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DEALING WITH A CLUSTER OF LARGE CENTRALIZED MUNICIPAL WASTEWATER TREATMENT PLANTS. A CASE STUDY

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ABSTRACT

The article deals with a cluster of large centralized municipal wastewater treatment plants (LCMWWTPs) assessing the main economic, energy, environmental and management aspects. With reference to the case study of the Regi Lagni system (Southern Italy), composed of five WWTPs for an overall effective population of 2,235,800 inhabitants the study focused first on the multi-disciplinary characterization of the system investigated and then on potential future upgrading options, identifying the best suitable solution. For the scope, several indicators such as running costs, energy consumptions, Greenhouse Gas Emissions (GHG), sludge for landfilling and two scenarios were defined. The first scenario focused on the role of anaerobic digestion while the dewatered sludge was sent to landfill. The second scenario implemented the same operations of the previous one although the construction of a thermal treatment plant for the dewatered sludge was also planned. Results showed how LCMWWTPs could be characterised by low resilience; the upgrading

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of plants to comply with the increasingly stringent legal limits was difficult, especially where works were carried out to ensure continuity of operation. Multi-criteria analysis allowed the cluster system based on anaerobic digestion to be the best solution from an economic, energy and environmental point of view.

Keywords: Energy consumption, GHG emissions, Regi Lagni, running costs, sludge management, wastewater engineering

1. INTRODUCTION

Wastewater treatment approaches vary from traditional centralised systems to fully decentralised on-site systems. Centralized systems, usually publicly owned, collect and treat large volumes of wastewater for large communities (Crites and Tchobanoglous, 1998; Massoud *et al.*, 2009). Conversely, decentralised on-site systems treat wastewater from individual homes and buildings (Brown *et al.*, 2009). Between these two extremes, there are other intermediate treatment systems as reported in Libralato *et al.* (2012), and herein described.

Centralization consists of a sewer system collecting wastewater that is conveyed to a wastewater treatment plant (WWTP) generally located outside of the limits of the city (Wilderer and Schreff, 2000). Centralization has been the most widely adopted design solution in the previous century and has also been tackled systematically on a scientific level (International Water Association (IWA) specialist group on design, operation and costs of large wastewater treatment plants). The Satellite Treatment Plant (STP) facilities are integrated with centralised systems for solids processing. The sludge produced by the purification treatment of isolated houses, for example by septic tanks or Imhoff tanks, is transported with tankers to centralized plants equipped with dedicated pre-treatment (Libralato *et al.*, 2012; Lee *et al.*, 2018). The Semi-centralised supply and treatment systems (SESATS) is used for villages and suburbs that cannot always be connected to centralized sewer systems and treatment plants as well as when pumping stations and transfer pipelines are cost-prohibitive (Weber *et al.*, 2007). The arriving wastewater is first mechanically pre-treated in a compact plant with integrated fine screen and grit/grease chamber; after intermediate storage, wastewater is treated full-biologically in a compact reactor. In the Great Block system, wastewater from individual buildings (i.e., schools) can be managed with complete recycle systems (Libralato *et al.*, 2012). It represents a highly useful solution for arid and semi-arid areas such as the Mediterranean countries; the recovery of rainwater and the treatment of grey water also for their reuse reduces the demand for drinking water (Lazarova *et al.*, 2003; De Gisi *et al.*, 2016). In the cluster systems, typically, 4 to 12 or more houses are grouped to form a cluster system for improved wastewater management (Brown *et al.*, 2009; Libralato *et al.*, 2012). Cluster systems are favourable in areas that are more densely populated or that have poor soil conditions and adverse topography. Finally, in the individual system, the treatment is carried out at home level; different schemes are available such as the NoMix approach where urine and faeces are separated directly at source via an ad hoc WC (McCann, 2010; De Gisi *et al.*, 2014a).

Each system certainly has its own advantages and disadvantages. Several studies have investigated these advantages, criticisms and limitations considering social, economic and environmental issues (Wilderer and Schreff, 2000; Massoud *et al.*, 2009; Libralato *et al.*, 2012; Yung *et al.*, 2018). Although the present world seems to be moving towards decentralised systems, mainly due to significant investments to upgrade facilities at the end of their life cycle, it resulted that none of the approaches could be excluded a priori;

generally, the different systems can be integrated with each other on the basis of the specific required situation (Wilderer and Schreff, 2000; Libralato *et al.*, 2012).

The above classification of treatment systems did not take into account that in some territories the concept of centralization was so extended that a cluster of large centralized WWTPs was constructed. In general, the term "cluster" refers to a grouping of interconnected WWTPs; the joint management of sludge, which is also facilitated by the presence of a single water service operator, is an example of relationship between the WWTPs in the cluster. In such a cluster, in order to optimise the system's costs/revenues, the operation of the individual plants was integrated; the flows of one plant (i.e., sludge) were linked to those of another plant.

Although the literature on the topic was extensive, there is very little information about a cluster of large centralized WWTPs. However, the study of a cluster of this type can provide useful information on important aspects such as the resiliency of WWTPs, understood as the ability of the plant to comply with substantial changes (i.e., new inlet organic loads, the need to meet more stringent discharge limit values), or whether, at the end of their life cycle, what is the most sustainable upgrading scenario. These issues are particularly relevant in view of the considerable investments that will be made in the next few years in renovating the integrated water system (De Gisi *et al.*, 2014b; Dürrenmatt and Wanner, 2014).

Thus, the aim of the paper was to study a cluster of large centralized municipal WWTPs assessing the main economic, energy, environmental and management aspects. With reference to the case study of the Regi Lagni system (Southern Italy), composed of 5 large WWTPs for an overall potentiality of 2,235,800 effective populations equivalent (where, PE corresponds to a five-day biodegradable organic load of 60 g BOD_5/d), the study focused first on the multi-disciplinary characterization of the cluster investigated and then on potential future technological and management upgrading options; in this way it was possible to discuss the best suitable solution from an energy, economic and environmental point of view. Performance evaluation involved the use of various sources; in the case of the estimation of the Greenhouse Gas (GHG) emissions produced by a WWTP, the free-available ECAM (Energy Performance and Carbon Emissions Assessment and Monitoring) 2.0 tool was used (http://wacclim.org/ecam-tool/). The assessment of the impact of each plant on the receiving water body, the estimate of costs and energy consumption, of waste produced by the cluster of WWTPs, where not directly supplied by the operator, was carried out on the basis of the indications contained in Teodosiu *et al.* (2015), De Gisi *et al.* (2015) and Sabia *et al.* (2016), respectively.

2. METHODOLOGICAL APPROACH

2.1 Case study description

The Regi Lagni system was an ancient hydraulic reclamation structure, essentially made up of a network of canals dug into the land to drain the waters of an often marshy territory, extending about 100,000 hectares in the productive heart of the provinces of Naples and Caserta (ENEA, 2010a). The canal works, started in Roman times, saw a strong commitment to the hydraulic reorganization during the Spanish Viceregno at the beginning of 1600. The reclamation had put an end to the centuries-old problem of the flooding of the *Clanio* stream in "Campania Felix" and mitigated malaria in the hinterland. In 1973, the choleric infection that affected the area of Naples justified the beginning of very heavy interventions of urgent hygienic sanitary reorganization of the area. Five large centralised municipal WWTPs were realized, which discharge directly into the main channel of the Regi Lagni system (Fig. 1).

Figure 1. The anthropic basin of the Regi Lagni system: (a) Hydrographic sub-basins; (b) Main river and the 5 large WWTPs.

The treatment plants were supposed to "once and for all" clean up the sanitation situation of the drainage water and allow the bathing of the waters north of Naples. The construction of the WWTPs was financed by the Italian Government through the Cassa del Mezzogiorno, as part of the "Progetto Speciale n. 3 per il disinquinamento del Golfo di Napoli" (De Feo *et al.*, 2009).

