# Application of a decision support tool for industrial and agricultural water reuse solutions in international case studies

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## ABSTRACT

Treated wastewater is expected to constitute an essential part of the urban water cycle as an additional water resource in water-scarce or densely populated regions in the future. As decisions on the implementation of water recycling measures should always consider local conditions, the project 'MULTI-ReUse: Modular treatment and monitoring for wastewater reuse' has developed a comprehensive sustainability assessment tool, designed to support decision-makers in examining the technical feasibility, economic viability, ecological compatibility and social acceptance of alternative service water supply solutions at local level. This article describes the structure of this sustainability assessment tool and its underlying multi-criteria assessment approach based on 23 evaluation criteria. Already in the development phase, the tool was tested in a German and a Namibian case study. Both case studies are presented with a special focus on the technologies used and the results of the analysis with the sustainability assessment tool. Case study testing proved that the tool is applicable in various environmental and societal settings with widely differing climatic conditions, limited resource availability, for varying feed water qualities and water quality requirements. The comprehensive, straightforward assessment approach enabled the local users to identify the most sustainable supply system or strategy for their decision case.


**Key words** | assessment framework, multi-criteria decision analysis, practical implementation, water management, water reuse

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## HIGHLIGHTS

- The paper presents a multi-criteria assessment approach based on 23 evaluation criteria that can be used to assess the technical feasibility, economic viability, ecological compatibility and social acceptance of alternative service water supply solutions at local level.
- Assessment results from two different case studies comparing different solutions for industrial and agricultural water reuse are presented.



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## INTRODUCTION

In many countries, the effluent of wastewater treatment plants (WWTPs) is discharged into receiving waters without further use. In the long run, it is expected that treated wastewater will, as an additional water resource in water-scarce or densely populated regions, constitute an essential part of the urban water cycle, also in Germany. Although widespread use of water reuse technologies is currently hampered by insufficient public acceptance or regulatory obstacles, analyses and forecasts generally attest Germany – just as many other European countries – a high water reuse potential across all sectors of about 144 million m$^3$ per year that could be reached by as early as 2025 (Wintgens *et al.* 2006). The concepts of 'circular economy' and 'water smart societies' reinforce the importance of water reuse in European countries and beyond the near future as the use of wastewater and the recovery of byproducts can open up new business opportunities and help to cover the costs of new, innovative and adapted plants so that energy, nutrients, metals and other byproducts can be recovered (Water Europe 2016).

Currently, global annual freshwater withdrawal amounts to 4,000 km$^3$ per year and about 75% of the water is used for agricultural production (WWAP 2019), wherein an overwhelming proportion is used for irrigation of arable fields. The need for irrigation is the highest in water-scarce regions. Consequently, in these regions, a large fraction of treated or untreated wastewater is used for irrigation. For example, in Israel, 86% of wastewater is reused providing about 50% of the national irrigation water demand (Tal 2016). To meet the urgent need for additional irrigation water in countries of the European Union (EU), the European Commission adopted new rules to stimulate and facilitate water reuse in the EU for agricultural irrigation in May 2020 (European Commission 2020). So far, irrigation has played only a marginal role in Germany, comprising about 2.2% of the agricultural area (Statistisches Bundesamt 2014). Due to very rigid legal regulations, treated wastewater is used in a few exceptional cases only. However, facing a series of dry years and a predicted increase of dry seasons in the next decades due to climate change, there is increasing pressure on these water resources.

In contrast, water recycling in industry and commerce already plays a major role in several sectors in Germany. The process industry is a major water user and an important solution provider for innovative products, technologies and services that enable more sustainable water management. Technologies and concepts for water reuse promote the economical use of water resources, make companies independent from freshwater resources and thus bring clear locational advantages, both in Germany and internationally (competition for water use, quantitative and qualitative water shortage/stress). Some process industries, which require large quantities of water, have been recycling or reusing water for a long time. In the paper industry, loop separation and counterflow control as well as extensive mechanical circuit water purification are state of the art (Lyko 2014). The steel industry also circulates large quantities of water, especially for cooling and gas scrubbing, e.g. circuits between 500 and 5,000 m$^3$/h in blast furnaces or between 500 and 3,000 m$^3$/h in steelworks (Track & Kozariszczuk 2018). The aim is to reduce freshwater and wastewater costs, but also to recover resources or energy, for example.

The aim of the transdisciplinary research project 'MULTI-ReUse: Modular treatment and monitoring for wastewater reuse' was the development of advanced modular treatment process technologies to provide service water that is ideally suitable for industrial and agricultural purposes which do not require water of a quality suitable for drinking. Process technologies, for instance new reverse osmosis (RO) membranes and ultrafiltration (UF), were developed to process different qualities and quantities of treated wastewater to provide water that is fit for purpose and suitable to substitute the use of other drinking water resources at an economically competitive level (Schramm & Zimmermann 2018).

In order to examine advantages and disadvantages of the service water supply using MULTI-ReUse technologies with the current water supply concept, a comprehensive sustainability assessment tool was developed and applied in national and international case studies. In the subsequent sections, the methodological approach and the structure of this sustainability assessment tool are described. Furthermore, the applicability of the tool to assess the advantages of water reuse solutions compared with existing supply systems in an industrial and an agricultural context is demonstrated in a German and a Namibian case study.

## MATERIALS AND METHODS

### Multi-criteria evaluation approaches

In order to select a scientifically sound and practicable assessment methodology for the multi-criteria decision support tool, widely used multi-criteria analysis (MCA) approaches and procedures for the inclusion of quantitative and qualitative data were examined for their applicability and suitability for the comparative assessment of different water reuse solutions in national and international contexts. A focused literature review on methods for the sustainability assessment of technologies and measures in the context of water reuse was performed, considering selected peer-reviewed articles found in the Web of Science or Scopus databases. In total, 47 publications from the years 1998 to 2017 were recorded in the literature database and analyzed with regard to the evaluation method used, the evaluation object and the case study region. From these literature sources, it was possible to differentiate between 25 evaluation procedures, which consider at least one or, in some cases, also several evaluation dimensions in the evaluation process.

