Multicriteria performance analysis of an integrated urban wastewater system for energy management

Valeria Puleo, Vincenza Notaro, Gabriele Freni and Goffredo La Loggia

ABSTRACT

The optimization and management of an integrated urban wastewater system is a complex problem involving many processes and variables. The possible control options are defined by several management strategies that may differently impact the economic, operational or environmental performance of the system. The present paper aims to contribute to the environmental and energy sustainability of urban wastewater systems by means of a multicriteria performance analysis. The paper begins with a complete analysis of the system performance in several fields of interest (energy, environment, quality of service, operation, economy and financial resources), and it highlights the management strengths and weaknesses in each subsystem. The analysis was carried out by means of a prototype, developed during the ALADIN project, which enables understanding the system, planning effective improvement actions and assessing their possible effects in each part of the urban water cycle. To demonstrate the potential of such an approach, it was tested on an actual integrated urban wastewater system in Sicily.

Key words | decision support systems, energy management, integrated urban wastewater system, performance indicators

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INTRODUCTION

In recent decades, the optimization of energy consumption for exploiting water resources has become a research topic of growing importance in the context of rising energy and material costs, water shortages and climate change.

Energy is needed in every phase of water use, from extraction to conveyance, treatment, use, and disposal (Plappally & Lienhard 2012). The amount of energy consumed is strictly related to the water system location, resource availability and quality, area topography, supply network topology, and water and wastewater treatments.

Currently, energy costs represent about 35% of the operating costs of water utilities, and this share is expected to increase due to the tightening of drinking water and environmental regulations and the higher water demand as a result of population growth (Puleo *et al.* 2016).

The European Environmental Agency (2012), as well as academia and the water industry, has shown interest in investigating water-energy interactions and their related greenhouse gas (GHG) emissions in urban water systems (Pandey *et al.* 2011; Hendrickson & Horvath 2014; Kanakoudis & Papadopoulou 2014; Kanakoudis 2015; Puleo *et al.* 2015). Understanding such relationships is important for achieving sustainable and cost-effective water management (Puleo *et al.* 2014). Several studies have already been carried out in Australia (Kenway *et al.* 2015) and the United States (Sanders & Webber 2012).

The growing interest about energy consumption, both in terms of its cost and environmental impacts, has led to sustainable energy management practices, mainly in high energy consuming parts of systems (Plappally & Lienhard

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2012), such as in integrated wastewater systems. Assessing the energy balance of these systems is difficult mainly due to the lack of disaggregated data related to the contributions of wastewater treatment plants (WWTPs) and sewer networks (SNs) (Petit-Boix *et al.* 2015).

Therefore, in the present study, a multicriteria performance analysis aimed at optimizing the energy efficiency and minimizing the environmental impacts of an integrated urban wastewater system (including both the SNs and WWTPs) has been carried out. Although the main objectives were linked to energy and environmental issues, other performance aspects, such as the operation and maintenance, quality of service and economic and financial resources, have been considered because they are unavoidable for a reliable performance analysis.

The analysis was carried out by means of a prototype developed during the project ALADIN, '*Recupero di Acqua ed energia dispersa nel cicLo idrico integrAto. SalvaguarDia ambientale tramite Innovazione, moNitoraggio, ottimizzazione*' ('Energy and water saving in the integrated water cycle. Environmental protection by means of innovation, monitoring, optimization'), funded by Linea di Intervento 4.1.1.1 PO-FESR Sicilia 2007–2013, as already presented by Puleo *et al.* (2016). The prototype helps in understanding the system, planning effective improvement actions, and assessing their possible effects in each part of the urban water cycle.

The paper is organized as follows. First, a brief literature review is provided. Second, the methodology and case study are presented for an actual integrated wastewater system of a small town in southern Sicily. Finally, the results obtained are discussed, and some conclusions are drawn.

LITERATURE REVIEW

The WWTP, where urban wastewater is collected and conveyed by SNs to be depolluted before being discharged into a water body, can be considered to be the part of an urban water cycle that is usually affected by high levels of energy consumption.

The amount of energy required by a WWTP depends on the flow rates and pollution loads, treatment stages, operation and maintenance measures, and energy efficiency of the devices installed. Stillwell *et al.* (2010) stated that energy consumption data can reveal when a WWTP has malfunctioned. In the literature, several studies have been carried out to analyse energy in WWTPs and to propose improvement measures (Barry 2007). A benchmarking analysis of the electric power consumption of WWTPs in Japan (Mizuta & Shimada 2010) reports values of the specific power consumption (SPC) ranging from 0.44 to 2.07 kWh/m^3 for oxidation ditch plants and from 0.30 to 1.89 kWh/m^3 for conventional activated sludge plants without sludge incineration. The authors assessed that the SPC value was affected more by the scale of the plant (in terms of its equivalent inhabitants) rather than by different kinds of wastewater treatment processes. Stenstrom & Rosso (2008) reported their assessment regarding the relationship between the aeration system and energy consumed. They stated that the fine bubble air diffusers, with high efficiency in terms of oxygen transfer rates, required a greater amount of energy compared to mechanical aeration devices (0.54 and 0.90 $\text{kgO}_2\text{/kWh}$, respectively). In addition, greater installation depths and fouling of the air diffusers can further contribute to the increase in energy consumption due to the major head losses.