The five WWTPs, having been built in compliance with the rules and design criteria in force in the 1970s, were inadequate to date; the plant structures and equipment have become obsolete and the new environmental regulations have imposed stricter limits. In this respect, Table 1 showed how the PE of today (PE_{eff} = PE effectively served by the WWTP) were different from the project one (PE_{des} = PE related to the project configuration); Acerra, Foce Regi Lagni and Napoli Nord WWTPs were oversized compared to current requirements ($PE_{eff/}PE_{des}$ << 100%); on the other hand, the Area Nolana and Area Casertana WWTPs were overloaded by 130.5% and 106.5%, respectively.

Table 1. The "Regi Lagni" system wastewater treatment plants (re-elaborated Pica *et al.*, 2016).

The inlet organic load, expressed as BOD_5 concentration (BOD = Biochemical Oxygen Demand at five days), classified wastewater as medium (around 200 mg/l) and high composition (300 mg/l). Instead, TSS concentrations (TSS = Total Suspended Solids) were in most cases less than 350 mg/l and therefore of low composition. Total nitrogen (TN) concentrations made it possible to classify wastewater with a medium (around 40 mg/l) and high (around 85 mg/l) nitrogen composition.

The values of the BOD_5/NH_4-N ratios showed a low ability to remove nitrogen compounds by conventional denitrification and nitrification processes (Tab. 1).

The five WWTPs were designed according to the full-treatment scheme, thus equipped with primary sedimentation, activated sludge-based oxidation and anaerobic digestion. In addition, due to the high overall PE (PE_{des} = 800,000), a thermal treatment plant for dewatered sludge was also built at the Area Casertana WWTP.

Data from Pica *et al.* (2016), referring to the 2010 context, showed a different state of quality of the plants and its Unit of Process (UoPs) (Tab. 2), although managed by the same operator. The Area Nolana and Area Casertana WWTPs showed a good quality.

Table 2. Treatment schemes and status of the unit of process (UoP) (re-elaborated Pica *et al.*, 2016).

With the exception of the Area Casertana WWTP, everyone had problems with the sludge line; anaerobic digestion, one of the most delicate processes in the plant, was out of service. Nitrogen removal processes, with the exception of the Area Nolana WWTP, had not been implemented.

The "desolate" situation described above had legal and political implications; in many cases, some WWTPs had been confiscated by the Competent Authority, precisely because of frequent violations of environmental protection laws.

2.2 Methodology for assessing WWTPs cluster performance

The methodological approach provided first for the evaluation of the performance of the Regi Lagni system (or cluster) in its current configuration and then for the evaluation of the cluster, having hypothesized different technological solutions for WWTPs upgrading. Because of the complexity of the problem, a multi-criteria approach was adopted.

By referring to the cluster boundary, the following indicators were identified and quantified (the so called *system-indicators*): (I_{1C}) Energy consumption, (I_{2C}) GHG emissions production, (I_{3C}) Wastes for landfilling, (I_{4C}) Running costs, (I_{5C}) Impact on the receiving water body. In detail, I_{1C} measured the consumption of electricity from the national grid for the WWTPs operation. I_{2C} quantified the GHG emissions produced by the treatment processes. I_{3C} considered the total waste produced by the 5 WWTPs, which in turn consisted of screening waste, sand, oil, greases and sludges. I_{4C} quantified the running costs of the plants while I_{5C} measured the overall impact of the 5 WWTPs on the receiving water body. These indicators work on a cluster scale.

However, their quantification included an evaluation at the scale of each WWTP. For example, considering the I_{1C} indicator, its value at cluster scale was calculated as the sum of the energy consumption of each WWTP (I_{1WWTPi}): $I_{1C} = I_{1WWTPi}$ with $i = 1, ..., 5$. The same approach was followed for the remaining indicators (I_{2C}-I_{4C}). The I_{5C} indicator is detailed subsequently.

Finally, in order to compare the proposed technology upgrading scenarios, a composite indicator was constructed. The most important elements of the multi-criteria approach are illustrated below.

2.2.1 Evaluation database

The data used in the study and shown in tables 1 and 2 were part of a broader study conducted by ENEA in 2010 under the “Regi Lagni project” (ENEA, 2010b). For each plant, there was a detailed report showing the performance in terms of pollutant removal and the quality status of the process units; reports were available online (ENEA, 2010a). Instead, the determination of energy and environmental performance, running costs as well as the quantity of dewatered sludge produced by the plants, where the previous reports were lacking in terms of data (Tab. 3), was done according to the methodologies and databases described below.

Table 3. Input data availability for the evaluation of the current cluster.

2.2.1.1 Energy

The energy consumption of a municipal WWTP was assessed on the basis of the unit values of the consumption of each UoP. With reference to the data reported in Campanelli *et al.* (2013) and at 1 m^3 of inlet wastewater in the plant, the following values were assumed: 0.07 kWh/m^3 for initial pumping (Archimedes screw, centrifugal pumps); 0 kWh/m^3 for the screening (coarse and fine, compaction); 0.02 kWh/m^3 for the sand and oils removal (air blower, crane bridge movement, extraction pump and air lift); 0.05 kWh/m^3 for (pre)denitrification (mixer); 0.38 kWh/m^3 for oxidation of the carbon/nitrification fraction (air diffusion system); 0.095 kWh/m^3 for recirculation of the mixed liquor (pump); 0.025 kWh/m^3 for the return activated sludge recirculation (pump); 0.01 kWh/m^3 for secondary sedimentation (movement of the bridge crane); 0 kWh/m^3 for filtration; 0 kWh/m^3 for extraction of primary and secondary sludge (pumps); 0.015 kWh/m^3 for the aerobic stabilisation of sludge (mixing system); 0.015 kWh/m^3 for the mechanical dewatering of the sludge.

The above data showed a zero value for some UoP and therefore the energy consumption was negligible.

Energy production from anaerobic digestion was assessed, in the absence of site-specific data, according to Metcalf and Eddy (2003), by adopting a specific daily production of 20 l/PE/d, corresponding to about 0.075 Nm^3 of biogas per 1 m^3 of wastewater. This was a “prudential” value, slightly lower than that reported in the literature (Metcalf and Eddy, 2003) for an anaerobic digester operating under mesophilic condition (20-40 l/PE/d). With reference to a biogas with a methane content (CH_4) of 60% and an electric motor efficiency of 30% (for the conversion of biogas into electrical energy), a specific electric energy production of 1.6 kWh/Nm^3 of biogas was assumed (Campanelli *et al.*, 2013).

The energy requirements of each WWTP therefore took into account both the energy consumed in the plant and the self-produced energy used for internal uses.

2.2.1.2 GHG emissions

The evaluation of the GHG emissions produced by the single WWTP involved the use of ECAM 2.0, a tool developed as part of the WaCCliM project (http://wacclim.org/ecam-tool/).

ECAM considered three types of GHG emissions: direct greenhouse gas emissions; indirect GHG emissions associated with grid electricity consumption; all other indirect emissions. Direct emissions included (i) emissions from the maintenance trucks, (ii) CO_2 (carbon dioxide), CH_4 and NO_2 (nitrogen dioxide) emissions from on-site stationary fossil fuel combustion, (iii) CH_4 and (iv) NO_2 from sewers or biological wastewater treatment. The other indirect emissions, instead, included (i) emissions from manufacturing of chemical used, (ii) emissions from the construction materials used, (iii) CH_4 and NO_2 from wastewater discharge without treatment, (iv) CO_2, CH_4 and N_2O from sludge transport off-site and (v) NO_2 from effluent discharge in receiving waters. Other emissions, such as end-user emissions or CO_2 produced by microbial rupture of organic matter in activated sludge reactors (considered to be a source of biogenic nature, although the literature is controversial on this point), were not included in ECAM (ECAM 2.0 manual, 2017).

