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## A decision support tool for water and energy saving in the integrated water system

Vincenza Notaro<sup>a\*</sup>, Valeria Puleo<sup>a</sup>, Chiara Maria Fontanazza<sup>b</sup>, Mariacrosetta Sambito<sup>c</sup> and Goffredo La Loggia<sup>a</sup>

<sup>a</sup>*Dipartimento di Ingegneria Civile Ambientale Aerospaziale e dei Materiali, University of Palermo, Viale delle Scienze, 90128 Palermo, (Italy)*

<sup>b</sup>*Faculty of Engineering and Architecture, University of Enna "Kore", Cittadella Universitaria, 94100 Enna, (Italy)*

<sup>c</sup>*Sering Ingegneria – Via E. Amari – 90132 Palermo (Italy)*

### Abstract

In the last decades, a growing attention on energy saving associated with water resources usage and leakages reduction has been recorded at both national and international level. Scientific research has focused on implementation of several methodologies aimed at the understanding of energy transformation processes occurring in the integrated water system.

The main concern is then identifying energy impacts associated to each macro-area of integrated water system, such as collection, treatment and distribution, and analysing the potential interactions between them. Unfortunately, only overall energy consumptions are usually available at national level. The main objective of the paper is to present a decision support tool, developed in the framework of the ALADIN project, able to analysing the water and energy balance in the integrated water service. In order to achieve a sustainable use of water resources, the tool allows an assessment of the energy impact of different macro - areas of integrated water system. Moreover, each macro - area can be treated as an element able to share energy with other elements, aiming to obtain an energy saving on the whole integrated water system. In this way, the decision support tool could suggest efficient solutions, according to the operator objectives, with regard to energy and water losses management. Therefore, the tool could provide guidelines for choosing the best management solutions, depending on the particular analysed system, and allow, at the same time, the energy and water resources saving. The proposed tool was applied to a complex water supply system, the Favara di Burgio system (Sicily, Italy) in order to show its reliability.

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\* Corresponding author. Tel.: +39-091-23896574; fax: +39-091-6657749.  
E-mail address: [vincenza.notaro@unipa.it](mailto:vincenza.notaro@unipa.it)

## 1. Introduction

Nowadays the topic of the energy savings associated with the use of water resources attracts a rising attention. One of the areas in which this issue is more critical is the management of the integrated water service. Due to increasing electricity prices and environmental concerns (i.e., greenhouse gas emissions), in the last few decades, water utilities have shown growing interest not only in water losses reduction but also in energy recovery and saving by seeking to better manage energy in integrated water systems. Energy is needed in every phase of water use, from extraction through conveyance, treatment, use, and disposal [1].

Energy consumption relies on water system location and its characteristics and, in particular, on resources availability and quality, the network topology, the area topography and water and wastewater treatments. Therefore, the understanding of the water-energy relationship is essential, especially for achievement of sustainable water management. However, it is well-known that the integrated water service management presents several problems due to the extension of the water supply networks, the difficulty in monitoring every point of the system, as well as the multiplicity and variety of water and wastewater treatment plants. As consequence, an efficient management of water service, focused on water and energy saving, is difficult to achieve.

The EU community as well as academia and water industries have shown interest in investigating water-energy interaction. Several studies have been already carried out in Australia and United State, but Europe still needs an integrated approach to improve energy management in urban water system [1] and [2].

The main share of operational cost required to supply water are linked to resource and pumping energy costs. The first one are strictly linked to the availability and quality of water; they depend on the level of treatment needed for water purification and can highly increase when freshwater resources are not available and desalination is considered as alternative [3]. As reported in Nogueira Vilanova and Perrella Balestieri [4], the energy intensity, expressed as energy for cubic meter of water, can vary from 0.25 kWh/m<sup>3</sup> to 4.5 kWh/m<sup>3</sup> depending on the source type (i.e., surface or groundwater), regardless the desalination process for which the energy intensity can run up to 15 kWh/m<sup>3</sup>.

