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Adoption of water reuse technologies: An assessment under different regulatory and operational scenarios

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ABSTRACT

Water reuse technologies may alleviate the water scarcity problems that affect many world regions, but their adoption is still limited. In particular, key actors in the adoption of water reuse technologies are water utilities, that provide both urban water and wastewater treatment services. Water utilities are embedded in the urban water system, which includes several stakeholders (urban water users, citizens at large, the environment) that may drive or pose barriers to water reuse adoption. Therefore, to ensure a smooth introduction of water reuse technologies, it is fundamental to understand how water reuse interacts with the existing urban water system and impacts its stakeholders. This paper contributes to the ongoing debate on water reuse by conceptualizing the interaction between water reuse technologies and the urban water system and its stakeholders, and addressing the adoption decision of water utilities by assessing its economic and environmental consequences. Based on a review of literature, policy and other secondary documents, and on primary data coming from interviews with experts from a water utility operating in Southern Italy, the study models the utility's response to a shift from urban to reuse water. It then simulates how reuse water introduction impacts on the utility and other stakeholders of the water system, under various regulatory and operational scenarios defined through a thorough analysis of policy documents and literature. Results show that the adoption of water reuse reduces the utility's margin by cannibalizing urban water demand, but appropriate policy measures may enhance the economic sustainability of reuse. System-level performances, such as impact on freshwater savings, costs for users, effects on the public budget, are also assessed, showing how different regulatory options moderate the intensity of impacts for the different stakeholders of the water system. Furthermore, the adoption of reuse water by the most distant users is found to enhance the economic sustainability of reuse and positively impact the utility's margin.

1. Introduction

Water scarcity is already a major problem for many communities (Zarei et al., 2020). Demand growth and climate change are likely to further exacerbate the issue (Hristov et al., 2021). As only a small part of the water on Earth is available as freshwater, conventional water sources are subject to increasing stress and over-exploitation (The United Nations, 2017). Indeed, around 88.2% of Europe's freshwater comes from rivers and groundwater, causing pressure on these sources (European Environment Agency, 2018). According to estimates by the European Environment Agency (2018), one third of the European territory is already subject to water stress, especially in Southern Europe. The reuse of treated wastewater could represent a valuable option to reduce the pressure on freshwater consumption (Almeida et al., 2013; Garcia and Pargament, 2015). Out of the 40,000 million m^3 of wastewater treated every year in Europe, only 964 million m^3 are reused (The European Commission, 2020). Therefore, there is a huge potential to reduce the pressure on freshwater and exploit this unconventional source.

Both non-potable (i.e., irrigation, industrial and urban uses) and potable applications are feasible (Gikas and Tchobanoglous, 2009), although the latter are more controversial due to health and social acceptance concerns (Hartley et al., 2019; Smith et al., 2018).

In spite of the recognized benefits of reusing wastewater, major barriers still hinder the selection and adoption of reuse systems, especially on a large scale (Bichai et al., 2018). Lee and Jepson (2020) offer a comprehensive literature review that summarizes the role of policy, economic, social, technical, legal, environmental barriers and drivers in determining the integration of water reuse into urban water systems. Among others, high initial investment in the absence of subsidies (The European Parliament and the Council of the European Union, 2020),

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uncertain acceptability of reusing wastewater (Garcia and Pargament, 2015; Smith et al., 2018), and coordination costs among actors (Daigger, 2009) are often cited.

Water utilities, namely the urban water operators,[1] as the actors who collect and treat wastewater, are a key stakeholder in the take-off of water reuse projects (Hartley et al., 2019), also because the consumption of reuse water has a profound impact on their economics (International Water Association, 2016). Furthermore, the introduction of reuse has cascading impacts on the entire water system and its stakeholders. If correctly implemented, water reuse could foster energy and water conservation (Reznik et al., 2019), by-products recovery (Jeffries, 2017), avoid discharge of pollutants in the environment (de Aquim et al., 2019), and yield economic benefits (The European Commission, 2015; Verhuelsdonk et al., 2021). Reuse technologies and practices may have beneficial impacts on local communities and the environment (De Paoli et al., 2016; Ruiz-Rosa et al., 2020) and are encouraged in the European policy framework (The European Parliament and the Council of the European Union, 2000, 2020), but their adoption cannot be taken for granted. Price regulation instruments and other policy measures are necessary to recover the water reuse costs and to achieve appropriate gaps between the relative prices of urban and reuse water, leading to resource savings.

This study aims at filling a research gap (Aldaco-Manner et al., 2019; Lee et al., 2021), by shedding light on the integration of water reuse in the existing urban water system, the impact of water reuse on the water system stakeholders, and analysing how the adoption of different price regulation and other policy measures can moderate the impacts of the adoption of water reuse technologies on the key stakeholders of the water system, i.e. the water utilities, water users, citizens at large and the environment (whole community and future users). Indeed, at the moment there is a limited amount of data currently available on this specific topic, as most studies on water reuse focus on technical aspects (Lee and Jepson, 2020), perceptions and acceptance around water reuse (Craddock et al., 2021; Smith et al., 2018), environmental results in terms of waste reduction or reduced carbon emissions, and energy efficiency (de Aquim et al., 2019). Moreover, very few works adopt an environmental economics and/or policy perspective.

The paper addresses the following research questions (RQs):

- RQ1: *How is the water reuse system integrated in the urban water system?*
- RQ2: *How do policy measures and operational characteristics facilitate the adoption of water reuse systems by water utilities?*
- RQ3: *How do different policy measures moderate the propensity of water system stakeholders* to adopt *water reuse?*

This analysis provides novel insights, as utilities and water system stakeholders are seldom taken into account when considering the implications of water reuse projects. While the public acceptability of reuse water applications has been explored in detail in the past literature (Saliba et al., 2018), the implications for the utilities and for other stakeholders of the water system have not been considered sufficiently. However, this is of paramount importance, as utilities and other stakeholders have the power to hinder or foster reuse water applications (Saliba et al., 2018) and understanding which conditions make these applications feasible will facilitate their implementation. This study is, to the authors' best knowledge, the first to quantitatively simulate the impact of water reuse adoption on the water system and its stakeholders. Simulations are built based on a model of the changes occurring in the operations of an Italian water utility active primarily in the urban water cycle (distribution of urban water, collection, and treatment of wastewater), calibrated on data from financial accounts, policy and grey documents as well as primary information collected through meetings and interviews. As such, it contributes to developing a higher understanding of the interplay between the urban water system and its stakeholders and the introduction of water reuse, a key field to investigate to stimulate the adoption and diffusion of water reuse among water utilities. Furthermore, this study is the first, to the authors' best knowledge, to simulate the impact of different policy and price regulation measures on the different stakeholders of the water system, and to see how different policy decisions modulate the impacts of reuse introduction on different stakeholders. As users of the water system may drive but also pose barriers (Garcia and Pargament, 2015) to the introduction of water reuse, investigating and deriving a first quantification of the effects of water reuse introduction on these stakeholders, and how such impacts are modulated by policy choices, is of paramount importance for a properly managed introduction of water reuse technologies.

The remainder of the paper is structured as follows. In Section 2, materials and methods are illustrated, and the model is presented also through a critical review of relevant literature. Section 3 reports the main results of the simulations. Finally, Section 4 outlines the discussion and conclusions.

[1] This paper refers to the conventional (i.e., not reused) water resource provided by the water utility through its urban networks as "urban water". In this paper, as the focus is on non-potable reuse, it overlaps with freshwater, and the terms are used interchangeably.

2. Materials and methods

The paper presents the results of a research that analysed the various impacts of water reuse adoption by a water utility. Following the research questions, the analysis leans on a model developed through three steps.