As examples of processes that only consider one of the presented assessment dimensions, mainly environmentally oriented assessment methods such as ecological risk analysis (El Heloui *et al.* 2016; Zaibel *et al.* 2016), ecological indicators (Carr *et al.* 2010; Uddin *et al.* 2014; Müller & Cornel 2017), life cycle assessment (Holloway *et al.* 2016; Kavvada *et al.* 2016), material flow analysis (Chen *et al.* 2012) or scenario-based hydrological modeling (Nies *et al.* 2016) could be identified. In the case of multidimensional methods, a distinction can be made between the methods usually declared as MCA, which are typically carried out in the form of a utility analysis, and the MCA approaches based on sequencing methods such as the analytical hierarchy process (Aydiner *et al.* 2016) or linear programming (Chu *et al.* 2004). The strongly economically oriented cost-benefit analysis (Haruvy 1998; Hernández et al. 2006; Chen *et al.* 2015) represents a third form of MCA that, together with the utility value analysis, is one of the most frequently used methods in the publications examined.

For the adaptation within a decision support tool, a large part of these procedures had to be excluded due to the one-dimensionality of the assessment, an undue degree of complexity of the assessments (e.g. goal, aspiration or reference level models and outranking methods) or the expectation of insufficient data availability for further use within the intended evaluation tool.

Based on these considerations, value measurement models were found to be best suitable for the assessment purposes of the MULTI-ReUse tool. Value measurement models are based on the idea that a numerical use value is calculated for each criterion. Afterwards, all the use values of the single criteria are ultimately synthesized to a global score using criteria weightings. The weighting and aggregation of the partial results can take place in a variety of ways and, if necessary, also lead to cost-benefit and cost-effectiveness considerations.

The final MCA approach developed within the project is based on 23 easy to handle and comprehensive evaluation criteria in four dimensions covering environmental impacts (e.g. net energy consumption, space requirement and volume of residual substances), social factors (e.g. compliance with national strategies, increasing environmental awareness and health risks), technical feasibility (e.g. anticipated expense for implementation, flexibility, adaptability and expandability) and economical viability (annual costs, potential for innovation leadership and competitiveness) of water supply alternatives (Table 1).

All criteria should be assessed individually for the particular case of application in order to identify advantages and disadvantages of the considered water supply variants. Results are presented in the form of normalized figures and graphic illustrations. In order to facilitate decision-making, the criteria assessments can be further combined to an overall assessment of each alternative based on the preference set by the decision-makers. The final result is a ranking of the individual alternatives that are assessed.

Based on this evaluation approach, sustainability assessments for two case studies were carried out based on different data sources. For the German case study, technical

**Table 1** | Overview of evaluation criteria considered within sustainability assessment covering four dimensions

| ID | Criterion | Possible indicator(s) and further information | Unit |
|---|---|---|---|
| ENV1 | Space requirement | Total space required by the processing plants (including all space requirements associated with water supply, e.g. pipeline network for water distribution, and all areas unusable for other purposes due to the plant) | $m^2$ or $m^2/m^3$ |
| ENV2 | Energy consumption | Specific net energy consumption per $m^3$ produced water (including all energy consumption for water treatment and water distribution, measurement, control and regulation technology, and lighting and ventilation of the company buildings) | $kWh/m^3$ |
| ENV3 | Consumption of process and operating resources | Specific consumption of treatment materials and disinfectants per $m^3$ of water produced (if necessary, accounted separately for individual substance classes) | $g/m^3$ |
| ENV4 | Accumulation of residues | Specific residues use per $m^3$ produced water (including all residues removed from the system and properly disposed) | $ml/m^3$ |
| ENV5 | Additionally available water volume | Volume of water additionally available (if necessary subdivided into different water quality levels for different types of use) | $m^3/a$ |
| ENV6 | Water quality | Reduction of the load for selected parameters that are critical for the intended use (only considering parameters relevant for the individual case) | 5-point scale from 'no reduction' to 'complete reduction' |
| ENV7 | Ecosystem services | Contribution to maintaining or increasing (supporting, provisioning, regulating and cultural) ecosystem services in the area under consideration and adjacent ecosystems | 5-point scale from 'negative' to 'positive' |
| SOC1 | Personnel requirements | Number of personnel required for operation and maintenance (taking into account all phases of system planning, construction and commissioning, operation, administration and monitoring) | 5-point scale from 'very high' to 'very low' |
| SOC2 | Accordance with guiding principles | Consistency with national water and sanitation strategies (depending on the location of the system and the intended type of use) | 5-point scale from 'large gap' to 'good correlation' |
| SOC3 | Strengthening environmental awareness | Potential to sensitize stakeholders to issues of sustainable resource use (e.g. motivation to conscious and sustainable water and energy use) | 5-point scale from 'no potential' to 'high potential' |
| SOC4 | Acceptance | Stakeholder's acceptance for the intended water reuse as well as for the product produced by recycled water usage | 5-point scale from 'no acceptance' to 'high acceptance' |
| SOC5 | Health protection | Health protection of the user in contact with pathogenic microorganisms from the reuse water | 5-point scale from 'unsatisfactory' to 'very good' |
| TEC1 | Integrability in existing infrastructure | Technical integrability of the process chain into the existing infrastructure (incl. times required for planning, construction and commissioning) | 5-point scale from 'impossible' to 'very good' |
| TEC2 | Flexibility, adaptability, expandability | Potential for structural adaptations (e.g. modularity, scalability) with regard to changing boundary conditions | 5-point scale from 'no potential' to 'very high potential' |
| TEC3 | Operational safety | Control and review of accident prevention measures as well as occupational health and safety | 5-point scale from 'defective' to 'very good' |

(*continued*)

**Table 1** | continued

| ID | Criterion | Possible indicator(s) and further information | Unit |
|---|---|---|---|
| TEC4 | Technical complexity | Minimum educational qualification required for operation (including monitoring, control) and maintenance of the system | 5-point scale from 'no qualification' to 'with work experience and further education' |
| TEC5 | Maintenance | Local availability of spare parts for repair services | 5-point scale from 'not available' to 'very good' |
| TEC6 | Process stability | Mean time to failure (MTTF) | years/failure |
| TEC7 | Tolerance of disturbance against external perturbations | Tolerance of the systems against natural risks and hazards, operating error, manipulation and vandalism | 5-point scale from 'inadequate' to 'high' |
| ECO1 | Overall costs | Specific annual costs (total) | EUR ct/$m^3$ |
| ECO2 | Market position, competition | Potential for regional innovation leadership through the expansion of know-how and image improvements | 5-point scale from 'no potential' to 'very high potential' |
| ECO3 | Added local economic value | Positive economic effects that can be assigned to the water reuse measure | EUR/$m^3$ |
| ECO4 | Opportunity costs | Follow-up costs of a system failure with disruption or interruption of water supply | EUR/d |

ENV, environmental impacts; SOC, social factors; TEC, technical feasibility; and ECO, economical viability.

and environmental data were taken directly from the pilot plant, which was operated as part of the project. Further information on economic and social aspects was provided by the case study owner, the local water company based on in-house cost calculations and expert guess. As the Namibian case study consists of a comparison of modified technical systems investigated in previous and current projects, named 'EPona: Water Reuse in Northern Namibia' and 'CuveWaters: Sustainable Water Management in Namibia', unpublished data were provided and modified by the project coordinators to match the MULTI-ReUse project's needs. Additional information was derived from structured interviews and expert estimates as part of the studies in the projects named above.

