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Enabling the uptake of circular water solutions

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ABSTRACT

This study advances the discourse on the transition from a linear to a circular water paradigm, within which water is reused and resources such as nutrients and energy can be recovered. The research provides an empirical evidence from demonstrative cases, identifying the technological, economic, socio-cultural, and regulatory factors that facilitate or impede the broader adoption of circular solutions in the water sector. It proposes an integrated system approach, which encompasses a comprehensive set of enabling instruments, including (a) the demonstration of the sustainability of circular water technologies at a system level, thereby providing a robust proof of concept; (b) a shift from a conventional financial cost-benefit approach to a business model predicated on circular value chains, underscoring the economic feasibility of these solutions; (c) the enhancement of social acceptance through active stakeholder engagement, thereby fostering a supportive community for these transformative changes; and (d) the adaptation of the regulatory framework to incentivise circular water solutions, such as the establishment of dedicated end-of-waste criteria to facilitate market access for recovered resources. The study concludes that a concerted effort is required to reconceptualise our water systems as circular systems, and to legitimise the role of circular water within our society and economy.

Key words: Circular water governance, Circular water systems, Regulations, Societal acceptance, Value chains, Wastewater resource recovery

HIGHLIGHTS

- Water-embedded resources can be transformed into valuable and high-quality products such as reclaimed water, energy, and/or recovered nutrients.
- A comprehensive package of technological, economic, socio-cultural, and regulatory support instruments is needed for the wider uptake of circular water solutions.
- The circular water paradigm requires to rethink the system with its current legal and social norms and practices.

GRAPHICAL ABSTRACT

1. INTRODUCTION

Circular economy (CE) is an emerging paradigm that moves away from the traditional linear view of 'make, use, and dispose' to one that is restorative and regenerative to keep resources at its highest value at all times. Closing-the-loop production in a CE can improve the efficiency of resource use and create a better balance between economy, environment and society (Ghisellini *et al.*, 2016).

Water is essential to the CE due to its importance for human life, its use and value in numerous economic sectors, and because of the energy and material it contains. Reduce–reuse–recycle interventions can be viewed as promising building blocks for a circular water system (Bouziotas *et al.*, 2019). Circularity is conceptually linked to both sustainability and resilience (Geissdoerfer *et al.*, 2017; Suárez-Eiroa *et al.*, 2021), providing opportunities and challenges for the transition towards a circular water economy. In addition, the interdependence to other sectors in the water–energy–food–ecosystem nexus requires changes throughout whole value chains (Makropoulos *et al.*, 2022).

While CE concepts are increasingly well established and technological advances have accelerated the adoption of CE models, the implementation is still in the early stages in most sectors (Ghisellini *et al.*, 2016). The principal challenges to achieving a CE are not only technological, but also governance related. For instance, in the water sector, emerging technologies allow for many resources to be recovered, but their uptake can be hindered by concerns over economic feasibility (Mallory *et al.*, 2020), uncertainty around the application of policy and regulatory frameworks (Owen & Liddell, 2016), and the need for long-term engagement with key stakeholders and the wider public (Frijns *et al.*, 2016).

Considering these challenges, the EU H2020-project NextGen (2018–2022) took an integrated approach addressing technological, environmental, economic, business, participatory, societal, regulatory, and governance aspects of the circular water economy. NextGen worked on 10 demo cases across Europe providing evidence demonstrating the feasibility of innovative circular water technologies (CWTs). The NextGen CWTs encompassed a wide range of water-embedded resources: water itself, energy and materials (e.g. nutrients). Technologies were demonstrated to promote alternative water sources obtaining high quality water for non-potable uses, including wastewater advanced treatments and rainwater harvesting and storage systems. Energy recovery practices were demonstrated such as heat recovery from wastewater and local reuse, biogas production from sewage sludge, and heat storage and recovery. Solutions were demonstrated for material recovery from sludge, protein production from wastewater and/or RO concentrate, and nitrogen and phosphorus removal and recovery (Frijns *et al*., 2023). During the project time, numerous meetings took place with demo case partners and relevant stakeholders (such as policy-makers) to shape the CWTs and discuss the opportunities and challenges for successful implementation.

The objective of this paper is to draw out overarching conclusions and recommendations from the lifespan of the project and the demonstrated CWTs, and contextualise these within wider scholarly debates around transitions to a circular economy. Insights relevant to the wider uptake of CWT from academic literature and experiences from the practices at the demo cases were discussed and enriched in the project's meetings. As a result, this paper presents a synthesis of empirical evidence from the whole of the NextGen project, with a focus on the wider societal and governance challenges that the project studied.

The paper is structured as follows. After an overview of the principles of the circular water economy, the technological, economic, socio-cultural, and regulatory conditions required for circular water solutions are presented. The key drivers, barriers, and support instruments are cross-checked with the empirical evidence from the demonstrated NextGen circular water solutions. Success factors related to circular water technology, economic viability, societal acceptance and adapted governance are described. We conclude with strategies that enable the further uptake of circular water solutions.

