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Analysis of the Water–Energy Nexus of Treated Wastewater Reuse at a Municipal Scale

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Abstract: Treated wastewater has the potential to be a feasible alternative to supply non-potable uses and avoid water scarcity in urban areas, but it is important to understand and compare the associated energy consumption and CO_2 emissions. This study presents a comparative analysis of the water–energy nexus associated with the traditional water supply and to the alternative reuse of treated wastewater, both for non-potable purposes. A case study of a Portuguese municipality was considered, regarding golf course irrigation and municipal gardens irrigation. A balance between production and demand was established, and the energy consumption and CO_2 emissions were calculated considering the supply with drinking water and with treated wastewater. Three scenarios were defined to analyze the water–energy nexus for different configurations of the potential end-uses: (1) golf course supply, (2) municipal irrigation supply and (3) simultaneous supply to the golf course and to municipal irrigation. A quality analysis was also carried out by comparing the records from discharged wastewater quality parameters with the limits presented in the legislation for each proposed non-potable use. The results show that all scenarios present significant annual savings from using treated wastewater instead of drinking water from the public network, especially scenarios 1 and 3, that consider the golf course irrigation (water costs decrease by about 60,000.00 EUR/year). Regarding the water–energy nexus, this study reveals that treated wastewater spends less energy on its production and supply and produces fewer CO_2 emissions. The energy savings can reach an average value of about kWh/year, with 5300 fewer kg of CO_2 emitted in the best scenario.

Keywords: treated wastewater reuse; water–energy nexus; urban non-potable supply

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1. Introduction

According to the European Environmental Agency [1], about 80% of Europe's freshwater use (drinking and other uses) comes from rivers and groundwater, which makes these sources extremely vulnerable to threats stood by over-exploitation, pollution and climate change. For the Mediterranean region, climate change projections anticipate more extreme heat events and less water [1]. To improve the resilience of the cities and prepare them to this new climate reality, it is essential to provide alternative water sources, such as wastewater reuse.

So far, only about 1 billion cubic meters of treated urban wastewater in Europe is reused annually, which corresponds to approximately 2.4% of the treated urban wastewater effluent, or less than 0.5% of annual EU freshwater withdrawals [1].

At a global scale, wastewater reuse has expanded through agriculture and garden irrigation, also reaching potable consumption through direct and indirect reuse. Treated wastewater is now a source for multiple purpose, bringing about many environmental and economic advantages, representing a cost-competitive alternative to other non-conventional sources such as seawater desalination [2]. When the reuse systems are correctly designed and operated, the development of the plants can be enhanced by the high content of nutrients in the reused water, improving productivity and allowing the replacement of chemical fertigation with the supply of nutrients contained in the irrigation water [3,4]. Rezapour et al. [5] revealed that irrigation with treated wastewater resulted in a significant increase in soil nutritional-chemical attributes, suggesting an increase in productivity. Wastewater reuse benefits not only farmers, due to the additional nutrients and regularity in their water supply, but also wastewater treatment plants (WWTP) managers who can reuse the treated effluent in the system, contributing to the closure of the water cycle and avoiding pumping the treated water into rivers or the sea [6]. Once the benefits for plants are assured, there is a need to investigate more important aspects related to wastewater reuse, such as the safety of users and economic and energetic issues. As for the first one, there is the need to define and comply with an adequate legal framework and to investigate the field conditions. An epidemiological survey carried out by Busgang et al. [7] over a period of one year analyzed the risk for gastroenteritis symptoms associated with graywater reuse and concluded that there was practically no difference in the prevalence of water-related diseases between users of graywater and potable water. On the other hand, [8] studied the impact of the conveyance and storage steps on the physical-chemical and biological quality of wastewater and realized that water quality varies all along the water route, from the wastewater treatment plant up to the irrigation site of the study cases.

In Portugal, Cardoso [9] assessed the potential of wastewater reuse for the irrigation of an existing golf course. The quality analysis revealed that nitrogen was preventing the reuse of the treated wastewater to irrigate the golf course and an improvement of the biological treatment stage was proposed. In that assessment, a survey was also carried out and revealed that in general, the participants had a positive opinion about reusing treated wastewater. However, lack of legislation about the use of this alternative source of water was blocking its implementation until 2019, when a decree-law was published [10], establishing the legal framework for the production of water to reuse (WtR), obtained from wastewater treatment, and intending to promote its correct utilization and avoid harmful effects for human health and for the environment. Moreover, the European Union recently published a regulation (EU 2020/741 [11]) establishing the minimum requirements for water quality and monitoring and provisions on risk management for the safe use of reclaimed water in the context of integrated water management. Although very focused on agricultural irrigation, this European regulation allows member states to use reclaimed water for other purposes, including industrial, recreational and environmental uses.