The environmental assessment was carried out on an annual basis. With reference to the Italian situation, the values of "Emission factor for grid electricity", "Annual protein consumption per capita" and "BOD_5 per person per day" were assumed of 0.410898038 $kgCO_2/kWh$, 40.88 kg/person/year e 60 g/person/day, respectively (provided by default by the tool, that allows only the country to be selected). The IPPC 5th AR (2014/2013) CCF was selected as "Global Warming Potential (GWP) source". The GWP values relative to CO_2 for a 100-year time horizon were: CO_2 = 1 CO_2 equivalents; CH_4 = 34 CO_2 equivalents; N_2O = 298 CO_2 equivalents.

ECAM also allowed to define the typology (i.e., activated sludge) and the functioning (well-managed, minor poorly aerated zones, some aerated zones, not well managed) of the biological treatment implemented in the plant as well as the sludge disposal method (composting, incineration, land application, landfilling and stockpiling). In this specific case, the landfill was the final destination of the sludge, which, once mechanically dewatered, was transported by means of transport to landfills for special waste.

Furthermore, evaluation with ECAM takes place at two stages, indicated *Tier A* and *Tier B*. The first (*Tier A*) allowed a preliminary evaluation of WWTP performance in terms of GHG emissions and energy consumed; as an input, several parameters were to be provided, as following reported: PE, energy consumed from the grid, volume of fuel consumed, volume of treated wastewater, volume of discharged wastewater to water body, running costs, energy costs, average Total Nitrogen (TN) at discharge, if you are producing biogas and/or if you are valorising biogas, the main treatment type (i.e., activated sludge, trickling filter, etc.) as well as the sludge disposal method (composting, incineration, landfilling, etc.). Instead, the *Tier B* offered a detailed assessment. In addition to the previous parameters, as the data input it was necessary to add the influent and effluent BOD load, the BOD removed as sludge, the BOD mass removed, if used, the type of fuel engines (i.e., methane) as well as the volume of fuel consumed. Furthermore, many other requests composed the so-called "advanced assessment" modules.

In this study, the GHG emissions were estimated with the *Tier B*.

2.2.1.3 Running costs

The running costs considered in the study related to the cost of (i) electricity, (ii) operating personnel and (iii) technical/managerial ones, (iv) reagents (sodium hypochlorite or peracetic acid for disinfection, ferric chloride or polyelectrolyte for sludge conditioning), disposing of (v) screening by-products (European Waste Code – EWC 19 08 01), (vi) oils and greases (EWC code 19 08 09), (vii) sands (EWC code 19 08 02), (viii) sludge (EWC code 19 08 05) and (ix) for maintenance. The unit cost of operating and technical personnel was 3.78 and 1.65 €/PE, in line with the literature related to large facilities (PE > 200,000) (De Feo *et al.*, 2012) as well as the values provided directly by the operator.

For reagents, values of 0.35 and 0.24 €/PE were assumed respectively for disinfectant and chemical used for sludge conditioning. The unit cost for the disposal of screening by-products and sand was 138 €/t; the cost for the disposal of oils and greases and for sludge was 100 and 200 €/t, respectively. The unit cost of electricity, both consumed and produced, was assumed to be 0.12 €/kWh.

The current cost, calculated as the sum of the above items (De Gisi *et al.*, 2015), was then increased by 10% to take account of general expenses and VAT (value-added tax).

2.2.1.4 Wastes for landfilling

The calculation of the wastes for landfilling required the prior identification of the system boundary which, in the case of a single WWTP, coincided with the physical boundary of the plant. In the absence of site-specific data, sludge production was estimated (primary and secondary) using the methodology reported in Sabia *et al*. (2016). The sludge from the plant was then sent to landfill via trucks. Taking into account that the sludge produced in the Regi Lagni system has long been sent to Apulia Region (De Feo *et al.*, 2017), a distance of 300 km was assumed between the centre of gravity of the basin and the landfill.

2.2.1.5 Environmental impact on water body

The environmental impact of the WWTPs cluster was calculated considering the environmental impact assessment methodology reported in Teodosiu *et al.* (2015). In particular, considering the single WWTP, the environmental impact (EI) on the water body was estimated with the following relation:

$$\mathrm{EI} = \frac{C_{\mathrm{det}} \cdot q_{\mathrm{det}}}{C_{\mathrm{max}} \cdot q_{\mathrm{max}}} \cdot \mathrm{IU} \tag{1}$$

where q_{det} was the average wastewater flow discharged by the pollution source (measured value), m^3/s; q_{max} was maximum contracted wastewater flow, according to the environmental permit, m^3/s; C_{det} was the average pollutant concentration (as given by a specific water quality indicator) in the effluent, mg/L; C_{max} was the maximum allowed concentration (MAC) for wastewater discharging into natural receivers, mg/L; IU importance unit (dimensionless).

Based on the available data, three common water quality indicators were used: BOD_5, TSS and TN. The maximum allowed concentrations, MAC, referred to the discharge limits imposed by Italian Law (D.Lgs 152/2006): BOD_5 = 25 mg/l; TSS = 35 mg/l; TN = 15 mg/l.

The importance units (IU), that in accordance to Teodosiu *et al.* (2015) was introduced in the method as an expression of the impact of the polluter upon the state of the receiving water body, was evaluated on the basis of the data available at the time of the assessment (year 2010). In this regard, the Campania regional environmental protection agency (ARPAC) classified all the sections of the Regi Lagni river as belonging to the fifth class of the chemical status (ARPA, 2010). According to the Water Framework Directive (EC, 2000), the fifth class had a "bad" meaning and as consequence, the river waters were highly contaminated. Based on Teodosiu *et al.* (2015), a value of 1 was given for waters with a bad chemical water quality class. This assignment covered all the 5 WWTPs of the Regi Lagni system. Finally, the environmental impact of the WWTPs cluster, represented with I_{5C} indicator, was calculated as the average value of the impact produced by each WWTPs.

2.2.2 Scenarios for future upgrading's

As explained later, following the assessment of the *status quo* of the Regi Lagni system, various technological solutions for the enhancement of the 5 WWTPs were considered. For this purpose, two alternative scenarios (clusters) were identified (Tab. 4).

Table 4. Scenario analysis of upgrading project actions.

The first scenario concerned the Regi Lagni system in its current configuration (Cluster A). The second scenario (Cluster B) provided for the recovery of all treatment units for each WWTP, considering both the water and sludge lines. The scenario therefore focused on the role of anaerobic sludge digestion; the dewatered sludge, after being stored on a common platform, was sent to landfill.

Instead, the third scenario (Cluster C) implemented the same operations as in the scenario B. Differently, the construction of a centralized thermal treatment plant for the dewatered sludge was also planned; the sludge output from the five WWTPs was thus sent to the thermal treatment plant located (virtually) in the Area Casertana WWTP. As can be seen from Table 2, a sludge incineration plant, although not functioning, was already realized at the Area Casertana site. In addition, for the third scenario, in order to calculate the GHG emissions due to transport, a standard distance of 5 km was assumed between each WWTP and the virtual thermal treatment plant. The consumption of fuel (methane gas) for incineration was estimated at 0.58 Nm^3 per kg of dry sludge (Mininni *et al.*, 2004), having assumed a dry content in the sludge of 30%.

Scenarios B and C involved the restoration of anaerobic digestion, which represents the most advantageous solution for high loaded WWTP equipped with primary sedimentation (generally, it is adopted for capacities greater than 50,000 PE). The adoption of a thermal process for scenario C was linked to the need to minimize the sludge to be disposed of in landfills, thus containing disposal costs as well as recovering energy from the combustion of sludge. These solutions were in line with literature (Panepinto *et al.*, 2016).

2.2.3 *Multi-criteria analysis methodology*

The two scenarios described above constituted the 2 alternatives in the context of the multi-criteria problem (De Gisi *et al.*, 2017, 2014b), whose goal was to identify the best solution.

The multi-criteria analysis provided for the definition of 5 indicators as previously reported (I_{1C}-I_{5C}).