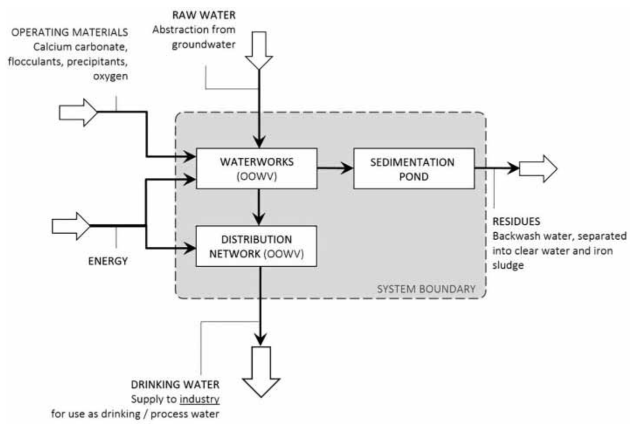


**Figure 1** | Process diagram for water supply option 1-A in Nordenham, Germany.

## Case study Nordenham, Germany

In North Germany, the water company Oldenburgisch-Ostfriesischer Wasserverband (OOWV) ensures water supply for municipal and industrial customers. In a pilot plant, OOWV already demonstrated water reclamation and reuse from the WWTP Nordenham with improved process technologies such as UF and RO (Figure 1). In the medium term, OOWV intends to substitute drinking water consumption in an industrial park in Nordenham by reuse water with low electric conductivity and low chlorine contents from a separate pipeline network. The demand for industrial service water is expected to increase by 800,000 $m^3$ per year. By using the sustainability assessment tool developed within the MULTI-ReUse project, OOWV aimed at performing a sound cost-effectiveness consideration for the planned water recycling project (option 1-B, Figure 2) by comparing it to the current water supply

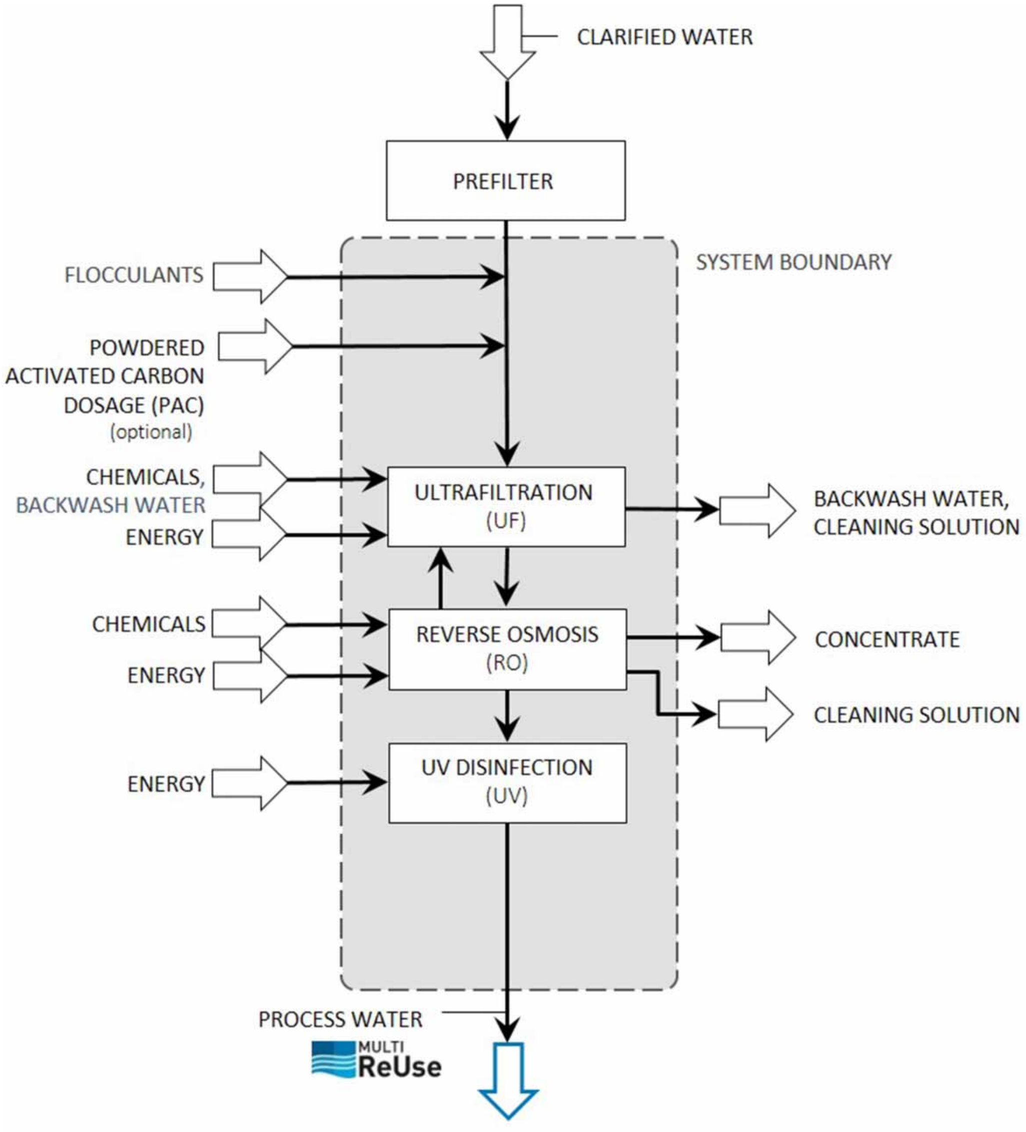


**Figure 2** | Process diagram for water supply option 1-B using the MULTI-ReUse process chain in Nordenham, Germany.

system (option 1-A, Figure 1). In order to ensure the selection of the most sustainable solution to cope with the local challenges identified for today as well as in long-term planning, the assessment is performed from a current point of view (year 2020) and with a view to the future (year 2030).