With regard to pumping energy costs, they are relevant on operational costs and even a small overall increase in pumping efficiency may result in significant cost savings [2, 5-7].

Another important factor affecting the amount of energy required to supply water is represented by water losses. A water leakage can be linked to the waste of the energy requested for resource extraction, conveyance and treatment; e.g. the presence of leakages leads to the use of oversized pumps, producing a proportional energy waste [8]. As broadly known, most of the inefficiencies occur before the water reaches the end user [4] [9]. Moreover, in supply systems where water is supplied only few hours per day or few days per week in order to cope with water shortage, the energy consumption increases further [10].

The relationship between energy cost and water losses has been also investigated in literature. An analytical relationship between energy efficiency in water supply system and leak size and location was proposed by Colombo and Karney [11] together with an analysis on the energy cost response versus system complexity (simulated by a growing number of loops). The authors also showed the impact of leaks and of the friction losses on electricity consumption in systems characterized by pump connected to storage [12] by highlighting the importance of the relative locations of the system components and of the pumping strategy.

Due to the high energy consumptions linked to water supply, several researchers have been investigated the drinking water systems implications in terms of greenhouse gas (GHG) emissions [12-14]. A review of the current methods of estimation finding in literature is presented in Pandey et al.[15]. As well as energy consumption, the GHG emissions abatement can be obtained by leak reduction [11].

To reduce energy consumption relating to the water resource management, several strategies can be proposed in term of system design, operation and maintenance improvements including an active control of water losses. Moreover, the use of renewable energy sources and the selection of a suitable energy tariff can further reduce energy cost [16].

The main objective of this study is to present a decision support tool, developed in the framework of the ALADIN project (funded by the “Linea di Intervento PON FESR della Sicilia 2007-2013”), able to analysing the water and energy balance in the integrated water service and help to the identification of mitigation strategies finalized to the efficiency improvement of the energy and water losses management. Due to the existing interactions between water losses, potential energy production and GHG emissions, the identification of reliable water and energy saving

strategies for a water system should require a system performance analysis based on several aspects. Namely, prior to start up any strategies, the most energy-intensive areas of the system should be highlighted. To this aim an energy balance could be useful to assess the energy use or energy flows of the water system, outline the possible actions and energy conservation measures and set a plan of action without negatively affecting the system processes or water quality.

The reliability of the proposed tool was tested on the water supply system named Favara di Burgio, located in the southern part of Sicily (Italy), which supply water to six different towns.

This paper is organized as follows: in section 2, after a brief presentation of ALADIN system framework, the tool procedure is described; in section 3, the case study is presented; in section 4, the results related to the adoption of water and energy saving strategies are presented and compared; and in section 5, the conclusions are drawn.

## 2. Materials and methods

As above mentioned, the methodology applied in the present study has been developed within the framework of the research project ALADIN. The basic idea is to contribute to environmental and energetic sustainability of integrated water systems by improving the knowledge about the energy and water flows considering both consumptions and possible exchange between different part of the system. To this aim, the whole integrated water system was divided in five sub-systems: water resources, water supply and distribution network, water treatment, urban drainage and wastewater treatment.

In order to better understand the framework within the decision support tool has been developed, a brief description of the ALADIN system is provided in the following.

The ALADIN system structure has three information sources outer layers (OPERATOR, KNOWLEDGE BASE and MONITORING) which provide inputs to the system core constituted by three main modules (OPERATIONAL ACTIONS, INTEGRATED MODEL and DSS) whose functions are interrelated and interdependent by exchanging input and output data (Fig. 1). Namely, firstly the ALADIN system receives input data from different information sources. These data are used to evaluate the water and energy balance of the analysed integrated water system or sub-system. The water losses and energy impact related to each sub-systems are highlighted.

