounting pressure on water resources. Rapid population growth, intensifying water scarcity, deteriorating water quality, and the vulnerabilities introduced by aging infrastructure highlight the need for holistic approaches that go beyond conventional centralized supply models. Traditional municipal water supply networks, while effective in delivering potable water to large populations, are often energy-intensive and susceptible to climate-induced extremes such as droughts, flooding, or infrastructure failures (IPCC, 2023; Par- aschiv et al., 2023). Consequently, there is an urgent need to integrate resource efficiency, resilience, and robustness into urban and regional water planning.

The energy–water nexus underscores that reducing water consumption often leads to lower energy use for pumping, treating, and distributing water (Kalbusch and Ghisi, 2016) —and conversely, curbing energy consumption can help alleviate water stress (Lee et al., 2017). Recognizing this synergy, contemporary research increasingly views water supply systems as potential levers for achieving broader sustainability goals, including greenhouse gas emission reductions and improved energy efficiency. Water reuse strategies, such as greywater

recirculation and rainwater harvesting, are gaining traction as methods to minimize mains water demand and reduce wastewater loads (Pinto et al., 2021; Yildirim et al., 2020; Garrido-baserba et al., 2024). These approaches, however, must be assessed in light of localized constraints—such as infrastructure capacity and public health regulations—to ensure practicality and social acceptance.

Despite growing interest in alternative water supply solutions, several barriers hamper their widespread implementation. Stakeholders often cite regulatory uncertainty, as evolving or incomplete guidelines on water reuse and emerging contaminants can increase both cost and complexity. This uncertainty may lead to additional treatment and monitoring requirements, increasing operation and maintenance costs, while also complicating system design through the need for dual plumbing, a heightened cross-contamination risk (Khan et al., 2024; Tolksdorf and Cornel, 2017), and challenges in establishing appropriate pricing structures for recycled water (Salgado et al., 2023). Social acceptance and end-user perceptions present key hurdles, especially for on-site greywater reuse or rainwater harvesting systems, where aesthetics, color, or turbidity can lower user confidence (Lambert and Lee, 2018). Additionally, investment decisions frequently prioritize immediate financial returns over longer-term societal benefits associated with resource circularity and resilience (Narayanan et al., 2021). Furthermore, institutional hurdles such as limited governmental prioritization,

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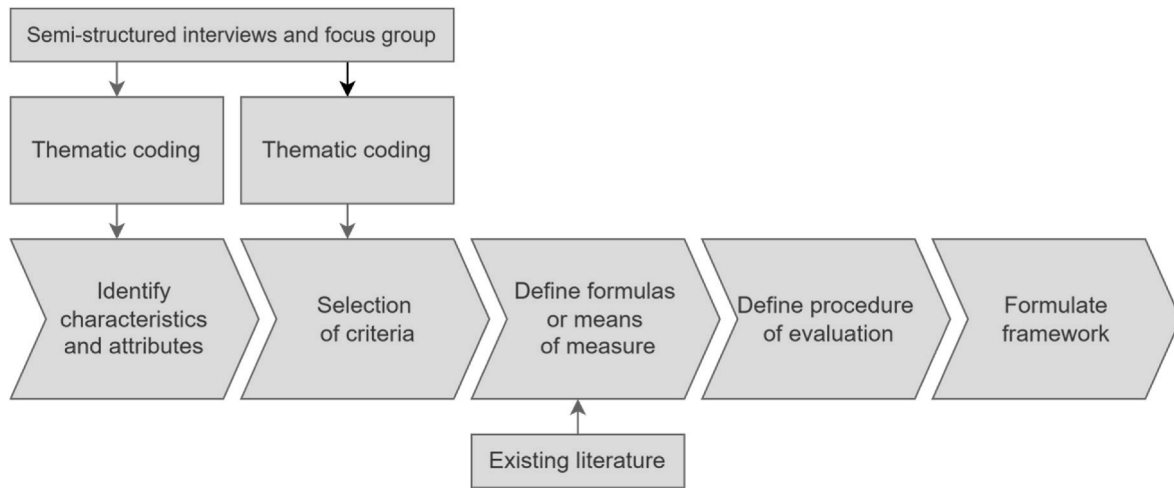


Fig. 1. Process of framework development.

unclear regulations and reluctance of water utilities to support implementation due to perceived operational risks and maintenance inhibit the emergence of such systems on a larger scale (Duran-Romero and Barquet, 2025; Hacker and Binz, 2021). These barriers underscore why a purely technological fix is insufficient without multi-stakeholder engagement, robust business models, and consistent policy frameworks.

As previous studies indicate, frameworks for evaluating the sustainability of water supply systems must consider environmental impact, economic feasibility, and public health risks (La Torre Rapp et al., 2024). Existing decision support tools for water reuse (DST4WR) utilize life-cycle assessment, life-cycle cost, multi-criteria decision analysis and microbiological risk assessment (Sampaio et al., 2024). However, they often focus on either economic aspects (e.g., net present value, return on investment) or purely environmental indicators (e.g., life-cycle greenhouse gas emissions), neglecting essential social or site-specific contextual factors (Wallin et al., 2021). Although there are studies that combine these approaches, very few integrate all relevant factors or have a standardized method linked to affected stakeholders. Sampaio et al. (2024) state that such a tool would be beneficial and should enable adaptation to local conditions.

Moreover, the technology readiness and reliability of novel water systems—ranging from household-level condensate capture to neighborhood-scale rainwater harvesting—are unevenly documented, posing challenges for risk-averse stakeholders (Gwenzi et al., 2015).

In light of these challenges, this paper develops and presents a conceptual framework for the development and assessment of sustainable water supply systems. Drawing on semi-structured interviews with stakeholders in multiple municipalities, as well as a synthesis of prior literature, this framework integrates energy, water, and economic metrics alongside health risk and resilience indicators. By emphasizing both local conditions (e.g., existing water infrastructure, rainfall patterns, energy grid constraints) and stakeholder-specific priorities (e.g., cost savings for property owners, regulations for utilities, and acceptance among end-users), the proposed framework seeks to enable a more robust, adaptable approach to planning and implementing alternative water systems. In so doing, it addresses the critical gap between academic research on decentralized water management and practical decision-making processes in municipalities and property development.

The remainder of this paper is structured as follows. First, the Method section outlines the semi-structured interviews and data-collection process used to capture stakeholders' insights. Next, the Interview Results section synthesizes key indicators—such as annual municipal water savings, energy savings, and potential health risks—that emerged as priorities for water-system decision-making. Based on

these insights, the Formulation of Conceptual Framework section proposes an integrated set of resource-related, social, and robust criteria, culminating in a tailored multi-criteria decision analysis (MCDA). Finally, the Discussion section examines the limitations of the framework and the broader implications for policy, building regulation, and the continuing evolution of sustainable water supply systems worldwide.

2. Method

The method follows the procedure illustrated in Fig. 1, where the primary identification of characteristics was conducted through semi-structured interviews. Expected results from the interviews serve as a foundation to find clear and measurable criteria for an extensive evaluation of the system from a water-energy perspective. The semi-structured interviews with support from existing literature also aimed to give insight into how the procedure of evaluation could be formulated as well as how computation of identified criteria can be executed.

2.1. Semi-structured interview and focus group

Given the number of entities involved within the area, it is vital that all possible criteria are identified to satisfy their needs. The method involves semi-structured interviews in addition to a focus group activity where reasoning and answers from the semi-structured interviews are discussed further to ensure that all perspectives have been covered. The interviews were conducted with representatives from different organizations, presented in supplementary data S1, working at various management levels within their respective organizations, including parties with direct responsibility for supplying water, consultants working mainly with installations or greywater reuse and property owners. Consultants play an important role in driving the development of new technologies that are used. Property owners are primarily responsible for investment in decentralized systems. Authorities issuing building codes and regulations may have a holistic view of possible regulatory barriers and consequences. All entities selected for interview operate within either Stockholm or Gothenburg, which are the two largest municipalities in Sweden in terms of number of inhabitants. The broad background was selected to achieve saturation early on during the interview process using a code meaning approach (Newcomer et al., 2015; Hennink and Kaiser, 2022).