In both temporal scenarios, option 1-A covers the service water supply for industrial customers in the City of Nordenham with drinking water from the municipal waterworks Großenkneten, Nethen and Sandlermöns. Thus, investment and operating costs for the provision of drinking water include plant-specific costs for groundwater extraction, intermediate storage und water pumping (including storage pumping stations).

Option 1-B describes an alternative supply utilizing reclaimed process water. In this option, investment costs for land, a separate non-potable water pipeline network, storage tanks as well as buildings including the plant engineering, plant and pump houses must be taken into consideration. Operating costs, such as energy costs for pumping (for water supply to the treatment plant, RO or UF and process water supply to the customer), are particularly relevant in this context. Cleaning chemicals, precipitants (ferrous or aluminum salts), disinfectants and personnel costs are further examples of expenditures that need to be assessed.

### Case study Outapi, Namibia

In the northern Namibian town of Outapi, a water reuse system for domestic wastewater of approximately 1,000 inhabitants has been operating successfully for more than 6 years. The system feeds a drip irrigation system with reuse water for the production of vegetables and fruit for human consumption. Due to the semi-arid climate, the reuse of water is a viable alternative for the cultivation of plants in the region. However, there are several alternatives of reuse systems available. Based on the developed sustainability assessment approach, the potential positive and negative impacts of three different water use options were assessed. Option 2-A is the above-mentioned system, which consists of an up-flow anaerobic sludge blanket (UASB), rotating biological contactors (RBC), and a micro-screen and ultraviolet (UV) irradiation for disinfection before the irrigation water is stored in a pond (Figure 3). In option 2-B, the micro-screen and UV irradiation of option 2-A is replaced by an UF as tested in the MULTI-ReUse project (Figure 4). The remaining system of this hypothetical option is identical to the first one. Option 2-C uses existing wastewater ponds that are already used for a large part of Outapi's wastewater disposal (Figure 5). These ponds are supplemented by a pre-treatment with either UASB reactors or a micro-screen, a stone filter for post-treatment after the ponds and an additional UF membrane for irrigation water production.

## RESULTS

### Tool description

Based on the considerations on different multi-criteria evaluation approaches and the selection of a suitable