2. METHODOLOGICAL APPROACH

As mentioned above, this paper brings together the results of a very large 4.5 year project with numerous solutions (technologies, concepts, models) demonstrated at 10 demo cases. The aim is to provide an overarching reflection of main lessons learned in relation to further upscaling the circular water solutions demonstrated. As a result, the evidence presented in this paper does not stem from a single methodology, but from a range of empirical studies undertaken through the life of the project. It is not feasible to describe each individual methodology in detail. Instead, this paper is structured like a targeted review paper, in that it brings together a body of work generated from the project and presents a synthesis of this work. Where the empirical evidence from the NextGen demo cases has already been published in peer-reviewed journals, those articles are cited. Where the work has not yet been published, project deliverables are cited instead to substantiate the evidence statements. Both the published articles and the project deliverables include more detailed methodological descriptions of data gathering and evidence generation.

The overall approach consisted of three main stages. First, an overview of drivers, barriers and support instruments was derived from the literature. In particular, papers that addressed relevant economic, societal, or governance issues for CWTs were analysed, in addition to the relatively few papers that presented an integrated approach on transitions (see Supplementary Material).

Second, facilitating and hindering conditions that emerged at the NextGen demo cases were derived from empirical social research with relevant stakeholders. The development of the CWTs, its benefits, challenges, and further opportunities were regularly discussed with stakeholders, including water industry experts, technology providers, researchers, policy/governance actors, representatives of other sectors and end-users. For this purpose, Communities of Practices were established at each demo site that warranted successful stakeholder engagement (Fulgenzi *et al.*, 2020).

Third, the findings from the literature and the empirical evidence from the demo cases were cross-checked and grouped into the key technical, economic, socio-cultural, and regulatory conditions. In two meetings with the NextGen demo case partners, these results were verified by indicating for each demo case the relevant factors for their respective CWT (see Supplementary Material). In addition, each demo case selected the required support instruments for a wider uptake of their CWT. From this assessment, the enabling strategies were derived and the strategy and planning discussed with the demo case partners.

3. RESULTS

This section presents the findings from the literature on the conditions needed and the factors found at CWT demonstrations shaping circular water solutions. First, the CE principles for water are described.

3.1. Circular water economy principles

Society and business have started to move away from a linear model of 'make, use and dispose' and instead developed closed looped systems that increase efficiency and optimise reuse. The European Union launched a new Circular Economy Action Plan in 2020 (EC, 2020). According to this plan: 'To achieve climate neutrality by 2050 and decouple economic growth from resource use, while ensuring the long-term competitiveness and leaving no one behind, the EU needs to accelerate the transition towards a regenerative growth model that gives back to the planet more than it takes and keep its resource consumption within planetary boundaries'.

The Ellen MacArthur Foundation, who are key leaders in the field of the CE, promote a CE based on the principles of designing out waste and pollution, keeping products and materials in use, and regenerating natural systems. 'A circular economy is one that is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles' (EMF, 2015). The overarching idea is to breakdown the connection between growth and finite resource consumption. The CE concept should not be mistaken with merely recycling, nor is CE synonym to sustainable development (Kirchherr *et al.*, 2017). A circular system is not necessarily sustainable due to environmental and social equity challenges.

Water has also predominantly been viewed in a linear way. Water is withdrawn from rivers, reservoirs, and groundwater aquifers; used by agriculture, industry, society and the environment; and then returned to the water basin directly or via a treatment facility. This current system is often inefficient as water is lost, polluted and wasted. Efforts are needed to improve the efficient use of water and reduce water pollution in society and business. The water sector itself is becoming more sustainable and energy efficient in its operation for the production of drinking water and treatment of wastewater. In addition, there is a need to shift from the short-sighted and unsustainable linear management approach (take–use–discharge) to a more circular water economy (Brears, 2020). Recently, important circular steps are being taken by closing water systems, reusing water, generating energy and recovering nutrients (e.g. Kakwani & Kalbar, 2020; Kehrein *et al.*, 2020). It is also becoming apparent that circular water systems challenge current water governance practices (Riazi *et al.*, 2023). The OECD (2018) defined water governance as 'the range of political, institutional, and administrative rules, practices, and processes (formal and informal) through which decisions are taken and implemented, stakeholders can articulate their interests and have their concerns considered, and decision-makers are held accountable for water management'.

The Ellen MacArthur Foundation have defined the following three CE principles applicable to water systems (Tahir *et al.*, 2018): (1) Design out waste and pollution: both by optimising the amount of energy and chemicals used in operation of water systems, and by substituting the need for water itself in agriculture and industry; (2) Keep products and materials in use: through the recovery and reuse of energy (heat, biogas) and materials (e.g. nutrients) from (waste)water; (3) Regenerate natural systems: by reducing water use and ensuring minimum disruption to natural water systems from human intervention. The circular water solutions demonstrated at the NextGen cases preserve natural capital, optimise resources and improve system efficiency, with a focus on keeping resources in use.

