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Life cycle energy and GHG emission within the Turin metropolitan area urban water cycle

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Abstract

The aim of this study is to analyze the urban water cycle in the Turin Metropolitan Area (Northwestern Italy), with a focus on quantifying the annual life cycle energy consumption and greenhouse gas emissions. The study made use Material Flow Analysis and Life Cycle Assessment methods for a defined urban water cycle system (ATO3) operated by one water utility (SMAT S.p.A.), and examines all main sub-systems of the entire urban water cycle. The study quantified the annual direct and indirect energy consumption and the direct and indirect greenhouse gas emissions related to system-wide energy consumption and the production and transportation of chemicals used in water treatment and wastewater treatment plants. It is found that the wastewater treatment consumes the biggest share of the total energy (44%), but a significant part of this energy demand is provided by the energy in biogas produced from wastewater sludge. On the basis of this study it was possible to provide strategic recommendations to the water utility on how to improve the water/energy/carbon nexus and contribute better to sustainability performance of urban water cycle systems.

Peer-review under responsibility of the Organizing Committee of WDSA 2014.

Keywords: Urban water and wastewater, life cycle assessment, energy consumption, greenhouse gas emission

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1. Introduction

The urban water is one important sector in the anthroposphere and shows growing interest for how to optimize the so-called water/energy/carbon nexus. The urban water cycle (UWC) has to be studied in its entirety – from the upstream raw water extraction to the downstream discharge of treated wastewater – to get the needed understanding of its system-wide contribution to energy efficiency and climate change. The method applied to perform this study are Material Flow Analysis (MFA) and environmental Life Cycle Assessment (LCA).

2. Literature review

Studies encompassing the entire urban water cycle are few. One of the first was published in 2004 (Lundie et al., 2004). It illustrated as a case study, the urban water system in the east Australian city of Sydney, evaluating the contemporary situation vis-à-vis alternative future scenarios. The authors underlined the importance of the cradle-to-grave approach as a useful tool for the assessment of financial, social and local environmental issues in planning the future. In an Oslo case study [1], the energy consumption and the environmental impacts were evaluated for each of the components of the UWC (WTP, water pumping, water pipelines, sewage pumping, wastewater pipelines and WWTPs). The research analysed the system for a seven year time period - 2000 to 2006. The annual average energy consumption was equal to 240.7 kWh per capita, where the WWTPs contributed to the major part of the environmental impacts. Another study has focused on Alexandria, Egypt [2]. In this system, the highest environmental impact is generated by the disposal of primary treated wastewater (68% of the total), followed by WTPs which are big energy consumers (18% of the total). In the case of Tarragona, Spain [3], a LCA analysis outlined that the main environmental impact of the UWC was due to the distribution network (35.2%) because of the city's topography and the distance from abstraction sites to consumers. The above literature review demonstrates that the MFA and /or LCA approach offer excellent opportunities for a quantitative study of the water/energy/carbon nexus of urban water cycles. Literature shows that there may be large differences from city to city in terms of the relative importance (regarding energy or GHG emissions) of each sub-system of the UWC. Such differences may be due to the presence of extensive pumping in the distribution network, different water or wastewater treatment solutions, and most important, different sewage sludge energy recovery solutions

3. Methodology

3.1. Case study presentation

Italian law 36/1994 assigned to local authorities in Italy (referred to in short as ATOs and specifically established within aggregated municipalities and provinces) the task of reorganizing the water treatment, distribution, wastewater transport and treatment services into a single Integrated Water Service (IWS). ATO3 represents the largest metropolitan area of the river Po basin and covers approximately 6,713 km^2 (Figure 1). ATO3 encompasses 306 municipalities grouped in 13 Mountain Communities and 13 Homogeneous Territorial Areas in the province of Turin, and caters to the needs of 2.4 million people [4].The only company in charge of the integrated water service in ATO3 is SMAT S.p.A.