Besides the reduction of wastewater discharged to the environment, the use of WtR has implications also in the corresponding energy consumptions that are associated with water pumping, treatment and distribution. In fact, there is an unquestionable connection between water and energy, which supports the need to consider an integrated approach of these two resources. Water is essential to energy production as energy is fundamental for urban, agricultural and industrial water supply and consumption. Energy and water fulfill reciprocal functions in which working on one of them relies on the status of the other in terms of cost and availability [12]. Matos et al. [13] presented a methodology to calculate the energy consumption and CO_2 emissions related with different types of reuses. Its application to a centralized and a decentralized greywater reuse system revealed that the first one needs a higher degree of treatment and spends more energy, leading to more CO_2 emissions to the environment. This interdependence—the water–energy nexus (Figure 1)—becomes more complex with economic growth, population increase, energetic crises and the impact of climate changes.

In this scope, this study intends to analyze the water–energy nexus associated with the use of treated wastewater in non-potable purposes, by comparing it to the traditional water supply (with drinking water). As explained above, this alternative source has the potential to be a feasible way to avoid water scarcity in urban areas, but it is important to understand the associated energy consumption and CO_2 emissions.

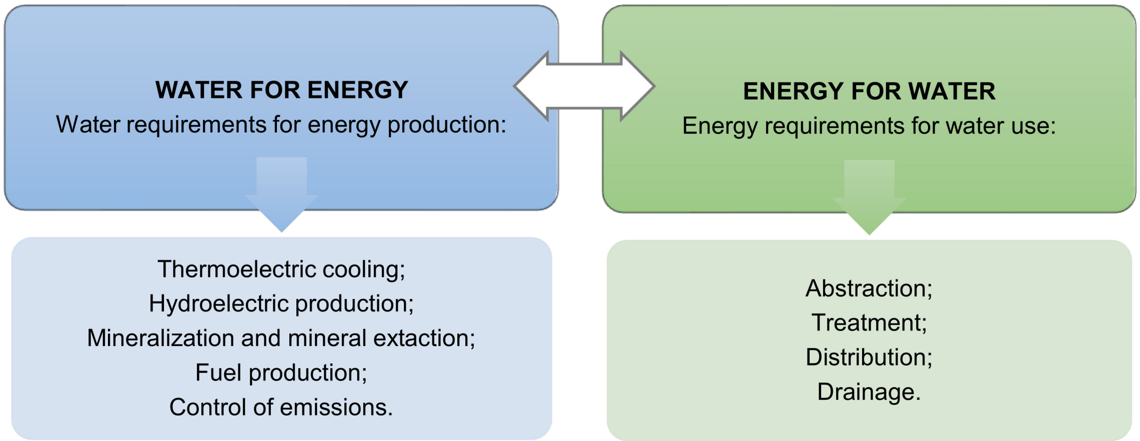

Figure 1. Water–energy nexus (adapted from APA [14]).

2. Methods

This work started with the calculation of the energy and CO_2 emissions associated with wastewater treatment and distribution, and also with drinking water treatment and distribution. The values obtained were then applied to a real case study in order to compare the differences between these two supply systems.

The values of energy and CO_2 emissions associated with wastewater treatment were determined with the methodology presented by Matos et al. [13], referenced in the previous section. Their work reveled a range of values of energy consumption, by stage, within a centralized wastewater treatment plant, part of which can be used to estimate the additional treatment needed to assure a safe reuse.

The energy associated with drinking water consumption is estimated with a different approach because the treatment processes are different. The most common source of drinking water, surface water, is extracted from rivers or lakes and may be turbid and contain impurities such as silt, algae, microorganisms, biological impurities and possibly larger ones such as plant materials, in addition to man-made organic or inorganic compounds (petrochemicals, pharmaceuticals, etc.). Surface water treatment stages typically include mechanical screens, sedimentation or flocculation tanks, rapid mixing tanks, filtration processes, and disinfection tanks. As an example, overall unit electricity consumption for US surface water treatment and supply is 0.079 kWh/m^3 [15]. This value is based on a unit electricity consumption of 0.073 kWh/m^3 for municipal surface water pumping with the balance expended for distribution pumping and primary treatment (e.g., softening, chlorination) of water prior to use. The *Building Energy Data Book* reports that 0.73 kWh/m^3 was consumed for pumping, treatment and distribution of water in Iowa, USA, whereas Massachusetts, USA, consumed only 0.4 kWh/m^3 [16].