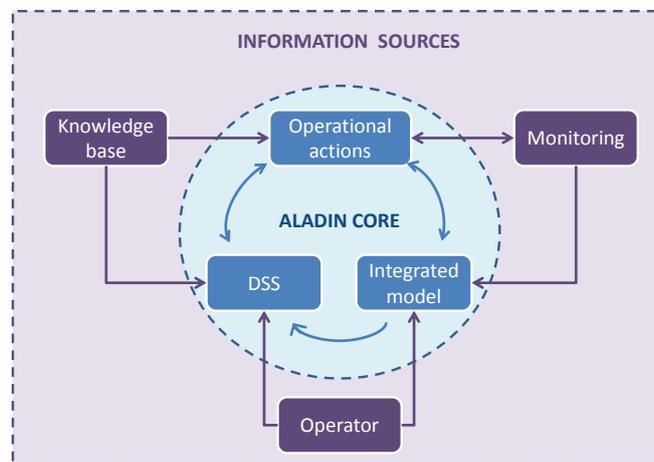


Fig. 1. ALADIN system structure

The results of water and energy balance are showed also in terms of performance indicators (PIs) related to different performance area such as: water leakages reduction, energy consumption, environmental impact, quality of service and financial cost. For each PI a suitable penalty curve was defined in order link a system performance score to each assessed PI value. The system performance was assimilated to the level of service, varying between a “no

service” and an “optimum service” condition, and the curve was built to penalise the behavior far from “optimum service” conditions. The performance score ranges between 0 and 5.

According to the performance values resulting from the water and energy balances, ALADIN system is able to suggest possible operational actions to improve system operations, taking into account the operator objectives (e.g. leakages reduction, pump optimization, carbon footprint abatement) and the technical feasibility. Therefore, the operator can choose among the proposed actions to build several improving scenarios and test them by means of the models integrated in the ALADIN core.

For each operator-based scenario the Decision Support System module evaluates a global system performance score with regard to each performance area by combining the PI performance into a composite indicator CP [17, 18]. Thus, a pairwise comparison between the improving and actual scenarios is carried out to obtain a scenario ranking for each investigated performance area: the global performance of each scenario is pair to pair compared with the others and a score equal to 1 is appointed when the performance is higher, while 0 when is equal or lower. The global score of each scenario results from the sum of all pairwise comparisons scores. Such ranking is useful to support the operator in the selection of the mitigation measures to improve the system performance in term of energy and water losses saving.

The ALADIN potential beneficiaries could be water utilities but also professionals and public administrations.

### 3. The case study

The reliability of the ALADIN system procedure was tested on the real water supply system “Favara di Burgio” (Fig. 2). This water supply system is located in the southern of Sicily (Italy). It supplies around 170.000 inhabitants living in six different towns: Sciacca, Ribera, Cattolica Eraclea, Montallegro, Siciliana, Realmonte, Porto Empedocle and Agrigento. The system layout is long about 132 Km with pipes in steel, cast iron and HDPE and diameters ranging between 80 and 800 mm. Fig. 2 shows also the percentages of pipe length per diameters. Approximately 100 km of the main pipes were reconstructed between 2002-2004. The system is currently supplied by two water sources (Fig. 3): the Favara di Burgio wells and the Sciacca piezometer, with an average flow rate equal to 320 l/s and 95.76 l/s, respectively. Three tanks (Favara di Burgio, Giraffe and Don Pasquale) are located along the main layout of the supply system, they fulfill to hydraulic disconnection, water storage and reserve functions. Water is pumped to Favara di Burgio tank by means of the pumping station, P1, whereas Giraffe and Don Pasquale tanks are fed by gravity. The system supplies twenty five local tanks, six of which by means of pumping stations (P2-P7). Table 1 reports the main features of the pumping stations operating into the system.