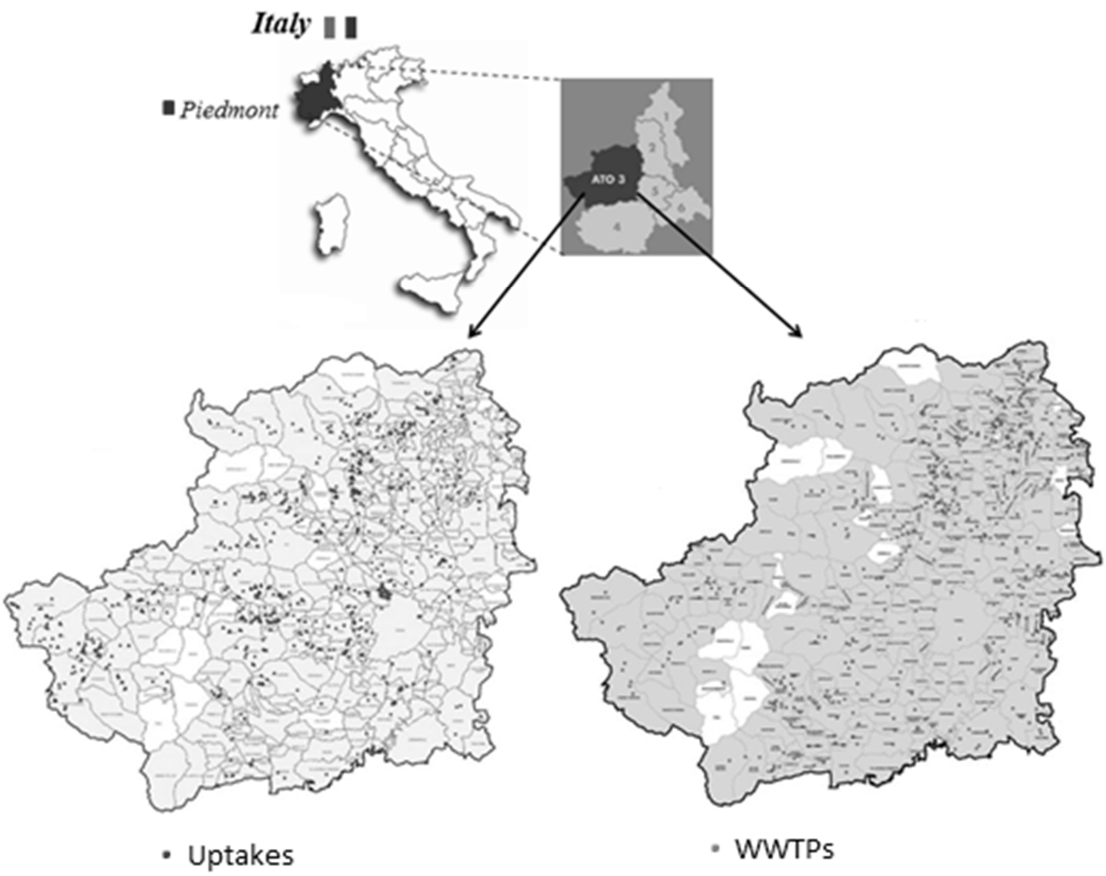

Fig. 1. Local framework of ATO3.

3.1.1. Raw water sources

Approximately 238 Mm^3/y of raw water is groundwater, with 1,550 points of uptake (see Figure 1), (70.8% of the total groundwater withdrawn from wells located mainly in plain areas correspond to around 168 Mm^3/y).

Table 1. Main features of the Integrated Water System (IWS) managed by SMAT SpA [5].

Indicator	Value
Municipalities served by WTPs	283
Number of WTPs	59
Population served	2,196,012
Distribution network [km]	11,843
Raw water treated [m^3]	246,276,277
Water supplied [m^3]	199,102,961
Municipalities served by WWTPs	285
Number of WWTPs	412
Population served by the sewer system	2,215,040
Sewer network [km]	7,923
Wastewater treated [m^3]	349,812,082

The surface water (17.5% of the total, corresponding to a 42 Mm^3/y uptake from Po river) and spring water (11.7% of the total, located in a mountain area and concerning about 28 Mm^3/y) are the main sources for the production of drinking water. It should be noted that in the case of ATO3, the complexity of the system leads to different values of treated water and population served for the WTPs and WWTPs included in the boundaries of the system, as shown in Table 1 [5].