A first literature review allowed to identify the main patterns through which the water reuse technology may be integrated in the urban water system (Section 2.1). This section allowed to set the boundaries of the study. Secondly, two literature reviews addressed the costs of water reuse systems and the policy measures that allow to recover such costs (Sections 2.2 and 2.3). Besides academic literature, the review covered various sources of secondary data, such as corporate reports and financial accounts of water utilities, policy and regulatory documents and grey literature reports. Lastly, semi-structured interviews with experts have been conducted to supplement literature insights (DiCicco-Bloom and Crabtree, 2006; Yin, 2009) (Section 2.4). An Italian utility was selected as a representative case to calibrate the model on, and from which to select managers as knowledgeable experts for the interviews (Voss et al., 2002). The utility operates in Southern Italy and manages an urban water distribution network of thousands of kilometres and a network of dozens of wastewater collection and treatment plants.

In the context of the focal utility, water reuse could reduce pressure on conventional water sources (mainly rivers, artificial and natural reservoirs), which are increasingly exposed to stress in the served area. Southern Europe population is increasingly experiencing water stress conditions caused by growing consumption for agriculture and cooling electricity plants and, on the supply side, climate changes (EEA, 2019). Rainfall is quite scarce in the region, with a mean annual value below 500 mm (Lopez, 2014). Water shortage episodes are occurring in summer across locations facing a high demand from tourists. In Italy, obligations on reuse water were defined in 2003 (Ministero dell'Ambiente e della Tutela del Territorio e del Mare, 2003). Reuse water has to meet quality standards that are stricter than standards for urban wastewater released in water bodies by treatment plants (Ministero dell'Ambiente e della Tutela del Territorio e del Mare, 2003, Annex 1; The Italian Parliament, 1999, Annex 5)· Treated urban wastewater becomes reuse water when it undergoes further treatment ("reclamation").

Interviews have been conducted to gain insights on water reuse practices and, once the model has been developed, to get a first feedback on results and to refine the model (Barratt et al., 2011; Baškarada, 2014). Interviews involved 2 main informers, a senior operations officer of the water utility (interview A) and an expert from the regulatory affairs department (interview B). Secondary sources of data, namely the utility's financial reports, media news on the utility and the communities served, and reports of regional and national policymakers, were used for triangulation, to corroborate the insights provided by the interviewees, so to reduce personal bias (Woodside and Wilson, 2003; Zainal, 2007).

Contacts with the managers of this water utility located in Southern Italy have been favoured by the authors' participation in a wider project, aimed at analysing the economic and technological feasibility of reuse water technologies to provide an unconventional water resource.

The results of pre-existing studies, secondary data from various sources, and primary data from interviewees are inputs to the development of a model of the utility's economic margin variation following water reuse introduction (Section 2.5). The model allows the introduction of selected operational characteristics of the reuse system and policy measures, and the impacts of the introduction of water reuse technologies are analysed through model simulations under various regulatory and operational scenarios. The model allows also to simulate the value of a set of key performance indicators (KPIs), introduced to gauge the impact of water reuse and the moderating role of policy measures on the water system stakeholders, such as the environment (local community and next generations), water end users, citizens (as taxpayers).

In so doing, this study answers to the research questions by yielding three main results: 1) a framework that illustrates the integration between the water reuse system and the existing water system (the utility and its users, and the stakeholders of the water system); 2) an assessment of the impacts of the adoption of water reuse technologies from a water utility on the stakeholders of the water system; 3) an analysis of the moderating impact and relative performance of different policy measures on the utility and other water system stakeholders.

2.1. Deployment patterns of water reuse systems: a typology

Whether reuse technologies are operated by water utilities or users, reuse water partially replaces urban water demand (Capocelli et al., 2019; Maier et al., 2022). In order for reuse to be economically sustainable for the water utility, the consequent additional revenues or cost savings should outweigh the additional costs of reuse technologies, also considering support policies (International Water Association, 2016), or possible revenues generated by previously unsatisfied demand in situations of scarcity (Sapkota et al., 2016). Alternatively, in cases of rationed demand owing to scarcity or demand peaks, reuse technologies may generate an additional source of water and allow the utility to serve a previously unsatisfied demand portion (Adapa et al., 2016).[2] In this paper, while recognising the relevance of the second option, the focus is on the first as a more likely short term outcome.

Different configurations of the reuse water system ("deployment patterns") have different implications for the utility's economics, and explain the heterogeneity of pricing and cost allocation approaches to reuse water across regulated utilities (Bui et al., 2019). They can be distinguished along three dimensions.

1. *Ownership of reuse technology.* The reuse technology investment can be made by the utility (Harris-Lovett et al., 2015) or the end user (Castillo et al., 2017). Developers can decide for a centralized (installed at the utility's premises) or decentralized system (installed at the end-user's premises) (Libralato et al., 2012; Trianni et al., 2021). Decentralized solutions (i.e. technology at the user premise) may yield lower investments and connection costs, although lower economies of scale are expected (Asano et al., 2007).
2. *Reuse loop topology.* The wastewater may be sourced by the utility or the user. Whenever the wastewater source or reuse technology are sited at the utility's premises, a dedicated delivery infrastructure will have to be developed (Asano et al., 2007; Daigger, 2009; Garcia and Pargament, 2015). The utility can implement demand-management strategies by sourcing the wastewater from the user in locations subject to scarcity, or characterised by high costs of urban water distribution (Madungwe and Sakuringwa, 2007).
3. *Effluent quality.* The effluent can be treated at various levels of quality. Reuse water can be made potable in compliance with strict standards (The European Parliament and the Council of the European Union, 2020) or undergo a non-potable reclamation.

Deployment patterns are summarized in Table 1. The models and simulations will refer to Pattern 1.1a in which the technology owner is the utility, the effluent quality is non-potable and the wastewater is sourced by the utility.

2.2. Costs and economic sustainability of water reuse

Wastewater treatment is usually divided into preliminary, primary, secondary, tertiary or advanced, depending on the degree of treatment and the effluent quality (Pescod, 1992). Reuse water has to undergo an advanced treatment ("reclamation") that is more costly than preliminary, primary and secondary treatment (Tchobanoglous et al., 2014). For any cost analysis of the reuse systems, a distinction between centralized and decentralized systems is vital (Salgot and Folch, 2018). While large-scale centralized systems benefit from scale economies, decentralized systems may facilitate the development of local water loops and ease the adoption of reuse technologies (Makropoulos et al., 2018). In both cases the lifecycle costs include capital and operational costs. More recently, the literature has shifted its attention to small-scale, decentralized technologies to enhance water reuse and reduce the stress on fresh water sources (Reynaert et al., 2021).

There are several such technologies that are suited to treat wastewater for reuse purposes, and they have different costs. For instance, effective solutions are membrane bioreactors (Sepehri and Sarrafzadeh, 2018) or high-voltage nanosecond pulsed electric field (Guionet et al., 2014).

In general terms, water reuse projects require substantial capital expenditures, which is one of the most important barriers to their implementation (Lee and Jepson, 2020). Capital costs include the cost for civil works, for the equipment, studies and projects, supervision, advisory, land acquisition (Pinheiro et al., 2018). They may be an important share of the total costs, especially if new infrastructure is required for treated water delivery (Zieburtz et al., 2019). In general, studies on capital expenditures considering different plant sizes and effluent qualities report the presence of economies of scale (Acampa et al., 2019; OECD, 2006) and of increasing costs for more advanced treatments (OECD, 2006).

Among the operational costs, labour and maintenance of components are usually the largest share (Lim et al., 2008), followed by energy (OECD, 2006). Only when the quality of the effluent increases sharply, the cost for reagents becomes prominent. More advanced treatments usually require higher amounts of energy, with impacts on costs and overall environmental impact (Pintilie et al., 2016).

Installation and operational costs vary notably according to the type of application, the size of the plant and the level of treatment performed – i.e., more advanced treatments will require more expensive machines and technologies. For example, Molinos-Senante et al. (2010) study an application that treats roughly 2,000,000 m^3/year of wastewater, where personnel and maintenance play the largest shares (personnel cost makes up roughly one third of the total operational expenses), and reagents and waste management are also considerable cost items. Similar

[2] This is particularly true when water is treated to potabilization, even though many social acceptance issues are still hampering this option (Smith et al., 2018).