Regarding SNs, the energy consumption is usually lower compared to WWTPs. The energy consumption is mainly related to the pumping stations required when some parts of the network have a lower elevation with respect to the main channel or when the WWTP cannot be reached by gravity. Pumping requirements are influenced by the topography, network length, WWTP location, population, population income, seasonality and climate. The complexity and nonlinearity of sewer system behaviour can be efficiently managed by a control system (Ostojin *et al.* 2011). In the case of diffuse and small municipalities, the contribution of SNs to the energy balance of the integrated wastewater system can be significant (Petit-Boix *et al.* 2014) due to the length of the pipeline (in which the length is determined by the WWTP location) and the arrangements of the WWTP stages (generally, only primary treatment stages are planned in the case of a small municipality).

Only a few studies in the literature have specifically focused on analysing the energy consumption in SNs. Some authors have applied LCA (Life Cycle Analysis) methods to evaluate the energy and environmental impacts of sewers with respect to only the operation and maintenance stages (Lemos *et al.* 2013; Petit-Boix *et al.* 2015); others have aggregated these impacts with those of the WWTPs (Cohen *et al.* 2004). Conversely, various studies are available in the literature regarding WWTPs; a comprehensive review of LCA methods can be found in a paper by Corominas *et al.* (2013).

The energy and environmental issues of wastewater treatment have inspired many researchers, public agencies and industries to explore new methods and measures (Longo *et al.* 2016). Performance indicators (PIs) have been recognized as an effective methodology to assess system conditions (Ashley & Hopkinson 2002) and to support in planning and management (Le Gauffre *et al.* 2007; Hosseini & Ghasemi 2012). The IWA (International Water Association) proposed a set of PIs grouped in six categories for both water supply (Alegre *et al.* 2006) and wastewater services (Matos *et al.* 2003) concerning environmental, personnel, physical, operational, quality of service, economic and financial aspects. Haider *et al.* (2013) reviewed the PI frameworks for water supply systems including those for which water utilities have limited data and resources. Moreover, the authors proposed specific indicators for small- and medium-sized water supply systems. The use of the PIs for energy efficiency has wider applications in water supply management (Kanakoudis *et al.* 2013), and recently, Teixeira *et al.* (2016) applied a short-list of PIs that were selected among those defined in international reports and literature to both water distribution networks and wastewater collection.

In Matos *et al.* (2003), various indicators were defined for drainage systems, and only a few were defined for WWTPs. Recently, several studies have been carried out to define key PIs for wastewater system benchmarking (Benedetti *et al.* 2008; Balmer & Hellström 2012), maintenance and rehabilitation strategy planning for SNs (Cardoso *et al.* 2006; Breysse *et al.* 2007) and cost effective and sustainable WWTP management (Quadros *et al.* 2010). An interesting literature review regarding WWTP energy PIs and methods for energy benchmarking was presented by Longo *et al.* (2016). The authors stated that, currently, a standard approach for WWTP energy performance evaluation does not exist, probably due to its inherent complexity.

Although several studies have been carried out to define PIs for water system energy analysis, an integrated approach which analyses the whole water cycle has not yet been presented in the literature.

METHODOLOGY

The ALADIN framework

The ALADIN prototype (Puleo *et al.* 2016) enables the evaluation of energy impacts related to each different macrosector of the urban water cycle, highlighting the main energy flows by means of an integrated approach. Moreover, it assesses the energy balance of the system and identifies possible energy-efficient solutions. The prototype is a web-based application that models the whole urban water system as sets of entities: water and energy entities. The former are grouped into five subsystems: (1) water resources; (2) water supply and distribution networks; (3) water treatment; (4) urban drainage and (5) wastewater treatment. The latter belongs to a water entity or is simply considered as supplementary (auxiliary) services. Thanks to its integrated approach, the prototype can be used to successfully analyse the whole urban water cycle or individual parts of it (e.g. a water distribution network or WWTP).

Several input variables describe each entity, depending on the selected class. For the water entities, it is possible to distinguish between the well, spring, water treatment plant, main water supply, distribution network, sewer, and WWTP. Moreover, further classes were arranged to consider the energy consuming devices (e.g. pumps, agitators) as well as the renewable energy source (RES) power plants. The variables were selected by considering the data availability and soundness with respect to the project objectives. Several water utilities and professionals were interviewed during the start-up phase of the ALADIN project.

The input variables (e.g. yearly energy consumption, inlet water volume, average network pressure, maintenance costs, number of pumping stations, installed pump power) can be edited by operators or evaluated by parsing the output of remote monitoring systems or hydraulic modelling software. With ALADIN, the goal is to run offline simulations with any software and subsequently upload the output files. Each file is parsed to extract information that is properly handled for the purposes of ALADIN. At the time of writing, four different file parsing extraction methods have been already implemented, following the output of well-known software, EPANET 2.0 (Rossman 2000), SWMM 5.1 (Rossman 2015) STOAT (STOAT 2012) and WEST (WEST 2015), but other forms of output can be added in the future. Specifically, the file parsing occurs as a plugin of the prototype core; hence, introducing a new software means simply developing a new plugin.

Once the input variables are defined, the prototype calculates the water and energy balance as well as the system performance.

The water balance is defined according to Italian law DM 99/97 (Ministero dei Lavori Pubblici 1997), in which the rates are easily overlap with the well-known IWA water balance (Lambert 2002). The energy balance considers both energy consuming and producing devices. For each class or subsystem, the energy rate is determined in terms of both the electrical energy consumption and production. The system performance is evaluated using the ALADIN PI panel, which refers to the water loss reduction, energy consumption, environmental impact, quality of service, and operational, economic and financial aspects, and enables the multicriteria analysis that is presented in the following section.