The most common CE strategies are: Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, and Recovery (known as the R-strategies; see Moraga *et al.*, 2019). However, some of these strategies refer to general resources and industrial productions that do not fit adequately the water context. Morseletto *et al.* (2022) have re-calibrated the CE strategies for water into three blocks: (1) decreasing: avoid, reduce, and replace; (2) optimising: reuse, recycle, and cascading; (3) retaining: store and recovery. In NextGen, emphasis is on the demonstration of technologies for recycling (treating previously used water for the benefit of further uses) and recovery (extracting nutrients, other valuable materials and energy from water).

Rethink is considered as a stand-alone and overarching strategy. Rethink means reconfiguring and re-conceptualising the water system, together with all water using sectors, to favour a more circular utilisation of water. It implies the re-design and restructuring of the contextual setting and potentially every operative aspect of the water use such as practices, processes, policies, facilities, technologies, and way of thinking (Eneng *et al.*, 2018); a systematic change in the whole water value chain (Smol *et al.*, 2020). This transformational change implies a system thinking at multiple levels (from individual to international) in which solutions are applied (Iacovidou *et al.*, 2020; Afghani *et al.*, 2022) and embedded in a resilient system (Delgado *et al.*, 2021; Bouziotas *et al.*, 2023).

NextGen included the rethinking strategy as a system-level characteristic of the circular water economy, building on Rockström *et al.* (2009) *Planetary Boundaries*. Aiming for a sustainable CE, societal values are included as a key characteristic, in line with Raworth (2017) *Doughnut Economics*. This approach emphasises to not only reduce the impact of the water cycle on the ecological ceiling, but also strengthen the values for the social foundation (Suárez-Eiroa *et al.*, 2021). In this project, the three categories of characteristics defined for the delineation of the concept of CE for the water sector (Segrave *et al.*, 2020) are used: (1) resource flows: physical characteristics of (parts of) the water cycle in relation to the environment; (2) societal values: socio-political characteristics of (parts of) the water cycle; (3) system properties: system-level characteristics of (the whole) water cycle.

Finally, an important characteristic of NextGen is that the circular water solutions at the demo cases are, in one way or the other, connected to other sectors such as agriculture, energy, industry, and housing. It is indeed the very essence of circularity, which unlike the notion of sustainability, creates interdependencies between sectors. This interconnection to other sectors is even more necessary in the field of water, since it is present in many, if not nearly all, sectors of activity (Nika *et al.*, 2020; Smol *et al.*, 2020; Makropoulos *et al.*, 2022).

3.2. Conditions needed for circular water solutions

While CE concepts are increasingly well established, they remain largely in the early stages of implementation in most sectors (Ghisellini *et al.*, 2016). Technological advances have accelerated the adoption of CE models in some areas, but progress is often slow. Some now suggest that the principal challenges to achieving a CE are not technological, but governance related. For instance, in the water sector, current and emerging technologies allow for many resources to be recovered, but their uptake can be hindered by concerns over economic feasibility, and uncertainty around the application of policy and regulatory frameworks (Owen & Liddell, 2016). Previous work around water reuse has also identified a number of governance related challenges to further development in the sector (Frijns *et al.*, 2016). These relate to uncertainty over regulatory requirements, and the need for long-term engagement with key stakeholders and the wider public. International case studies on water reuse disclosed the demand for an adapted governance framework with robust institutional arrangements (Smith *et al.*, 2018; Riazi *et al.*, 2023), taking a hydro politics approach (Koseoglu-Imer *et al.*, 2023). Applying CE principles to the water sector requires a holistic vision to pick the most circular solution (Viles *et al.*, 2020). The circularity of water follows a fit-for-purpose approach. This approach means creating new water loops, new water sources and qualities, new actors, new responsibilities, but also potential health and environmental risks. Thus, the move from a linear to a circular water system requires an approach integrating physical, socio-political, and system-level characteristics (see above, Segrave *et al.*, 2020).

In this study, four categories are identified from the CE literature that feature this integrated approach and define the conditions required for circular water solutions: technology, economic, socio-cultural, and regulatory conditions. In total, 12 key drivers, 20 key barriers, and 20 key support instruments divided over the four categories are disclosed (see Table 1). The conditions are further described in the following.

3.2.1. Technology conditions

The first condition is, arguably, to have innovative, operational CWTs. Assembly of efficient technologies concerns the optimisation of existing ones in view of the development of new innovative circular systems, regarding the recovery of water, resources and energy. Some of these CWTs are already well developed and proved efficient today, while others and the circular system in general are still at the prototype stage (Kakwani & Kalbar, 2020; Kehrein *et al.*, 2020). The maturity of the technology needs to be demonstrated. Innovation, price and knowledge and expertise (e.g. accessible data, Liu *et al.*, 2021) are key drivers and barriers for the development of CWT. Physical conditions, i.e. fit to existing infrastructure, considerations on space, odour, noise, are relevant to CWT uptake as well.

Technological innovation turns wastewater treatment plants into energy and raw materials factories. Specific for the recovery of products, a key barrier is that either the quality (e.g. due to contaminants or impurities) or the quantity (compared to conventional production systems) is not yet adequate or sufficient for a successful market uptake (Gherghel *et al.*, 2019; Kehrein *et al.*, 2020).