The session was divided into one individual part and one group interview or discussion part. The individual part was used to allow representatives to give an individual answer to each question, and the

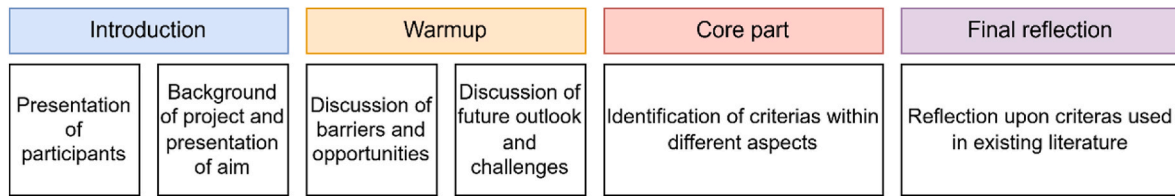


Fig. 2. Layout of semi-structured interviews.

group discussion part was used to allow the participants to discuss the question with each other to identify potential answers related to the answers of other participants.

2.1.1. Layout

A similar approach as Bearman (2019) suggested was used when planning the layout of the interviews which is presented in Fig. 2. A



Fig. 3. General criteria identified during the interviews.

Table 1

Suggested indicators to be measured were determined based on the criteria identified for each aspect. In some cases, a criterion was divided into two or three separate criteria, depending on how it was discussed during the interview. The criteria listed in the table reflect the way each aspect was addressed in the discussions. S means that the stakeholder identified the indicator while L means that the indicator was found in literature.

Aspect	Criterion identified	Suggested indicator needed to quantify criteria	Source	Suggested metric	
Total flow	A	Total water use	Annual total water utilized	S	m ³ /yr
	A	Municipal water demand	Annual municipal water utilized	S	m ³ /yr
	B	Wastewater volume impact	Annual greywater volume (released)	S	m ³ /yr
			Annual blackwater volume (released)	S	m ³ /yr
			Annual stormwater volume (released)	S	m ³ /yr
			Annual condensate volume (released)	S	m ³ /yr
	B	Water retention within building	Maximum volume that can be stored locally	S	m ³
			Impact on wastewater treatment efficiency	Efficiency of biological treatment	S
	B	Impact on wastewater treatment efficiency	Average temperature of incoming water	S	
			Impact of water use during lifetime	LCA of total water used (embodied water, operational water, recurrent water)	S
D	Maximum water use	Peak municipal water demand	S	m ³	
		Peak water demand	S	m ³	
		Ability to supply water locally	Annual volume of water produced or recovered locally	L (Namavar et al., 2023)	m ³
E	Ability to supply water locally	Water resource recovery as a reference to total water demand	L (Kakwani and Kalbar, 2022)	%	
		Peak energy demand	S	kW	
Recycled water use	F, G, I	Water circularity	LCEA (embodied energy, operational energy, recurrent energy)	S	MWh/functional unit. (ex. m ²)
			Energy produced locally as a reference to bought energy	L (Al et al., 2020)	%
Energy performance	J, K	Maximum energy demand peak	Seasonal coefficient of performance	L (Al et al., 2020)	–
			Energy storage capacity	L (Al et al., 2020)	kWh
	L	Impact of energy during lifetime	Annual energy utilization	S	KWh/yr, m ² (bought, primary etc.) or other
			Total energy consumption	Bought annual energy consumption	L (Boverket, 2020)
	N	Energy self-sufficiency	Energy consumed due to production and treatment of water	S	kWh/m ³ total water consumed
			Efficiency of installed systems	–	
	P	Energy storage	–		
			Energy consumption with relation to national regulations	–	
	Q	Total energy consumption	–		
			Energy efficient production and treatment of potable water (mains water)	–	
R	Energy efficient production and treatment of potable water (mains water)	–			
		–			
Climate impact	S	Global warming mitigation of system within building	Carbon dioxide equivalent of system	S	CO ² -eq.
			Carbon dioxide equivalent of system boundaries building/site boundaries	S	CO ² -eq.
Microbiological security, public health	U, V	Risk of leakage and microbial contamination- through QMRA	Effect on disease burden	L (Åström et al., 2016)	Disability-adjusted life year per person per year (DALY ppy)
			Impact of social health of users of system	L (Portman et al., 2022)	%
Public health, societal acceptance	X, AF, AG	Impact of social health of users of system	Price of energy, water or rent	S	EUR, USD, etc.
			–		
Economic performance, societal acceptance	Y, AC	Economic incentive for user	–		
			–		
Economic performance	Z, AA, AB	Economic incentive for investment	Return of investment (ROI)	S	%EUR, USD/functional unit (ex. m ²)
			Life-cycle cost (LCC)	S	
Recycled flow, energy performance	H, M	Impact on water and energy infrastructure	Total cost of water infrastructure	S	EUR, USD, etc.
			–		
Societal acceptance	AD, AE, AF, AH	Green value for the user	Green building certifications	S	–
			Complexity of system	– ^a	– ^a
			System scalability	– ^a	– ^a
			Maintenance interruptions	System average interaction frequency index	L (IEEE, 2001)
Resilience and flexibility	AI	Inbuilt redundancy of energy and water supply	System average interruption duration index	L (IEEE, 2001)	Minutes, hours, etc.
			Autonomy duration (water supply)	L (USEPA, 2014)	Hours, days, etc.
			Autonomy duration (energy supply)	L (Rodrigues et al., 2020)	Hours, days, etc.
	AJ, AK, AL	Maturity of system	System autonomy duration (energy and water supply)	L (USEPA, 2014; Rodrigues et al., 2020)	Hours, days, etc.
			Technology readiness level	L (APRE, 2022)	–
			–		

^a No specific indicator was identified during the interview.

short introduction initiated the interviews by presenting the background of the project, the aim and results of other similar interviews. During this section the participants were given the opportunity to interrupt and ask follow-up questions to elucidate potential concerns. In addition,

participants were also given the opportunity to present themselves to the other participants to give an opportunity to understand each other's roles and perspectives.

The layout of the interviews was based upon area of interest, here

Table 2
Default inclusions in each system boundary for the 11 indicators for the national criteria.

	Building/site	Upstream/downstream	Life cycle
Annual total water utilized	W_{in}	$W_{in} + W_{loss}$ (leakage)	$W_{in} + W_{loss} + W_{embodied} + W_{recurrent}$
Water resource recovery as a reference to total water demand	WC_{local}	$WC_{municipal}$	–
Bought energy consumption	E_{local}	$E_{local} + E_{pumps} + E_{treatment}$	$E_{embodied} + E_{recurrent}$
Return on investment	Based on direct utility savings	Included avoided infrastructure costs	–
Life-cycle cost	Direct investment and cost	Includes avoided infrastructure costs	–
Annual energy utilization using national method	Calculated using local building regulation	–	–
Global warming potential (GWP100)	$E_{operational} \cdot EF_{grid}$	$(E_{pumps} + E_{treatment}) \cdot EF_{grid}$	$GWP_{embodied} + GWP_{recurrent}$
QMRA	Risk at point use	Risk at source + treatment efficiency	–
Technical readiness level	Technology maturity at building level	–	–
Energy produced locally as a reference to bought energy	Local production and utilization	Site specific production and utilization	–
System autonomy duration (SAD)	Critical time for building	Critical time for district	–

called “aspects”, identified by La Torre Rapp et al. (2024). These aspects include System water throughput (total volume of water supplied, treated, or reused within the system), Recycled water use (the role of recycled water in meeting demand), Source-demand distribution (the allocation of water sources within the building or between neighboring buildings), Economic performance (financial and economic implications of the system), Energy performance (energy demand and utilization affected by the system, including interactions with related services such as heating and cooling), Climate impact (potential implications for greenhouse gas emissions), Societal acceptance (user and stakeholder acceptance, including perceptions of safety, aesthetics, and trust), Microbiological security (potential risk of microbial contamination and pathogen growth), Public health impact (effects on well-being of affected users), and System resilience (ability of the system to withstand and adapt to changes in water demand, supply, or external disruptions).