Table 1
Deployment patterns of reuse systems: Typology (Own elaboration).

		Reuse loop topology			
		Wastewater sourced by the utility		Wastewater sourced by the user	
		Effluent quality		Effluent quality	
		Non-potable	***Potable***	***Non-potable***	***Potable***
		Outer loop: Reuse water delivered to users	Inner loop: Reuse water supplied to the urban water distribution network	Inner loop: Reuse water recirculated into the user system	Outer loop: Reuse water supplied to the urban water distribution network
Reuse technology ownership	***Utility***	Pattern 1.1a: technology located (i) at the utility premises (upstream of delivery infrastructure) or (ii) at the user premises	Pattern 1.1b: technology located at the utility premises	Pattern 1.2a: technology located at the user premises	Pattern 1.2b: technology located at the nearest urban water distribution network
	User	Pattern 2.1: technology located at the user premises		Pattern 2.2: Technology located at the user premises	

conclusions are reached by (Li et al., 2017), who also include energy among the most impactful cost items (up to 20% of the total costs).

Hernandez-Sancho et al. (2011) analysed the performance of 341 wastewater treatment plants to come up with a cost function of the technologies. Their findings suggest that advanced and tertiary treatments alone have an additional average cost of 0.085 €/m^3 on top of more basic treatments, while the average costs of a generic wastewater treatment plant are in the order of 0.37 €/m^3. For tertiary treatment, other studies highlight an average cost between 0.026 and 0.132 €/m^3 (Ozgun et al., 2021), and advanced treatments are reported to cost around 0.350 €/m^3 (Ruiz-Rosa et al., 2016, 2020).

The cost for reuse water is mentioned as a major barrier to its adoption, when it is higher than the cost for abstracting water from rivers and groundwater bodies. For example, the cost for reuse water in Italy is between 0.0083 and 0.48 €/m^3 (IMPEL - European Union Network for the Implementation and Enforcement of Environmental Law, 2018). However, reuse in areas subject to water shortages may be economically viable, because the costs of reclamation operations for industrial uses range from 0.08 to 0.6 €/m^3 depending on the typology of the reclamation plant and other process conditions; instead, costs of the conventional resource range from 0.13 to 0.5 €/m^3 in most cases, making reuse a potentially cost-efficient option (Regione Puglia, 2019).

For the sake of simulations performed in this article and based on the presented review, an average cost (including operational and capital expenditures) for reuse water of 0.5 €/m^3 will be considered. This number is in line with other case studies reported in the literature (De Paoli et al., 2016). To better calibrate the cost parameter, a sensitivity analysis has also been performed in the simulations, considering the range of values retrieved from this literature review, namely from 0.2 to 0.8 €/m^3.

2.3. Policy and price regulation measures for water reuse

When pricing reuse water, specific issues arise.[3] Incentives to consume reuse water are present if its unitary rate is lower than conventional urban water (De Paoli et al., 2016; Molinos-Senante et al., 2013), but the price difference between urban and reuse water may be low or even negative, because of high reuse costs or subsidization and failure to properly account for environmental externalities in urban water tariffs.[4] Therefore, pricing of reuse water should comply with full cost recovery in a comprehensive way, taking into account direct and indirect costs and benefits such as the lower pressure on freshwater reserves (De Paoli et al., 2016; Ruiz-Rosa et al., 2020). Price regulation is considered one of the most effective ways to foster reuse systems, even though most existing water reuse applications are subsidized (Wilcox et al., 2016). Price regulation measures for reuse water vary substantially depending on the source of revenues that cover reuse costs (Hernández-Sancho, 2018).

Firstly, reuse costs may be allowed in the wastewater treatment tariff. Where wastewater release in the environment should be discouraged, for example in dry areas or touristic destinations, higher quality standards are imposed. In such cases, the usual wastewater

[3] In Europe, price regulation of water-related services is based on full cost recovery and polluter pays principles (The European Parliament and the Council of the European Union, 2000). All incurred costs, including environmental and resource costs, should be covered from revenues. However, urban water tariffs are often subsidized due to political and affordability concerns, and may not reflect resource scarcity (BIO by Deloitte, 2015; Gawel and Bedtke, 2019).

[4] To achieve incentivizing price differentials, some measures have been proposed (e.g., Italy grants discounts on urban water for industrial users who reuse wastewater for their processes, while in Catalonia (Spain) a tax on the usage of non-reused urban water was introduced (BIO by Deloitte, 2015). However, this paper reviews only policy measures specifically targeted at recovering reuse costs.

Table 2
Policy measures.

Policy measure	Type	Source of revenues
Allowance of reuse costs in urban water tariffs	Cross-subsidization	Urban water users
Coverage of reuse costs through transfers from the public budget	Public subsidy	Citizens (taxpayers)
Reuse water sale	Market-based	Reuse water users

treatments already bring the effluent to reclamation level for environmental purposes (interview B). Reuse costs are entirely included into the wastewater treatment tariff, leading to reuse cross-subsidization from urban water users, because most reuse water operations are accomplished as part of wastewater treatment.[5] Indeed, reuse allows to "save a more precious resource" (interview B) and reduce pressure on freshwater reserves during shortage contingencies. Recovering reclamation costs through the regular wastewater tariff imposed on all users is acceptable as long as they reap indirect benefits from it, i.e. environment and resource conservation (Ruiz-Rosa et al., 2020).

A second option is the commercial sale of reuse water on the market, to industrial users, farmers or local governments for city or ecological services. For example, in Italy, non-potable reuse water may be sold, at the condition that it meets the technical quality standards and it is conveyed through a separate infrastructure (Ministero dell'Ambiente e della Tutela del Territorio e del Mare, 2003, Article 12). In this case it is the owner of the delivery infrastructure that sets the water price. Reuse water sales are also reported in other countries. For example, typical prices reported for reuse water range from 25% of urban water rates in Europe and Australia (Molinos-Senante et al., 2013), up to 33%–44% in Cyprus and Mediterranean islands (BIO by Deloitte, 2015; IMPEL - European Union Network for the Implementation and Enforcement of Environmental Law, 2018), to around 80% of urban water in California (Maier et al., 2022).

Finally, public subsidies are also admitted in many European countries. Since water reuse initiatives are deemed to be environmentally sustainable, they may be candidate for grants and other transfers through programs at regional, national or European levels (De Paoli et al., 2016).[6] Other public subsidization forms are proposed in literature, such as the coverage of a portion of reuse costs through local taxation (i.e., municipal charges) (De Paoli et al., 2016). Public subsidies avoid passing through the reuse costs to consumers, facilitating water reuse in areas where full cost recovery through tariffs could impair urban water affordability, or where political pressures impede tariff increases.

Table 2: resumes the main policy measures.

2.4. Model

The model focuses on industrial users, as Italian obligations on reuse water do not admit residents as users and forbid reusing water in irrigation if it comes in contact with raw crops and public green areas.[7] Furthermore, non-industrial users are subject to stricter regulations.[8] No changes in investment costs for the urban water infrastructure are assumed in the short term, as the shift from reuse water is assumed to be gradual.