The PIs were defined according to the literature (Matos *et al.* 2003; Alegre *et al.* 2006; Cabrera *et al.* 2010; Quadros *et al.* 2010) and slightly modified for the purposes of ALADIN. Some indicators were included to analyse other aspects, such as the system *exergy* (Hellström 1997); these have proven to be difficult to calculate because data are not readily accessible for many actual systems. Although most of the ALADIN indicators were taken from literature, the novel aspect of this study is the integrated approach applied to the whole urban water cycle. The full-list of indicators with their definitions, both for the water supply and wastewater systems, is not reported here to limit the length of the paper, but it is available by consulting the final reports of the project. A selection of the ALADIN indicators is provided later in the text, specifically regarding their application to the presented case study.

Starting from the results of the performance analysis, operator goals and technical feasibility, the ALADIN prototype notes the critical issues in the system and guides the operator during the selection of improvement actions. Namely, all the indicators with a performance score lower than a threshold value cause the automatic selection of a set of improvement actions stored in the prototype database. Such a selection can be refined by choosing among the proposed overall objectives of the interventions and answering a technical feasibility questionnaire.

The ALADIN embedded actions are mainly focused on various aspects of urban water system management, such as water losses, energy consumption and GHG emission reduction. Nevertheless, as mentioned above, the financial and operational aspects linked to the quality of service are also considered. For each improvement action, a folder with the technical features and the possible influences on the system efficiency is also provided.

To verify the effects of the selected actions on the system performance, the operator can define several scenarios based on his own objectives. A user interface is used to implement the actions in the system by providing spreadsheets accurately developed by experts and enabling editing of the correlated input variables. Such data are again processed by the prototype, then the PIs and water and energy balances are provided for the new scenarios. In the end, a decision support tool provides a ranking of the operator-based scenarios.

Definitively, the ALADIN prototype can be summarized in four steps (Figure 1): (1) data acquisition; (2) data processing; (3) analysis and decision support tools; and (4) the scenario creator tool. ALADIN receives input data from different information sources (Step 1); after processing the data (Step 2), these data are used to evaluate the water and energy balances as well as the performance of the analysed urban water system or subsystem (Step 3). The contributions of each subsystem to the whole system performance are highlighted according to the ALADIN performance aspects: energy, environment, quality of service, operation and maintenance, economic and financial resources. Starting from the actual scenario (S0) results, attained from the analysis tool, the operator can define improvement scenarios (Step 4) and verify their suitability with respect to his own objectives. The comparison between these scenarios, including S0, is facilitated through the decision support tool (Step 3), which provides a scenario ranking.

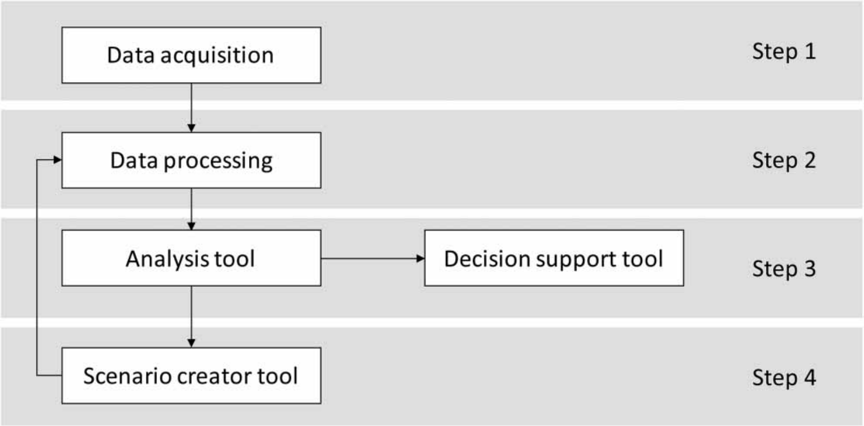


Figure 1 | The ALADIN prototype structure.

The multicriteria performance analysis and decision support

As mentioned above, the multicriteria performance analysis is carried out using PIs. First, each PI is normalized by means of a benchmark value, which is selected according to the judgement of the professionals involved as project partners and also to the literature review and field data. Since the objectives of the operator can change with the context of the system, such values are editable. Second, a performance score for each normalized PI is obtained by means of a penalty curve, which is suitably defined by considering the judgements of the experts and statistical data collected from government and research agencies at the national and international level.

The performance score is adapted to the level of service required, ranging from a 'no service' to 'optimum service' condition, and the penalty curve is devised to penalize behaviours far from the 'optimum service' conditions. The performance score range is as follows:

0 no service
1 unacceptable
2 poor
3 sufficient
4 good
5 optimum

Once the PI performance scores are elaborated, a two-level aggregation procedure is performed. Namely, for each water entity, the first level procedure aggregates the PI score belonging to each performance aspect, while the second level aggregates these performance scores by classes of entities.

The first level aggregation procedure is conducted using a composite indicator (*CI*) (Fontanazza *et al.* 2012) as a global function obtained by combining all the PI scores. The general formulation is as follows:

$$CI = \sum_i Score_i \cdot w_i \tag{1}$$

where w_i is the weight assigned to each PI. The relation $\sum_i w_i = 1$ is also imposed. Several weighting techniques are available in the literature that rely on statistical models or on expert judgement (JRC 2008). Herein, the skilled project partnership provided the PI weights that reflect the relative importance of each indicator with regard to its performance aspect. Then, the second level aggregation is determined by the average of the *CIs* for each performance aspect.