Coagulation is necessary when the impurities are so small that settling velocities are negligible or when colloidal forces hold the particles in suspension. Coagulants are added to destabilize colloidal suspensions to promote agglomeration of particles. Common coagulants include aluminum sulfate and ferrous sulfate and coagulant aids based on synthetic polymers. Anionic or cationic polymers, as well as non-ionic polymers, are added as flocculation aids at amounts on the order of 0.1–1 mg/L [17]. Energy consumption associated with utilization of polymers for coagulation is reported to range from 0.4 to 0.7 kWh/m^3 [18].

Filtration is a polishing step that removes impurities remaining after the settling and coagulation stages. Some flocs are carried over to accomplish the removal of minute microbial impurities that would otherwise escape through the porous granular media filter [19]. Direct filtration is employed when the turbidity levels are below 20 NTU. The energy consumed by these gravity filters is found to be in the range of 0.005 to 0.014 kWh/m^3.

Chlorination of surface water is found to consume energy similar to ground water chlorination, between 2×10^{-5} to 5×10^{-4} kWh/m^3 [20].

The energy consumption of surface water treatment plants with high-rate clarification in the US city of Lincolnton, North Carolina (34,000 m^3/d), is about 0.009 kWh/m^3 and in Tampa Bay, Florida (250,000 m^3/d), is about 0.012 kWh/m^3 [21]. Plappally and Lienhard [22] reported ranges of energy expenditure for water treatment in several countries: Spain is seen to have the highest upper limit energy consumption (0.11 to 1.5 kWh/m^3) for water treatment. Spain uses reverse osmosis desalination to treat some water and these processes can be very energy intensive. Canada is also found to have a high energy intensity (0.38 to 1.44 kWh/m^3) due to the use of high-energy membrane processes, such as ultrafiltration, and smaller plant sizes.

To calculate the energy consumption associated with the use of drinking water in this study, the reported values proposed in the bibliography for the energy consumption (kWh/m^3) for each stage of treatment were considered and are summarized in Table 1. The CO_2 emissions were determined with the value proposed by Silva-Afonso et al. [23], of 369.23 g of CO_2 emitted per kWh of electricity.

Table 1. Summary of unitary energy consumption for different stages of water and wastewater treatment.

		Energy Consumption (kWh/m^3)	
		Min	**Max**
Potable water treatment	Pressurized Filtration	0.014	
	Pre-oxidation With Ozone	0.008	0.022
	Coagulation-Flocculation	0.4	0.7
	Multilayer Filtration	0.005	0.014
	Disinfection With Chlorine	0.00002	0.0005
	Transportation	0.073	
Additional wastewater treatment	Pressurized Filtration	0.014	
	UV-B or Chlorine	0	0.066

3. Case Study

Description

The case study used in this work was the municipality of Espinho, a coastal region integrated in the metropolitan area of Porto, located 20 km south of Porto city, Portugal. This municipality is served by separative drainage networks, with physical separation between rainwater and sewage. The treatment of the urban wastewater is carried out at the Espinho wastewater treatment plant. After renovation works in 2007, this infrastructure is now expected to treat in 2030 wastewater from about 194,000 inhabitants, providing a secondary treatment level [24]. The treatment is composed of the following processes (Figure 2): preliminary treatment (screening and sand and grease removal), primary sedimentation and biological treatment with activated sludge (aeration tank and secondary sedimentation). The plant has also a sludge treatment process (digestion and dewatering), production of biogas (for sludge heating and energy production) and a deodorization system. Recorded values of monthly treated wastewater are presented in Table 2, where it is possible to see a slight seasonal variation, with more water being treated in the rainfall period (November to April) than in the summer months, likely due to rainfall-derived inflow/infiltration into the wastewater networks.

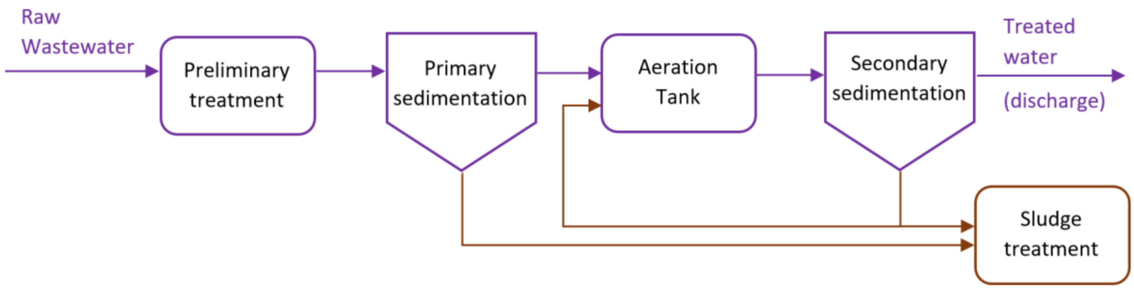

Figure 2. Schematic configuration of Espinho WWTP.