Importantly, these aspects are not used directly as evaluation indicators. Instead, they function as guiding dimensions that support stakeholders in defining appropriate, context-specific criteria and metrics for system performance assessment.

In practice, each aspect can be interpreted across different disciplines or system boundaries, for example cost of system (Chen et al., 2023) or financial relief due to reduced stress of infrastructure (De et al., 2018). Accordingly, these aspects served as a guide for participants to identify criteria within their respective discipline or system boundaries, see supplementary data S1 and S2. While perspectives frame the broader stakeholder views or system boundaries, aspects provide concrete domain-specific dimensions that can be applied within each perspective to develop tailored evaluation criteria or metrics. Due to the interconnected nature of these concerns, some overlap exists between perspectives, reflecting that they are strongly interconnected. Thus, the structure of the interview should be understood as a guide that helps the stakeholders to define all criteria of interest rather than exhaustive lists of all aspects and perspectives.

The participants were also encouraged to propose criteria from other disciplines or system boundaries of their own choice.

To extract an appropriate criterion from the semi-structured interviews, thematic coding was used. Statements are filtered on the basis of whether they can be used to formulate one or many criteria. Examples include statements like “decoupling of water demand” and “how much water is used by the facility” or “system that can provide resilience of the water supply during droughts or halt flooding during heavy rain”.

2.1.2. Identification of indicators

The indicators presented in this paper were derived by operationalizing the core criteria of relevance identified during the stakeholder interviews. Where stakeholders explicitly proposed indicators as existing industry benchmarks, these were adopted directly into the framework. In the case where priorities were expressed qualitatively, existing

literature was used to derive suitable indicators to provide a quantitative measure and were selected based on their ability to reflect the concern raised by the stakeholders and standardized indicators already used or indicators identified in the literature within the area.

2.2. Formulation of framework

The semi-structured interviews aim to give insight into the construction of all base steps of the suggested framework as well as important criteria to consider: Setting the system boundaries, understanding the local prerequisites, selecting appropriate system solutions, and assessment and analysis. The process thus involved understanding the system boundary and preferred criteria, the indicators of importance for determining the site potential, the selection of systems, and criteria for evaluation.

2.3. Proof of concept

To demonstrate the framework’s applicability, a proof of concept was performed for a theoretical residential building in Stockholm, Sweden utilizing indicator values derived from existing literature. In addition, a sensitivity analysis was performed to test robustness of system ranking.

3. Results

3.1. Identified criteria

Stakeholder priorities were observed to diverge slightly. The property owner mainly focused on value creation for the tenants, by underscoring the importance of system legibility, operational reliability and property value, while consultants, particularly those specialized in greywater reuse, focused on the broader social benefits of local recovery. Following the stakeholders’ engagement, a total of 30 general criteria were identified across the 10 aspects; energy performance and societal acceptance generated the highest number of criteria, with 9 and 6 respectively. During the interview, many suggested indicators were expressed as a measure of impact of a certain metric (lower energy demand, water demand), see Fig. 3, and can thus be interpreted in a generally broad way. In addition, a few criteria regarding microbiological security and health were identified where only risk of leakage was mentioned by the participants. However, a discussion about ensuring system robustness through sufficient measurable precautions to prevent negative health effects followed. The discussion that followed the identification of criteria “F”, “G”, “J”, “K”, “H”, and “M” resulted in difficulties in stating single indicators representing the entire criterion. The initial criteria were rephrased because some recurred multiple times across different aspects. In addition, since some criteria, such as “F” and “G”, were interpreted as rather redundant during the discussion they

were joined into one criteria.

A total of 30 criteria were identified after processing, each one of which requires one or more indicators to be quantified: a total of 60 indicators shown in Table 1. These involve indicators such as operational impacts, investment efforts needed (energy or cost), as well as reference values, to enable comparison. Since the discussion revolved around what to compare the assessed system with, or just assessing the prevailing system itself, both indicators referring to previous performance of the system and indicators referring to national average are included in the table as it aims to list all possible parameters potentially needed based on interviews.

A majority of the identified criteria and indicators refer to processes within the buildings itself, such as energy and water savings, while others focus on indirect impact of the system from a societal level, such as reduced investment cost of infrastructure, or impact of treatment efficiency of wastewater facilities. Regional criteria and conditions can impact how well a system is performing and thus also results in minor or no impact in the total system analysis (Golzar and Silveira, 2021). The parameters are therefore arranged at a system level spanning from national criteria to regional, and project specific criteria to allow for adaptability depending on condition of the assessed site.

3.2. Suggested national criteria, indicators and metrics

Here follows suggested national criteria as well as definitions and metrics. Since all criteria may be evaluated different depending on scope and system boundaries, Table 2 provides a holistic overview of what each system boundary may include.

3.2.1. Annual total water utilized

Regardless of the specific water source utilized, the total volumetric water demand can serve as a metric for determining the resource efficiency of a system. While traditional buildings rely almost exclusively on municipal water to meet functional needs, including showering, washing, flushing and domestic hot water (DHW), decentralized systems

3.2.2. Water circularity

Greywater reuse, or other systems that utilize water from released water sources create a decoupling between total water demand and municipal water demand. Thus, such a system will not reduce the total water demand but rather increase the circularity. Water circularity (WC) is therefore a measure of how much water is recirculated (see eq. (1)).

$$WC = \frac{\sum_{k=1}^j \text{Water utilized from source}(j)}{\sum_{n=1}^m \text{Water utilized for service}(n)} \quad (1)$$

3.2.3. Total energy utilized

The change of energy consumption as a consequence of the system can occur on different levels of society, and different systems affect different parts of it. On local level (within the building envelope) operational demand such as heating, cooling and electricity could be affected; either by reduction of existing demand or as a consequence of larger energy demands for pumps or for a treatment process (Knutsson and Knutsson, 2021). Embodied energy (EE) such as equipment needed for a certain system solution also contributes to the energy consumption of a system either as initial EE or as recurrent EE (Proenç et al., 2013; Crawford and Pullen, 2011) seen in eq (2). may be considered for a life-cycle perspective. On a social level, energy demand may originate from the treatment of raw water and wastewater, and pumps, see eq (3). A reduced amount of water demand may thus lead to lower energy demand on a societal level. Initial and recurrent EE also occur in terms of infrastructure installed. In addition, it is important to consider changes to for example reduce wastewater treatment on the societal level since lower temperature may impact the biological treatment degradation and hence then energy consumption of the treatment infrastructure as well as energy recovery (Golzar and Silveira, 2021). The system boundaries may be defined only including operational energy or expand to be more similar to a life-cycle energy assessment depending on the size of the assessed site or the need of the stakeholder.

$$\text{Local energy consumption} = \sum \begin{matrix} \text{Heating} \\ \text{DHW} \\ \text{Space heating} \\ \text{Ventilation} \end{matrix} + \sum \begin{matrix} \text{Cooling} \\ \text{Space cooling} \\ \text{Ventilation} \end{matrix} + \sum \begin{matrix} \text{Electricity} \\ \text{Demand} \\ \text{Production} \\ \text{Treatment} \\ \text{Pumps} \end{matrix} \left(+ \sum \begin{matrix} \text{Initial EE} \\ \text{Equipment} \end{matrix} + \sum \begin{matrix} \text{Recurrent EE} \\ \text{Replace. prod.} \end{matrix} \right) \quad (2)$$

$$\text{Societal energy consumption} = \sum \begin{matrix} \text{Treatment} \\ \text{Potable water} \\ \text{Wastewater} \\ \text{Production of el.} \\ \text{Energy recovery} \end{matrix} \left(+ \sum \begin{matrix} \text{Initial EE} \\ \text{Equipment} \\ \text{Infrastructure} \\ \text{e.g Pumps} \end{matrix} + \sum \begin{matrix} \text{Recurrent EE} \\ \text{Replace. prod.} \end{matrix} \right) \quad (3)$$

might use local recovered sources to meet these. Therefore, the assessment focus shifts from potable intake to total water throughput. The measurement can thus be done either on component level or at the primary source intake, depending on how the analysis is performed.