The *CIs* calculated for the whole system are input to the decision support tool. Then, for each investigated performance aspect, a pairwise comparison is carried out between the scenarios; the global performance of each scenario is compared pair to pair with the others, and a score equal to 1 is assigned to the specific scenario when the performance is higher, while 0 is assigned when the performance is equal or lower. The global score of each scenario results from the sum of all pairwise comparison scores. The greater the scenario score is, the better its overall performance is. Therefore, the decision support tool provides a ranking of the operator-based scenarios.

THE CASE STUDY

The case study analysed herein is an integrated urban wastewater system located in southern Sicily. It collects and treats sewage flows corresponding to an 84,000 population equivalent (p.e.). The SN is 8.5 km long (as main pipes), and the wastewater flows by gravity to a wet well before being pumped to the WWTP by means of three submersible pumps in parallel, each with a nominal power of approximately 40 kW. Primary, secondary, and tertiary stages and sludge treatment characterize the WWTP (Figure 2). The primary treatment stage consists of a mechanical screen, dissolved air flotation and an equalization tank; the secondary treatment stage removes both nutrient (phosphorus and nitrogen) and organic materials by means of anaerobic/anoxic and aerobic stages and a secondary clarifier; the tertiary stage consists of effluent filtration prior to disposal into the receiving water body. Finally, the sludge treatment includes an aerobic digestion unit, a gravity thickener, drying beds and then landfilling. In the oxidation basin and sludge digestion unit, fine bubble air diffusers are installed. The WWTP requires a great amount of energy for both the pumping and process units.

For the sake of clarity, the energy consuming devices of the whole system are listed in Table 1. The contribution of the SN to the system energy balance is approximately 20% of the total amount. In the WWTP, the primary and secondary treatment stages are responsible for the greatest energy consumption, with approximately 780 and 761 MWh per year, respectively. The effluent filtration requires 614 MWh/yr. Finally, the sludge treatment is surely the least energy consuming stage (approximately 288 MWh/yr), but the landfilling costs can be higher due to the lack of an efficient dewatering stage (e.g. sludge belt press) to sufficiently and consistently reduce the water amount or, rather, sludge volume.

Both the SN and WWTP were analysed by means of the ALADIN prototype. The PIs considered in this study are reported in Table 2; they represent a subset of the

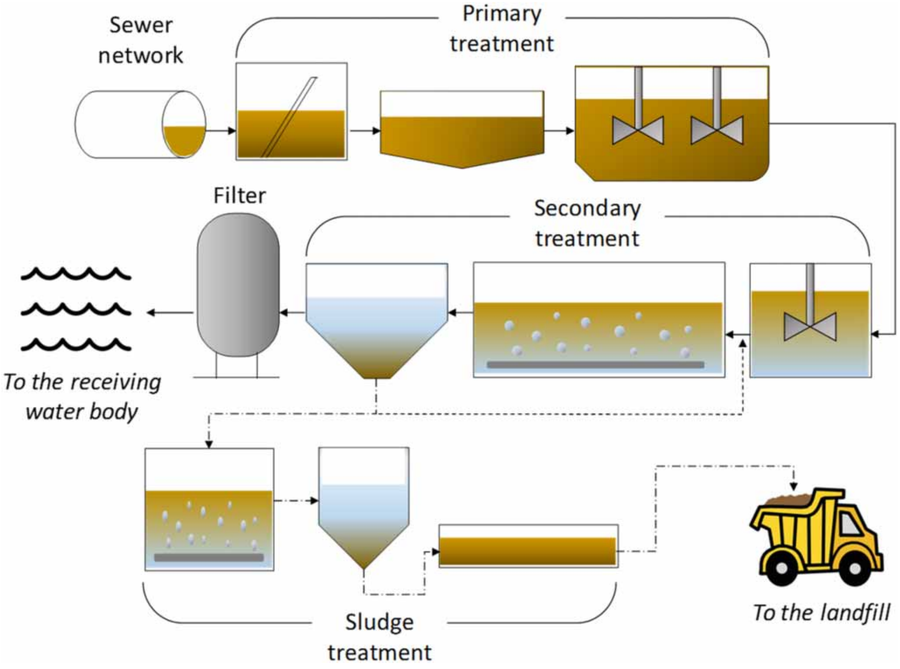


Figure 2 | The analysed integrated urban wastewater system outline.

Table 1 | Energy consuming devices installed in the system

No. items	Energy consuming devices	Stage	Installed power (kW)	Average yearly energy (MWh/yr)
4 (incl. 1 backup pump)	Submersible pumps	Sewer network	152	597
2	Screw pumps	Primary	38	147
6 (incl. 2 backup pumps)	Submersible pumps	Primary	124	356
4 (incl. 1 backup pump)	Pump boosters	Tertiary	154	614
8	Mixers	Primary/Secondary	96	461
2	Air compressors	Secondary/Sludge treatment	110	865
		All stages	**674**	**3,040**

ALADIN indicator panel. Unfortunately, the exergy indicators were not applied due to the lack of sufficient information about the compound fluxes in the wastewater treatment stages. The results obtained for the actual scenario (S0) show that the system was characterized by the following: (i) significant energy consumption both in the SN and WWTP, except for the clarifier and sludge treatment processes; (ii) lower reactive energy; (iii) no sustainable sources of energy; (iv) a lack of maintenance and control; (v) and sufficient SN economic management. Several technical actions were automatically selected by the ALADIN prototype and refined according to the following objectives: energy saving, reduction of the environmental impacts, and enhancement of the operation and maintenance activities without changing the system outline. The resulting set of feasible technical actions was then combined to define ten scenarios aimed at improving the system performance (Table 3). Therefore, the issues strictly linked to the wastewater treatment process (e.g. sludge dewatering) were not considered in the analysis. The environmental impacts were evaluated as GHG emissions according to the national energy mix defined by the Italian Energy Authority (GSE). Consequently, for this study, the energy average cost was fixed at 0.16 €/kWh, and the emission unit was fixed at 0.49 kg CO_{2eq} per kWh.