The preference index, indicated with PI and defined as the parameter that aggregates the information of the evaluation criteria (or indicators), was the result of the following relation (Sabia *et al.*, 2016):

$$PI_i = \sum_{j=1}^{m} \bar{x}_{ij} = \sum_{j=1}^{m} x_{ij}.w_j \tag{2}$$

Where, x_{ij} is the performance of the alternative i-th (i.e., each cluster) with respect to the j-th evaluation criterion (I_{1C}-I_{5C}). Instead, the normalized value was calculated with the following relations:

$$\bar{x}_{ij} = x_{ij}/Max(x_j) \tag{3}$$

$$\bar{x}_{ij} = Min(x_j)/x_{ij} \tag{4}$$

Where, the selection of the relation depends on the nature of the criterion, if it was to maximize or minimize in respect to the general goal (to select the best scenario). In the specific case, all criteria were to be minimized.

The method described above allowed to evaluate the single cluster in respect of the five criteria described above and, further, to identify the best suitable cluster, representing by the scenario with the highest value of PI.

In order to verify the goodness of the obtained solution, three different weighing vectors were considered, corresponding to three different decision makers: environmentalist, water service operator/manager, balanced. The environmental decision-maker (Env) was the one who attached the greatest importance to pro-environmental criteria; the following condition was defined: Impact on the water body (I_{5C}) = GHG emissions (I_{2C}) > Wastes for landfilling (I_{3C}) = Energy balance (I_{1C}) > Running costs (I_{4C}). On the other hand, the decision-maker in the water service (Ser) was the one who attached the greatest importance to the pro-management criteria; the following condition was therefore defined: Running costs (I_{4C}) = Impact on water body (I_{5C}) > Wastes for landfilling (I_{3C}) = Energy balance (I_{1C}) > GHG emissions (I_{2C}). Finally, the balanced decision-maker (Bal) was what he considered the 5 indicators to be equally important.

The application of the SAW-PCT (Simple Additive Weighting - Paired Comparison technique) method reported in De Gisi *et al.* (2014b) made it possible to determine, with reference to criteria I_{1C}, I_{2C}, I_{3C}, I_{4C} and I_{C5}, respectively, the following weights: V_{Env} = (0.167; 0.167; 0.067; 0.300; 0.300); V_{Ser} = (0.167; 0.167; 0.300; 0.067; 0.300); V_{Bal} = (0.200; 0.200; 0.200; 0.200; 0.200).

3. RESULTS AND DISCUSSION

3.1 *Cluster performance in current configuration*

Assessing the performance of the cluster in its current configuration initially included a detailed assessment of the performance of each WWTP.

Results in terms of BOD_5, TSS and TN removal showed diverging values (Tab. 5); a total of 4 out of 5 plants did not comply with the discharge limit values (25 mg/l) for BOD_5. As well as, with reference to the TN, the output values were on average higher than the set limit (15 mg/l). In addition, Napoli Nord and Area Casertana WWTPs also showed overruns in TSS, highlighting difficulties in the solid/liquid separation of secondary sedimentation. Only the Area Nolana WWTP showed excellent performance with reference to all the considered parameters.

The results in terms of performance were essentially in line with the technological level and operating status of the UoPs of the WWTPs (Tab. 2).

Table 5. Main pollutants removal efficiency and comparison with the Italian legal limits (re-elaborated Pica *et al.*, 2016) [(a)].

The good performance of Area Nolana WWTP was the result of the upgrading actions carried out in the past years and reported in detail in Pica *et al.* (2012). The other plants, although operated by the same operator, were not subject to an adjustment.

The experience described in Pica *et al.* (2012) in Area Nolana WWTP allowed to explain the difficulties encountered during the upgrading of the plant; adaptation made necessary to tackle an increase in the inlet organic load (BOD_5) or to comply with the new stringent limits for nitrogen compounds. The adaptation had to be carried out in such a way as to avoid interruption of the treatment service. The procedure implemented by ENEA (Italian National Agency for New Technologies, Energy and Sustainable Economic Development) and here briefly described, had initially provided for storage of the inlet wastewater (approximately 3000 m^3/h) for a sufficient time to perform the work of interconnection of the new biological line with the existing operating lines. Subsequently, the new denitrification, nitrification/oxidation unit was realized and an additional secondary sedimentation unit was activated. The most arduous part of the work involved the construction of connecting pipes between the secondary sedimentation tank and the existing splitter (location of the sludge recirculation pumps) without interruption of operation. The large tubing (700mm diameter) had required the construction of a special metal carpentry that had allowed the tubing coming from secondary sedimentation to reach the central part of the existing splitter; in this way, the hydraulic load of the side wells of the aerated mixture was discharged into the metal carpentry. Pica *et al.* (2012) also pointed out how the implemented procedure resulted in only about 0.65% increase in the total cost of the revamping project. The above procedure was successfully applied to Area Nolana WWTP only, although it could also be extended to the other WWTPs of the Regi Lagni system.

The experience described above, in addition to showing why Area Nolana worked, had highlighted how large centralized WWTPs could show a limited resilience; the upgrading of the plant, only for adaptation to the increasing inlet organic load, could be difficult to implement in the hypothesis of ensuring the continuity of service operation.

The subsequent analyses (costs, energy, etc.) confirmed the results of the treatment yields, although other interesting aspects were highlighted.

Table 6. Running costs, energy consumption, GHG emissions and waste produced by the Regi Lagni WWTPs system on annual basis.

The analysis of running costs, for example, made it possible to identify the unusual behaviour of Foce Regi Lagni WWTP (Tab. 6). The per capita value of 21.8 €/PE/y was symptomatic: the plant had a higher value when PE increased, thus not respecting the laws of economy of scale (Lubello and Breschi, 2000). Nevertheless, running costs were substantially in line with the literature related to large WWTPs, where Kampet (2000) referred to a per capita cost in the range of 20-30 €/PE/y for plants with a potential > 100,000 PE.

The study of the individual cost items (Fig. 2a-f) showed that for Foce Regi Lagni and Napoli Nord WWTPs, the largest item concerned the disposal of sludge, with a percentage value of 51 and 44%, respectively. These values were wide-ranging the 34% reported in Campanelli *et al.* (2013). However, for the other plants, the main items were the cost of reagents (25% for Acerra WWTP and 27% for Area Nolana) and of the operational staff

(28% for Area Casertana WWTP); there was basically a good balance between costs. The operational staff of Area Casertana WWTP was in line with 27% reported in Campanelli *et al.* (2013).

Figure 2. (a-f) Costs; (g-l) Energy consumption per Unit of Process (UoP); (m-r) GHG emissions. In the figure, (a, g, m) = Napoli Nord WWTP; (b-h-n) = Acerra WWTP; (c-i-o) = Area Nolana WWTP; (d-j-p) = Foce Regi Lagni WWTP; (e-k-q) = Area Casertana WWTP.

The energy consumption analysis showed values in line with the economy of scale (Tab. 6), with variable values in the range 12.3-58.1 kWh/PE/y. The specific consumption of Foce Regi Lagni and Area Casertana WWTPs were lower compared to those reported in literature; in this respect, the Federal Environmental Agency (2007) reported 32 kWh/PE/y for PE > 100,000, while Thöle (2008) and Haberken *et al.* (2008) showed a range of 20-42 kWh/PE/y and 25-80 kWh/PE/y, respectively. Acerra and Area Nolana WWTPs were in line with the aforementioned literature.

The items that mostly contributed to total energy consumption were oxidation (57-76%), initial lifting (11-14%) and lifting of the return activated sludge (4-5%) (Fig. 2g-l). The Area Nolana WWTP was the only one with an energy consumption related to nitrogen removal processes, in line with the technological status shown in Table 2. In addition, it (Area Nolana) showed a much lower percentage of energy consumption (57%) due to the oxidation of the carbon fraction compared to other plants; moreover, this percentage was in line with Menendez *et al.* (2010), which reported a value of 60%.