Costs. Urban water costs (C^U) [€/m^3] represent the variable unitary cost sustained by the utility for the urban water cycle – i.e. to provide urban water and collect and treat wastewater. It mainly includes labour, materials and external services, environmental and resource costs (wastewater treatment, potabilization, losses, telemonitoring and control), energy and wholesale water costs. Reuse costs (C^R) [€/m^3] represent the unitary costs sustained by the utility for the reuse water cycle, including investment for the installed capacity of the reuse system and variable operational costs. q^U [m^3/user-year] represents the average yearly consumption of urban water from industrial users, q^R [m^3/user-year] the average yearly consumption of reuse water from industrial users, and N [users] the number of industrial users. N^U users consume urban water. Among them N^R users consume reuse water, taking advantage of the installed reuse capacity, equal to k^R [m^3/user-year]. The yearly total costs (TC) borne are the sum of C^U and C^R, multiplied by the respective yearly average level of consumption of urban and reuse water from industrial users (q^U and q^R) and the number of users consuming those types of water (N^U and N^R). The decreased consumption of urban water reduces the costs for urban water services.

$$TC^{noreuse} = C^U \cdot q^U_{noreuse} \cdot N^U \tag{1}$$

$$TC^{reuse} = C^U \cdot q^U_{reuse} \cdot N^U + C^R \cdot q^R \cdot N^R \tag{2}$$

$$\Delta TC = TC^{reuse} - TC^{noreuse} = C^U \cdot q^U_{reuse} \cdot N^U + C^R \cdot q^R \cdot N^R - \left(C^U \cdot q^U_{noreuse} \cdot N^U\right) \tag{3}$$

Demand. When reuse water is made available free of charge, the urban water demand is modelled through the following linear-log equation:

$$\ln q^U_{reuse} = \alpha + \beta^U \cdot ln\left(p^U\right) + ln\left(1 - DR \cdot \frac{q^R}{q^U_{noreuse}}\right) \tag{4}$$

where β^U is the own-price elasticity of urban water, p^U [€/m^3] is the average urban water price for the industrial user (including fixed access fees and variable tariffs). DR is the displacement rate of urban water due to the availability of reuse water (i.e., the amount of urban water not consumed because of the availability of 1 unit of reuse water) and $q^U_{noreuse}$ is the baseline quantity of urban water (i.e., consumption of urban water in case of no reuse). The quantity q^R of reuse water consumed by industrial users is given by

$$q^R = k^R \tag{5}$$

where k^R is the reuse capacity per user, set exogenously.

When reuse water is offered for sale, the demands of urban and reuse water are modelled through the following linear-log equations:

$$\ln q^U_{reuse} = \alpha' + \beta^U \cdot ln\left(p^U\right) + \gamma \cdot ln\left(p^R\right) \tag{6}$$

$$\ln q^R = \alpha'' + \beta^R \cdot ln\left(p^R\right) + \gamma \cdot ln\left(p^U\right) \tag{7}$$

where β^U is the own-price elasticity of urban water, β^R is the own-price

[5] E.g., in the Italian region of Apulia, Article 1 of Regional Law n.27/2008 and Article 1.4 of Regional Regulation n.8/2012 specify that reclamation operations are considered in the urban wastewater treatment tariff when they are necessary to reach the objectives of the local Water Protection Plan (Regione Puglia, 2015, p.37).

[6] At European level, examples include the European Regional Development Fund, the Cohesion Policy Fund, the European Agricultural Fund for Rural Development, the European Maritime and Fisheries Fund, the European Fund for Strategic Investment, funds from research programs such as Horizon 2020 (BIO by Deloitte, 2015; De Paoli et al., 2016).

[7] Ministerial Decree 185/2003, Articles 3 and 14.

[8] EU Regulation 2020/741.

elasticity of reuse water, γ is the cross-price elasticity of one type of water to the price of the other (assumed to be symmetric). k^R is now set endogenously to match q^R, the demand for reuse water.

Revenues and margin. R [€/year] represents the yearly revenues obtained by the utility. The tariff is made up by a unitary rate for water distribution (D) [€/m^3], and a unitary rate for wastewater collection and treatment (CT) [€/m^3], besides a fixed access fee (A) [€/user-year]. In the case of sale of reuse water, revenues may be collected through a non-null market price for reuse water p^R [€/m^3]. The decreased consumption of urban water reduces the sales of urban water to users, and consequentially it reduces the revenues for urban water services.

$$R^{noreuse} = (D + CT) \cdot q^U_{noreuse} \cdot N^U + A \cdot N^U \tag{8}$$

$$R^{reuse} = (D + CT) \cdot q^U_{reuse} \cdot N^U + A \cdot N^U + p^R \cdot q^R \cdot N^R \tag{9}$$

$$\Delta R = R^{reuse} - R^{noreuse} = (D+CT) \cdot N^U \cdot \left(q^U_{reuse} - q^U_{noreuse}\right) + p^R \cdot q^R \cdot N^R \tag{10}$$

The margin M [€/year] is defined as the difference between revenues R and total costs TC, and margin variation ΔM [€/year] as the difference of margins between the cases when reuse water is introduced and not introduced in the urban water system.

$$M^{noreuse} = R^{noreuse} - TC^{noreuse} \tag{11}$$

$$M^{reuse} = R^{reuse} - TC^{reuse} \tag{12}$$

$$\Delta M = M^{reuse} - M^{noreuse} = \Delta R - (\Delta C) \tag{13}$$

Parameters. Model parameters have been set to be a realistic representation of the studied utility. In particular, financial statements of the studied utility were used to model the unitary cost of urban water distribution, wastewater treatment and collection. Based on that, interviews with experts were used to build on data from company disclosures to estimate the average consumption of urban water from industrial users. Such data were then integrated with the local authority's tariff plan to retrieve information on the tariffs of urban water services. Finally, a thorough literature review on the analysis of the demand of urban and reuse water was carried out to calibrate the model with realistic values of own and cross-price elasticities[9], and of the substitution rate between urban and reuse water (Maier et al., 2022). Economic literature on water consumption and its response to changes in price has consistently found rigid demand functions (Marzano et al., 2018). In general, the demand elasticity to own-price for reuse or recirculated water is found to be rigid but to a lower degree compared to urban water (Renzetti, 1988).

Table 3
Table of parameters.

Parameter	Description	Value	Source
$q^U_{noreuse}$	Average consumption of urban water without reuse	3,000 [m^3/user-year]	Interview A
C^U	Average unitary operational cost	1.18 [€/m^3]	Utility's 2019 financial statements
C^{EN}	Average unitary energy cost	0.235 [€/m^3]	Utility's 2019 financial statements
N	Number of industrial users	1,000 [users]	Interview B
A	Access fee – Urban water	334.75 [€/user-year]	Authority's 2020 tariff plan
D	Unitary rate (tariff) – water distribution	1.71 [€/m^3]	Authority's 2020 tariff plan
CT	Unitary rate (tariff) – wastewater collection and treatment	0.49 [€/m^3]	Authority's 2020 tariff plan
DR	Displacement rate of urban water	0.82	Maier et al., (2022)
C^R	Cost of reuse water	0.5 [€/m^3]	(De Paoli et al., 2016; Hernandez-Sancho et al., 2011; Ruiz-Rosa et al., 2016)
β^U	Own-price elasticity (urban)	−0.4	See end-of-page note 9
β^R	Own-price elasticity (reuse)	−0.6	See end-of-page note 9
γ	Cross-price elasticity	0.2	See end-of-page note 9

Table 4
Performances and key performance indicators.

Stakeholder	KPI	Definition	Description
Environment	Freshwater savings [m^3/year]	$(q^U_{noreuse} - q^U_{reuse}) \cdot N^U$	Urban water saved yearly
	Freshwater savings rate	$\frac{(q^U_{noreuse} - q^U_{reuse}) \cdot N^U}{N^R \cdot k^R}$	Savings of urban water per reuse capacity unit
Industrial water users	Average urban water price [€/m^3]	$(D + CT) + \frac{A}{q^U_{reuse}}$	Average expense for urban water
	Average water cost [€/m^3]	$\frac{R^{reuse}}{q^U_{reuse} \cdot N^U + q^R \cdot N^R}$	Average expense for urban and reuse water
	Water cost savings rate [€/m^3]	$\frac{R^{noreuse} - R^{reuse}}{N^R \cdot k^R}$	Average water cost savings per unit of installed reuse capacity
Water utility	Margin [€/year]	M^{reuse}	Yearly margin
	Margin variation rate [€/m^3]	$\frac{M^{reuse} - M^{noreuse}}{N^R \cdot k^R}$	Margin variation per unit of installed reuse capacity
Citizens (taxpayers)	Public budget burden [€/year]	$C^R \cdot k^R \cdot N^R$	Yearly transfer from the public budget
	Subsidy rate [€/m^3]	$\frac{C^R \cdot N^R \cdot k^R}{N^R \cdot k^R}$	Public budget transfer per unit of installed reuse capacity

Parameters and assumed values, as well as reference sources, are reported in Table 3.