RESULTS

The indicator panel was applied to all the improvement scenarios. Then, the composite indicators (CIs) were calculated for the SN (Figure 3(a)) and WWTP (Figure 3(b)) as well as for the whole integrated urban wastewater system (Figure 3(c)) by averaging the two CIs. These results enabled us to underline the contributions of the SN and treatment plant to the global performance of the urban wastewater system for all the aspects described by the CIs: energy (*En*), environment (*Ev*), quality of service (*Qs*), operation (*Op*), economic and financial resources (*Fi*).

The technical measures applied to the SN were limited to improving the pumping station and operation and maintenance action efficiency. The results show that S7, S8, S9 and S10 were the best scenarios for the SN with the same score for all performance aspects (Figure 3(a)).

For the WWTP, the reduction in the energy consumption due to inverter installation as well as the application of a photovoltaic (PV) power plant in the nearby available area caused an increase in the performance, as shown in S4, S8, S9 and S10 (Figure 3(b)). In S2, the replacement of the pump motors, high-efficiency pumps, only slightly changed the performance score because the current motors already have a good power factor, probably due to a previous power correction (see Table 2, En05). The small wind turbine enabled the sludge treatment stage to be self-powered only if the inverter in the air-compressor reduced the energy consumption (S5). The S1, S2, S6 and S7 scenarios had the lowest environmental performance because the energy consumption reduction alone was not sufficient to reduce the GHG emissions.

The quality of service composite indicator (*Qs*) exhibited a modest variation among the analysed scenarios.

Table 2 | The PIs for the SN and WWTP and the values and performance scores (in brackets) related to the actual scenario S0

Performance indicator		Formulation	U.M.	Scenario S0	
				SN	WWTP
En02	Energy consumption per cubic metre of the discharged volume	Global energy consumption/discharged volume	kWh/m^3/yr	0.0811 (***0.33***)	–
En03	Pumping energy consumption	Energy consumed for sewer pumping/pumped volume	kWh/m^3/yr	0.0811 (***1.65***)	0.0455 (***2.60***)
En04	Standardized energy consumption	Energy consumed for sewer pumping/standardization factor	kWh/m^3/m	0.0074 (***1.39***)	0.0052 (***2.77***)
En05	Reactive energy consumption	Reactive energy consumption for pumping/total energy consumption for pumping ×100	%	0.2300 (***5.00***)	0.0977 (***5.00***)
En06	RES energy coverage ratio	RES energy production/global energy consumption × 100	%	0.0000 (***0.00***)	0.0000 (***0.00***)
En07	Photovoltaic (PV) plant producibility	PV plant energy production/PV nominal power	kWh/kW	0.0000 (***0.00***)	0.0000 (***0.00***)
En08	Wind power producibility	Wind power production/total wind turbine nominal power	kWh/kW	0.0000 (***0.00***)	0.0000 (***0.00***)
En09	Energy consumption per population equivalent	Global energy consumption/population equivalent	kWh/p.e./yr	–	29.0846 (***2.02***)
En10	Energy consumption per cubic metre of the treated volume	Global energy consumption/treated volume	kWh/m^3/yr	–	0.3320 (***2.60***)
En11	Energy consumption per cubic metre of the treated volume in the primary stage	Global energy consumption/treated volume in the primary stage	kWh/m^3/yr	–	0.1059 (***0.14***)
En12	Energy consumption per cubic metre of the treated volume in the biological stage	Global energy consumption/treated volume in the biological stage	kWh/m^3/yr	–	0.1035 (***2.87***)
En13	Energy consumption per cubic metre of the treated volume in the clarifier	Global energy consumption/treated volume in the clarifier	kWh/m^3/yr	–	0.0000 (***5.00***)
En14	Energy consumption per cubic metre of the treated volume in the tertiary stage	Global energy consumption/treated volume in the tertiary stage	kWh/m^3/yr	–	0.0834 (***0.00***)
En15	Energy consumption per cubic metre of the treated volume in the sludge digestion stage	Global energy consumption/treated volume in the sludge digestion stage	kWh/m^3/yr	–	1.9593 (***2.43***)
En16	Energy consumption per cubic metre of the treated volume in the sludge dewatering	Global energy consumption/treated volume in the sledge dewatering stage	kWh/m^3/yr	–	0.0000 (***5.00***)
Ev01	Global GHG emissions per population equivalent	Total GHG emissions in the WWTP/population equivalent	tCO$_2$eq/p.e./yr	–	1.40E-02 (***2.02***)
Ev02	Global GHG emissions per cubic metre	Total GHG emissions in the sewer system/discharged volume	tCO$_2$eq/m^3/yr	3.92E-05 (***4.95***)	–
Ev03	Pumping station GHG emissions per cubic metre	Pumping station GHG emissions/pumped volume	tCO$_2$eq/m^3/yr	3.92E-05 (***1.65***)	2.20E-05 (***2.60***)
Ev04	PV energy-avoided GHG emissions per unit power	PV energy production × GHG conversion coefficient/ PV nominal power	tCO$_2$eq/kW/yr	0.0000 (***0.00***)	0.0000 (***0.00***)