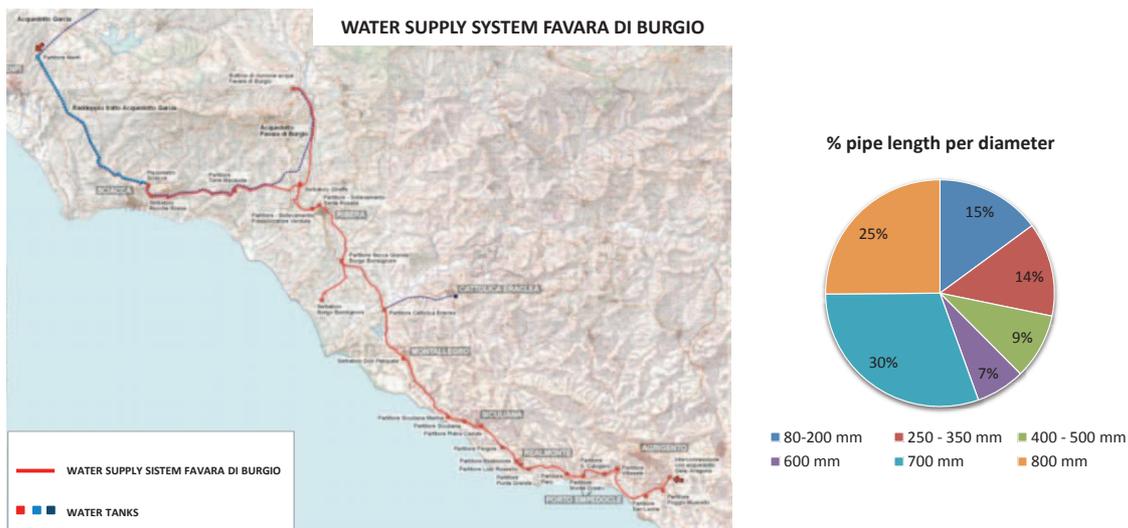


Fig. 2. The case study water supply system “ Favara di Burgio” (in the southern of Sicily, Italy)

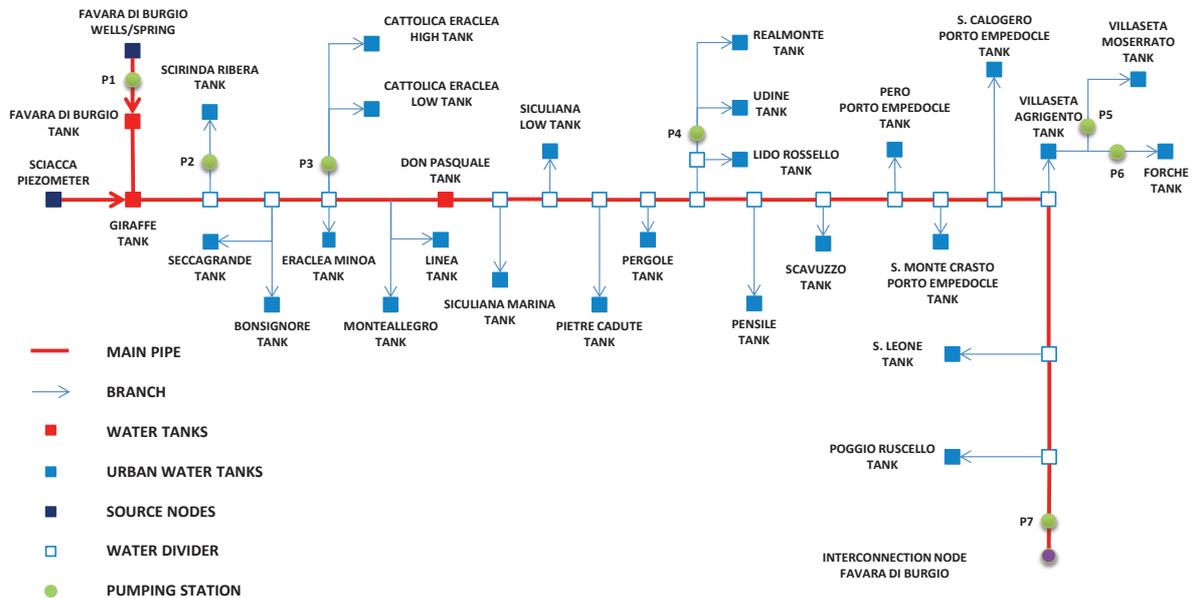


Fig. 3. Schematic of Favara di Burgio water supply system

Table 1. Main features of the pumping stations operating into the system.