The assessment of GHG emissions focused on other interesting aspects. Firstly, the low Table 6 values of GHG were broadly linked to biological treatment; the latter was incomplete (i.e., not-well managed) and consequently the GHG was lower than in the case of complete treatment (Yoshida *et al.*, 2014). The detailed analysis showed that the malfunctioning plants (i.e., Foce Regi Lagni and Napoli Nord WWTPs) were characterised by high percentages of GHG emissions due to CH_4 and NO_2 from untreated wastewater. Instead, with reference to the most performing plants (i.e., Area Nolana WWTP), the higher GHG emissions were due to the production of energy to be used in the water line (71-78%), to indirect GHG emissions (10-14%) and to GHG emissions for the management of sludge (8-10%).

Finally, the study of the per capita production of wastes destined for disposal also revealed the anomalous behaviour of Foce Regi Lagni WWTP (Tab. 6); the per capita value (54 kg/PE/y) was far greater than that of the other plants (23 kg/PE/y). Most probably, this was due to the treatment cycle implemented, based exclusively on gravity thickening and mechanical dewatering, the latter not perfectly efficient. With regard to the Napoli Nord WWTP, the sludge production was substantially in line with De Feo *et al.* (2012); assuming a specific production of 50 kg/PE/y, there was a per capita sludge production of 51 kg/PE/y.

The above results made it possible to quantify the I_{1C}-I_{5C} indicators, thus extending the evaluation on a cluster scale. Results showed current cost values (I_{1C}), energy consumption (I_{2C}), GHG emissions (I_{3C}) and landfill waste production (I_{4C}) of 18.8 €/PE, 24.7 kWh/PE, 113.5 $kgCO_{2,eq}$/PE and 33.1 kg/PE, respectively (See cluster A, Fig. 3).

Figure 3. (a) Running costs, (b) energy consumption, (c) GHG emissions, (d) wastes for landfilling and (e) environmental impact on the water body for the clusters under investigation. Cluster A = Scenario composed by the 5 WWTPs that implement the current technologies (status quo); Cluster B = Scenario subject to structural and

technological upgrading with sludge management by anaerobic digestion; Cluster C = As in the case of the scenario B, but with a sludge-fired centralized thermal plant, which treats the dewatered sludge of all 5 WWTPs.

As far as waste is concerned, it was found to be composed of screening waste, sands, oils & greases and dewatered sludge. Stored in suitable areas, they were destined for landfill disposal, jointly managed by the unique operator (Fig. 4).

Figure 4. Mass balance of waste generated by each WWTP and by the Regi Lagni system as a whole in the current configuration (Cluster A).

In terms of impact on the receiving water body, the I_{5C} indicator, calculated as the average value of impacts on the water body of each WWTP, showed a value of 0.839. Such a high value was largely attributable to the low treatment yields of the main polluting parameters such as BOD_5, TSS and TN, as shown previously. In particular, among all the plants, Napoli Nord WWTP contributed mostly (Fig. 5).

Figure 5. Impact on the receiving water body of the 5 WWTPs and of the cluster.

The analysis of the cluster in its initial configuration was subsequently used to compare the goodness of the WWTPs upgrading hypotheses, as herein described.

3.2 *Cluster performance in future configurations following plant upgrading*

Two alternative scenarios were considered. The first would have provided for the recovery of all UoPs and the putting into operation of anaerobic digestion, for all facilities of the system. The second, in addition to the contents of the previous scenario, would also have provided for the construction of a centralized thermal treatment plant for the treatment of the dewatered sludge produced by the Regi Lagni WWTPs, thereby minimising the transport of sludge to landfill. In this respect, previous Figure 3 showed the simulation results for both scenarios.

It was possible to observe how all the indicators, with the exception of GHG emissions (I_{3C}), showed an increase with respect to the *status quo*; bringing the plants to comply with the legal limits, there was inevitably an increase in running costs, energy consumption and wastes for landfilling.

The multi-criteria evaluation, whose theoretical bases are given in section 2.2.3, allowed to identify the best scenario, that was the one based on the upgrading of plants by the operation of anaerobic digestion of sludge (Fig. 6a).

Figure 6. Preference Index score for the identification of the best management scenario (cluster) varying decision-makers: Considering (a) the GHG emissions estimated with ECAM 2.0, (b) a further reduction in GHG emissions of 50%.

The scenario in question was the best from a multi-criteria point of view, despite the presence of a thermal treatment plant that could have allowed to minimize the sludge to be sent to landfill. The result thus obtained was validated by varying the weights to be attributed to the criteria, and considering, therefore, three different types of decision-maker (De Gisi *et al.*, 2014a).

The multi-criteria evaluation carried out by imposing a reduction of the GHG emissions of 50% in cluster C showed greater competitiveness of the thermal-based scenario. In particular, the “so cleaner” cluster C was the best solution for both the environmental and the water service operator decision-maker. Such a higher preference index was linked to a 50% reduction in GHG emissions as well as a reduction in running costs, estimated at around 30%; the latter was the result of lower consumption of methane as additional fuel. In this respect, Mininni *et al.* (2004) showed how the replacement of the traditional incineration, based on the fluidised bed technology (which is the one implemented in ECAM 2.0), with one able to integrate evaporation and fluidised bed technology (the so called integrated fluidised bed technology) allowed to obtain a drastic reduction of fuel consumption and as a consequence, also the GHG emissions linked to this aspect would be reduced.

4. CONCLUSIONS

The analysis of the Regi Lagni case study, that is to say of the system of large plants built in the 70's and according to a vision that favoured large centralized WWTPs, showed a limited resilience of the plants with respect to the plant adaptations; such adaptations were necessary for various reasons as dealing with increases in the inlet organic load or the compliance with new discharge limit values, as in the case of nitrogen compounds. From the five considered plants, only Area Nolana WWTP, which was previously adapted to meet the increase in its influential organic load, demonstrated any problems in complying with the legal limit values. However, the lack of resilience, required the use of special engineering solutions; the concept was to adapt the plant without interrupting operation.

The case study also highlighted the importance of adopting suitable approaches for adapting the WWTPs cluster; a multi-criteria approach, able to take into account the economic, energy, GHG emissions, waste production as well as the impact on the receiving water body, was a very reliable tool. In this specific case, the cluster based on the re-functioning of anaerobic digestion for all the plants represented the best solution from a multi-criteria point of view, positioning it more successfully than in the case of the scenario based on the construction of a centralised sludge thermal treatment plant.

Although the results obtained cannot be extended to the case of other WWTPs clusters around the world, they can be used as a reference in all similar situations, characterized by the presence of a cluster of large WWTPs interconnected (i.e., in sludge management), a single water service operator as well as the need to adapt the plants since they have reached the end of their life cycle.

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DECLARATION OF INTEREST

None

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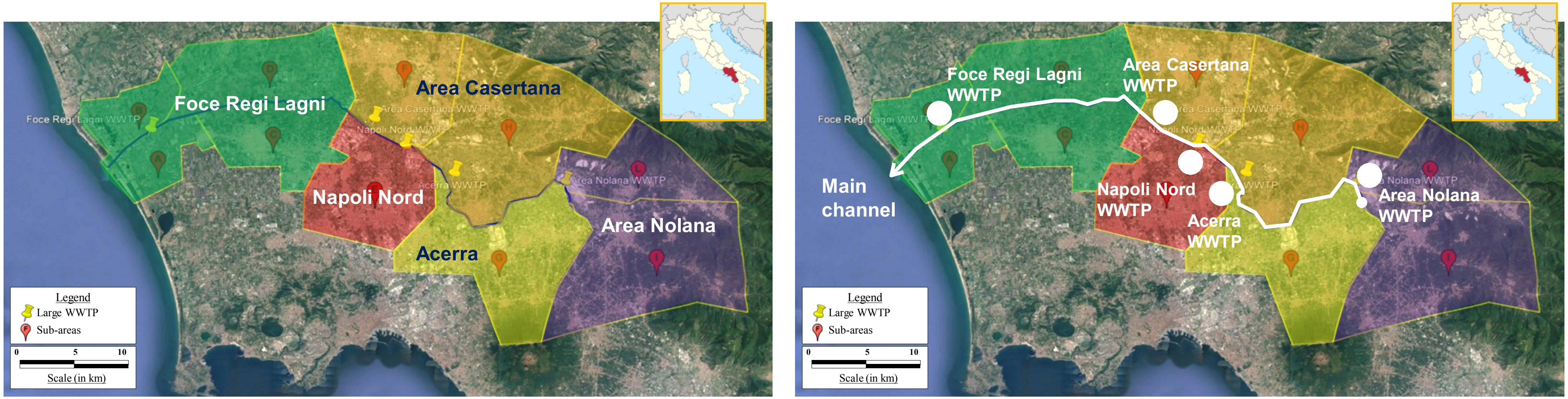


(a) (b)

Figure 1. The anthropic basin of the Regi Lagni system: (a) Hydrographic sub-basins; (b) Main river and the 5 large WWTPs.