3.1.2. Water Treatment Plants (WTPs)

SMAT manages 59 WTPs (see Table 1), the most relevant WTPs which take raw water from the Po river are PO 1 and PO 2 with a total production capacity of 86,400 m^3/d to date, and PO with 130,000 m^3/d. These Po river WTPs account for 16% of the water produced and distributed by SMAT. Since 1994, a lagoon has been facilitating a further improvement in the quality of the drinking water.

3.1.3. Wastewater Treatment Plants (WWTPs)

There are 412 WWTPs managed by SMAT (see Figure1) but the main WWTP is located in Castiglione T.se and is the largest biological, physical and chemical treatment plant in Italy. It includes the water line composed of two similar sections of grid screens, primary sedimentation, pre-nitrification, biological treatment, phosphorous removal and filtration and the sludge line with the anaerobic digestion. In this line the cogeneration and permits the production of more than 25 GWh/y of electricity and more than 18 GWh/y of thermal energy annually [5].

3.2. Modelling the ATO3 case

The methodologies adopted in this work to evaluate the energy consumption and the emissions of each phase are Material Flow Analysis (MFA) and environmental Life Cycle Assessment (LCA). The scope of MFA is to obtain the water balance all along the complex structure of urban water cycle systems within ATO3 with its boundaries and inflows/outflows as shown in Figure 2. An MFA for ATO3, is defined by its geographical boundaries and the current water and wastewater system elements that serve about 90% of the population of the ATO 3, as specified in Table 1. Within this spatial boundary, there are several numerous of raw water and many WTPs characterized by different dimensions and adopting different technologies. From these plants, potable water is pumped into the distribution networks. Wastewater, collected by the sewer systems, is then sent to different WWTPs, again of varying capacities and using different technologies. It is difficult, from a practical point of view, to collect data on every single flow from source to sink, owing to the complex networks in ATO3. However, aggregated data about total energy consumption, chemicals usage, etc. in the whole of ATO3 is accessible thanks to SMAT's annual environmental sustainability reports [5]. The dotted line defines the boundary of the system, the blue arrows symbolize the water flows through the system.

LCA permits the evaluation of the potential environmental impacts of a given UWC system, considering the entire life cycle of the services provided by the water utility, from raw material extraction to the end-of-life treatment and final disposal. By combining MFA and LCA, it is possible to estimate the environmental impacts caused by energy consumption and raw materials (e.g. the chemicals used in WTPs and WWTPs).

This study investigates the annual aggregated energy consumption and GHG emissions of all UWCs across the ATO3 for year 2012. Regarding the energy consumption, it was evaluated the direct energy consumption within the system – for treatment, pumping and heating - and the indirect energy consumption for the production and transportation of chemicals. Data for direct energy consumption have been obtained from a SMAT sustainability report [5], while data for the indirect consumption have been evaluated by multiplying the masses of chemicals used in the ATO3 WTPs and WWTPs (obtained from the said report) by the corresponding specific electricity-use factors (obtained from the Ecoinvent database [6]).

To express the emissions in terms of CO2-equivalents, this study made use of the guidelines of the International Greenhouse Gas Protocol [7]; which discriminates between three scopes of emissions:

- Scope 1: Direct GHG emissions owing to direct energy consumption from sources that are owned or controlled by the entity (e.g. fossil fuel used on site);
- Scope 2: Indirect GHG emissions owing to the consumption of electricity generated off site but purchased by the entity (e.g. electricity purchased from the national grid). The main factor influencing such emissions is the national

electricity mix made by 51.5% natural gas, 26.4% renewable sources, 16.9% coal, 2.2% oil, 1.3% nuclear and 1.7 % other sources [8]. The GHG emission factor for the Italian electricity mix is 0.4 kg CO_2/kWh [7].

Emissions due to biogas combustion (assumed to be complete and resulting only in the emission of biogenic carbon dioxide) have not been accounted for the GHG emissions.