Pumping station	Q (l/s)	Pump head (m)	Pump power (kW)	Pumped water volume (m <sup>3</sup> /yr)	Energy consumption (kWh/yr)
P1	312.00	9.75	23.94	9839232.00	448225.51
P2	49.14	234.88	184.75	1549679.04	1618410.00
P3	15.36	143.41	10.43	484392.96	299154.00
P4	14.76	107.83	34.15	465471.36	209714.40
P5	22.71	78.30	26.88	716182.56	235468.80
P6	70.46	210.00	204.20	2222026.56	1788792.00
P7	68.75	3.45	51.17	2168100.00	91366.80

As first step the water and energy balances of the actual system configuration were carried out. To this aim several data characterizing the system (e.g. the annual input water volumes, the annual water volumes supplied to each local tank, the annual energy consumptions and the flow rate of each pumping station) were input in ALADIN system.

The water balance for the actual system revealed an input volume drawn from the sources equal to 13.111.407,36 m<sup>3</sup>/year, a supplied volume at the twenty five urban tanks equal to 9.889.374,24 m<sup>3</sup>/year and a Non Revenue Water (NRW) volume equal to 3.222.033,12 m<sup>3</sup>/year corresponding to about the 25% of the input volume. According to the IWA water balance procedure, NRW volumes can be distinguished in real and apparent losses. In the present study the apparent losses were neglected because electromagnetic flow meters with high accuracy and equipped with automatic meter reading technology are located upstream the urban tanks. The total cost of the water volumes drawn from resources is equal to € 1.716.993.

With regard to the energy balance, the actual energy consumption is totally linked to the seven pumping stations operating in the system. Its value is about 4.691.132 kWh/year, with a total energy cost equal to € 1.071.627 and a cost per cubic meter of water drawn by the sources equal to 0,13 €/m<sup>3</sup>.

To estimate the GHG emission linked to the actual energy consumption, the water sources (the environment) and the urban tanks (the users) were assumed as the system boundaries and the year was selected as time period of the analysis. The national energy mix defined by the Italian Energy Authority (GSE) was used for estimating carbon emission due to energy transport and production. Namely, according to the GSE, the Italian energetic mix has an average cost of 0.08 €/kWh and produces 0.49 kg<sub>CO<sub>2</sub>eq</sub> per kWh, thus the actual production of GHG is equal to 2266 t<sub>CO<sub>2</sub>eq</sub> per year.

#### 4. Results analysis and discussion

The water and energy balance results highlight that the actual system is affected by high percentage of leakages and a great amount of energy consumption for pumping water volumes which are not supplied to the final user (urban tanks).

When dealing with water supply system, employing measures aimed at leakage reduction may affect the system energy balance and carbon footprint because water volumes flowing through pumping stations are usually reduced. Moreover, the energy required for pumping water could be reduced by adopting more efficient pumps and/or supplied by more energy sustainable systems such as photovoltaic (PV) panels. Each mitigation measure could affect both water and energy balance and obviously water supply carbon footprint as well.

In the present study some feasible technical solutions were identified and combined together in order to define several scenarios aimed at improving the system performances in terms of water and energy saving. The feasible measures investigated were:

- A. carrying out a water leak detection and repair campaign on system branch only (the system main pipes were reconstructed between 2002-2004) in order to reduce to 16% the water losses affecting the actual system;
- B. replacing all pumping stations with more energy efficient pumps having  $\eta=0.75$ ;
- C. replacing the more powerful pumping stations (P2 and P6) with more energy efficient pumps having  $\eta=0.75$ ;
- D. replacing the less powerful pumping stations (P1, P3, P4, P5 and P7) with more energy efficient pumps having  $\eta=0.75$ ;
- E. installing photovoltaic PV panels in order to cover the 40% of energy request by the less power pumping stations (P1, P3, P4, P5 and P7);

For all tested scenarios the water volume supplied at each one of the twenty five urban tanks was the same of the actual scenario and equal to 9889374.24 m<sup>3</sup>/year overall.