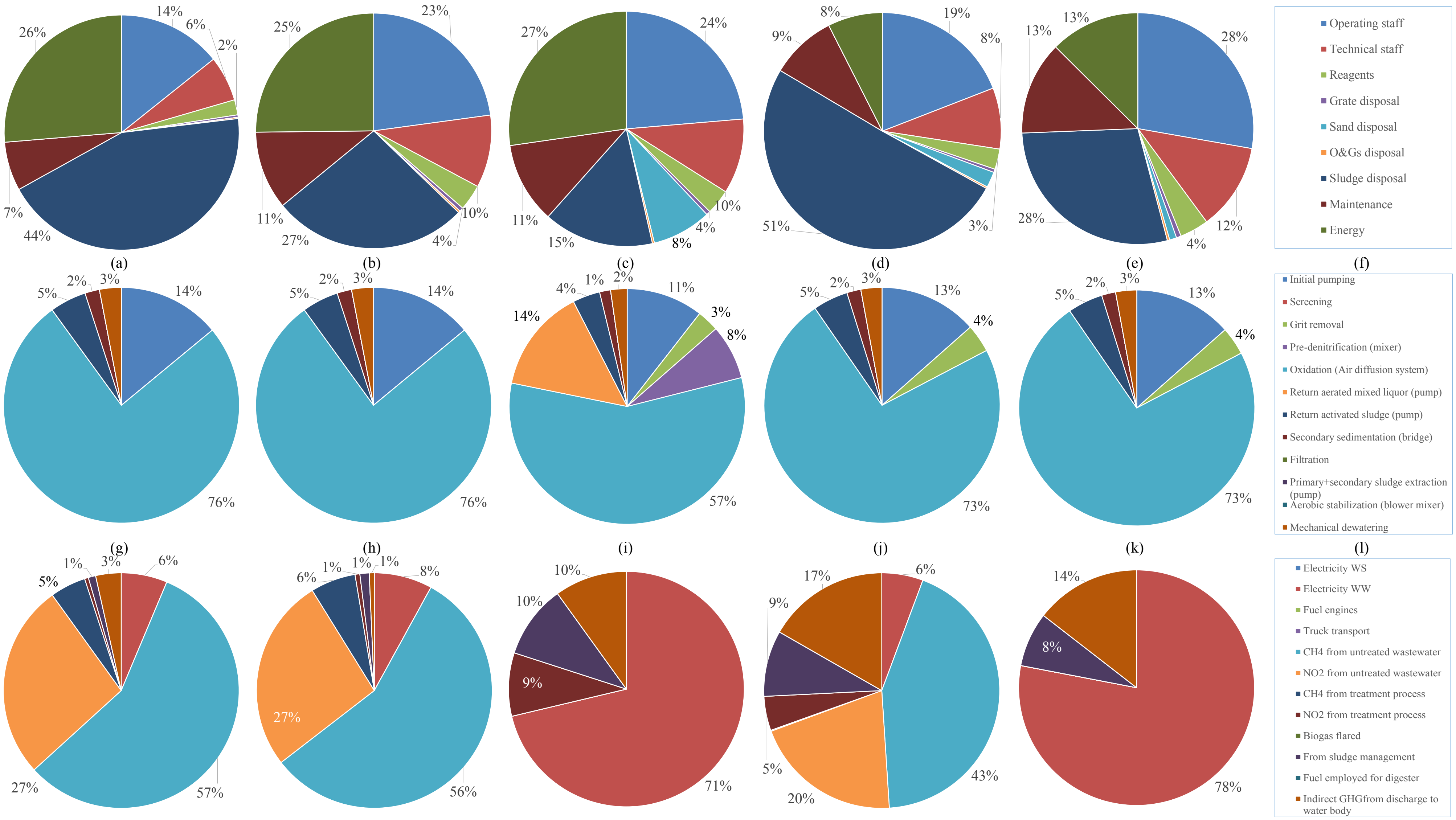
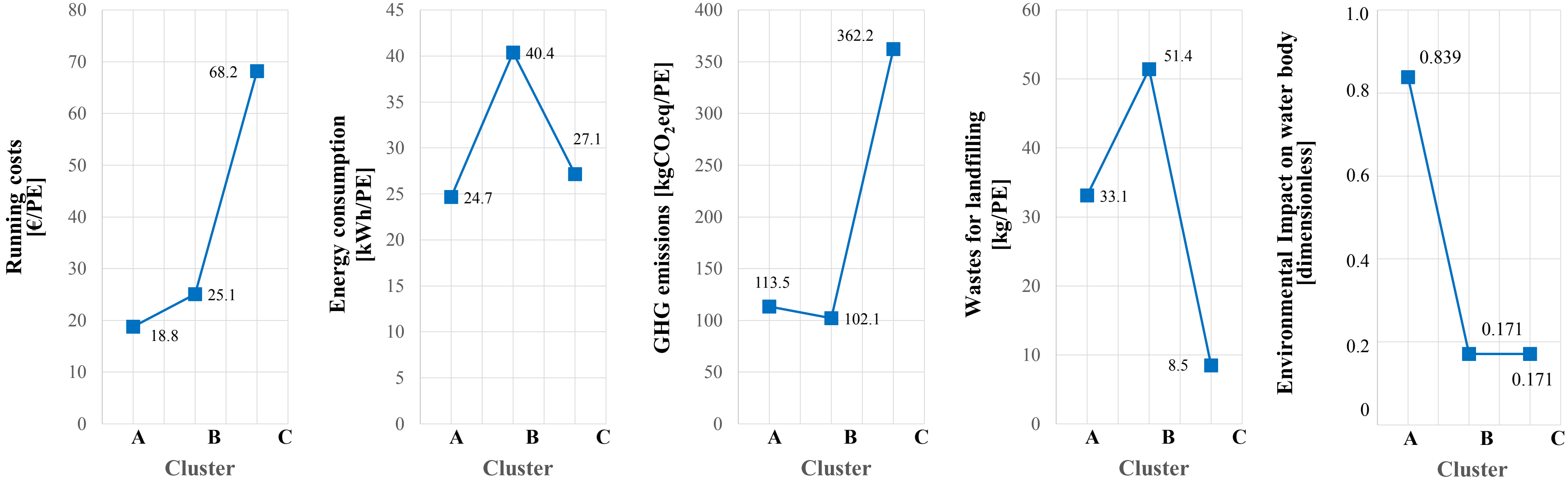


Figure 2. (a-f) Costs; (g-l) Energy consumption per Unit of Process (UoP); (m-r) GHG emissions. In the figure, (a, g, m) = Napoli Nord WWTP; (b-h-n) = Acerra WWTP; (c-i-o) = Area Nolana WWTP; (d-j-p) = Foce Regi Lagni WWTP; (e-k-q) = Area Casertana WWTP.



(a) (b) (c) (d) (e)

Figure 3. (a) Running costs, (b) energy consumption, (c) GHG emissions, (d) wastes for landfilling and (e) environmental impact on the water body for the clusters under investigation. Cluster A = Scenario composed by the 5 WWTPs that implement the current technologies (*status quo*); Cluster B = Scenario subject to structural and technological upgrading with sludge management by anaerobic digestion; Cluster C = As in the case of the scenario B, but with a sludge-fired centralized thermal plant, which treats the dewatered sludge of all 5 WWTPs.