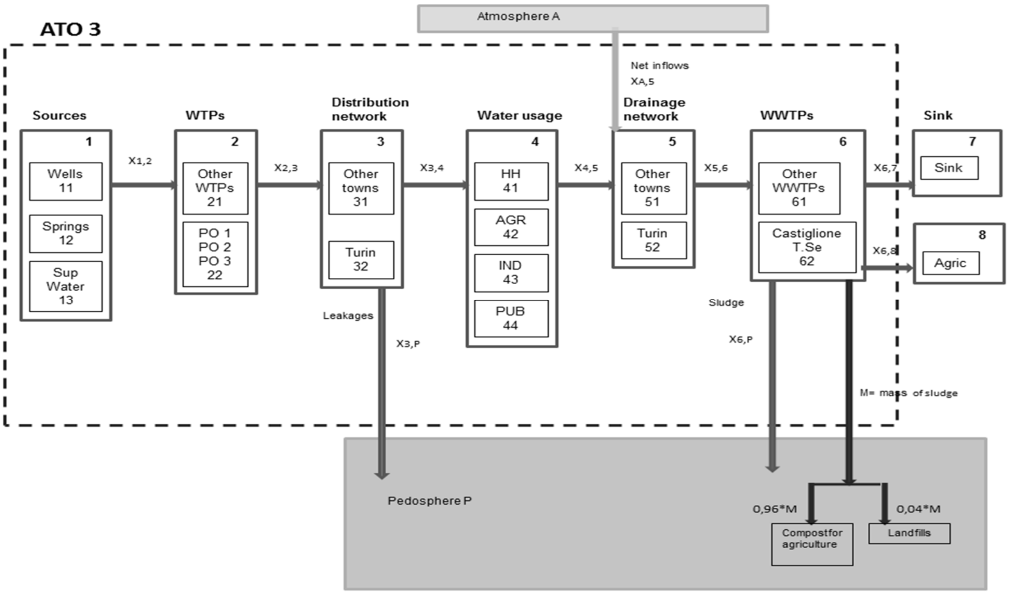

Fig. 2. ATO3 Urban Water Cycle.

4. Results

4.1. Direct and indirect energy consumption

The total energy consumption, including the electricity purchased from the grid the thermal energy and the energy from the fossil fuels, for year-2012 [5] is equal to 331,866MWh/y. In order to present the results of this study and to facilitate the comparison among different systems at any time, per capita and per cubic meter of water indicators were chosen by considering the specific population and the flow rate of each phase. The contribution for each subsystem is reported in Table 2, these values cannot be compared directly, but could be useful for a comparison with analogous indicators of the respective phase of other areas. As reported in Figure 3 (A), the *wastewater treatment* sub-system accounts for the highest share of the total energy consumption.

For the energy balance two important positives were accounted: for the sub-system *Raw water extraction*, the production of 7 GWh/y of electricity in Balme hydroelectric plant, sold to external users and, for the sub-system *Wastewater treatment*, the production of 36,5 GWh/y of electricity in the main WWTP in Castiglione T.se. This electricity is produced from the combustion in CHP (Combined heat and Power) engines of biogas, produced during the anaerobic digestion of the sludge (25,07 GWh/y), and methane (10,25 GWh/y) and is used within the plant. Another minor contribution is given by 1,2 GWh/y of electricity auto-produced by the photovoltaic system installed in the WWTP in Castiglione T.se. Such values were subtracted to the respective amount of total energy consumption in order to obtain the net energy consumption that represent the energy purchased from the national grid and is equal to 4,037 MWh/y for the *Raw water extraction* and 58,865 MWh/y for the *Wastewater treatment*.

The overall net energy consumption of the Turin metropolitan area is equal to 230,695 MWh for the year 2012. The contributions to the net energy consumption are reported in Figure 3 (B), The major part of the energy was consumed in the distribution. Possibly this is due to the fact that in ATO3 there are several municipalities (as the Mountain communities) at altitudes higher than the level of the WTPs.

Table 2. Direct energy consumption of Turin metropolitan area UWC [5].