3.2.4. Return on investment (ROI)

Many of the property owners expressed an interest in assessing the economic performance of the system, specifically ensuring that the cost of investment (COI) does not exceed the associated cost benefits, thereby resulting in a positive net profit (NP). A common way to quantify this performance is by estimating the return on investment (ROI), calculated

Table 3
Suggested regional and project related indicator.

Suggested regional and project related indicators
Peak energy load (kWh)
Peak water load (m ³)
Energy storage (kWh)
Wastewater released (m ³)
Seasonal coefficient of performance (–)
Embodied energy of system (MJ)
Embodied GWP of system (Ton CO ₂ -eq)
Energy utilized for production and treatment of cold water and wastewater per utilized volume (kWh/m ³)
Cost of infrastructure needed (EUR, USD, etc.)
Rate of acceptance of source and purpose of tenants (%)

using eq. (4). This formulation represents a simple, undiscounted ROI and does not account for the time value of money.

$$ROI = (NP/COI) \cdot 100 \quad (4)$$

3.2.5. Life-cycle cost (LCC)

If more than one system is assessed (i.e. the multi-criteria decision analysis is intended to be performed) the period of time used for evaluation should be selected such as only multiples of each system's solution lifespan is used, even if 50 years of lifespan has been used. Due to existing standards, long lifespans up to and beyond 80 years have also been used (Davis et al., 2025). Thus, the lifespan selected can be specified depending on the aim of the project. Calculation of the life-cycle cost is done according to equation (5), where the total cost of the system comprises capital cost (CC), operational cost (OC), maintenance cost (MC) and disposal cost (DC).

$$LCC_{system} = \sum CC + \sum OC + \sum MC + \sum DC \quad (5)$$

3.2.6. Global warming potential

The global warming potential in this context includes two components: embodied greenhouse gas emissions and emissions associated with the reduced use of primary resources such as energy or water. Depending on stakeholder priorities, either or both components can be included within the defined system boundaries. It is ultimately up to the stakeholders to determine what to consider, although standardized methods are available to guide this process. (Huang et al., 2024). A life-cycle assessment (LCA) approach is therefore appropriate, with the assessment period aligned to the timeframe used for estimating life-cycle cost savings.

3.2.7. Risk of leakage and microbiological contamination

Given the potential risk of contamination or leakage affecting water sources, it is recommended to conduct a Quantitative Microbiological Risk Assessment (QMRA). A QMRA helps to identify and illustrate potential risks within the system and can be applied through various frameworks. The assessment can provide results at different levels of detail, depending on the context, such as for groundwater sources or greywater systems (Åström et al., 2016; Shi et al., 2018).

Many system solutions propose the use of water sources that, if left untreated, may pose health risks, such as greywater, rainwater, or blackwater (Schets et al., 2010; Shi et al., 2018). The stakeholders emphasized the importance of conducting some form of risk assessment to help quantify and better understand these potential hazards. A quantitative microbiological risk assessment could therefore ensure the disease burden is not too high. For example, for greywater use in agriculture and drinking water guidelines, the suggested benchmark from world health organization (WHO) is $\leq 10^{-6}$ disability-adjusted life year (DALY) loss per person year (pppy) (Shi et al., 2018; Mara and Kramer, 2008). Although, a benchmark or threshold may vary depending on type of exposure (e.g., air, water, food, etc.) and summing up all of these might result in a larger exposure than 10^{-6} . The 10^{-6} threshold can also be considered stringent and thus very difficult to achieve in certain

settings without unrealistic cost. (WHO, 2022; Duncan, 2011). Recognizing that a proposed system solution can involve multiple different exposure routes, a cumulative DALY is appropriate to estimate.

3.2.8. Technology readiness level

Stakeholder interviews underscored that technological robustness and maturity are critical for implementation. Consequently, the framework adopts a technology readiness level (TRL) to quantify this aspect. The nine-level indicator scale, defined by the European commission provides a standardized method for positioning projects and evaluating technological maturity (Commission, 2017a). By applying this, the stakeholder can distinguish between technologies where only basic principles have been demonstrated (TRL 1) and those where the actual system is proven in an operational environment (TRL 9) (APRE, 2022).

3.2.9. Energy consumption according to national standard

Many certification methods and national energy efficiency goals are closely linked to the energy consumption of the building itself, and hence, also of great interest for the stakeholder. To align the development of water systems with national energy goals of achieving energy efficient buildings, the energy consumption, according to the national regulation (primary energy consumption, bought energy etc.) should be depicted. Many stakeholders mentioned during the interview process that they are principally restricted by these even if they aim to achieve a lower energy consumption than the regulations, since certification criteria sometimes are set as a percentage of the national regulation limits. Given that the national regulations differ depending on the country, and that "bought" energy or "consumed" unit of energy does not always align with the calculation of the energy performance with regards to the national standard, a suggested criterion is thus to use the national regulations of which energy performance is calculated to display.

3.2.10. Self-sufficiency of energy

De-coupling of energy demand and purchased energy may arise in the case of a certain system solution without leading to a reduction of energy demand; thus, the self-sufficiency of energy (SSoE), just as circulation of water may be important to establish, especially for greywater reuse (Knutsson and Knutsson, 2021). Energy demand will here only refer to operational energy demand and not embodied energy nor energy demand for production and treatment of municipal water but may as well include that if the framework is used for assessment of buildings that hold such a service. SSoE can consequently be calculated as in eq. (6).

$$SSoE = 1 - \left(\frac{\sum \text{Purchased energy}}{\sum \text{Operational energy demand}} \right) \quad (6)$$

3.2.11. Resilience

Current national security underscores the need for robust systems that maintain core function during infrastructure stress or disruptive events (Madni and Jackson, 2009). While efficiency metrics focus on