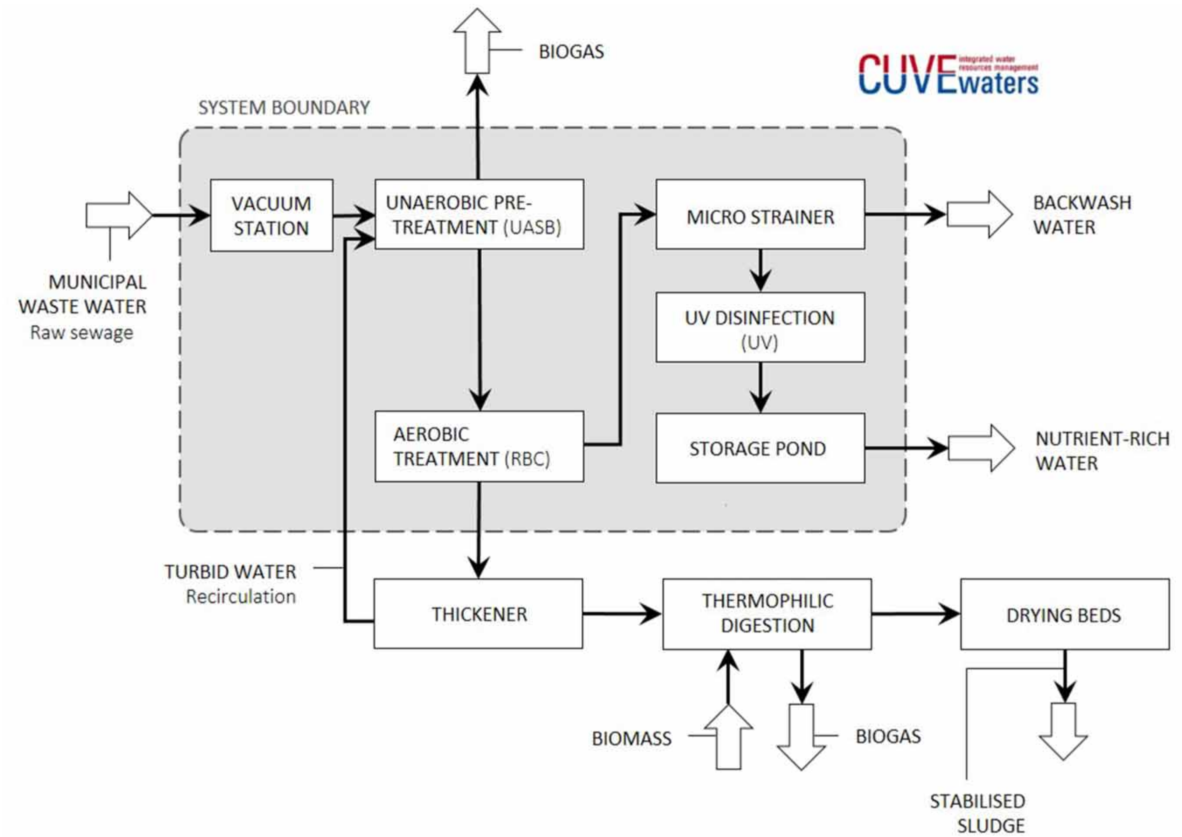


**Figure 3** | Process diagram for water supply option 2-A in Outapi, Namibia.

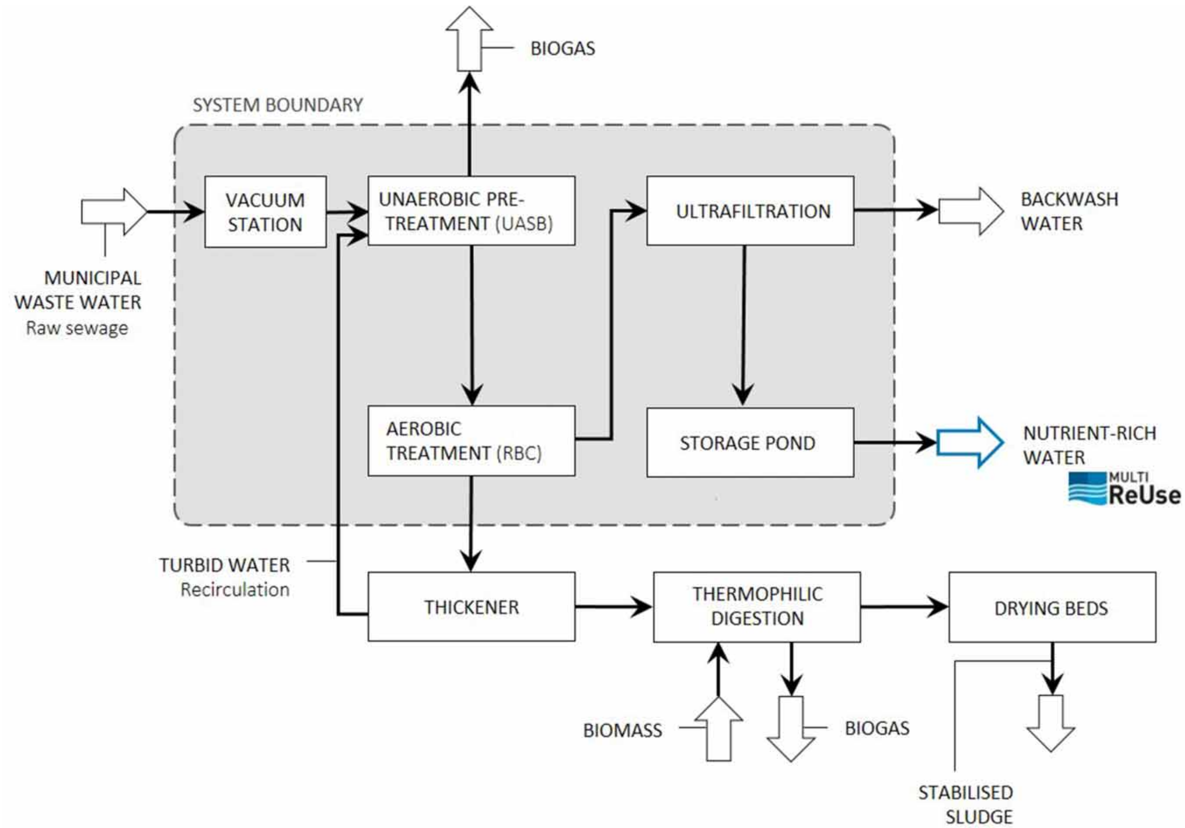


**Figure 4** | Process diagram for water reuse option 2-B using the MULTI-ReUse process chain in Outapi, Namibia.

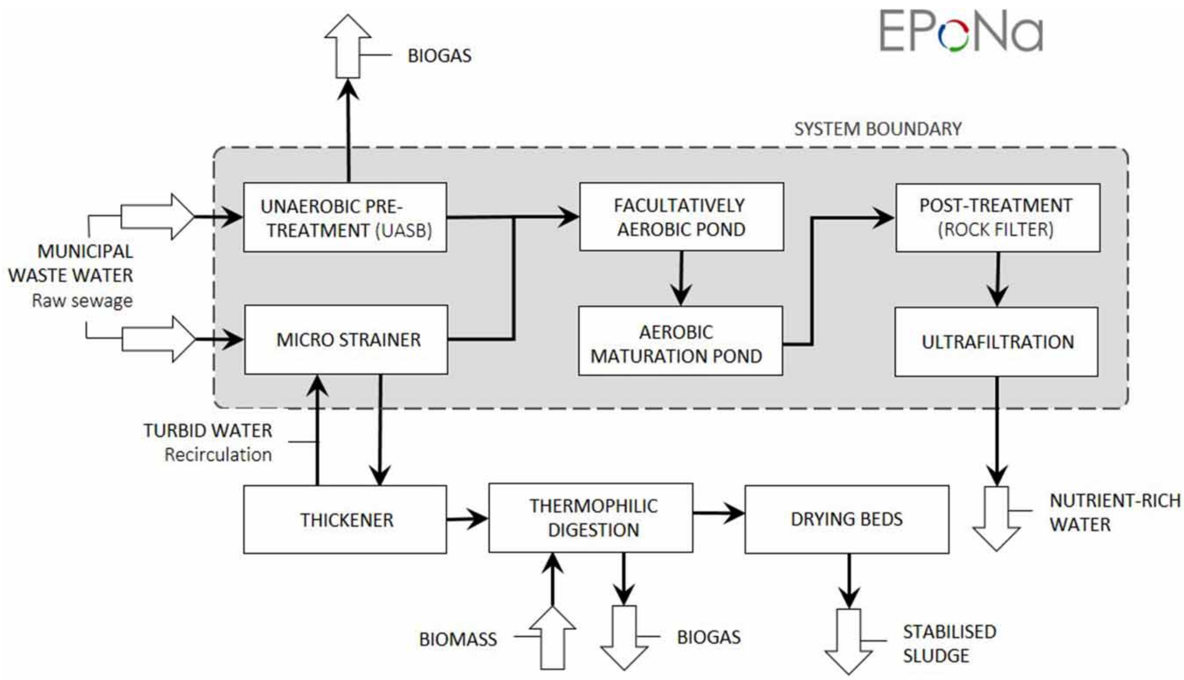


**Figure 5** | Process diagram for water reuse option 2-C in Outapi, Namibia.

assessment approach described above, a multi-criteria decision tool has been developed and tested for various case studies. It is intended to be used by water treatment plant (WTP) and WWTP managers, municipal decision-makers, operators of industrial plants and consulting engineers in an initial phase of the planning process. It allows the decision-makers to evaluate and compare the sustainability of conventional water supply and innovative process chains for water reclamation and reuse for service water supply considering the case-specific environmental and societal settings.

The tool is suitable for comparing a minimum of two and up to five water supply variants in parallel. On the basis of a checklist, termination criteria are verified at the beginning of the sustainability evaluation. The termination criteria include core requirements, such as water demand, social acceptance of water reuse and disposal options for residues. The total of 23 evaluation criteria recorded apply to the categories of environment, social issues, technology and economics. Criteria that are to be assessed qualitatively can be entered using 5-level Likert-type scales. Based on the input data, the tool creates an integrated assessment of the water supply variants to be compared. To provide the user with an overview of the data entered, input data are presented in the form of separate bar charts per indicator. The diagrams can be used to check the data entered.

The centerpiece of the calculations is the MCA approach: In the context of a utility value analysis, in a first step, utility values between 0 and 1 are calculated for each criterion and each of the variants, whereas a higher utility value is always indicating a higher consistency of the solution with the respective target. Scaling and standardization are performed depending on the case-specific minimum or maximum values for the indicators which are derived from the input data inserted for the different options and regulatory thresholds – where applicable. With the purpose of simplification of the assessment in the initial phase of planning that the tool is designed for, input values between minima and maxima are determined by linear interpolation, accepting inaccuracies in the scale of values, at least for some of the criteria proposed.