Attention should be paid to the environmental purpose of circular technologies. Developing closed-loop production processes should not increase the pressure on the environment and create negative effects outside the process. The recovery process may cause emissions and the risk of accumulating contaminants needs to be prevented seeing the impacts contaminants can have on the environment and human health (Guerra-Rodríguez *et al.*, 2020; Kehrein *et al.*, 2020). In short, the circular technologies should be sustainable at a system level, taking multidimensional benefits and impacts at the system level into account (Iacovidou *et al.*, 2020). This is in particular valid for balancing greenhouse gas emissions (e.g. through energy required for recovery processes) with environmental benefits from circular systems.

For the uptake of CWTs, it will be a key prerequisite that the CWTs are effective and efficient with a high technological readiness level, and that they are sustainable at a system level. Successfully demonstrating a CWT, with proof of concept, quality control, performance data, and technology verification, will support the implementation and upscaling of CWT. Likewise, possible environmental and health risks need to be addressed, for which an integrated risk management approach needs to be adopted.

3.2.2. Economic conditions

The transition to a CE is becoming increasingly important in the business strategy of water companies as an economic or market driver (Salminen *et al.*, 2022). Savings can be achieved by reduced treatment of discharge costs, and benefits are envisaged from reduced use and recovered products. However, this business strategy often requires high upfront investments, and the economic merits are challenged by the current low prices of water

Table 1 | CWT drivers, barriers, and support instruments.

Technology drivers	Technology barriers	Technology instruments
Technology innovation	Immaturity of the CWT	R&D/Proof of Concept
Price and affordability of CWT	Lack of knowledge and expertise	Public evidence database of circular water schemes
Ageing infrastructure	Associated environmental and health risks	Master list of water quality parameters and risk database
	Existing infrastructure	Quality control and monitoring procedures
	Inadequate quality or quantity of recovered product	Environmental Technology Verification
Economic drivers	**Economic barriers**	**Economic instruments**
Business strategy	Poor economic viability	Tariff structures that favour reuse and tax water use
Reducing costs of wastewater discharge or treatment	Low price of water and virgin materials	Subsidies for secondary materials and recycled water
Financial benefits of recovered by-product/reduced water use	High upfront investment costs	Investment grants (ESG/green bonds)
	High price of recovered products	Risk sharing in PPP arrangements
	Challenges in finding partners in new value chain	Market place to connect producers and consumers
Socio-cultural drivers	**Socio-cultural barriers**	**Socio-cultural instruments**
Increased water awareness	Negative attitudes towards CWT	Information sharing and public outreach campaigns
Responding to environmental challenges	Communication challenges with authorities	Active stakeholder engagement
Positive brand image	Reluctance to collaborate with other sectors	Socio-political work to push CWT
	Hesitant culture in water organisation	Independent review panels
	Lack of trust in institutions (for monitoring and control)	Positive framing of reused water/recovered product
Regulatory drivers	**Regulatory barriers**	**Regulatory instruments**
Regulatory requirement	Current legislation hinders reuse	Stricter environmental regulations
Demands set in environmental permit	Lack of clear policy for resource recovery	Improved clarity of Water Reuse Regulation
Availability of public financing	Complexity of environmental permits	Planning & building framework adapted for small-scale CWT
	Unpredictability of (future) legislation	Simplified process for achieving end-of-waste status
	Variation in regulations in EU countries	Better aligned EU directives (with circularity emphasis)

and linear resources and high market prices of the recovered products that are not yet competitive (van Leeuwen *et al.*, 2018). On the other hand, as the technology develops its economic balance sheet should improve; perceived economic viability changes as the TRL level improves.

It is essential to be innovative and to develop products with high added value. Recovered by-products from (waste)water, such as calcite, can become profitable by establishing themselves in niches, on a small scale. Niche markets are highly specialised and often dependent on production quality. Niche markets are guided by economies of scope rather than by economies of scale.

An often mentioned and rather obvious precondition is, that the CWTs are economically viable (Mallory *et al.*, 2020; Mannina *et al.*, 2022). However, CWTs do not have to be economically viable per se. In general, system services such as water reuse, climate mitigation or reduction of pollution are not profitable. In many asset decision making frameworks, there can be an overemphasis on the need for selected technologies to be economically viable, and that in itself can present a barrier to the uptake of CWTs when they are considered alongside other, more established technologies. In order to 'level the playing field' for CWTs, decision making frameworks need to give greater weight to strategic environmental and social priorities.

Moreover, more advanced use of economic instruments such as pricing, taxing and subsidies can improve the competitiveness of circular products (Salminen *et al.*, 2022). De-risked financing can be used to support investment in CWTs and progress the technological development. To overcome market difficulties, government subsidies or incentive regulation (e.g. carbon tax) can be a solution. Utilities must be given better incentives for using sustainable water solutions, e.g. by investment grants such as the ESG (Environmental, Social, and Governance) or green bonds.