Outputs: Reuse effects on the utility and other water system stakeholders. Through model simulations under different policy and operational conditions, various system-level performances are computed to quantify the reuse effects on stakeholders, holding as baseline the "no reuse" scenario (formalized in the Appendix, Table A1). Table 4 reports the KPIs.

3. Results: model simulations

The effects of reuse introduction for the different stakeholders are obtained under different policy scenarios, assigning the parameter values of Table 3 to the cost, revenues and demand equations 1–10 and computing the utility's economic margins through equations (11) – (13). The policy scenarios considered are the ones in Table 2 and are compared with the "No policy" scenario that depicts reuse introduction without any policy or price regulation measure (costs borne by the utility but not recovered) and to the baseline scenario of no reuse (Appendix, Table A1). In all policy measures simulations, users are assumed to be homogeneous in their consumptions and costs to be served.

All the model simulations are run by increasing k^R, the water reuse installed capacity per user, from 0 up to 3,000 [m^3/user-year]. k^R is exogenously set under the cross-subsidization and public subsidy policy scenarios while it depends on the reuse water price in the reuse water sale scenario.

An additional simulation ("Location") analyses the role of

[9] Papers reviewed include (Arbués et al., 2010; Angulo et al., 2014; Bruneau et al., 2010; Bruneau and Renzetti, 2014; Dupont and Renzetti, 2001; Féres et al., 2012; Gracia-de-Rentería et al., 2020; Gracia-De-Rentería et al., 2019; Renzetti, 1992, 1988; Reynaud, 2003).

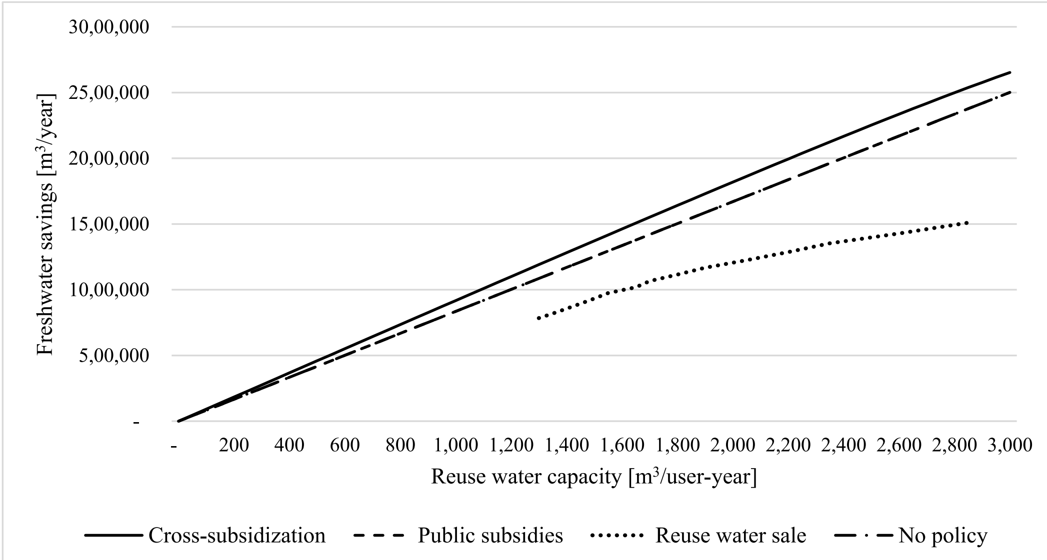

Fig. 1. Freshwater savings [m^3/year] under different policies.[10].

Table 5
Freshwater savings rate under different policy scenarios.

k^R	No policy	Cross-subsidization	Public subsidies	Reuse water sale
1,500	0.835	0.914	0.835	0.622
1,750	0.835	0.912	0.835	0.609
2,000	0.835	0.909	0.835	0.584

operational conditions for reuse water delivery, assuming that 20% of the users are located more distant from urban water sources and the utility's potabilization facilities. Therefore, they require higher operational costs to be served through urban water networks. This is operationalized through increasing values of the energy costs needed to serve dispersed users, which increases up to 30% compared to the baseline value in Table 3. It is assumed that only this subset of users increasingly shifts to reuse water. The control variable is once again k^R. Only results on the utility KPIs are presented in the "Location" simulations.

3.1. Reuse effects on the environment: urban water savings

The effects of reuse adoption on the environment are analysed in terms of reduced pressure on freshwater, through savings in urban water consumption. Fig. 1 shows how the freshwater savings [m^3/year] brought by water reuse vary with k^R. The different lines of Fig. 1 refer to savings under each policy scenario, including the "no policy" scenario.

The cross-subsidization policy yields the largest resource savings. Indeed, in addition to urban water substitution with reuse water supplied as a free resource, urban water consumption decreases due to price elasticity effect (reuse costs are allowed for in the tariff of wastewater treatment tariff, causing an urban water tariff increase). The options of public subsidies and no policy measure perform equally well as a second-best in reducing the consumption of urban water, missing the price elasticity effect of cross-subsidization[11]. Selling reuse water saves urban water only to a lower degree. Indeed, reuse water consumption decreases as it is not anymore free of charge. Furthermore, any price-cost margin realized from the sale is transferred to urban water users through a reduction of the wastewater treatment tariff, increasing further the demand of urban water.

In order to make sense of the benefit produced by each unit of reuse technology capacity installed, Table 5 reports the Freshwater savings rate for 3 different values of k^R, chosen in the central range of simulated reuse capacity, and for the different policy options.

3.2. Reuse effects on the users: costs of water supply

A second run of simulations address the effects of reuse adoption on the users, in terms of the costs borne for water supply. Figs. 2 and 3 show respectively how the Average urban water price [€/m^3] and Average water cost [€/m^3] paid by industrial users vary with k^R. The different lines refer to costs under each policy scenario, including the "no policy" scenario.

As shown in Fig. 2, as k^R increases, with the cross-subsidization policy the average price of urban water increases exponentially. This is due to two main contributions: the reuse cost recovery through an increase of the urban wastewater tariff and the spread of the yearly fixed access fee on progressively lower quantities of urban water consumed. Only the second effect is still in place for the no policy and public subsidies options, which show considerably lower average urban water price increases. When reuse water is sold, this effect is also counterbalanced by the pass-through of the price-cost margin to lower urban water tariffs and a tamer decrease in urban water consumption, resulting in lower urban water prices.

As it may be seen in Fig. 3, considering the average cost sustained by users for all water, the conditions of no policy measure (reuse costs are not recovered by the water utility) and public subsidies (reuse costs are covered through taxation from the public budget) are the most favourable, as reuse water is provided for free without an impact on the urban water tariffs. Conversely, the water reuse sale scenario has the largest unitary water cost, given that reuse water is not provided for free but for a market price. The cross-subsidization option is positioned in the middle: reuse water is provided for free, but incurred costs are recovered by increasing urban water tariffs.

In order to make sense of the impact produced by each unit of reuse technology capacity installed, Table 6 reports the Water cost savings rate for 3 different values of k^R, which have been chosen in the central

[10] Note: Only a limited acceptable range of reuse water prices (25%–100% of urban water price) are considered. The extreme levels of k^R would correspond to out of range reuse water prices.

[11] In these cases, the only effect of price elasticity is due to the spread of the fixed portion of the tariff (access fee) on progressively lower quantities of urban water due to the displacement effect of reuse water, but there are no increases in the unitary rate tariffs.