The total utility value of a variant is calculated by aggregating the partial values, taking into account the specification of different weighting scenarios, and presented in the form of a summary table. The tool creates a ranking list, which takes into account the user's preference in addition to a set of nine predefined weighting scenarios, and spider graphs, which allow for a direct comparison of individual variants.

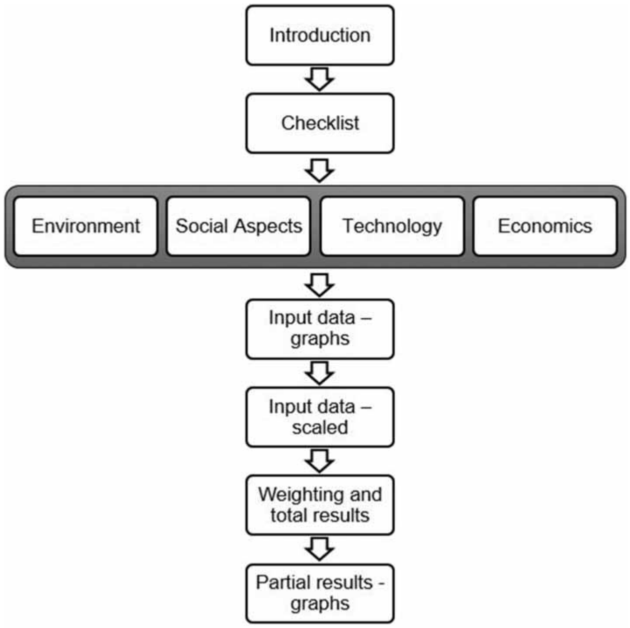


**Figure 6** | Process scheme of the MULTI-ReUse sustainability assessment tool.

A process scheme of the MULTI-ReUse sustainability assessment tool is depicted in Figure 6.

## Assessment results – case study Nordenham, Germany

The application of the decision support tool for the assessment of the northern German case study confirms that currently the existing water supply system is preferable from a technical, social and economic perspective (Figure 7). For example, the specific energy requirement for the provision of process water from water reuse (option 2-B) is approximately 1 kWh/m$^3$, whereas the total specific energy demand for drinking water supply (option 1-A) is only 0.7 kWh/m$^3$ on average (Sattig 2019). The calculated specific costs for the process water supply are thus about 10% higher than the costs for a process water supply from drinking water resources.

However, as an increase in water abstraction or an installation of additional extraction wells is restricted by

| No. | Weighting scenario | Environment | Social aspects | Technology | Economy | Option 1-A Drinking Water (2020) | Option 1-B MULTI ReUse (2020) | Option 1-A Drinking Water (2030) | Option 1-B MULTI ReUse (2030) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | User's choice | | | | | | | | |
| 2 | Example from **MULTI ReUse** | 26% | 13% | **38%** | 23% | 0,697 / 1 | 0,592 / 2 | 0,632 / 1 | 0,619 / 2 |
| 3 | Focus **Environment** | **40%** | 20% | 20% | 20% | 0,674 / 1 | 0,590 / 2 | 0,612 / 2 | 0,618 / 1 |
| 4 | Focus **Social aspects** | 20% | **40%** | 20% | 20% | 0,748 / 1 | 0,668 / 2 | 0,692 / 2 | 0,715 / 1 |
| 5 | Focus **Technology** | 20% | 20% | **40%** | 20% | 0,725 / 1 | 0,619 / 2 | 0,669 / 1 | 0,653 / 2 |
| 6 | Focus **Economy** | 20% | 20% | 20% | **40%** | 0,693 / 1 | 0,611 / 2 | 0,611 / 2 | 0,638 / 1 |
| 7 | Focus **Environment + Social aspects** | **30%** | **30%** | 20% | 20% | 0,711 / 1 | 0,629 / 2 | 0,652 / 2 | 0,666 / 1 |
| 8 | Focus **Environment + Technology** | **30%** | 20% | **30%** | 20% | 0,662 / 1 | 0,605 / 2 | 0,641 / 1 | 0,635 / 2 |
| 9 | Focus **Technology + Economy** | 20% | 20% | **30%** | **30%** | 0,709 / 1 | 0,615 / 2 | 0,628 / 2 | 0,646 / 1 |
| 10 | Equal Weighting | 25% | 25% | 25% | 25% | 0,710 / 1 | 0,622 / 2 | 0,640 / 2 | 0,656 / 1 |

**Figure 7** | Assessment result for case study in Nordenham (options 1-A 'drinking water', 1-B 'MULTI-ReUse' for a current point of view (2020) and with a view to the future (2030)) from the sustainability assessment tool with total utility values and ranking positions of the options (right columns).

current water rights for this location, water reuse should still be considered as an alternative to drinking water supply in the future. It is expected that water reuse will reduce the pressure on scarce regional groundwater resources in the long run by meeting the increased industrial water needs with appropriate water quality at acceptable prices. Other contributions to the protection of ecosystems, that can already be recognized today, include a reduced land requirement, a potential improvement in the discharge quality with regard to the annual loads (especially regarding the discharge of trace organic contaminants) when dosing the powdered activated carbon and a reduction in the entry of pathogenic germs into the surface water by membrane installations (Figure 8). Significantly lower chlorine and salt contents of the reuse water also enable multiple water recirculation within industrial processes, so that the