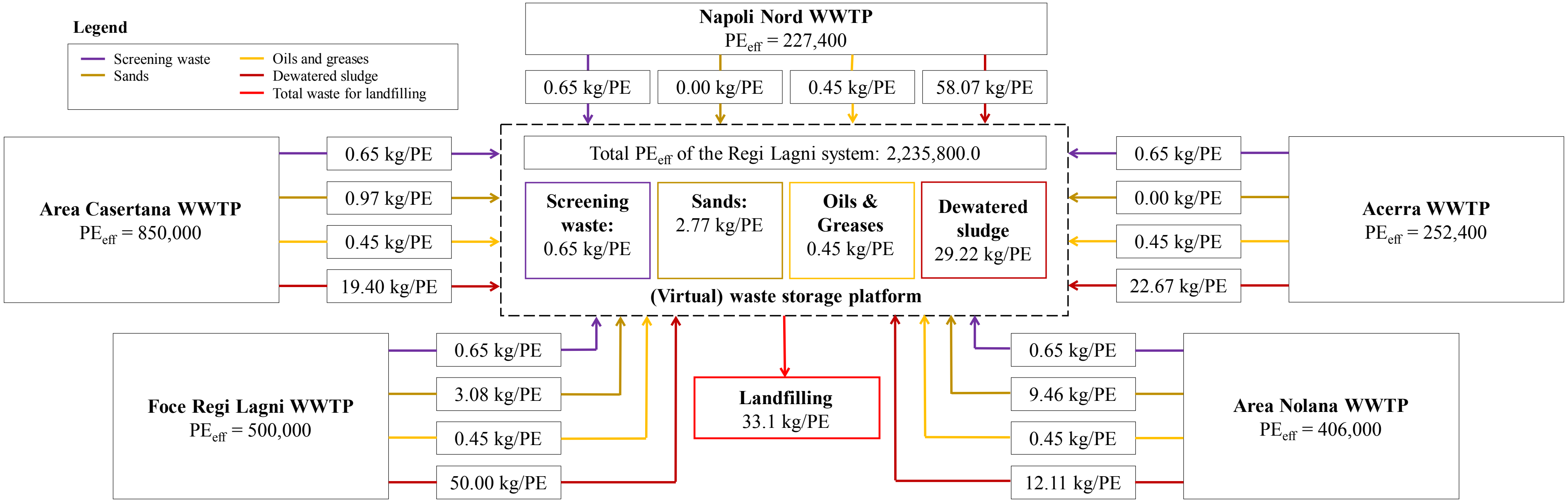


Figure 4. Mass balance of waste generated by each WWTP and by the Regi Lagni system as a whole in the current configuration (Cluster A).

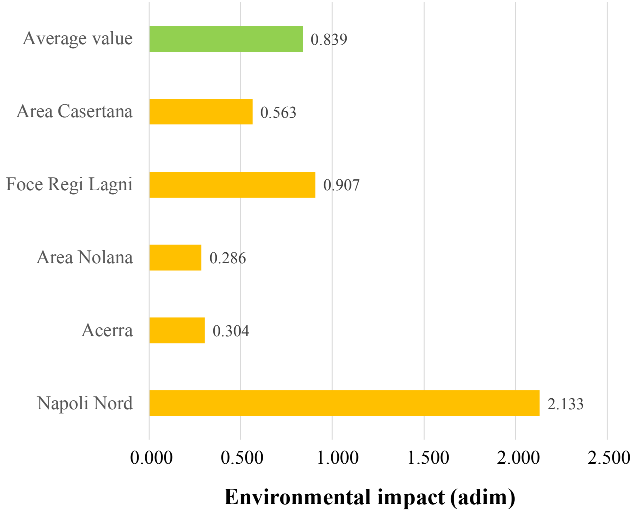
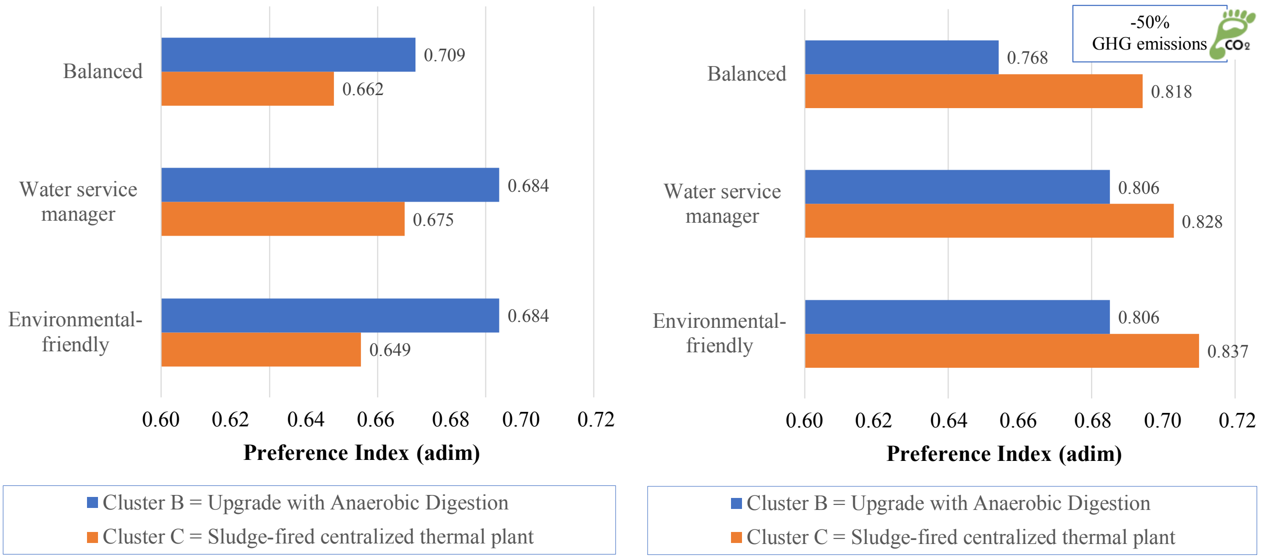


Figure 5. Impact on the receiving water body of the 5 WWTPs and of the cluster.



(a) (b)

Figure 6. Preference Index score for the identification of the best management scenario (cluster) varying decision-makers: Considering (a) the GHG emissions estimated with ECAM 2.0, (b) a further reduction in GHG emissions of 50%.

Table 1. The "Regi Lagni" system wastewater treatment plants (re-elaborated Pica *et al.*, 2016).

Parameter	**Unit**	**WWTPs**				
		Napoli Nord	**Acerra**	**Area Nolana**	**Foce Regi Lagni**	**Area Casertana**
PE_{des}(a)	-	886,000	828,000	311,000	632,000	800,000
PE_{eff}(b)	-	227,400	252,400	406,000	500,000	850,000
PE_{eff}/PE_{des}(c)	%	25.7	30.5	130.5	79.1	106.3
Average flow rate(d)	m^3/d	64,602.7	48,986.3	84,164.4	105,369.8	150,575.3
BOD_5	g/m^3	211.2	309.1	289.4	284.7	338.7
TSS	g/m^3	458	175	204	117	184
Total Nitrogen	g/m^3	45.7	82.4	67.5	75.9	73.4
BOD_5/NH_4-N	adim	4.62	3.75	4.28	3.75	4.61
Propensity to removal nitrogen(e)	-	medium	poor	medium	poor	medium

(a): PE_{des} = population equivalent related to the project configuration; (b): PE_{eff} = population equivalent effectively served by the WWTP; where PE = corresponds to a five-day biodegradable organic load of 60 g BOD_5/d; (c): Plant load percentage; (d): Flow rates were measured; (e): The ratio expresses the capacity to remove nitrogen by means of a biological process (i.e., activated sludge, as in our case). According to De Feo *et al.* (2012), based on the value of the BOD_5/N-NH_4 ration, the following classes can be used: < 4 (poor), 4-6 (medium), 6-8 (good), > 8 (excellent).