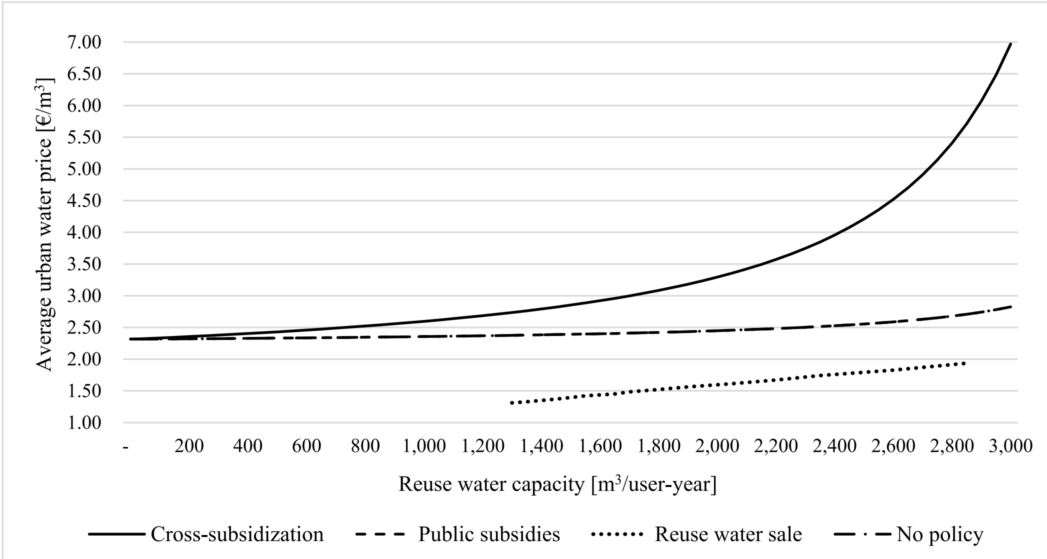

Fig. 2. Average urban water price [€/m^3] for different policy options.

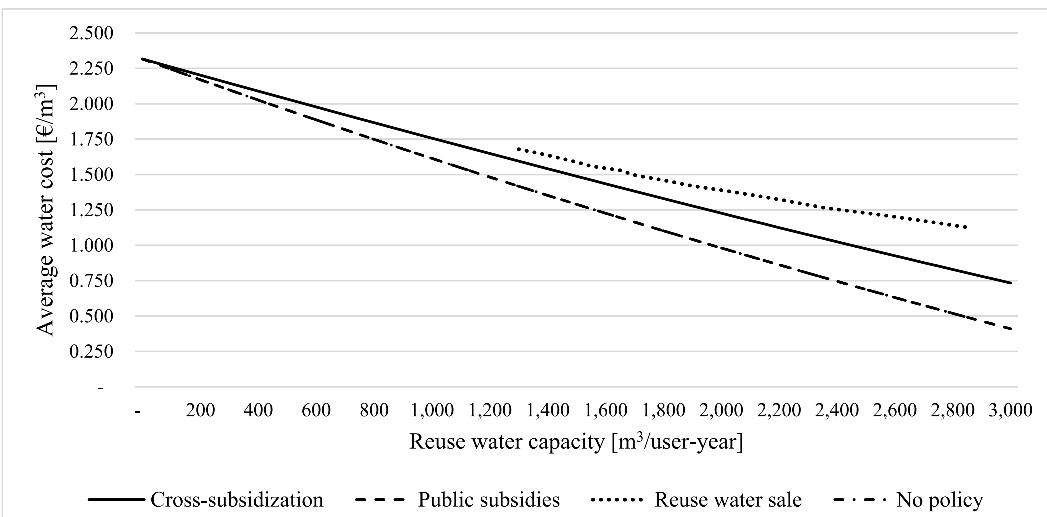

Fig. 3. Average water cost [€/m^3] for different policy options.

Table 6
Water cost savings rate [€/m^3] under different policies.

k^R	No policy	Cross-subsidization	Public subsidies	Reuse water sale
1,500	1.841	1.529	1.841	0.888
1,750	1.841	1.526	1.841	0.874
2,000	1.841	1.523	1.841	0.836

range of simulated reuse capacity, and for the different policy options.

3.3. *Reuse effects on the water utility: margin variation*

Simulations are also used to assess the impact of reuse introduction on the economic margin of the water utility. Fig. 4 shows how the Margin [€/year] of the utility varies with k^R. The different lines refer to margins under each policy scenario, including the "no policy" scenario.

As shown in Fig. 4, the scenario of no policy, where the utility does not recover reuse costs, is the least favourable for the utility's margin, which becomes negative for high levels of k^R. The options of cross-subsidization and public subsidies perform better and similarly well, with a slight edge of the second policy option. The advantage of public subsidies is due to the fact the recovery of costs happens through a lump-sum transfer without rate increases in urban water tariffs, which contribute to cannibalizing urban water demand. Finally, the most favourable scenario for the utility's margin is given by the reuse water sale policy, where the utility is able to counterbalance the loss of urban water revenues through margins made from the reuse market. However, it needs to be noted that the margin made by the utility is always lower than the one in the no reuse scenario, and that it decreases linearly with the increase of reuse water availability for any policy options.

To measure the economic effect of reuse adoption on the utility, Table 7 reports the Margin Variation Rate [€/m^3] for 3 different values of k^R, chosen in the central range of simulated reuse capacity, and for the different policy options.

3.4. *Reuse effects on the public budget: impact on the public budget*

For what concerns the impact on the public budget, the only differential measures are Public subsidies, which imply a Subsidy rate as

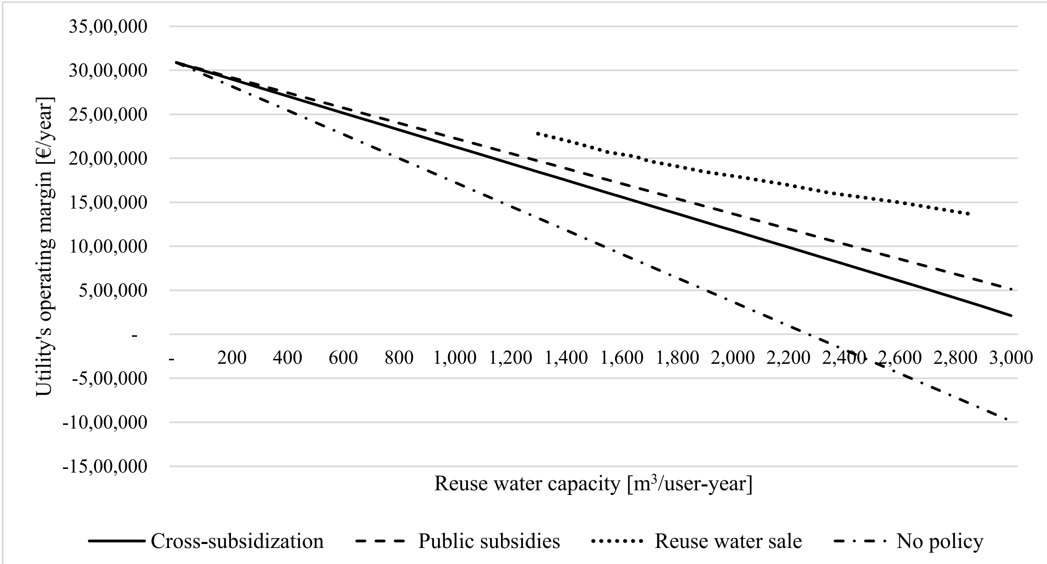

Fig. 4. Utility's margin [€/year] under different policies.