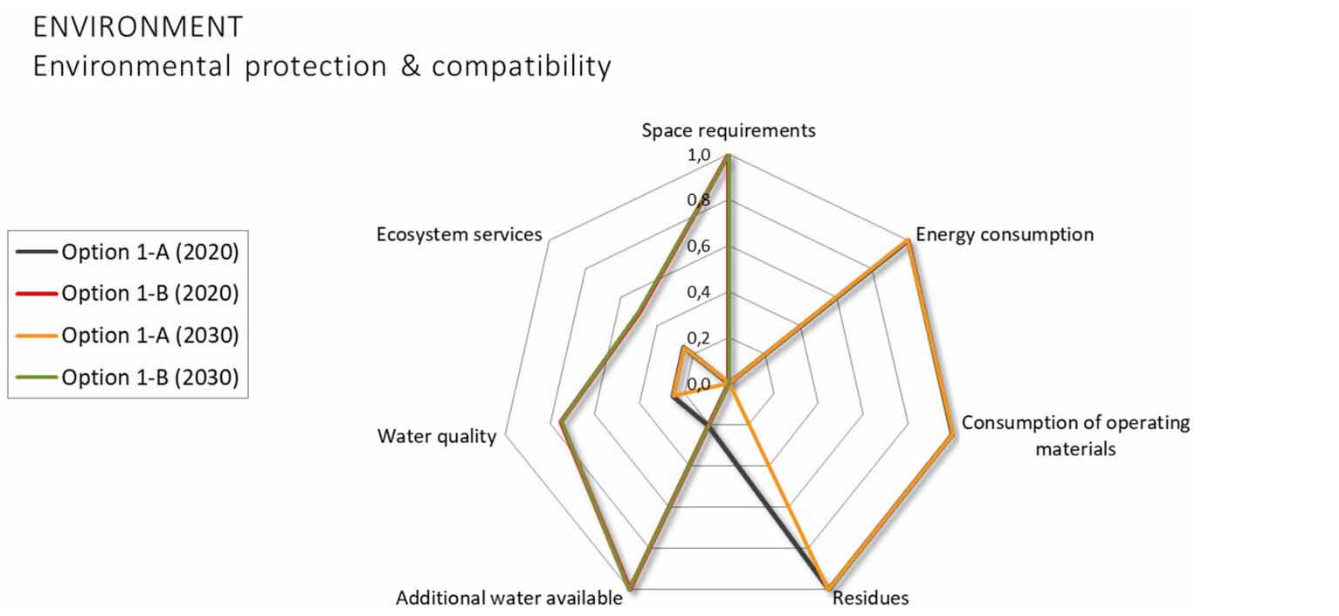


**Figure 8** | Spider diagram of the assessment result for the case study Nordenham with regard to environmental criteria (scale: normalized non-dimensional utility value between 0 (minimum) and 1 (maximum)).

consumption of water resources for production can even be reduced. In addition, option 1-B also allows greater flexibility in terms of quantity and quality requirements for customers, and it makes a greater contribution to local value creation and increases environmental awareness. Furthermore, the use of the MULTI-ReUse approach (option 1-B) leads to a minimized use of cleaning chemicals (e.g. flocculants and precipitants) in the various process steps.

## Assessment results – case study Outapi, Namibia

The sustainability assessment of the three options in the Namibian case study shows that option 2-A is the most sustainable system for water reuse, followed by option 2-B and option 2-C (Figure 9). This is mainly due to the good environmental performance of option 2-A. In all weighting scenarios, option 2-C ranks last as it seems to combine all the disadvantages of the other two options. Option 2-A also has the highest utility value when greater weight is given to individual assessment dimensions, thus focusing on either environmental, social, technical or economic criteria (Figure 9). If both environmental and social assessment criteria are given greater weight, option 2-A remains the most sustainable option, followed by option 2-B and finally option 2-C. The ranking does not change even if technical and economic aspects or ecological and technical aspects are given priority.

In terms of environmental criteria, option 2-A is the most sustainable option as it is more water and energy efficient, produces less residues and requires fewer chemicals for operation (Figure 10). Option 2-A is followed by option 2-B, *inter alia*, because of its lower specific space requirements.

Within the social dimension, options 2-A and 2-B achieved equal scores. Both options perform better than option 2-C in terms of human resource requirements and consistency with national water and sanitation strategies. In terms of technical criteria, all three options considered have their strengths. In particular, option 2-C scores better than the other two options in terms of integration into the existing infrastructure and availability of spare parts. Options 2-A and 2-B are more adaptable than option 2-C.

Apart from this, option 2-A has slight advantages compared with the other two options in terms of the technical complexity of the plant and option 2-B in terms of process stability. When focusing on economic aspects, option 2-A proves to be the most sustainable option due to its ability to innovation leadership and its lower opportunity costs (follow-up costs due to a system failure). In contrast, option 2-C has the comparatively lowest specific annual

| No. | Weighting scenario | Environment | Social aspects | Technology | Economy | Option 2-A *UASB-RBC-UV-pond* | Option 2-B *MULTI-ReUse* | Option 2-C *UASB-ponds-UF* |
|---|---|---|---|---|---|---|---|---|
| 1 | User's choice | | | | | | | |
| 2 | Example from **MULTI ReUse** | 26% | 13% | **38%** | 23% | 0,558 | 0,490 | 0,310 |
| | | | | | | 1 | 2 | 3 |
| 3 | Focus **Environment** | **40%** | 20% | 20% | 20% | 0,629 | 0,494 | 0,272 |
| | | | | | | 1 | 2 | 3 |
| 4 | Focus **Social aspects** | 20% | **40%** | 20% | 20% | 0,540 | 0,476 | 0,320 |
| | | | | | | 1 | 2 | 3 |
| 5 | Focus Technology | 20% | 20% | **40%** | 20% | 0,529 | 0,486 | 0,322 |
| | | | | | | 1 | 2 | 3 |
| 6 | Focus **Economy** | 20% | 20% | 20% | **40%** | 0,553 | 0,473 | 0,473 |
| | | | | | | 1 | 2 | 2 |
| 7 | Focus **Environment + Social asp** | **30%** | **30%** | 20% | 20% | 0,584 | 0,485 | 0,296 |
| | | | | | | 1 | 2 | 3 |
| 8 | Focus **Environment + Technolo** | **30%** | 20% | **30%** | 20% | 0,550 | 0,490 | 0,297 |
| | | | | | | 1 | 2 | 3 |
| 9 | Focus **Technology + Economy** | 20% | 20% | **30%** | **30%** | 0,541 | 0,479 | 0,330 |
| | | | | | | 1 | 2 | 3 |
| 10 | Equal Weighting | 25% | 25% | 25% | 25% | 0,563 | 0,482 | 0,313 |
| | | | | | | 1 | 2 | 3 |

**Figure 9** | Assessment results for the case study in Outapi (options 2-A 'UASB-RBC-UV-pond', 2-B 'MULTI-ReUse' and 2-C 'USAB-ponds-UF') from the sustainability assessment tool with total utility values and ranking positions of the options (right columns).