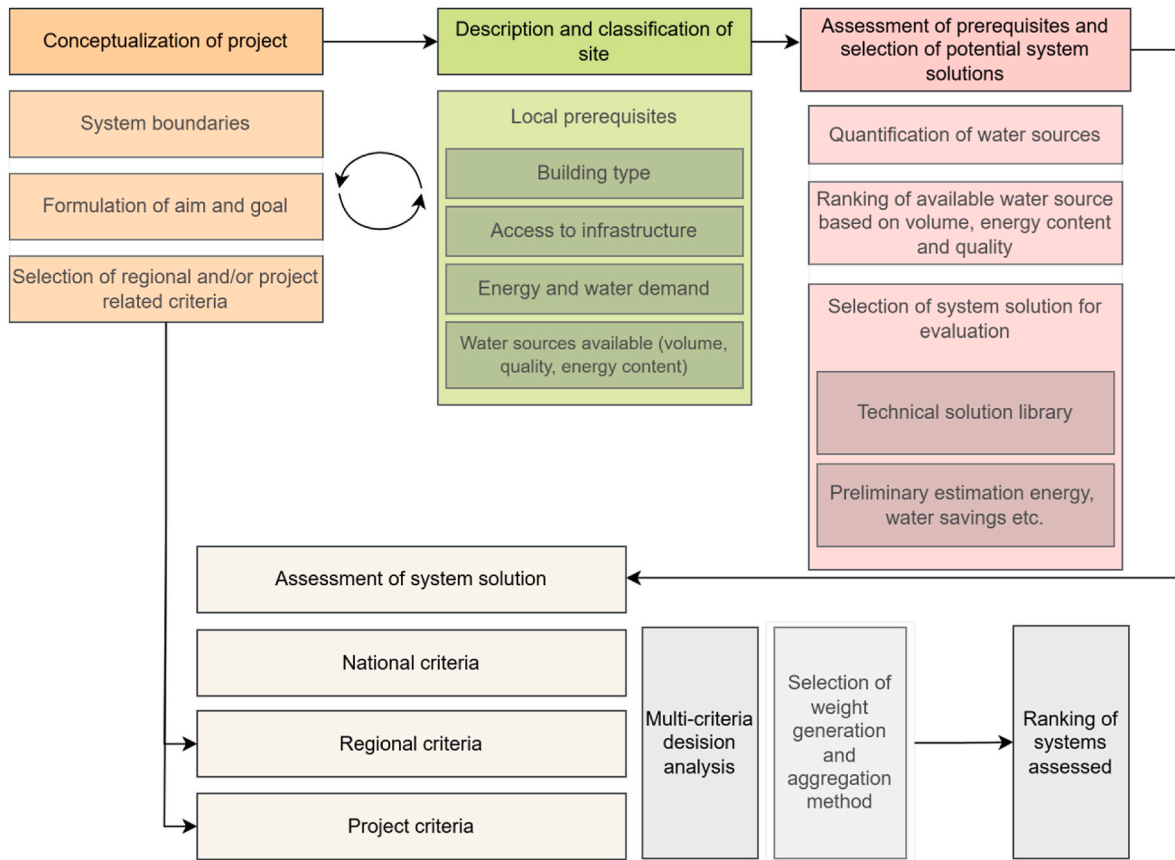


Fig. 4. Outline of conceptual framework.

resource saving, system resilience evaluates the capacity for a system to sustain normal service if any or all utility networks fail. In this framework, resilience is quantified through the autonomy duration (AD) of each resource (i). AD estimates the temporal window of duration in which a system satisfies internal demands only using local reserves. The AD for any given supply (water, electricity, district heating, etc.) is determined by the ratio of available stock in reserve ($S_{reserve}$) and the total net rate of depletion (\dot{D}_{net}) as shown in eq. (7). The system autonomy duration (SAD) can then be computed according to eq. (8). The temporal unit (hours, days) should be selected based on the expected timeframe of the disruption. Decision makers may also employ more sophisticated probabilistic modeling or dynamic simulations within the framework if the specific urban context require higher granularity.

$$AD = \frac{S_{reserve}}{\sum \dot{D}_{net}} \quad (7)$$

$$SAD = \min(AD_{water}, AD_{energy}) \quad (8)$$

3.2.12. Suggested regional and project related criteria

The interview showed that each site of consideration may suffer from different challenges, certain criteria may be more important than others. This can include constraints in water and energy infrastructure, infrastructure development, limitation of any water resource, periods of heavy rain or long droughts (IPCC Masson-et al., 2021) or limitations in terms of access to freshwater and thus having to rely on desalination plants. In addition, property owners also showed an interest in being able to obtain an increased property value when improving the energy and water performance of a building, as well as being able to deliver this message in a clear way to tenants. A set of criteria have thus been identified that can serve as a basis; these include criteria that are strongly linked to regional restriction or project goal. Such criterion

could be peak demand reduction, that refers to the maximum demand that occurs during a certain period of a certain resource of use such as water, electricity, district heating, district cooling or wastewater volume. This may be important in regions subjected to constrained infrastructure and can serve as an indicator of how well the system performs on a societal level. The assessment should follow regional or national procedures when determining the maximum water flow or energy or other metrics described by my local regulations. Additional regional criteria suggested are “change of wastewater volume”, “retention volume”, “energy storage”, “economic incentive of tenant”, see Table 3 for listing of all suggested criteria based upon the interviews.

3.3. Formulation of conceptual framework

The Decision Support Framework (DSFW) consists of five major parts that comprise the main activities for selection and development of a sustainable water supply system, see Fig. 4. These are:

- **Conceptualization of project:** The main goal of the project is defined which sets the boundary condition in terms of critical criteria and system boundaries for evaluation as well as magnitude.
- **Description and classification of site:** Local conditions are identified in order to facilitate selection of system solution for evaluation. This includes identification of potential of prevailing water sources (rainwater, greywater, blackwater, etc.) as well as, if the site itself has limited access to any infrastructure managing demand-driven or released water sources.
- **Technical Solution Library:** By representing the site prerequisites using previous steps, facilitation of system selection can be done in conjunction with a repository of water and energy-efficient system solutions (such as greywater reuse, low-flow water fixtures, rainwater harvesting etc.)

Table 4
Proposed procedure for classification of site of investigation.

Feature	Means of measure
Type of building	Residential, office, school, other
Annual energy demand	Demand of either all systems providing energy or selected energy system (electricity, heating cooling) if overall choice of system is determined.
Annual water demand	Demand of all water sources or selected water sources if the overall choice of system is determined.
Access to water infrastructure	Degree of access: <ul style="list-style-type: none"> • Full access to supply and wastewater collection • Limited access to supply and wastewater collection • No access to supply and wastewater collection
Access to energy infrastructure	Degree of access: <ul style="list-style-type: none"> • Full access to heating supply cold supply and electricity. • Limited access to heating supply, cold supply and electricity. • No heating supply cold supply and electricity.
Energy content, water sources	kWh/m ³
Quality of water sources	Degree of contamination (COD, BOD etc.)
Volume of water sources	m ³ /year

- **System assessment:** Based upon defined goals and core criteria a set of parameters are selected for evaluation. This includes energy savings, water savings, cost savings, robustness based upon stakeholder interview. The possibility of adding project specific parameters is also available to align results to local conditions or stakeholder-specific goals.
- **Multi-Criteria Decision Analysis:** Core criteria enable holistic overview of selected system solutions by displaying direct impact such as energy savings and return of investment and indirect implications of the system such as robustness, resilience and maintenance demand. Since this is intended to be a multi-stakeholder approach, or "holistic" DSFW it is important to emphasize the inclusion of mandatory criteria from different stakeholder types. Those criteria may be excluded only if they are clearly not relevant in project specific context.

3.3.1. Conceptualization of project

The formulation of the project specific aims and goals helps identify the core criteria and the appropriate system boundary for evaluation. A core feature of the framework is the modular boundary logic, which allows for adaptation based on the specific objective of the assessment. Rather than enforcing a static boundary, the framework required the

user to define the scope of the analysis. This ensures that it remains scalable and can serve stakeholders focusing on building level performance and authorities focusing on city-wide infrastructure. Consequently, three distinct system boundary levels are suggested: a direct, one-site, boundary where energy and water flows within the building is addressed; a displaced, upstream and downstream boundary where potential energy and water flows entering or released from the site are addressed, or a life-cycle boundary where the embodied energy and water of the whole system are included.

3.3.2. Description and classification of site

Initial identification of the site is performed to enable an overview and to detect critical systems with high potential. This includes "types of building", "energy demand", "water demand" etc. see Table 4. An iterative procedure is possible to use to align overall goal with local condition of selected site or area. By identifying these criteria, the stakeholder can get a clear overview of the status of the building or location and thus frame the approach of development of the water system. By identifying constraints such as access to critical infrastructure or available water source volume, critical points of approach can easily be identified, and thus serve as a foundation when deciding system solutions for evaluation. In addition, by identifying the energy potential (defined as the energy that can be extracted from available water

Table 5
Calculation of national criteria for multi-criteria decision analysis.