Additionally, in a CE, new value chains need to be developed, with circular business models that include societal values within economic cost-benefit analyses. Moving from a linear to a CE entails a shift from a financial cost-benefit approach to a business model based on circular value chains. However, finding partners in the circular value chain is difficult (Kehrein *et al.*, 2020). Organising new efficient collaborations and business arrangements that distributes optimally risks and benefits among public and private sectors is required for the successful development of circular business models.

3.2.3. Socio-cultural conditions

One of the main drivers for the CE is the urgent climate change crisis. Pressure from society to respond to environmental challenges such as climate change, including the increased awareness of water quantity and quality problems, drive the water sector towards a more sustainable and circular operation (Salminen *et al.*, 2022).

At the same time, circular solutions such as water reuse are hampered by fears of negative attitudes and low acceptance by the public and by water professionals. This has to do with perception (e.g. the yuck factor) but also with a lack of trust in the water organisations and involved governmental institutions (Smith *et al.*, 2018). Active stakeholder engagement and public participation will enable the societal acceptance of circular water solutions. Proper public engagement from the start will be needed to ensure public acceptance and overcome the yuck factor. Information sharing and public campaigns will enable acceptance, but early consultation and ensuring long-term collaboration will be necessary as well. Building confidence and gaining trust through consultation and independent review panels allows for a location specific approach that deals with uncertainty regarding risks and their perception. Public acceptance can be further enhanced by legitimisation strategies such as the use of long-term narratives and positive framing around the benefits of circular water solutions so that recycled water becomes 'normalised' (Binz *et al.*, 2016; Smith *et al.*, 2018; Afghani *et al.*, 2022).

Another socio-cultural barrier that needs to be addressed relates to the challenge for new collaboration and business models, that require new competences, partnerships with other sectors and interaction (communication) with authorities (Kakwani & Kalbar, 2020).

3.2.4. Regulatory conditions

Supportive regulations are essential for an efficient circular transition. Regulations must first of all authorise the development of the CWTs, and set standards regarding product quality and its use. Unfortunately, current regulations act mainly as a barrier due to e.g. cumbersome permit practices, lengthy end-of-waste status procedures, restrictive conventional urban planning, and lack of comprehensive (EU water) policies (Cipolletta *et al.*, 2021; Qtaishat *et al.*, 2022; Salminen *et al.*, 2022). Indeed one of the main barriers to the uptake of circular schemes is the cost and complexity of achieving legal end-of-waste status for materials recovered from water and wastewater systems (e.g. nutrient products and cellulose fibres). This legal status is often required to ensure the products can be brought to market.

The key challenge in developing circular regulations is to balance between sustainability gains and environmental protection, i.e. to compromise between excessive precaution and insufficient safety. Overly stringent quality standards need to be avoided as they could discourage the development of CWTs (such as for water reuse) by imposing burdensome treatment and/or costly monitoring requirements (Frijns *et al.*, 2016).

Regulations should go hand-in-hand with adapted governance and a supportive institutional framework. On one hand, the availability of public financing can drive R&D and investment in CWTs. But there is also a lack of capacity and governmental incentives and poor understanding of responsibilities (Ddiba *et al.*, 2020). Circular water schemes often span the jurisdictions and responsibilities of multiple regulatory and administrative bodies. Fragmentation of responsibilities constrains the wider adoption of for example water reuse practices (Riazi *et al.*, 2023). Transitioning to a CE requires policy coherence, coordination and collaboration among stakeholders across governance levels. Studies showed that since CE creates interdependence between stakeholders and goods, a multi-level governance or a hybrid governance structure could be an effective solution for a circular transition (Maaß & Grundmann, 2018; Bauwens *et al.*, 2020).

In a European context, where water can be considered as a transnational good, a harmonised regulation is essential for the development of a European circular market. The EU Circular Economy Action Plan (EC, 2020) aims to streamline regulations made fit for a sustainable future. The EU relevant stakeholders should consider circular water challenges beyond traditional sectoral governance paths. Indeed, the CE brings together a number of policy and regulatory regimes resulting in potential gaps and overlaps that affect the feasibility of circular water solutions. Tensions between different regulatory frameworks need to be reconciled as the CE is very much a transition from waste management and disposal towards value creation within and between sectors (Frijns *et al.*, 2021).

3.3. Findings from CWT demonstrations

In this section, the factors derived from the CE literature as presented in Table 1 are verified with the synthesised empirical evidence from the NextGen demo cases. In a NextGen strategic planning meeting, the respective representatives of each demo case indicated which of the drivers and barriers they encounter and which support instruments would enable the further implementation and upscaling of one of their key CWTs. The findings (see Supplementary Material) are in accordance with the literature.

All drivers identified from the literature were selected by at least one demo case as a top driver for their CWT. *Responding to environmental challenges* is listed the most (six times) as demo case representatives emphasised climate change as an important driver.

All barriers identified from the literature were selected by at least one demo case for their CWT. The barrier selected most is *Lack of clear policy for resource recovery* (nine times). Four demo cases did not select socio-cultural aspects as a barrier.

All support instruments identified from the literature were selected by at least one demo case for their CWT. All 10 demo cases listed as main support instruments *Provide proof of concept* and *Ensure active stakeholder engagement*. *Arrange for subsidies for secondary materials and recycled water*, *Lobby to put circular solutions on the socio-political agenda*, and *Build a positive storyline around reused water and recovered product*s are listed by nine of the 10 demo cases.