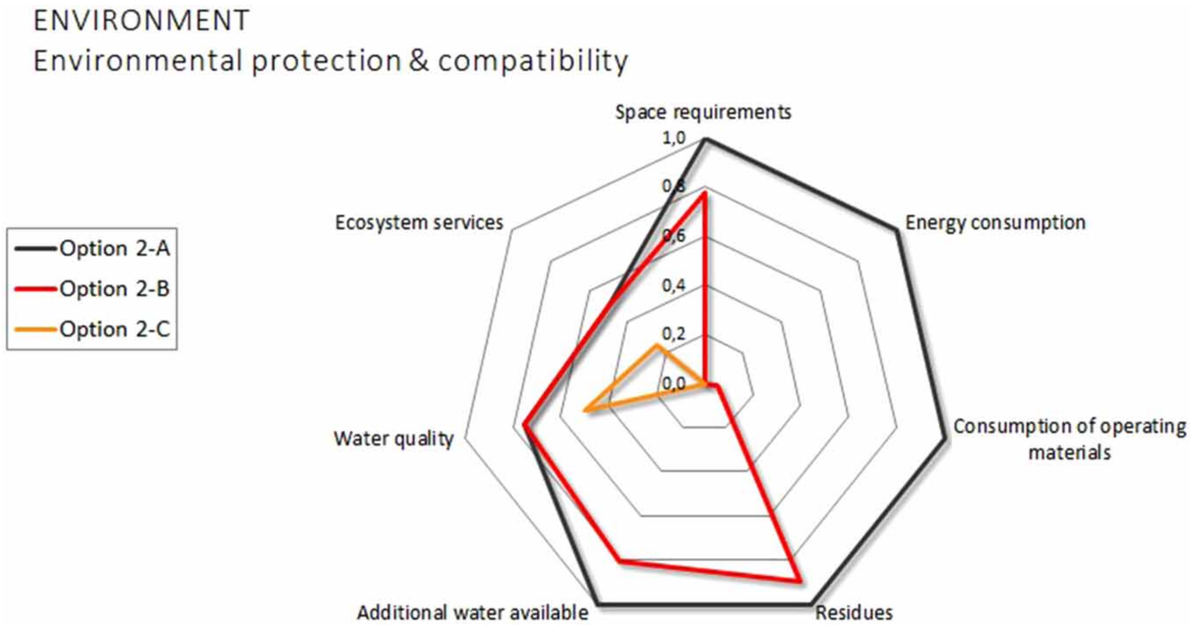


**Figure 10** | Spider diagram of the assessment results for the case study Outapi with regard to environmental criteria (scale: normalized non-dimensional utility value between 0 (minimum) and 1 (maximum)).

costs. All three options considered show a comparable contribution to local value creation.

## DISCUSSION

One of the key objectives of the MULTI-ReUse project was to develop a sustainability assessment tool to evaluate different water recycling solutions against the current system configuration in order to identify the most sustainable water supply system for the future. This represents a major challenge since current water supply systems regularly developed historically, are economically written off and optimized in a way that they can operate efficiently in large scale implementation. In contrast, innovative water reuse technologies are usually making use of different water treatment technologies and are currently implemented on much smaller scales. Thus, it is a really challenging task to find common system boundaries and comparable water supply systems. The MULTI-ReUse assessment tool helps the user to identify the advantages and disadvantages of different system configurations. However, a mandatory requirement for its application is the existence of basic concepts for water reuse which have to be developed and made comparable by the tool user individually.

Another challenge in meeting this objective was to identify a suitable multi-criteria assessment methodology that is comprehensive enough to deal with the diverging objectives attached to such decision cases and at the same time offers the highest level of flexibility to be applicable in various contexts. As described, the development of the MULTI-ReUse decision support tool was based on a focused review of existing multi-criteria approaches for water reuse technologies and a structured compilation and review of criteria lists, including experts from different disciplines served to ensure a common understanding of terminology and consideration of contradicting stakeholders' viewpoints of water reuse technology implementation. However, it must be stated that the MCA approach used allows only for a rather superficial assessment of the considered solution. Nevertheless, the practice partners involved in the development process of the MULTI-ReUse tool, attached great importance to define such rather simple but holistic approach as this enables them to provide key information relevant in an early planning phase of water reuse projects, as a more detailed assessment of the solutions for implementation planning has to be carried out in-house using specific modeling and calculation approach. Thus, creating a consistent approach for detailed assessments that is useful for all types of users is very difficult to find and might not be appropriate.

The limitations of the MCA approach used in the tool are principally based on data requirements and data availability at such an early phase of the planning process which might force the user to incorporate expert judgements in the weighting of individual indicators required for aggregation along the evaluation and in the evaluation of (especially qualitative) indicators themselves, which could potentially result in uncertainty and inconsistency if the assumptions made are not adequately documented. This is, however, a common issue of MCA approaches. Depending on available data for a given case study, this uncertainty can be reduced through the higher employment of measured or modeled data, keeping the use of assumptions to a minimum. Furthermore, social science approaches can be used to reduce the impact of subjective rating within the MCA approach.

A subsequent challenge was to transfer this assessment approach into a tool, providing transparent and applicable decision support to its different user groups. The application of the decision support tool for the sustainability assessment of the two case studies provided its developers with key insights about advantages as well as limitations that were necessary to modify the prototype of the tool and transform it into the practice-oriented tool. The involvement of hypothetical end users in the evaluation of the application tests has helped to reveal lack of understanding, gaps and inconsistencies.

As the implementation of water reuse technologies is occasionally hampered by risk concerns and lack of social acceptance, these factors should be considered in decision-making in an early phase of planning. Further development requirements for the tool exist, in particular with regard to a stronger incorporation of risk management approaches requiring additional data. However, by focusing on local-scale evaluations of comparable technical solutions, the tool provides accessible, lean and yield results that are directly relatable and actionable for stakeholders and decision-makers.

## CONCLUSION

The application of the developed decision support tool in two international case studies proved that the tool is applicable in various environmental and societal settings with widely differing climatic conditions, limited resource availability, for varying feed water qualities and water quality requirements. Due to its user-friendly design, a transparent valuation approach as well as the clear and comprehensible presentation of results, the local users became more aware of the strengths and weaknesses of the considered option and were able to identify the most sustainable supply system or strategy for their decision case. However, due to its simplified semi-quantitative approach, the assessment tool is designed and more suitable for the application in an early planning phase. Thus, the decision support tool can be a good starting point to foster in-house and local discussion on the implementation of water reuse solutions. As the approach requires information input from various sources, it is well suited for collaborative decision-making. In order to make it also suitable as a decision-support tool in the following implementation phases, future research should focus on connecting models and tools to the MULTI-ReUse decision support tool that allow for a more detailed and reliable assessment of preselected water supply options.

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## DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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