Ev05	Wind power-avoided GHG emissions per unit power	Wind power production × GHG conversion coefficient/wind turbine nominal power	tCO$_2$eq/kW/yr	0.0000 (***0.00***)	0.0000 (***0.00***)
Qs01	Remote control degree	Number of remote control units/number of control units × 1100	%	0.0000 (***0.00***)	0.0000 (***0.00***)
Qs06	Sewer coverage area	Population served by the sewer system/total resident population × 100	%	100 (***5.00***)	–
Op01	Sewer inspection	Length of sewers inspected/total sewer length	–/yr	0.0000 (***0.00***)	–
Op02	Sewer cleaning	Length of sewers cleaned/total sewer length	–/yr	0.0000 (***0.00***)	–
Op03	Manhole chamber inspection	Number of manhole chambers inspected/total number of manhole chambers	–/yr	0.0000 (***0.00***)	–
Op06	Pump inspection by power	Total nominal power of the pumps and related ancillaries subject to inspection/total nominal power of the pumps	–/yr	0.0000 (***0.00***)	0.0000 (***0.00***)
Fi01	Unit total cost per p.e.	Running costs plus capital costs related to the sewer system/total population equivalent served by the sewer system	€/p.e./yr	–	9.4770 (***3.94***)
Fi02	Unit total cost per sewer length	Running costs plus capital costs related to the sewer system/total sewer length at the reference date	€/km/yr	11,009.8 (***2.80***)	–
Fi03	Unit capital cost per population equivalent	Capital costs related to the WWTP/population equivalent at the reference date	€/p.e./yr	–	0.0000 (***5.00***)
Fi04	Unit capital cost per sewer length	Capital costs related to sewer system/total sewer length at the reference date	€/km/yr	0.0000 (***5.00***)	–
Fi05	Maintenance costs	Maintenance costs/running costs × 100	%	0.0000 (***0.00***)	0.0000 (***0.00***)
Fi06	Unit investment	Cost of investments/population equivalent	€/p.e.	–	0.0000 (***0.00***)
Fi07	RES unit investment	Investments for RES installation/total RES nominal power	€/kW	–	–
Fi08	Unit revenue	Total revenues/total population equivalent	€/p.e./yr	–	10.512 (***2.62***)
Fi09	Average energy charge	Energy sale revenues/RES energy production	€/kWh	–	–
Fi10	Average sewer charge	Sewer service revenues/discharged volume	€/m^3	0.07 (***3.75***)	–
Fi11	Average WWTP charge	WWTP service revenues/treated volume	€/m^3	–	0.12 (***4.20***)
Fi12	Total cost coverage ratio	Total revenues/total costs during the assessment period	–	5.50 (***5.00***)	1.11 (***5.00***)
Fi13	Operating cost coverage ratio	Total revenues/running costs during the assessment period	–	5.50 (***5.00***)	1.11 (***5.00***)

Table 3 | The investigated feasible improvement actions and scenarios

		Scenarios									
Improvement actions		**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**
A0	Use of a pump control unit (inverter) to manage different operational conditions[a]	x			x	x	x	x	x	x	x
A1	Use of a compressor control unit (inverter) to manage different operational conditions	x			x	x	x	x	x	x	x
A2	Use of an agitator control unit (inverter) to manage different operational conditions										x
B	Replacement of all pump motors (standard efficiency IE1) with high efficiency motors (premium efficiency IE3, $\eta = 0.91$), according to Standard IEC 60034-30		x	x							
F0	Installation of a PV power plant ($P = 455$ kWp)			x	x				x	x	x
F1	Installation of a small wind turbine ($P = 100$ kW)					x					
G	Process monitoring and WWTP control strategy									x	x
N	Inspection and cleaning of all the pumps and related ancillaries (one time per year)						x	x	x	x	x
O	Maintenance of the sewer system: (i) sewer inspection (20% total length/year), (ii) sewer cleaning (15% total length/year), and (iii) manhole chamber inspections (at least, one time/manhole/year)							x	x	x	x
P	Pumping station monitoring with a remote control system (stand-alone)			x	x	x	x	x	x	x	x

[a]The screw pumps are not considered.

However, it revealed the effects of monitoring the pumping station (S3–S10) and the biological processes in the WWTP (S9, S10). The quality sensor (e.g. O_2, NH_4^+) installations could potentially reduce the energy consumption up to 30% due to regulating the air in the oxidation basin according to the pollution load, which changes during the day. A 25% reduction was considered in this study.

The *Op* indicator value was only non-zero for the S6, S7, S8, S9 and S10 scenarios, in which maintenance actions were considered. While the WWTP performances had the same values (5), the SN performance was very low in S6, where only the pumping station maintenance was considered. The other scenarios had good SN performance values due to SN inspection and cleaning. For the WWTP operation and maintenance, air-diffuser cleaning could have also been considered, but it was not easy to estimate its influence in terms of energy reduction (Stenstrom & Rosso 2008).