The factors found are further described in the following, with reference to the NextGen evidence published in peer-reviewed journals or project deliverables instead to substantiate the evidence statements (available at Results – NextGen Water; https://nextgenwater.eu/results/.

3.3.1. Technology factors

At the 10 NextGen demo cases, 26 CWTs have been implemented and tested. The demonstrated solutions displayed that technically wastewater can be transformed into valuable and high-quality products such as reclaimed water, energy (biogas and heat), and/or recovered materials (including nitrogen and phosphorous). These products can act as alternative sources to cover a range of (non-potable) water demands, energy needs and the production of fertilisers and other commercial goods (NextGen deliverables D1.3, D1.4, D1.5, D1.7). For example, the pilot plant in the Costa Brava (Spain) demo case, consisting of ultrafiltration and nanofiltration with regenerated membranes, produces 2 m^3/h reclaimed water; with 80% removal of trace organic compounds, meeting the quality requirements for private irrigation (D1.3). At the Braunschweig (Germany) municipal WWTP (380,000 p.e.), nutrient recovery was successfully demonstrated with a $>$80% P-recovery into struvite (potential of 300 ton/year) and 85–97% N-recovery into ammonium sulphite (potential of 2,000 ton/year) (D1.5). Solutions included as well the use of alternative water sources, e.g. in a new community under development at Filton Airfield (UK) rainwater harvesting and grey water recycling would result in 78% water demand minimisation and 46% reduced wastewater amount (D1.8; Kim *et al.*, 2022).

Life Cycle Assessments demonstrated that CE concepts and technologies can lead to a lower environmental footprint of wastewater treatment, considering the value of recovered products and the substitution of conventional alternatives from the linear economy (D2.1). However, experience from the NextGen demo cases confirmed that recovery comes with a downside. Although circular water solutions can lead to a lower environmental footprint, the recovery and reuse process often requires more energy and may accumulate contaminants. A system perspective, e.g. total energy balance, needs to be taken. For example, the anaerobic membrane bioreactor at Spernal (U.K.) yields the potential for an energy-neutral wastewater scheme, but the energy-intensive degassing of treated effluent can offset the energy gain from the biogas produced (D1.4).

Through quantitative microbial risk assessment of water reuse the potential for safe implementation of water reuse applications for almost all tested treatment configurations was demonstrated (D2.1). The sewer mining demo case in Athens (Greece), consisting of an on-site compact hybrid MBR/UV treatment system, produced water of excellent quality with complete elimination of organic carbon and pathogenic content (D1.3; Plevri *et al.*, 2021).

Regarding the sustainability at system level, resilience assessment at the Westland (Netherlands) demo case revealed that incorporating more circular dimensions leads to a more resilient regional water system (D2.3; Bouziotas *et al.*, 2023).

3.3.2. Economic factors

The economic assessments of the NextGen demo cases provided important lessons on site-specificity and competitiveness of circular solutions. For example, a payback period analysis of the rainwater harvesting system for the Filton Airfield neighbourhood (U.K.) revealed that a 600 m^3 tank would be cost effective at 5% discount rate and a water price of 3 £/m^3 (D1.8; Kim *et al.*, 2021). In general, within the given market and regulatory context small-size local circular solutions do have a higher specific treatment cost, and the price of reuse water is not always competitive with the current local drinking water price. But other aspects need to be considered: for example in several cases anaerobic wastewater treatment resulted in a cost for CO_2-eq reduction that is lower than the current CO_2-eq price. Still, overall few circular technologies are cost effective with regards to climate mitigation (D2.2).

Although P recovery from sludge at one demo case (Altenrhein, Switzerland) was cost effective compared to mineral P, most nutrient recovery systems are not profitable at this stage, as the revenues from fertilisers are lower than the cost of the recovery (D2.2). However, the cost effectiveness of the assessed technologies is expected to improve as they are further developed and reach market maturity. For example, the economic evaluation of the demo case in Athens showed that the sewer mining technology is a viable and profitable scheme that will be even more attractive if economies of scale and environmental costs–benefits are included (D2.2; Liakopoulou *et al.*, 2020).

To enable the market uptake, a circular business canvas has been established and 23 circular value chains from the 10 NextGen demo cases have been identified (D5.2). For selected CWTs, a market assessment and business plans for spinoffs have been developed. Every economy needs a market place where producers and consumers meet and trade, therefore NextGen developed an online marketplace for the circular water economy (D5.5). Establishing such a market based on value chains will enable a positive circular business model.

3.3.3. Socio-cultural factors

Public acceptance is of utmost importance as the people are end-users of water and its recovered resources. In contrast to the general belief, most people are positive towards reclaimed water and recovered products. A large NextGen survey was conducted in the UK, the Netherlands and Spain, that revealed a generally positive attitude, i.e., 70–80% of the respondents indicated to (strongly) support using recycled water for drinking purposes and eating food grown with recovered nutrients (D4.2; Shannon *et al.*, in prep.).