Criterion	Indicator	Normalization
Total water use	Annual total water utilized	$1 - \frac{\text{Annual total water utilized}_{\text{system}}}{\text{Baseline}}$
Water circularity	Water resource recovery as a reference to total water demand	WC_{system} see eq.1
Total energy utilized	Bought energy consumption	$1 - \frac{\text{Annual bought energy utilized}_{\text{system}}}{\text{Baseline}}$
Economic incentive for investment	Return on investment	$\frac{ROI_{\text{system}}}{\text{Baseline}}$
Economic incentive for investment	Life-cycle cost	$1 - \frac{LCC_{\text{system}}}{\text{Baseline}}$
Energy consumption with relation to national regulations	Annual energy utilization using national method	$1 - \frac{\text{Annual energy utilized}_{\text{system}}}{\text{Baseline}}$
Climate impact	Global warming potential (GWP100)	$1 - \frac{GWP100_{\text{system}}}{\text{Baseline}}$
Risk of leakage and microbial contamination	QMRA ^a	$\begin{cases} 1 & \text{if } DALY_{\text{total}} \leq 10^{-6} \\ \frac{\log_{10}(DALY_{\text{tot}}) - \log_{10}(10^{-4})}{\log_{10}(10^{-6}) - \log_{10}(10^{-4})} & \text{if } 10^{-6} \leq DALY_{\text{total}} \leq 10^{-4} \\ 0 & \text{if } DALY_{\text{total}} \geq 10^{-4} \end{cases}$
Maturity of system	Technology readiness level	$\frac{TRL}{9}$
Energy self sufficiency	Energy produced locally as a reference to bought energy	See eq. 6
Resilience	System autonomy duration (SAD)	$\begin{cases} \frac{SAD_i}{SAD_{\text{max}}} & \text{if } SAD_{\text{max}} > 0 \\ 0 & \text{if } SAD_{\text{max}} = 0 \end{cases}$

^a The limits can be adjusted to fit project goals or local context.

Table 6

Project description, system boundaries, and energy and water potential.

Goal	Reduce energy within the water infrastructure, and reduce constrains on the wastewater treatment infrastructure and achieve a better energy performance while keeping the users trust and willingness to utilize the systems						
Regional and project criteria	<ul style="list-style-type: none"> • Wastewater released • Energy used for production and treatment in relation to total consumed volume • Acceptance/willingness of users 						
System boundaries	Operational phase of the water and energy system within the building as well as the treatment and production of wastewater and municipal water at the water utility (displaced boundary)						
Building type	Residential building						
Access to infrastructure	Energy and water demand						
Full access to supply and wastewater collection	Primary energy: 17.5, 20, 37.5 kWh/m ² , yr (DWH, electricity, space heating)		Water sources available based on La Torre Rapp et al. (2024)				
Full access to heating supply. and electricity. no use of district cooling	Water demand: 140l/p, d where 34l/d, p of DWH		Rank	Volume [m ³]	Energy content [(kWh/m ³)]	Total energy content [MWh]	Quality [-]
	1	GW (3 600)	1	GW (639)		GW (138)	RW (4)
	2	BW (1 000)	2	BW (54)		RW (93)	GW (2.5)
	3	RW (144)	3	GW (39)		BW (54)	BW (1)

sources per unit volume, measured in kWh/m³, the selection of appropriate system solutions is further facilitated. This potential may include thermal energy (sensible heat for preheating, latent heat for cooling), or chemical energy (for biogas production) but is dependent on local conditions.

3.3.3. Technical solution library and indication of system possibilities

By classifying the available water sources and infrastructure, a holistic view of the water and energy potential of each source can be established, utilizing the values for typical building types identified by La Torre Rapp et al. (La Torre Rapp et al., 2024). This assessment provides the foundation for selecting appropriate solutions for the site, which are then prioritized for evaluation. A repository of technical solutions (Table S2), provides an overview of compatible water sources and the specific energy type provided, facilitating system selection for a specific target building, or project site.

3.3.4. Assessment of system solutions

Based upon core criteria and their relevant measurable indicators as well as project specific criteria, an assessment of the performed system should be conducted. Each of the indicators can be estimated either by simulation or assumption, which makes it possible for the stakeholders to choose the level of detail, hence accuracy. The 10 predefined national measurable criterion display a profound view of how the systems perform in aspects covering direct and indirect impacts. System solutions impacting released water sources will demonstrate reduction in wastewater systems (covered by the indicator “water demand”) and thus impact on key infrastructure further downstream.

3.3.5. Multi-criteria decision analysis (MCDA)

The MCDA framework utilized the national criterion alongside selected regional and project-related criteria, with each being normalized to a dimensionless scale. To ensure adaptability, the framework accommodates various normalization techniques, presented in Table 5, depending on the unit and nature of the indicator. For criteria where a higher value is inherently positive and lacks upper theoretical limit (e.g. return on investment), the highest-performing system serves as the benchmark (value = 1). Conversely, for indicators where a lower value (>0) is preferred (e.g. annual water utilization, life-cycle cost, global warming potential or energy utilization), the worst-performing system serves as a benchmark. Indicators already on a dimensionless scale (e.g. water circularity or energy self-sufficiency) the absolute value can be employed directly. Criteria like the health indicator measured in DALYppp generates numbers that can differ significantly. This makes it difficult to perceive the risk. Hence, a logarithmic scale can be used (Block et al., 2024) instead with upper and lower limits. All systems performing worse than upper limit received 0 and all systems above received 1. System performing in between normalization using a

distance to target log ratio. This facilitates the integration of diverse criteria and trade-offs, enabling decision-makers to balance competing objectives. Consequently, municipalities and project owners can conduct scenario analyses to test the impact of different weights on system rankings.

Before aggregation, the user may employ a threshold analysis to ensure that evaluated systems align with overarching policy or specific project goal. By establishing a threshold for specific indicators, either defined within the national, regional or project level, the system assessed can be flagged or excluded regardless of performance in other indicators. System that passes initial analysis can then be evaluated using a weighted scoring method.

3.3.6. Weighting protocol

The framework is designed to be weight-agnostic, allowing future users to select the most appropriate method depending on data availability and the project's governance requirements. A three-tiered weighting protocol is proposed:

- Subjective methods: If stakeholders are available, methods like eigenvector (Takeda et al., 1987), pairwise comparison or others, through for example an analytical hierarchy process (AHP) can be used to capture expert priorities tailored to the goal of the project. While these weights reflect local values, they are inherently subjective and vary depending on participants.
- Objective methods: In order to derive objective weights, that are not dependent on a stakeholder group methods like the automatic democratic method (ADM) can be employed (Tofallis, 2013). The method identifies the optimal common weights by minimizing the sum of absolute difference between each system's maximum achievable score, determined using data envelopment analysis (DEA), and the computed score. There are several approaches to this, such as choice of minimizing function or utilizing upper and lower boundaries (Tofallis, 2022). Other methods involve maximizing deviation method (Wang, 1997), TOPSIS and entropy method. Another simple methods involve setting the weights equal, which could be the base if no stakeholder or information is available, which is a popular method in sustainable energy decision making (Wang et al., 2009).
- Combination: A combination of both an objective and a subjective method can be employed where either the product of the two weights or a linear combination of those are used (Wang et al., 2009).

3.3.7. Selection of MCDM-method

The assessment scale significantly influences both data availability and the relationships between selected indicators. As the scale increases the likelihood of co-linearity increases; in these scenarios, distance-based methods such as TOPSIS or VIKOR are preferred compared to WSM. In contrast, outranking methods like ELECTRE and PROMETHEE

Table 7

Assumptions made to compute indicators for each system assessed.