For each improving scenario, the hydraulic analysis was performed by means of EPANET model. The model has provided also the pumps energy consumption. In table 2 were summarized the improvement measures characterizing the seven scenarios employed, in order to improve the actual system performance (scenario 0) in terms of water and energy saving. Table 2 shows also the related NRW percentage together with the energy and cost saving with respect to scenario 0. The economic saving was obtained by comparing the sum of the annual capital and operational costs linked to each proposed scenario with the annual operational cost of the actual system. Namely, the scenario 1 was only focused on water leakages reduction while the scenarios 2 and 3 were aimed at the energetic improvement of the pumping systems by replacing pumps with more efficient ones. Scenarios 5, 6 and 7 combine together water losses reduction and pump replacement measures. Finally, in scenario 4 and 7 were considered the energetic improvement of the less power pumping systems together with the installation of photovoltaic panels in order to cover the 40% of energy demand by the less power pumping stations. The results highlight the scenario 7 as recommendable because it is characterized by the major water and energy saving with NRW equal to 16% and energy saving equal to -24.5% and with a reduction of the total costs equal to -7.4% with respect to the actual scenario. Therefore, the identified solution could be auto-financed by the water utility using the related operational cost economies.

The proposed scenarios were closer analysed by means of some performance indicators representative of the system performance with regard to several area such as water leakages reduction, energy consumption, environmental impact or GHG emission and financial cost (Table 3). The system performance related to the water leakages was expressed by means of a single PI (W1); three PIs (E1, E2 and E3) were used to analyse the system

energy behavior. The environmental impact in terms of GHG emission and adoption of photovoltaic PV panels was analysed by means of two indicators G1 and G2 and finally eight PIs (F1-F8) were adopted to investigate the financial costs related to each scenario.

Table 2. Actual and improving system scenarios with the resulted water and energy saving.

Scenario	Improvement measures	Input volume (m <sup>3</sup> /yr)	NRW (%)	Energy consumption (kWh/yr)	PV energy yield (kWh/yr)	Energy saving (%)	Capital cost (€/yr)	Operational cost (€/year)	Economic saving (%)
0	-	13111407	25%	4691132	-	-	-	2983620	-
1	A	11800267	16%	4361502	-	-7.0%	39852	2771705	-5.8%
2	B	13111407	25%	4029096	-	-12.0%	68991	2855169	-2.0%
3	C	13111407	25%	4299384	-	-8.4%	51635	2894131	-1.3%
4	D+E	13111407	25%	4420844	405457	-13.1%	34157	2944659	-0.2%
5	A+B	11800267	16%	3811028	-	-17.5%	105109	659664	-7.3%
6	A+C	11800267	16%	3996998	-	-14.8%	88840	2688439	-6.9%
7	A+D+E	11800267	16%	3936997	430427	-24.5%	75078	2688439	-7.4%