Table 7
Utility's Margin variation rate [€/m^3] for different policies.

k^R	No policy	Cross-subsidization	Public subsidies	Reuse water sale
1,500	(1.360)	(0.955)	(0.860)	(0.660)
1,750	(1.360)	(0.954)	(0.860)	(0.664)
2,000	(1.360)	(0.954)	(0.860)	(0.659)

Table 8
Margin [€/year] and Margin variation rate [€/m^3] for different levels of energy cost of served users (baseline, 15% above baseline, 30% above baseline).

k^R	Energy cost	Margin	Margin variation rate
1,500	$C^{EN} = 0.235$	2,680,427.07	(1.360)
	$C^{EN} = 0.270$	2,689,259.94	(1.330)
	$C^{EN} = 0.306$	2,698,092.81	(1.301)
1,750	$C^{EN} = 0.235$	2,612,452.80	(1.360)
	$C^{EN} = 0.270$	2,622,757.56	(1.330)
	$C^{EN} = 0.306$	2,633,062.32	(1.301)
2,000	$C^{EN} = 0.235$	2,544,500.21	(1.360)
	$C^{EN} = 0.270$	2,556,276.11	(1.330)
	$C^{EN} = 0.306$	2,568,052.02	(1.301)

transfer from the public budget of 0.5 €/m^3, for each m^3 of reuse water.

3.5. Reuse operational conditions: reuse delivery to distant users

Table 8 reports the utility's margin for significant levels of k^R of the "Location" simulation. In particular, delivering reuse water to users located at higher distance, causing a greater cost of energy per user, is shown to benefit the utility, i.e., to mitigate the margin erosion by yielding larger operational costs savings compared to urban water.

3.6. Robustness checks: sensitivity analysis

In order to investigate the robustness of the generated results to variations of the most uncertain parameters, it was decided to perform a sensitivity analysis, running the simulations and recomputing the model outcomes with different values of such parameters. In particular, the parameters noted to be more uncertain, and so to potentially carry the highest variance, were the unitary cost of reuse water and the displacement rate. The unitary cost of reuse was assessed to be ranging in the [0.2; 0.8] interval according to the review carried out in Section 2.2, while the displacement rate was heuristically chosen to deviate with a ±15% compared to its baseline value. This reflects the possibility that the introduction of reuse water may bring an almost complete substitution of urban water, or that, at the other extreme, rebound effects on the total usage of resource may be larger (Zink and Geyer, 2017). Table 9 reports the values assumed by the KPIs for variations of such parameters.

As it may be noted, while the changes of particular parameters do influence the numerical outcomes of the simulations, the main results show to be robust, in particular in highlighting the most (or least) effective options for the different performance measures, and in providing a ranking of the relative effectiveness of different policy options in achieving any predefined KPI.

4. Discussion and conclusions

The results presented in Section 3 show that the adoption of water reuse technologies by a water utility produces different effects on the multiple stakeholders of the water system, and that policy and price regulation measures moderate the relative importance of these effects. The utility's margins are reduced not only by the frequently cited additional investment and operational costs (Lee and Jepson, 2020; Sokolow et al., 2019), but also by the cannibalization of urban water revenues. On the positive side, the simulations quantify the cost savings obtained through replacing part of urban water with reuse water for distant users, confirming the possible operational efficiency of water reuse (Priadi et al., 2017). Indeed, moving to more favourable operational conditions may lead the utility's margin to raise by up to 0.06 [€/m^3] relatively to the baseline. Also in this more favourable case, the results show lack of structural economic sustainability of reuse water for the utility, calling for policy interventions to ensure cost recovery.

4.1. Policy measures evaluation

Having considered different policy scenarios, it is possible to draw some conclusions on their relative effectiveness. Analyzing the moderating effects of different regulatory scenarios on the impacts on the water system stakeholders, similarly to the no policy option, public subsidies perform well towards environment and urban water users. Indeed, since the public subsidies option does not directly impact on the price of urban water, it does not have differential impacts on the price paid by urban water users and thus it achieves the same result in

Table 9
Sensitivity analysis (NP = No Policy; CS = Cross-Subsidization; PS = Public Subsidies; RS = Reuse water Sale); values shown for $k^R = 1500$[a].

		DR = 0.82; $C^R = 0.5$				DR = 0.97; $C^R = 0.5$				DR = 0.67; $C^R = 0.5$
		NP	CS	PS	RS	NP	CS	PS	RS	NP
Urban water savings	**Value**	1,252,569.15	1,371,541.16	1,252,569.15	932,945.75	1,481,381.94	1,597,512.28	1,481,381.94	932,945.75	1,023,612.26
	Policy performance	Mild	Max	Mild	Min	Mild	Max	Mild	Min	Mild
Water cost	**Value**	1.29	1.49	1.29	1.59	1.22	1.43	1.22	1.59	1.35
	Policy performance	Max	Mild	Max	Min	Max	Mild	Max	Min	Max
Variation in utility's margin	**Value**	(2,039,443.50)	(1,432,156.03)	(1,289,443.50)	(971,181.72)	(2,274,992.30)	(1,671,584.83)	(1,524,992.30)	(971,181.72)	(1,803,746.35)
	Policy performance	Min	Mild	Strong	Max	Min	Mild	Strong	Max	Min

aThe table does not report for brevity the results of the impact on the public budget KPI, which is differential only for the "Public subsidies" policy.

reducing the demand for urban water. In this case, the demand for urban water diminishes mostly for the availability of an alternative source. Furthermore, the public subsidies option is to prioritize for preserving the utility's margin, since it covers the costs it suffers for reuse without cannibalizing the demand for urban water. On the negative side, public subsidies have a significant impact on taxpayers by covering the additional cost of reuse through the public budget.

The cross-subsidization option, instead, achieves the largest environmental benefits: besides allowing an alternative free water resource (reuse water), it makes the conventional scarce resource (urban water) more expensive. This policy option performs moderately well in granting low water cost for users, since increases in the urban water tariff are balanced by the availability of an alternative free resource. Besides, the margins for the utility are moderately well preserved, as costs for reuse are covered, although at the expense of cannibalization of urban water. However, its main weakness resides in the increase in urban water tariffs. In the model presented, the increased urban water tariff is borne by industrial users who are also the ones who reuse water. This implies that, as the tariff for urban water increases to cross-subsidise reuse water, users will be more incentivised to further replace their urban water consumption with reuse water. Therefore, if the policy objective is to maximise resource savings and reuse water is sufficiently available, this is the most favourable option. The relevance of this result may be further discussed in cases where the group of users who reuse water and urban water users do not perfectly overlap. In these cases, the negative economic impact (i.e. the increased urban water tariff) and the related environmental benefits (i.e. urban water savings) are spread out also on the users who do not reuse water and therefore softened. Literature considers viable this option because also these users gain indirect environmental benefits from the diffusion of reuse water, in terms of higher environmental quality and resource availability for future uses (De Paoli et al., 2016; Ruiz-Rosa et al., 2020).

Finally, selling reuse water is the most effective measure to grant the utility a sizeable margin. Relatively to the No policy scenario, the utility can compensate the cannibalization of urban water demand through revenues from the sale of reuse water. However, the policy is weaker in terms of environmental benefits since it leads to lower resource savings, and leaves water users with comparatively high cost for water compared to the No policy scenario. Indeed, the pricing of reuse water and the lowering of urban water tariffs through the margin pass-through decrease the incentives for substitution. Table 10 reports a comparison of system-level performances across the different policy measures.

The results presented in this paper extend and complement the existing debate in management, engineering and environmental economics around the potentialities and impacts of water reuse. In particular, it sheds light on the integration of water reuse within the urban water system. Furthermore, it highlights the impact of reuse on the water system stakeholders and how such impact is moderated by policy and operational conditions. In so doing, it contributes to the debate on water reuse policies designed at a broader level than single communities or utilities (Lee and Jepson, 2020).