Table 2. Treatment schemes and status of the unit of process (UoP) (re-elaborated Pica *et al.*, 2016).

Unit of process	**WWTPs**[(a)]				
	Napoli Nord	**Acerra**	**Area Nolana**	**Foce Regi Lagni**	**Area Casertana**
Water line					
Initial pumping	(yes; 😐)	(yes; 😐)	(yes; ☺)	(yes; 😐)	(yes; ☺)
Screening	(yes; ☺)	(yes; ☺)	(yes; ☺)	(yes; 😐)	(yes; ☺)
Sand removal	(yes; ☹)	(yes; ☹)	(yes; ☺)	(yes; 😐)	(yes; ☺)
Oils removal	(yes; ☹	(yes; ☺)	(yes; ☺)	(yes; 😐	(yes; ☹)
Primary sedimentation	(yes; ☺)	(yes; ☺)	(yes; ☺)	(yes; ☺)	(yes; ☺)
Pre-denitrification	(no)	(no)	(yes; ☺)	(no)	(no)
Oxidation	(yes; 😐)	(yes; 😐)	(yes; ☺)	(yes; 😐)	(yes; ☺)
Secondary sedimentation	(yes; 😐)	(yes; ☺)	(yes; ☺)	(yes; ☺)	(yes; ☺)
Filtration	(no)	(no)	(yes; ☺)	(no)	(no)
Disinfection	(yes; ☺)	(yes; ☺)	(yes; ☺)	(yes; ☺)	(yes; ☺)
Sludge line					
Pre-thickening	(yes; 😐)	(yes; ☺)	(yes; ☹)	(yes; ☺)	(yes; ☺)
Aerobic stabilization	(no)	(no)	(no)	(no)	(no)
Anaerobic Digestion (AD)	(yes; ☹)	(yes; ☹)	(yes; ☹)	(yes; ☹)	(yes; ☺)
Post-thickening	(yes; ☹)	(no)	(yes; ☺)	(no)	(yes; ☺)
Sludge chemical conditioning	(yes; ☺)	(yes; ☺)	(yes; ☺)	(yes; ☺)	(yes; ☺)
Mechanical dewatering	(yes; 😐)	(yes; 😐)	(yes; ☺)	(yes; 😐)	(yes; ☺)
Thermal drying/incineration	(no)	(no)	(no)	(no)	(yes; ☹)
Engine energy production from biogas	(yes; ☹)	(yes; ☹)	(yes; ☹)	(yes; ☹)	(yes; 😐)

[(a)]: In the round brackets: yes = the unit of process is available, no = otherwise; UoP status: ☺ = works well; 😐 = not well managed; ☹ = does not work.

Table 3. Input data availability for the evaluation of the current cluster.

Input data	**Unit**	**WWTPs[(a,b)]**				
		Napoli Nord	**Acerra**	**Area Nolana**	**Foce Regi Lagni**	**Area Casertana**
Electricity consumption	kWh/m^3	(yes; 0.56)	(no)	(yes; 0.48)	(yes; 0.16)	(yes; 0.22)
Dewatered sludge production	kg/m^3	(yes; 0.56)	(yes; 0.32)	(yes; 0.16)	(no)	(yes; 0.30)
Sand production	kg/m^3	(yes; ~0)	(yes; ~0)	(yes; 0.125)	(yes; 0.04)	(yes; 0.015)
Biogas production	m^3/d	(yes; ~0)	(yes; ~0)	(yes; ~0)	(yes; ~0)	(yes; 838.7)
Persons employed	Person	(yes; 68)	(yes; 47)	(yes; 48)	(yes; 69)	(yes; 84)
Running costs	€/m^3	(no)	(no)	(no)	(no)	(no)

(a): In the round brackets: yes = yes, the data is provided by the WWTP operator; no = otherwise, the data was estimated; (b): The number in brackets is the value of the data provided by the WWTP operator.

Table 4. Scenario analysis of upgrading project actions.

N.	Scenario/Cluster	Concerned WWTPs	Characteristics of the interventions	
			Water line	**Sludge line**
A	Current configuration. Anaerobic digestion not working.	-	-	-
B	Upgrading based on Anaerobic Digestion.	Acerra, Foce Regi Lagni, Napoli Nord, Area Nolana.	Recovering of all UoPs; Pre-denitrification; Oxidation/nitrification well managed.	Recovering of all UoPs; Anaerobic digestion well managed; Mechanical dewatering well managed; Energy recovery from biogas.
C	As in the case of the previous scenario, but with a thermal treatment plant.	Acerra, Foce Regi Lagni, Napoli Nord, Area Nolana, Area Casertana.	As in the previous scenario.	As in the previous scenario; Realization of a centralized waste-to-energy plant for the incineration of sledges produced by the Regi Lagni system WWTPs.

Table 5. Main pollutants removal efficiency and comparison with the Italian legal limits (re-elaborated Pica *et al.*, 2016) (a).

Parameter	**Unit**	**LVs(b)**	**WWTPs(c)**				
			Napoli Nord	**Acerra**	**Area Nolana**	**Foce Regi Lagni**	**Area Casertana**
BOD_5	g/m^3	25	(33.8; ☹)	(34.0; ☹)	(20.2; ☺)	(45.6; ☹)	(50.8; ☹)
TSS	g/m^3	35	(87.0; ☹)	(21.0; ☺)	(24.5; ☺)	(32.7; ☺)	(40.4; ☹)
TN(d)	g/m^3	15	(38.4)	(15.6)	(13.5)	(60.7)	(38.2)
$\%BOD_5$	%	≥80	(84.0; ☺)	(89.0; ☺)	(93.0; ☺)	(84.0; ☺)	(85.0; ☺)
% TSS	%	≥90	(81.0; ☹)	(88.0; ☺)	(88.0; ☹)	(72.0; ☹)	(78.0; ☹)
%TN(d)	%	70-80	(16.0)	(81.0)	(80.0)	(20.0)	(47.9)

(a): Average values considering the year of observation; (b): Limits refer to plants with capacity > 100,000 PE; (c): In the round brackets: the value: ☺ = compliance with the discharge limit value of the D.Lgs 152/2006; ☹ = not in compliance; (d): the WWTPs under investigation discharge into a non-sensitive area; therefore, they are not subject to the nitrogen limit value.

Table 6. Running costs, energy consumption, GHG emissions and waste produced by each WWTP of the Regi Lagni WWTPs system on annual basis.

N.	**WWTP**	**PE$_{eff}$(a)**	**Running costs**		**Energy consumption**		**GHG emissions**		**Wastes for landfilling(b)**	
			[€]	**[€/PE]**	**[kWh]**	**[kWh/PE]**	**[t$_{CO2eq}$]**	**[kg$_{CO2eq}$/PE]**	**[t]**	**[kg/PE]**
1	Napoli Nord	227,400	6,622,869.9	29.1	13,204,800.0	58.1	29,358.0	129.1	13,454.9	59.0
2	Acerra	252,400	4,641,822.1	18.4	8,940,000.0	35.4	32,585.0	129.1	5,999.2	24.0
3	Area Nolana	406,000	7,136,448.2	17.6	14,745,600.0	36.3	39,901.0	98.3	9,201.8	23.0
4	Foce Regi Lagni	500,000	10,887,889.3	21.8	6,153,600.0	12.3	64,550.0	129.1	27,088.4	54.0
5	Area Casertana	850,000	12,730,086.8	15.0	12,091,200.0(c)	14.2	87,455.0	102.9	18,247.4	21.0

(a): Population equivalent that effectively loads the plant; (b): Wastes (solid and liquid) produced in the plant and destined for landfilling; (c): It refers to the net value as the difference between the energy needs of the plant and the energy produced in the plant through the anaerobic digestion of sludge.