Citizen engagement and public acceptance has been effectively enhanced through an Augmented Reality app and a Serious Game in which the general public can visualise and experience circular water solutions. An Augmented Reality app CirculAR and the NextGen Serious Game were built and demonstrated for that purpose. Results show the high potential of increasing public understanding and acceptance through AR (D3.6; Katika *et al.*, 2022) and SG (D3.7; Evans *et al.*, 2023; Khoury *et al.*, 2023).

Stakeholder engagement around the demonstration cases was organised through Communities of Practices (CoPs). In these CoPs, the circular technologies are discussed within their institutional contexts through open dialogue and social learning among the stakeholders. These CoPs extend beyond the exchange of information to actual consultations, making it possible to co-design the technologies and fit the innovations to the local needs and settings. The CoPs positively contributed to engagement and interaction of stakeholders, change in stakeholders issue frames, and stakeholder awareness of role and competence (D3.5; Fulgenzi *et al.*, 2020).

3.3.4. Regulatory factors

Meeting regulatory requirements is part of the NextGen CWT developments. For example, the MBR effluent characteristics of the sewer mining demo case in Athens (Greece) lie within the limits set in the Greek wastewater reuse legislation for unrestricted irrigation and urban use (D1.3; Plevri *et al.*, 2021).

A comprehensive assessment of the regulatory framework for circular water solutions in the countries of the NextGen cases confirmed the barriers concerning inconsistent policies, unfitting building and planning regulations, complex permitting, too strict standards, etc. (D4.3; Qtaishat *et al.*, 2022).

Based on the experimental evidence from the NextGen demo cases, several policy recommendations were derived (Frijns *et al.*, 2021), highlighting among others a better alignment between directives and incentivise circularity, and the need for an improvement of clarity and transparency for the new EU Water Reuse Regulation. For example, include the water sector in energy efficiency and renewable energy strategies, but improve alignment with environmental ambitions. The recently proposed revision of the Urban Wastewater Treatment Directive is a step in the right direction towards a CE, as it seeks to drive the water and wastewater sector towards energy neutrality, and provides greater incentive for water reuse and the recovery of biogas and phosphorus.

NextGen recommends the creation of dedicated end-of-waste criteria for simpler and less costly routes to market for recovered resources (D4.3). Many gaps and hurdles still exist, although the recently revised Fertilising Products Regulation opens the single market for fertilisers produced from recovered or organic materials, including those from (waste)water.

4. DISCUSSION

In this section, the strategies to support the circular water economy and rethink the CE water system are discussed.

4.1. Strategy to support wider uptake of circular water solutions

The empirical evidence from the CWT demonstrations shed thorough light on the conditions required for the wider uptake of circular water solutions. Key is a robust proof of concept of the sustainability of CWTs at a system level. A business model predicated on circular value chains is to be applied, underscoring the economic feasibility of these solutions. Active stakeholder engagement has to foster social acceptance and a supportive community for these transformative changes, and an adapted regulatory framework must incentivise circular water solutions.

What also emerges from the analysis of needs for a circular transition is that the conditions found are interconnected. Contrary to what it seems, the technological factor alone is not the only, nor even the main, challenge faced. Indeed, the system and its environment around the development of the CWT must be favourable. Elaboration of a system approach around this multi-disciplinary field is probably the main challenge to overcome.

In a working session with all NextGen partners, the strategy and respective planning on a short to long term was discussed. There was agreement that for an effective transition, the efforts coming from all four categories of instruments is needed, starting simultaneously now. Regulatory changes can be incurred at rather medium term, providing a great incentive to technological innovations, and although socio-cultural changes often take a long-term perspective, the current socio-cultural drivers for circularity, sustainability and climate change measures will push the regulatory changes already now. Having on a short time proper economic instruments (such as tax relief on secondary materials) will drive circular innovations, that at the same time push the proof of concept and economic viability of water reuse and drives demand of recovered products. Thus, an EU strategy for the uptake of circular water solutions would have to consist of a comprehensive ‘package’ of enabling instruments at short-term. This will support the *Reduction of use of resources* and *Reuse and recycling of water* and enable the wider uptake of *Recovery of products* (see Figure 1).

4.2. Rethink the CE water system

On the long term, experience from the NextGen demo cases regarding the enabling conditions underscores the need to *Rethink the CE water system* (Figure 1). The circular water paradigm challenges the fundamental linear approach that sits at the heart of the current policy frameworks, economic systems and social norms that surround water and wastewater. The linear approach is built on the guiding premise to take raw water from the