Sub-system	MWh/y	Population served	Cubic metres treated	kWh/cap y	kWh/m^3
Raw water extraction	11,997	2,196,012	264,276,277	5.46	0.05
Water treatment	69,757	2,196,012	264,276,277	31.77	0.26
Distribution	98,754	2,196,012	199,102,961	44.97	0.50
Wastewater transport	7,158	2,215,040	349,812,082	3.23	0.02
Wastewater treatment	147,569	2,215,040	349,812,082	66.62	0.42

The indicator in term of energy per unit of length is useful in account of the cost for the water distribution: it must be considered that the drinking water is transferred by a pressure system while the sewage is collected by gravity. For the distribution network, the value was equal to 8.3 kWh/m, while for the sewage network, it was 0.9 kWh/m.
The consumption of thermal energy has been evaluated for the *Water treatment* phase as the heat to warm the locals and the laboratory of the main WTPs on the Po river, equal to 4,9 GWh/y from the local district heating of Turin. In the phase *Wastewater treatment* the amount of thermal energy used is 51,197 MWh/y of which 18,780 MWh/y are produced from the combustion of biogas.
The datum concerning the energy necessary for the auto traction is aggregated for the overall system, hence the total value (1440 MWh/y) has been divided by five and for each phase resulted to be 288 MWh/y.

The total indirect energy consumption owing to the production and transport of chemicals to the WTPs and WWTPs, have been estimated and listed in Table 3 with the respective indicators.

The contributions due to the production of each chemical are reported in Figure 3 (C, D). Polyaluminium chloride accounts for the largest portion of the indirect energy consumption as far as water treatment is concerned, while ferric chloride as far as wastewater treatment is concerned.

Table 3. Indirect energy consumption of Turin metropolitan area UWC.

MWh/y (% of total)				kWh/cap/y	kWh/m^3
Sub-system	Energy for chemicals production	Energy for chemicals transportation	Sum indirect energy for chemicals	Sum indirect energy for chemicals	Sum indirect energy for chemicals
Water treatment	9,503 (44.8)	164 (26.3)	9,667 (44.2)	4.40	0.04
Wastewater treatment	11,720 (55.2)	460 (73.7)	12,180 (55.8)	5.50	0.03
Total	21,223 (100)	624 (100)	21,847 (100)	-	-

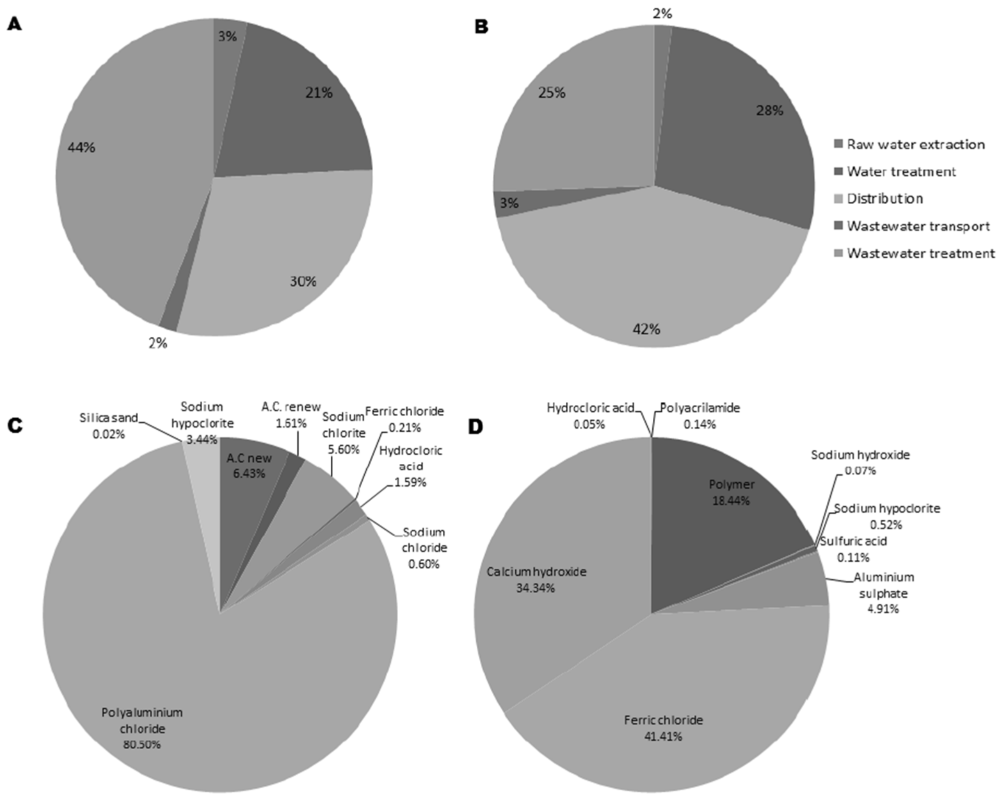

Fig. 3. Contribution to total energy consumption (electricity + heat + fossil fuel) (A), net electricity consumption (B), energy consumption for chemicals production WTPs (C), energy consumption for chemicals production WWTPs (D).