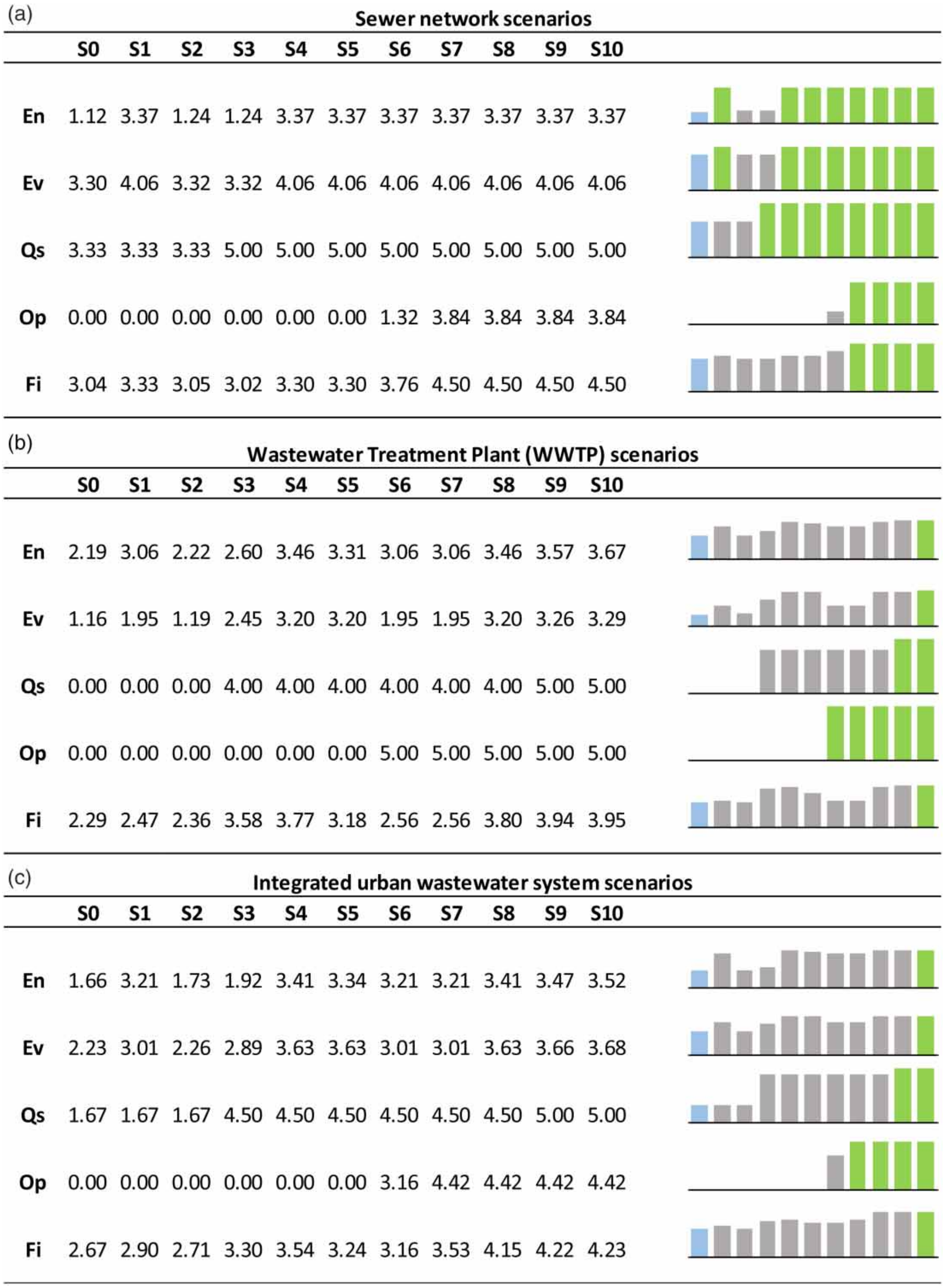
Finally, the *Fi* indicator provided the performance related to economic aspects (e.g. costs and revenues) linked to the implementation of the improvement measures. All scenarios indicated a higher performance with respect to the actual scenario (Figure 3(c)).

To determine the best scenario, the ALADIN decision support tool was applied to the *CI* results related to the whole integrated urban wastewater system. In Figure 4, the average scores among the pair comparisons are shown. The S10 scenario had the greatest score (0.92), while the S9 and S8 scenarios were second and third in the final ranking, respectively. The S8 scenario had a score of 0.62; hence, it was the winner in more than half of the pair comparisons, requiring only six of the 10 proposed actions. Both the reduction in the energy consumption linked to the pumps and compressors as well as the application of RESs benefitted scenarios S10 and S8. Nevertheless, scenario S10 also considered improvement actions on the mixers and on the process control by means of using quality sensors (Figure 5).

CONCLUSIONS

The key features of the prototype developed during the ALADIN project were presented by analysing an actual integrated urban wastewater system.

Concisely, the project aimed to develop a tool for water utilities but also for professionals and public administrators



(a) Sewer network scenarios

	S0	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
En	1.12	3.37	1.24	1.24	3.37	3.37	3.37	3.37	3.37	3.37	3.37
Ev	3.30	4.06	3.32	3.32	4.06	4.06	4.06	4.06	4.06	4.06	4.06
Qs	3.33	3.33	3.33	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
Op	0.00	0.00	0.00	0.00	0.00	0.00	1.32	3.84	3.84	3.84	3.84
Fi	3.04	3.33	3.05	3.02	3.30	3.30	3.76	4.50	4.50	4.50	4.50

(b) Wastewater Treatment Plant (WWTP) scenarios

	S0	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
En	2.19	3.06	2.22	2.60	3.46	3.31	3.06	3.06	3.46	3.57	3.67
Ev	1.16	1.95	1.19	2.45	3.20	3.20	1.95	1.95	3.20	3.26	3.29
Qs	0.00	0.00	0.00	4.00	4.00	4.00	4.00	4.00	4.00	5.00	5.00
Op	0.00	0.00	0.00	0.00	0.00	0.00	5.00	5.00	5.00	5.00	5.00
Fi	2.29	2.47	2.36	3.58	3.77	3.18	2.56	2.56	3.80	3.94	3.95