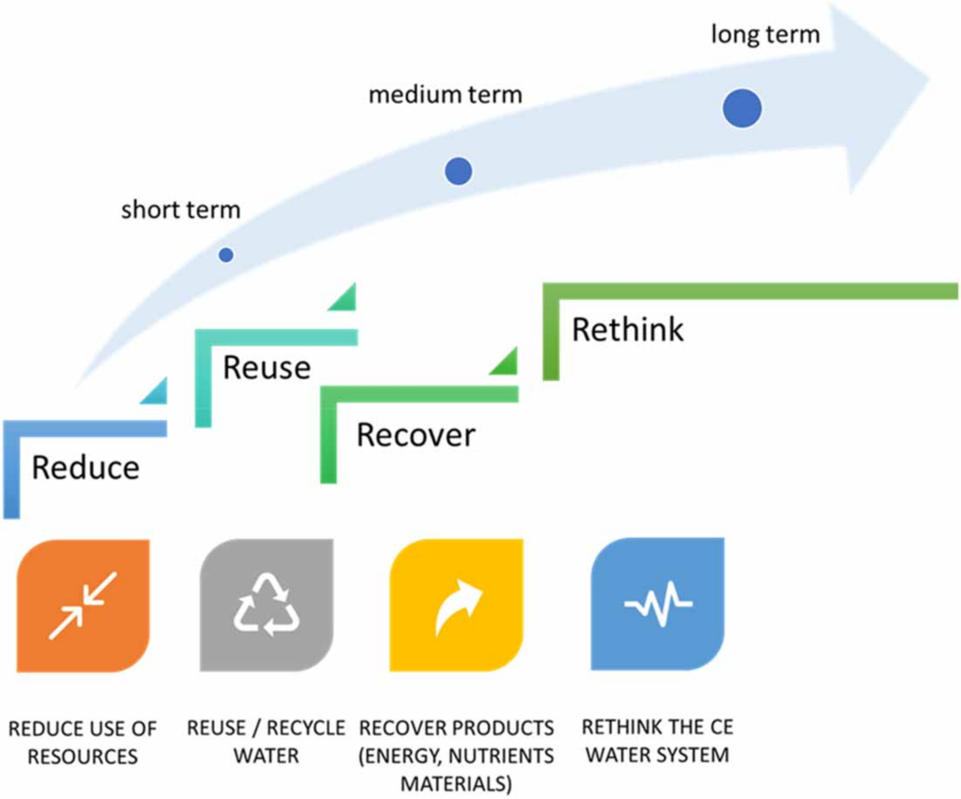

Fig. 1 | Strategy roadmap for the wider uptake of circular water solutions.

environment, use it, and dispose of wastewater back in the environment, with the dual overarching aims of maximising public health protection and minimising cost. Rethinking the system requires rethinking those overarching aims. New objectives such as environmental improvement and generating wider social value need to be considered alongside the necessity to protect public health. Rather than minimising costs, the emphasis should shift towards developing longer term economic potential. Shifting those fundamental guiding premises would alter the basis on which policy and regulatory frameworks, economic governance models and operational strategies for the water sector are designed.

A system-level change with a focus on legitimising CWTs in society and the economy (Afghani *et al.*, 2022) has to come from all actors across the whole water value chain. First, the water sector is in the driver's seat. Over the last decade, the water sector has shifted towards providing services in a more sustainable way by using fewer resources and energy inputs. The next step is to do so in a more circular way by recovering and reusing water, nutrient and energy, not only within the water sector itself, but also as part of the overall CE. Second, governments will play an essential role in unlocking the transition towards sustainable and circular business models. The transition towards value creation within and between sectors requires an adapted regulatory framework that incentivises circular water solutions. Both the EU and national governments need to provide policy coherence, and facilitate coordination and collaboration among stakeholders and across governance levels. Governments are requested to not only encourage research and innovation and provide funding, but to rethink the support system based on circular value chains.

A limitation of this study is that an actual transition push has not been undertaken other than engaging stakeholders and sharing insights on the steps to be taken. This is upon relevant organisations to do, mainly outside the water sector, e.g. national and regional government to adapt towards a CE policy framework (within their regulatory context), and industry to establish business models for circular value chains. Valuable lessons in this transition phase are still to be learned.

5. CONCLUSION

CWTs at high technology readiness level are already becoming available for the reuse of water and recovery of products from wastewater. However, support will be needed for the wider uptake of circular solutions in the water sector. The main drivers, barriers and support instruments were derived from the academic literature, and the facilitating and hindering conditions that emerged in practice were derived from NextGen demo cases. Cross-checking these findings, 12 key drivers, 20 key barriers, and 20 key support instruments were revealed. The empirical evidence from the NextGen demo cases confirmed that technological, economic, socio-cultural and regulatory support instruments are necessary. The transition from a focus on waste management and disposal towards value creation within and between sectors asks for an adapted governance framework. As an overarching conclusion, a comprehensive set of enabling instruments is required, as all four conditions for a circular water economy will have to be successfully created simultaneously:

- CWTs, that are sustainable at the system level;
- economic viability, based on circular value chains;
- societal acceptance, along with engaged stakeholders;
- adapted governance, with supportive regulations.

Establishing that package of instruments is a central recommendation from this study. Joint efforts are needed to rethink the system and transform to a circular water economy, especially since the circular water paradigm challenges the business-as-usual linear management approach, which is well embedded into current legal and social norms and practices. To rethink the system and overcome such challenges, a focus on legitimising circular water in our societies and our economies is necessary to build the trust needed to enable widespread uptake of circular water solutions.

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DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

The authors declare there is no conflict.

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