4.2. GHG emissions

In Scope 1, all direct GHG emissions from fossil fuels used for transportation to operate the plants and the emissions due to the combustion in boilers for the internal heating, were considered. However, due to lack of sufficiently detailed empirical data, it was only possible to collect aggregated information for the total consumption of fossil fuels for the auto traction (gasoline, LPG). This total amount of fossil fuel consumption was as a simplified approximation equally divided among each of the 5 sub-systems of UWCs (assuming in lack of better alternatives that each sub-system of the UWC consumes almost the same quantity of fossil fuel) and the resulting emissions are around 287 ton CO_2-eq .

The emissions related to the thermal energy consumed in the WTPs (4.9 GWh/y) produced from methane, have been calculated by a stoichiometric balance considering the complete combustion of methane and are equal to 242 ton CO_2-eq, whereas the emission generated from the combustion of methane in the *Wastewater treatment phase* is equal to 9,913 ton CO_2-eq. Scope 2 includes emissions from the direct consumption of electricity from the grid. In the sub-system *Raw water extraction*, owing to the energy generation at the Balme hydroelectric plant, around 2,800 ton CO_2-eq of emissions were avoided. In the sub-system *Wastewater treatment,* the GHG emissions from biogas combustion are biogenic and not included in this analysis.

The emissions generated for the production of the chemicals used in WTP are 6,252 tons CO_2-eq and in WWTPs are 7,461 tons CO_2-eq.

Figure 4 presents the percentage of GHG emissions generated by each chemical used in WTP and WWTPs: polyaluminium chloride contributes to the biggest share of emissions for the WTPs and ferric chloride for WWTPs.

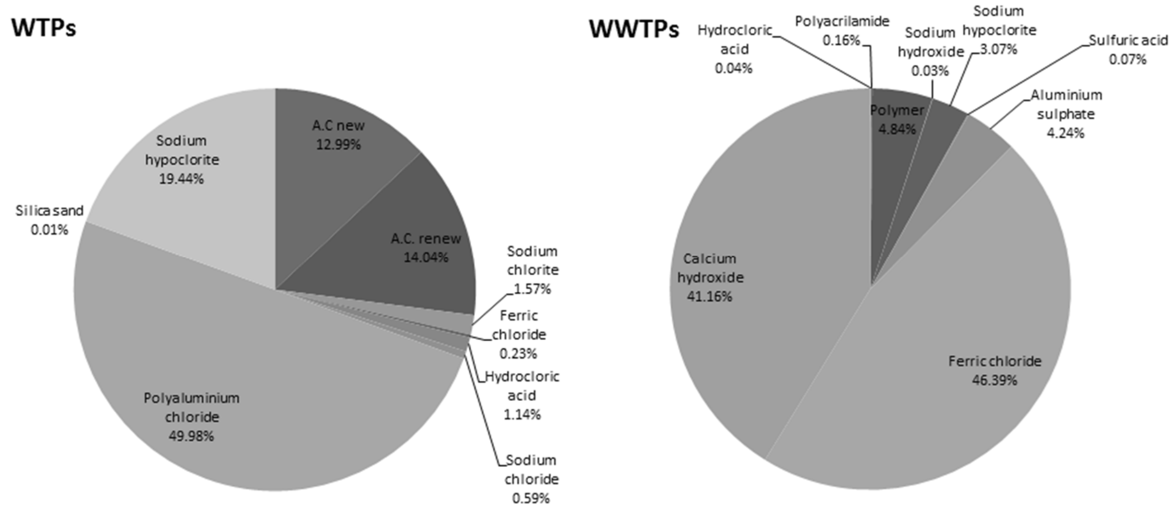

Fig. 4. Annual GHG emissions from production of chemicals consumed in Turin Metropolitan Area UWC, year 2012.