Indicator	Assumptions Linear system	Greywater recovery for water supply to showers and bathroom sink	Greywater recovery for flushing of toilets
Total annual water utilized	40 m ³ /p (Swedish statistics, 2024). 140 l/d p	(Segerström, 2022)	
Water resource recovery as a reference to total water demand	No water source recovery	58.2% hot water reduction and 5.8% cold water reduction (Knutsson and Knutsson, 2021)	16.7% cold water reduction (Knutsson and Knutsson, 2021)
Bought energy consumption	25 kWh/m ² PE. 0.7 factor for district heating (Boverket, 2017). district heating price of 0.85 SEK/kWh (Egüez, 2021)	15.9 kWh/m ² for heating cold water to hot water (Knutsson and Knutsson, 2021)	25 kWh/m ² (Boverket, 2017)
Return on investment	No investment done	Installation and maintenance cost based on Wallin et al. (Wallin et al., 2021) adjusted to number of people.	Based on Wallin et al. (Wallin et al., 2021) with omission of heater.
Life-cycle cost	Omitted	Omitted	Omitted
Annual energy utilization using national method	The building has energy class C; primary energy is used. District heating is assumed to be used for heating purposes. ^a	District heating. Energy reduction due to less DHW and energy for treatment included. 0.7 and 1.8 in primary factors for DH and electricity (Boverket, 2020).	Energy reduction for treatment included. 0.7 and 1.8 in primary factors for DH and electricity (Boverket, 2020).
Global warming potential (GWP100)	0.064 kg CO ₂ -eq/m ³ for production. 0.014 kg CO ₂ -eq/m ³ for water network and 0.35 kg CO ₂ -eq/m ³ for treatment. 0.0504 kg CO ₂ -eq/kWh electricity (Stockholm vatten et al., 2025). 0.046 kg CO ₂ -eq/kWh district heating (Stockholm Exergi, 2024).		
QMRA	Omitted	Omitted	Omitted
Technology readiness level	Actual system proven in operational environment (Comission, 2017b)	System prototype demonstration in operational environment (Comission, 2017b)	Actual system proven in operational environment (Comission, 2017b)
System autonomy duration	No backup system exists	Water tank exist but there is no backup for electricity for pumps.	Water tank exist but there is no backup for electricity for pumps.
Energy produced locally as a reference to bought energy	No energy recovered or produced locally	58.2% hot water reduction and 15.9 kWh/m ² for heating cold water to hot water (Knutsson and Knutsson, 2021)	No energy recovered or produced locally
Wastewater released	Same volume as annually utilized	58.2% hot water reduction and 5.8% cold water reduction (Knutsson and Knutsson, 2021)	16.7% cold water reduction (Knutsson and Knutsson, 2021)
Energy used for prod. and treat. per consumed volume of water	0.49 kWh/m ³ for production and 0.61 kWh/m ³ for treatment (Stockholm vatten et al., 2025)	0.66 kWh/m ³ for treatment and 1 kWh/m ³ for pressurizing water circuit (Knutsson and Knutsson, 2021)	
Acceptance/willingness to use system	Standard system used today, 100% acceptance	Based on Lambert & Lee (Lambert and Lee, 2018), white collar worker. Assumed to be equal to drinking water perception	Based on Lambert & Lee (Lambert and Lee, 2018), white collar worker

^a The Swedish building regulations currently being renewed but since there are not fully established yet. The current energy regulations regarding primary energy factors etc. are used.

are more complex and are more suitable for MDCA experts (Daugavietis et al., 2022) but offers ability to handle uncertainty and vagueness (Velasquez and Hester, 2013) just like DRSA (Cinelli et al., 2014) which could be more useful at large policy-driven scales. Furthermore, the choice of normalization techniques must align with the selected method as well as weight generation can be used, the combination can also differ depending on the situation, where studies have shown that vector normalization is the most suitable for TOPSIS, but linear MAX-method is more suitable when number of alternatives are <5 and the MIN-MAX-method is prefer for a larger set for TOPSIS (Satabun, 2013)

4. Proof of concept

To show the framework work in action, a typical residential building of 3000 m² located in central Stockholm has been selected for demonstration. The building is assumed to be fully integrated with current energy and water infrastructure, thus, consisting of a linear water system. The energy demand is assumed to fulfill current energy requirement for newly construction in Sweden with a total energy consumption of 75 kWh/m², yr of primary energy and a water consumption of 134 l/day and person. To simplify the calculation, bought energy is assumed to be to be 17.5, 20, and 37.5 kWh/m², yr primary energy for heating of water (district heating), facility electricity (ventilation, lights and elevators etc.) and energy for space heating (district heating). Since the energy related to the tenant itself is not included in the Swedish building regulation requirement it is not included here.

System goal is to reduce overall wastewater release, keep the overall energy needed for production and treatment of water low and at the same time not lower trust or willingness of user to use the system. Thus, the selected criteria were “wastewater release”, “energy utilized for production and treatment of cold water and wastewater per utilized volume”, and “acceptance of users”. The system boundaries therefore

include the building itself as well as affected infrastructure such as production and treatment of water, see Table 6.

Considering the large volume of greywater, it has great potential to reduce the wastewater release of this resource are utilized. However, the energy content is very low considering the rainwater, but since the great energy content comes from the possibility of utilizing it for (evaporative) cooling, which is not a demand in the assessed building addressing the greywater use is appropriate. The selected systems for assessment were therefore local recirculation of GW from showers and wash basin to showers and washbasins (system 2), and local recirculation of GW from showers and wash basins to WC (system 3). Since no actual building is assessed, typical values from literature are used as a foundation to compute each score, see Table 7. Indicators with insufficient literature data tied to specific theoretical building access such as life-cycle cost and quantitative microbiological assessment, where omitted, but remains integral to the framework for users with access to site-specific simulations or empirical data.

The objective approach automatic democratic method (ADM) was selected to generate weight. To maintain the multidimensionality of the framework and prevent edge solutions involving only one of two criteria, the lower boundary of the weights was set to 1/2n and the upper boundary to 2/n, where n is the number of criteria. The maximum achievable score was found to be 0.32, 0.37, and 0.32 for system 1, 2 and 3 respectively. The final common weights are presented in Table 8, yielding an aggregated score of 0.29, 0.37. and 0.32 for systems 1, 2 and 3 respectively which meant that system 2 was the favorable.

4.1. Sensitivity analysis

To determine if the model is robust or not, a Monte Carlo simulation was performed. 10 000 simulation with and without constraints (no upper or lower boundary) were done. For the constrained case the

Table 8

Values and scores for each indicator and system. Bold values represent the largest value and therefore the reference point.

Indicator	Unit	Weights	Sys 1		Sys 2		Sys 3	
			Value	Norm.	Value	Norm.	Value	Norm.
Annual municipal water utilized	m ³	0,036	3833	0	3833	0	3833	0
Water resource recovery as a reference to total water demand (water circularity)	–	0,143	0	0	0,185	0,185	0,126	0,126
Bought energy consumption	MWh	0,036	269,0	0	226,6	0,2	269,9	0
Return on investment	–	0,143	0	0	17,5%	1,0	1,9%	0,1
Life-cycle cost	–	0,036	–	–	–	–	–	–
Annual energy utilization using national method	kWh/m ²	0,036	75,0	0,16	88,8	0,00	75,5	0
Global warming potential (GWP100) ^(a)	kg CO ² eq.	0,036	13456	0	11566	0,140	13289	0,012
QMRA	–	0,036	–	–	–	–	–	–
Technology readiness level	–	0,143	9	1,0	7	0,8	9	1,0
System autonomy duration	–	0,036	0	0,0	0	0,0	0	0,0
Energy produced or extracted locally as a reference to bought energy	–	0,036	0	0	0,193	0,193	0	0
Wastewater released	m ³	0,107	3833	0	3123	0,185	3348	0,126
Energy used for prod. and treat. per consumed volume of water	kWh/m ³	0,036	1,10	0,086	1204	0	1,17	0,027
Acceptance/willingness to use system	%	143	100	1	38	0,28	83	0,83
Aggregated weighted sum	–	–	–	0,29	–	0,37	–	0,32

^a Only GWP due to water and energy consumption (scope 1 and 2) are included in this example.