Table 3 Performance indicators selected for the case study application

Performance Indicator	Formulation	U.M.
<b>W1</b> Non-revenue water ratio	NRW / Input system volume	%
<b>E1</b> Energy consumption per cubic meter of inlet system volume	Global energy consumption / Input system volume x 100	kWh/mc/yr
<b>E2</b> Pumping energy consumption per cubic meter of pumped volume	Pumping energy consumption / pumped volume	kWh/mc/yr
<b>E3</b> Photovoltaic energy coverage ratio	PV energy production / Global energy consumption x 100	%
<b>G1</b> Pumping stations GHG emissions	GHG emissions / pumped volume	tCO <sub>2</sub> eq/mc/yr
<b>G2</b> Avoided GHG emissions from photovoltaic electricity	PV energy production x GHG conversion coefficient / PV nominal power	tCO <sub>2</sub> eq/kW/yr
<b>F1</b> Electrical energy costs ratio	Energy cost / Global operational cost x 100	%
<b>F2</b> Imported (raw and treated) water costs ratio	Imported water cost / Global operational cost x 100	%
<b>F3</b> Leakages survey cost ratio	Leakages survey cost / Global operational cost x 100	%
<b>F4</b> Investments for asset replacement and renovation ratio	Investments for asset replacement and renovation / Global investments x 100	%
<b>F5</b> Investments for energy consuming devices replacement ratio	Investments for energy consuming devices replacement / Global investments x 100	%
<b>F6</b> Investments for RES installation	Investments for RES installation / Nominal RES power	€/kW
<b>F7</b> Average water charges for exported water per unit water volume	Average water charges for exported water / exported water volume	€/mc
<b>F8</b> Economic performance of pumping system	Energy cost / pumped volume	€/mc

Table 4 shows the PI values assessed for the actual system (scenario 0) and the proposed improving scenarios together with the related performance values obtained by means of user-based penalty curves implemented into ALADIN system.

Table 4. PIs and related performance values for actual and improving system scenarios

Performance Indicator	TESTED SCENARIO								
	0	1	2	3	4	5	6	7	
W1	PI value	24.57	16.19	24.57	24.57	24.57	16.19	16.19	16.19
	Performance	1.65	2.95	1.65	1.65	1.65	2.95	2.95	2.95
E1	PI value	0.36	0.37	0.31	0.33	0.34	0.38	0.33	0.34
	Performance	1.88	1.75	2.32	2.19	2.01	1.61	2.19	2.07
E2	PI value	0.27	0.28	0.24	0.25	0.26	0.26	0.25	0.26
	Performance	3.41	3.25	3.84	3.71	3.54	3.54	3.67	3.56
E3	PI value	0.00	0.00	0.00	0.00	9.85	0.00	0.00	11.14
	Performance	0.00	0.00	0.00	0.00	1.77	0.00	0.00	1.97
G1	PI value	0.000130	0.000136	0.000114	0.000119	0.000075	0.000125	0.000121	0.000075
	Performance	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
G2	PI value	0.00	0.00	0.00	0.00	5.52	0.00	0.00	5.52
	Performance	0.00	0.00	0.00	0.00	5.00	0.00	0.00	5.00
F1	PI value	35.92	35.95	33.03	33.94	35.07	33.25	33.96	33.96
	Performance	4.27	4.27	4.46	4.40	4.33	4.45	4.40	4.40
F2	PI value	57.55	55.75	60.14	59.33	58.31	58.10	57.48	57.48
	Performance	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
F3	PI value	0.00	1.27	0.00	0.00	0.00	1.32	1.30	1.30
	Performance	0.00	3.00	0.00	0.00	0.00	3.10	3.05	3.05
F4	PI value	0.00	100.00	0.00	0.00	0.00	37.91	44.86	68.38
	Performance	2.00	1.00	2.00	2.00	2.00	1.00	1.00	1.00
F5	PI value	0.00	0.00	100.00	100.00	100.00	62.09	55.14	31.62
	Performance	2.00	2.00	1.00	1.00	1.00	1.00	1.00	2.56
F6	PI value	0	0	0	0	60000	0	0	60000
	Performance	0.00	0.00	0.00	0.00	2.80	0.00	0.00	3.00
F7	PI value	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
	Performance	2.93	2.93	2.93	2.93	2.93	2.93	2.93	2.93
F8	PI value	0.06	0.06	0.05	0.06	0.06	0.05	0.06	0.06
	Performance	1.96	1.89	2.20	2.12	2.03	2.31	2.04	2.04

Performance: 0 = no service; 1 = unacceptable service; 2 = poor service; 3 = acceptable service; 4 = good service; 5 optimum service