The calculation of the emissions related to the transport of chemicals, required the identification of each supplier assuming truck transportation and a hypothetical consumption of 1 litre fuel for every 3 km, the GHG emissions can be calculated. The emissions calculated for chemicals transportation were approximately 144 tons of CO_2-eq and 431 tons of CO_2-eq for the WTPs and WWTPs respectively, refer Figure 5 for a summary of the emissions. As far as the emissions due to the electricity purchased from the grid, water distribution dominates with 42% of the total, the second phase is *Water treatment* with 28 % and *Wastewater treatment* came third with the 25%.

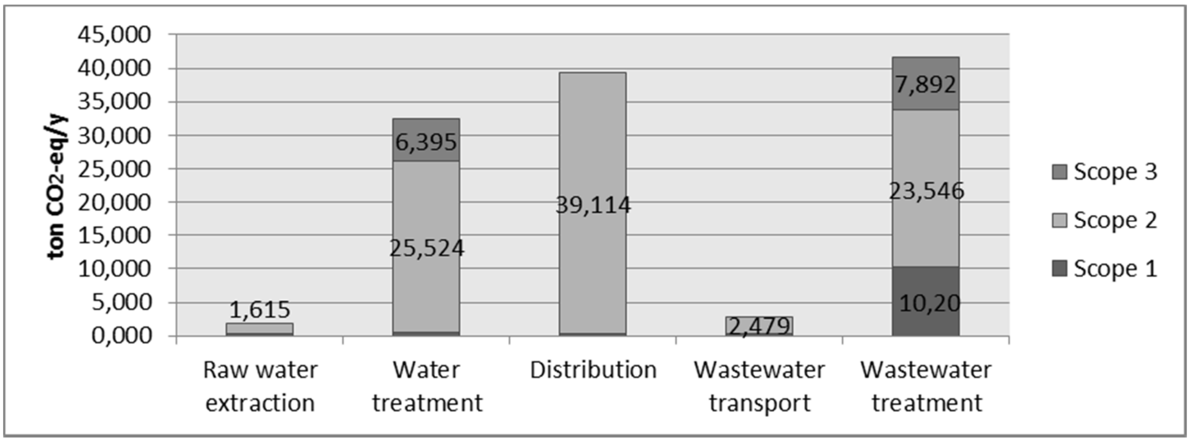

Fig. 4. Total annual GHG emissions of Turin Metropolitan Area UWC (year 2012).

5. Concluson

By applying an LCA approach, it was possible to analyze the entire urban water cycle in the Turin metropolitan area to obtain an overview of the associated energy consumption and the corresponding GHG emissions considering every sub-system in the urban water cycle. This approach enables the analyst to rank the parts/components/sub-systems in terms of energy consumption and GHG emissions, and based on this information, to develop strategies for the improvement of UWC energy consumption and sustainability.

In the case of this study, the main data source was a Sustainability Report compiled by SMAT S.p.A. (SMAT, 2012), which contains data for water and wastewater treatment that are aggregated within all parts of ATO3. This was an obstacle to performing a more in-depth analysis for each sub-system; however, even though detailed data were not available, the study has provided informative results. As far as direct energy consumption is concerned, *Wastewater Treatment* was responsible for the highest share but, thanks to the biogas produced in the main WWTP, it was possible to internally satisfy about the 40% of its energy requirements. Another important sub-system in term of energy use of energy was the *Distribution* of drinking water (42% by considering the electricity purchased from the grid), because of the relevant extent of the network, more than 11,000 km and probably of the peculiar geographical features of ATO3. An important factor that also influenced the overall extent of the emissions was the emission factor of the Italian electricity mix - 0.4 kg CO_2/kWh [5]. As a consequence of the aim of enhanced sustainability of the studied UWC , the annual direct and indirect energy consumption and GHG emissions should be systematically reduced. To fulfill this goal the following strategies would be important:

- First, biogas production should be increased (enhanced valorization of the produced biogas with pre-treatment and cogeneration system, and utilization of existing digester to treat also other suitable organic substrates);
- Second, chemicals consumption, particularly in WTPs, should be decreased if possible (or optimized with respect to raw water and produced water quality), and less environmentally impacting chemicals should be searched for;
- Finally, an enhancement of distribution network efficiency and water leakage reductions should be considered, aiming for a point of minimum leakage that is also economically attractive.

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