5. Contributions and implications for managers and policymakers

These results have relevant implications for water utilities managers and their investment decisions on water reuse technologies. The results indeed allow to point out relevant impacts of reuse water availability on the economics and on the demand of urban water, as well as the modulating role of policy and operational options. They show that the utilities' margins may suffer from the cannibalization of the urban water revenues. However, appropriate price regulation and policy measures can counterbalance the erosion of utility's margin, by providing the utility with revenues collected from the beneficiaries of reuse adoption, namely by internalizing the external effects of reuse. Furthermore, the study highlights impacts on a broader set of stakeholders, suggesting that, for a smoother introduction of water reuse technologies, utilities have to be aware of the consequence of reuse on the various stakeholders who may pose barriers or, on the contrary, drive reuse adoption (Lee and Jepson, 2020; Rupiper and Loge, 2019).

Policy measures work by making different stakeholders pay for the cost of water reuse. If no policy measure is put in place, the utilities bears the costs and it does not recover them through any mechanism. Cross-subsidization leans on the pass-through of reuse costs to the users of wastewater treatment services, a group who largely overlaps with the local community. Public subsidies put the burden of reuse costs on public budget, assuming that reuse benefits spread to the whole citizenship (and to future generations). Finally, permitting the sale of reuse water charges all the costs to reuse water users by establishing a market price for reuse water. Utilities should also be aware that serving distant users which require high operational costs to be reached through urban water networks may enhance the economic sustainability of water reuse.

The results may be useful to policymakers and regulatory authorities, by providing novel insights on the much-debated tensions between the environmental and economic performances of water reuse (Arden et al., 2020; Molinos-Senante et al., 2011). A result of general interest is that stakeholders, namely the environment (next generations), the utility, users and taxpayers may have misaligned interests with respect to the development of reuse systems, confirming the need of a holistic perspective and thorough cost-benefit analyses (Bichai et al., 2018). Complex policy decisions may have to be made. Indeed, fixing the trade-off between affordability of urban water and internalization of the positive externalities of water reuse on the environmental quality (Ruiz-Rosa et al., 2020) may lead to an uneven distribution of reuse cost.

Presented simulations are set in a scenario where reuse water gradually replaces urban water rather than complementing it in periods or

DR = 0.67; C^R = 0.5			DR = 0.82; C^R = 0.8				DR = 0.82; C^R = 0.2			
CS	PS	RS	NP	CS	PS	RS	NP	CS	PS	RS
1,144,845.31	1,023,612.26	932,945.75	1,252,569.15	1,436,366.08	1,252,569.15	998,362.53	1,252,569.15	1,301,876.83	1,252,569.15	864,104.22
Max	Mild	Min	Mild	Max	Mild	Min	Mild	Max	Mild	Min
1.54	1.35	1.59	1.29	1.61	1.29	1.70	1.29	1.37	1.29	1.48
Mild	Max	Min	Max	Mild	Max	Min	Max	Mild	Max	Min
(1,193,508.25)	(1,053,746.35)	(971,181.72)	(2,489,443.50)	(1,513,442.08)	(1,289,443.50)	(1,061,042.18)	(1,589,443.50)	(1,347,654.99)	(1,289,443.50)	(880,068.29)
Mild	Strong	Max	Min	Mild	Strong	Max	Min	Mild	Strong	Max

Table 10
Policy measures and system-level performances.

Performance	Stakeholder	No policy	Cross-subsidization	Public subsidies	Reuse water sale
Freshwater savings	*Environment*	Mild	Max	Mild	Min
Cost savings for water users	*Users*	Max	Mild	Max	Min
Utility's margin preservation	*Utility*	Min	Mild	Strong	Max
Public budget health	*Citizens*	Max	Max	Min	Max

times of scarcity. However, the economic sustainability of water reuse system could be enhanced if it were used also to satisfy previously unserved demand, generating additional revenues without cannibalizing existing activities (Capocelli et al., 2019; Sapkota et al., 2016), as also pointed out in Interview A. This is especially true if public resistance towards potable reuse water can be overcome through appropriate policy actions (Hartley et al., 2019). Furthermore, models and simulations conducted are based on price regulation and other policy measures that approximate the effect of more complex, real-world policy decisions. A finer-grained conceptualization of policies and recovered costs (e.g., distinguishing between the recovery of operational and investment reuse costs) would be interesting for further research. Furthermore, only stand-alone policy measures have been considered in this work, i.e. policies that are applied by themselves and not in conjunction with other options. Policy mixes (e.g., recovery of investment costs through public subsidies and of operational costs through cross-subsidization) may be also considered for further extensions, considering that cross-subsidization of reuse costs through urban water tariffs and municipal charges and the public subsidization of capital expenditures are often proposed or observed empirically (De Paoli et al., 2016; Ruiz-Rosa et al., 2020). Finally, additional incentivizing elements for the water utility may be considered. For example, water reuse sale may be complemented with incentive regulation measures, similar to the ones in the Italian regulation for "other activities related to environmental and energy sustainability".[12]

5.1. Limitations and avenues for further research

Some limitations of this study may be discussed. Given the paucity of public domain data on reuse technology costs and on the interaction between the reuse and the urban water system, this model has been calibrated on a single utility case and on selected information drawn from secondary sources. New studies that offer more information or opportunities to collect data across alternate settings and further generalize results are welcome to complement knowledge on the topic. Related to this, it is to be acknowledged that the scarcity of empirical and experimental data available limits the possibility to perform sophisticated validation at a statistical level. Given the study focus and context, such data could not be generated experimentally during the project. The results provided are clearly dependent on parameters used for simulations. However, it is important to note that even without returning experimental values for performance indicators the study results allow decision-makers to assess the different public policies by comparing the impacts of water reuse introduction on the water system stakeholders between the different policy scenarios.

The model and its parameters have been carefully calibrated based on a thorough analysis of existing academic and grey literature, triangulated with interviews with experts and actual data coming from financial disclosure of the reference utility. Also when full-scale qualitative validation is not feasible, qualitative validation may be performed (Shrestha et al., 2021). To perform qualitative validation, experts have been involved since the early stages in the model design and in the presentation of intermediate results (Kleijnen, 1998; Van Horn, 1971). Results have been shared and discussed with a panel of experts of the water sector in general meetings, in which more than 20 entities took part, including technology developers and providers, research institutions and public authorities, across Europe and Middle East. Finally, a quantitative validation technique used in situations where experimental data are not available, i.e. a sensitivity analysis on selected parameters (Kleijnen, 1998), was performed to obtain more robust results. Sensitivity analyses show that the model's main results are robust to changes of the most uncertain model parameters, namely the unitary cost of reuse water and the displacement rate linking the introduction of reuse water to a decrease in demand for urban water. It must be noted that these results hold for the choices of parameters and the range of sensitivity analyses considered. Therefore, the validity of such results for innovative small-scale water reuse technologies would be conditional to the fact that they are compatible with such parameters. Indeed, it should be considered that very innovative technologies may have characteristics that depart from the considered input variables.

Finally, this study has addressed the supply side of the emerging reuse water sector. Extensions of this study may aim at achieving a wider understanding of reuse water potential by also investigating the barriers and enabling factors experienced or perceived by large users that consider supplementing the urban water supply with reuse water.

Credit author statement

Enrico Cagno: Conceptualization, Methodology, Supervision, Writing- Reviewing and Editing.; Paola Garrone: Conceptualization, Methodology, Data curation, Writing- Reviewing and Editing.; Marta

[12] According to this policy, when revenues are collected from the sale of reuse water services and a margin is made from sales on top of reuse costs, the related margin is used to incentivize the utility to invest in reuse technologies. The cap on allowed revenues from urban water services is loosened by up to 75% of the reuse margin through an earning sharing mechanism, so that part of the margin generated by reuse operations is retained from the utility.

Negri: Investigation, Writing – original draft, Methodology.; Andrea Rizzuni: Investigation, Writing – original draft, Methodology.

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Appendix

Table A1
The baseline (“No reuse”) scenario

Variable	Parameter	Value
Number of industrial users who do not reuse	N^U	1,000 [users]
Number of industrial users who adopt reuse	N^R	0 [users]
Average consumption of reuse water by an industrial user	q^R	0 [m^3/user-year]
Location of users adopting reuse	L^R	Uniformly set at L^{MEAN}

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