For each performance area, a global system performance was assessed by combining together the performance score linked to each PI value into a composite indicator. Namely, in the present study the composite indicators were formulated as weighted average of the performance related to the PIs of a given group. Fig. 5 shows the global system performance linked to each scenario analysed with respect to water leakages reduction, energy consumption, environmental impact and financial costs. The reduction of 10% of water leakages applied in scenarios 1, 5, 6 and 7 corresponds to an increase in performance from 1.65 (unacceptable service) to 2.95 (acceptable service). With regard to energy consumptions all analysed scenarios show a poor service (with performance less than 3) due to the high water volumes pumped to supply urban tanks. However, scenario 4 and 7 have a good environmental performance and the last one shows the best financial performance corresponding to an acceptable level of service.

The global system performance were finally elaborated by means of a pairwise comparison procedure in order to obtain a scenario ranking for each investigated performance area (Table 5). The obtained scenario rankings confirm

the scenario 7 to be recommendable in term of water leakages, energy consumption, environmental impact and financial cost reduction.

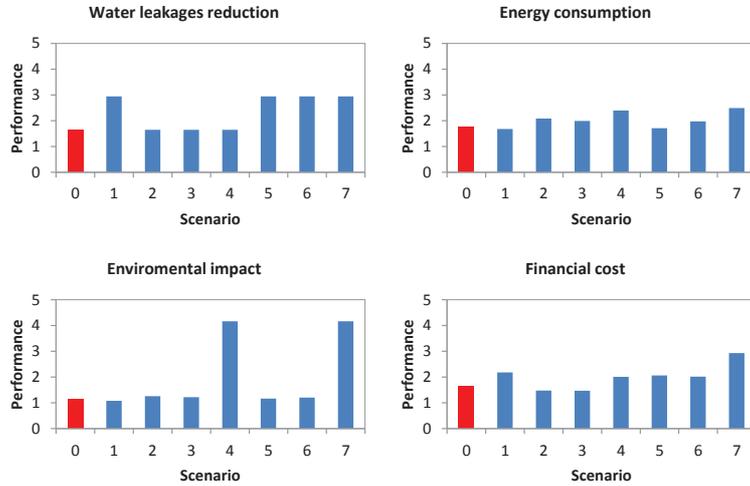


Fig. 5. Global system performance scores for each analysed scenario

Table 5. Scenarios ranking for the investigated performance area

Water losses reduction	Energy consumption	Environmental impact	Financial cost
1 - 5 - 6 - 7	7	7	7
0 - 2 - 3 - 4	4	4	1
	2	2	5
	3	3	6
	6	6	4
	0	5	0
	5	0	2
	1	1	3

### 5. Conclusions

In the present study was presented a decision support tool, developed in the framework of the ALADIN project, aimed at contributing to environmental and energetic sustainability of integrated water systems. The reliability of the proposed tool was tested on the real water supply system named Favara di Burgio, located in the southern part of Sicily (Italy), which supply water to six different towns.

Namely, the tool performed the Favara di Burgio water and energy balance and analysed the results in terms of performance indicators (PIs). According to the PI performances, the ALADIN system suggested possible operational actions to improve the case study operations, taking into account the operator objectives (e.g. leakages reduction, pump optimization, carbon footprint abatement, financial cost saving) and the technical feasibility. Therefore, the proposed actions were combined to build several operator-based improving scenarios.

For each performance area investigated (water leakages reduction, energy consumption, environmental impact and financial cost) the global system performance was evaluated by means of a composite indicator and a pairwise

comparison between the improving and actual scenarios was carried out to obtain a scenario ranking. Such ranking was useful to support the operator in the selection of the best mitigation measures (scenario 7). Namely, the identified solution could be auto-financed using the related operational cost economies.

Therefore, the presented tool has been useful to analyse the current system energy and water balance and to support the identification of possible solutions to improve system efficiency in terms of water and energy saving.

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