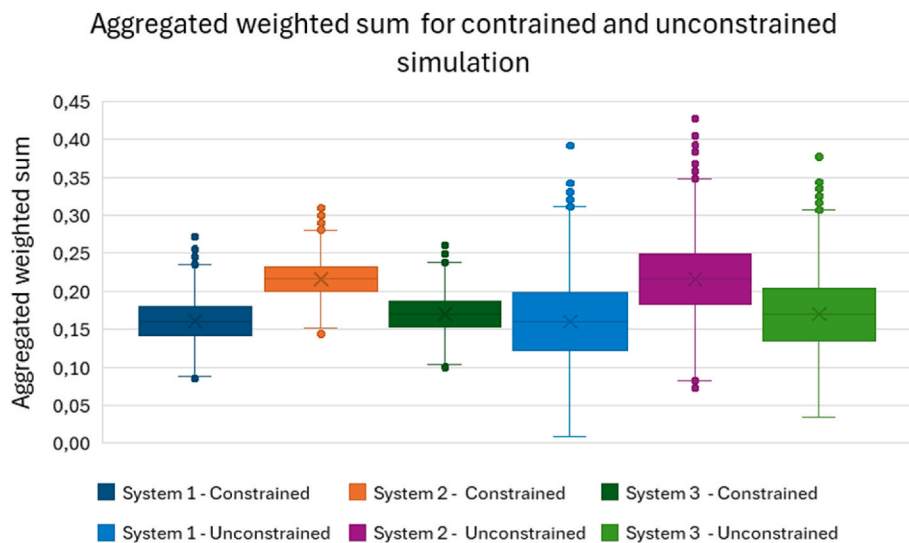


Fig. 5. Boxplot of the aggregated weighted sum of all the tried combinations for the constrained and unconstrained case.

system was favorable 108 times (1.1%), 9812 times (98.1%), and 80 times (0.8%) for system 1, 2 and 3 respectively. For the unconstrained case, the systems was favorable 1094 times (10.9%), 8159 times (81.6%), and 747 times (7.5%). Fig. 5 shows the aggregated weighted sum achieved for each system where system 2 achieved the highest value with minimal overlap with both system 1 and system 3.

5. Discussion

The majority of the parameters identified by stakeholders relate to either energy or water efficiency. This aligns closely with existing literature, where resource efficiency is often the primary objective in the development of new systems. A divergence among stakeholders was observed, where some, such as property owners, tended to focus primarily on reducing potential operational and investment costs. In addition, property owners often emphasized tenant perception, suggesting a willingness to promote energy- and water-efficient solutions as a means to enhance property value. This aligns with the objectives of certification systems such as LEED, BREEAM, or EnergyStar, which typically address a broad range of sustainability aspects. As these certification systems are incorporated and more frequently used within the building sector, stakeholders such as property owners and consultants within the buildings sector might tend to use these as a measure.

Some of the criteria that the stakeholders identified as important, such as complexity of the system or its adaptability, could be very difficult to quantify and thus take more effort to assess than what is returned in terms of impact (Ladyman et al., 2013; Clark and Jacques, 2012). Since system complexity could perceivably be associated with high maintenance costs or frequency of interruption of operation, it could instead serve as a proxy measure. In addition, since the technology readiness level captures the degree of maturity of a certain technology, potential complications could also be avoided and thus curb potential issues related to negative impacts from overly complex systems.

While the framework incorporates a range of criteria reflecting different perspectives, it may not capture all relevant viewpoints or potential advantages and disadvantages. This also includes the perceptions of occupants using the services influenced by the chosen system solution. Factors such as the turbidity and color of the water source may affect public acceptance. While stakeholders may not be directly impacted by these perceptions, they can influence user behavior, which in turn may have either positive or negative effects on outcomes like water and energy savings. As the framework evolves through iterative updates based on feedback, criteria could gain greater weight in the framework, as more stakeholders apply it.

Several of the identified criteria lack precise definitions and are subject to varying interpretations, influenced by factors such as system

boundaries, underlying assumptions, benchmarking methodologies, and project-specific constraints. Consequently, it is difficult to establish a uniform approach for calculating certain criteria, a limitation that applies to multiple elements within the framework. For example, determination of microbiological risks is complex, and several factors contribute to the uncertainties that arise, although protocols like QMRA (Quantitative microbiological risk assessment) provide an established method to quantify risk (Shi et al., 2018). However, it is important to acknowledge that the specific indicators for the criteria that were identified using literature due to absence of a clear indicator from the stakeholders involves a degree of interpretation. Halla & Merino-Saum (Halla and Merino-Saum, 2022) state that for urban sustainability indicator-assessment the choices made during the construction process shape the way the problem is understood. Consequently, defining a different indicator from literature, utilizing a different stakeholder group or focusing on a different geographical context might yield a different set of prioritized indicators, even if clear standardized metrics and indicators were selected. Nevertheless, the framework is constructed in such a way that indicators can be replaced and added for adequate geographical and project-related context, the purpose of the framework to provide a relevant assessment for support of decision-making for sustainable and energy efficient water supply systems remains. ISO-standards exist for some of the criteria, and it could be beneficial to utilize standard methods, unless the project requires other methods. As this is an initial step of developing a framework, further studies could focus on developing robust methods and apply simplification to calculations methods to enhance the usability. In addition, while new requirements of assessing GWP-contribution of a building, as in the case of the European union (EU, 2024), alignment to such procedures can result in better integration of the framework to already mandatory procedures and thus facilitate the use of the framework.

The identified criteria align to a large degree with previous studies of key performance indicators related to buildings. These include KPIs related to both flexibility and resource-wise aspects as well as self-sufficiency (Hadad et al., 2022b; Al et al., 2020). The overlap of criteria highlights the link between the assessment of smart buildings and overall building performance, suggesting the potential for integrating the water system evaluation framework presented in this work into existing assessment tools.

The comprehensive nature of the proposed assessment framework may pose a barrier to adoption if the process is perceived as overly complex. To enhance usability, future developments could focus on the implementation of an interactive online tool incorporating pre-assessed generic system configurations, thereby supporting decision-making in early stages. Introducing tiered levels of analytical detail based on user needs could further broaden the framework's applicability across a diverse range of decision-makers. Additionally, the integration of multi-criteria decision analysis (MCDA) software compatible with the structure of the proposed framework may offer further support and usability.

6. Conclusion

In this work, semi-structured interviews and a focus group were used to identify criteria that are of importance for stakeholders working within or in relation to water systems. The proposed Decision Support Framework (DSFW) provides a structured and adaptable methodology for evaluating energy and water efficiency systems in buildings. It is the product of a comprehensive, participatory process involving diverse stakeholders that enabled the identification of key criteria, establishment of guidelines, and compilation of a technical solutions library. It is based on a generalizable structure designed to ensure consistency and facilitate comparability across diverse applications. The partitioning of criteria into national level, regional level and project level enables adaptation to local prerequisites as well as comparison of systems with different local conditions and enables stakeholders to adjust the

criterion for project specific relevance.

The DSFW described here leverages Multi-Criteria Decision Analysis (MCDA) to evaluate and rank solutions, as demonstrated by the trade-offs in the proof of concept. By integrating 39 diverse indicators, the framework enables decision-makers to balance competing objectives, such as local resource recovery versus operational cost, into a single transparent decision-making process.

Our DSFW is designed to evolve through iterative updates based on feedback and real-world applications. Stakeholders at all levels can provide input on the effectiveness of the framework, enabling continual refinement of criteria, weighting guidelines, and the technical solutions library.

While the framework is designed as standalone methodological contribution, its usability could be further enhanced through a supporting digital tool. Such a tool could host a central repository of pre-defined performance data, thereby streamlining the comparison process. Regardless of the platform used, the MCDA logic within the framework ensures systematic, criteria-based approach that contributes to informed and balanced decisions, particularly in early planning stages where multiple objectives and trade-offs must be considered.

CRediT authorship contribution statement

Viktor La Torre Rapp: Conceptualization, Data curation, Visualization, Writing – original draft, Writing – review & editing. **Jesper Knutsson:** Conceptualization, Writing – review & editing. **Jörgen Wallin:** Conceptualization, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Viktor La Torre Rapp reports financial support was provided by Swedish Energy Agency. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.cesys.2026.100443>.

Data availability

The data that has been used is confidential.

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