(c) Integrated urban wastewater system scenarios

	S0	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
En	1.66	3.21	1.73	1.92	3.41	3.34	3.21	3.21	3.41	3.47	3.52
Ev	2.23	3.01	2.26	2.89	3.63	3.63	3.01	3.01	3.63	3.66	3.68
Qs	1.67	1.67	1.67	4.50	4.50	4.50	4.50	4.50	4.50	5.00	5.00
Op	0.00	0.00	0.00	0.00	0.00	0.00	3.16	4.42	4.42	4.42	4.42
Fi	2.67	2.90	2.71	3.30	3.54	3.24	3.16	3.53	4.15	4.22	4.23

Figure 3 | Composite indicators for each scenario regarding: (a) the sewer network; (b) the wastewater treatment plant; and (c) the whole integrated urban wastewater system.

to enhance the understanding of the whole urban water cycle, or parts of it, by means of a multicriteria performance analysis. In particular, the PI panel together with the water and energy balances provided information about the system or subsystem efficiencies in terms of water leakage, reduction, energy consumption, environmental impact, quality of service, and operational, economic and financial aspects. Moreover, the evaluation of the composite indicators (CIs) related to each performance aspect enabled us to obtain the global system performances for both the actual scenario and operator-based improvement scenario. Specifically, the prototype can simulate planned operational actions before investments are made by showing how the system performance changes. Starting from these results, the ALADIN prototype decision support tool provides a ranking among the implemented scenarios to enable an operator to make well-informed interventions on each part of the system in accordance with his own overall performance goals.

In this paper, the analysed system was limited to an integrated urban wastewater system, located in southern Sicily. The prototype was used to analyse two subsystems, the SN and the WWTP, highlighting the weaknesses of this integrated wastewater system specifically in the operational and energy fields. This initial analysis allowed us to identify possible management solutions specifically suited for the case study. Specifically, the solutions were aimed to automatically control the treatment processes, produce clean energy from renewable sources and maintain the system (especially the pumps and compressors).

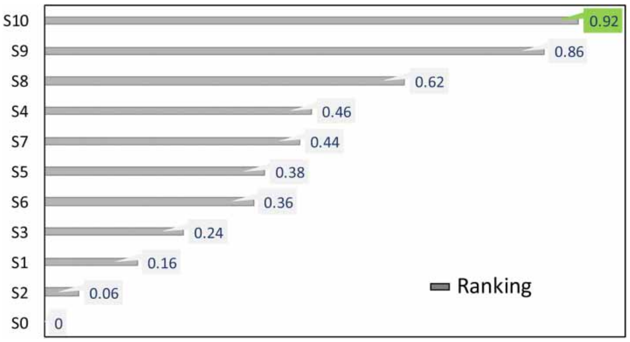


Figure 4 | The scenario average score among the pair comparisons.

The comparison analysis between the alternatives and combinations of the alternatives for 10 improvement scenarios allowed us to improve the performance of the system with percentage increases ranging between 60 and 300% for the different performance fields. The study highlighted that good performance could be achieved with the implementation of only a few management actions. Scenario S8 provided a global performance equal to 0.62 using only six of the proposed actions; the performance of scenario S7 (using five actions) was 40% lower (0.46), highlighting that the actions improved the performance.

The skilled partnership and analysis of the system, as carried out during the start-up phase of the project, allowed us to finalize objectives that could be favourably accepted by water utilities. The prototype does not directly consider the social aspects that have great relevance in the decision-making process, so further developments will include these by elaborating specific PIs.

Great efforts have been made to develop a user interface, but some issues have to be fixed in order to realize a commercially competitive product that can include a friendly user interface and the integration of spatial data

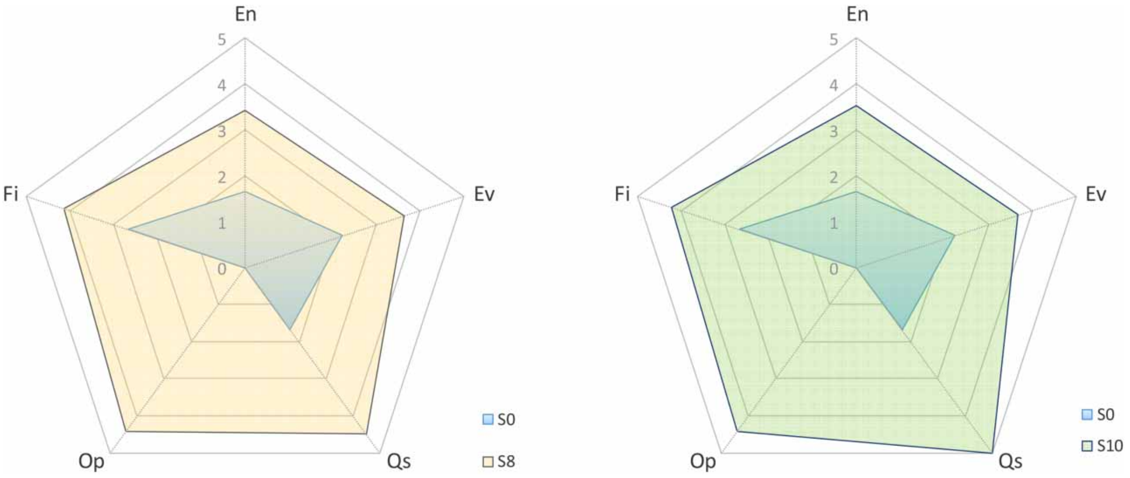


Figure 5 | Global performance: comparison between the actual scenario S0 with S8 (left) and S10 (right).

representation, such as a GIS (geographic information system). On the other hand, the ALADIN prototype only provides the basis for a more complex tool.

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