Table 2. Treated wastewater in Espinho WWTP in 2019.

WWTP Treated Wastewater Production (m^3/Month)	
Jan	490,640
Feb	464,960
Mar	489,212
Apr	541,324
May	445,484
Jun	369,777
Jul	410,535
Aug	390,572
Sep	357,648
Oct	377,284 *
Nov	454,306 *
Dec	522,696 *
TOTAL	**3,960,152**

* Estimated values: average from 2017 and 2018 records.

The management of this WWTP is a responsibility of the Multi-Municipal Water Supply and Drainage System of the Coastal Center of Portugal—*Águas do Centro Litoral, SA* (AdCL), which concerns 30 municipalities and a population of about 1.1 million people [24].

As stated previously, Portugal is investing in a strategy of promoting the reuse of wastewater to reduce water stress, which demands the definition of its legal framework. The Decree-Law 119/2019 [10] referred to in Section 1 allows the classification of the Espinho WWTP as a centralized system of treated wastewater production, managed by a single entity, able to produce WtR for internal and external consumptions. According to this decree, the consumption of WtR in green space and golf course irrigation may be defined as (1) *irrigation with access restrictions*—irrigation with WtR in areas with a limited period of irrigation and with no possibility for people to remain during that period and (2) *irrigation with no access restrictions*—irrigation with WtR in areas where it is possible for people to remain during irrigation periods. Regarding the WtR quality requirements, it explains that they must be accomplished by the producer at the delivery point, and also by the user at the consumption point. Another important aspect of this legislation is the concept of barriers that can be integrated into the supply system to permit a higher quality classification.

For the specific case of the municipality of Espinho, at this phase, the WWTP can provide B-class water: irrigation with restricted access (urban and agricultural uses), which includes, besides agricultural uses, the irrigation of gardens with restricted access, including recreational and sports areas. For this class, the treatment level on the WWTP must be higher than secondary (must include a disinfection system) and the configuration of the WWTP must be adapted to the one presented in Figure 3. However, if there is a possibility for people to remain in the area during irrigation periods, it is necessary for the B-class WtR to have one barrier. Thus, the installation of a post-disinfection unit in the irrigation area is suggested, corresponding to a barrier and making this system suitable for irrigation without restricted access, in accordance with the legislation.

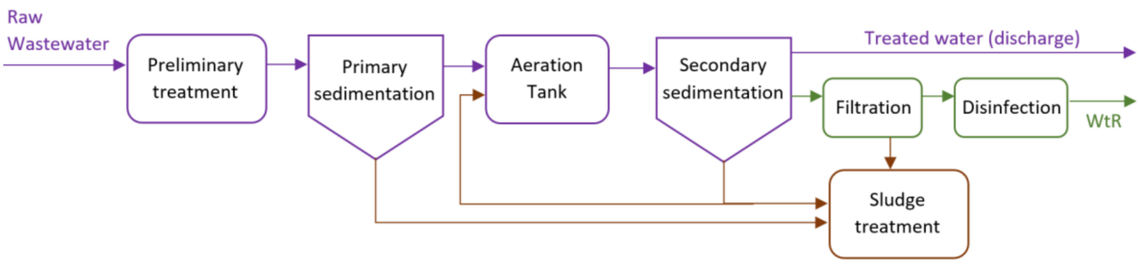

Figure 3. Schematic configuration of Espinho WWTP, with the additional processes needed to produce WtR.

Located in the south part of the municipality, near the WWTP, is the Oporto Golf Club, with 18 holes and a par of 71 [25], in a total area of 28 ha. It is composed of two types of grass watered by spray irrigation in the nighttime period: *Agrostis palustris* on the greens and multiple species of grass on the fairways [9]. Information collected directly on the course revealed that there are two groundwater extractions. However, nowadays, the extracted water does not meet the quality requirements for the lawn irrigation, because there are continuous records of saltwater intrusion in the groundwater extracted. The Club has already analyzed different solutions for this problem (using water from the potable public network, construction of lakes nourished by surface water flow, etc.) and reached a preliminary conclusion that the best option may be using treated wastewater from the nearby WWTP. Using potable water from the public supply network does not seems to be a sustainable option from both environmental and economical point of views.

Finally, in the Espinho municipality, potable water supply is provided by Lever Water Treatment Plant (WTP), which extracts water from the Douro River and carries out the following treatment stages (Figure 4): preliminary treatment (pressurized filtration), pre-oxidation with ozone, coagulation-flocculation, multilayer filtration and disinfection with chlorine [26].

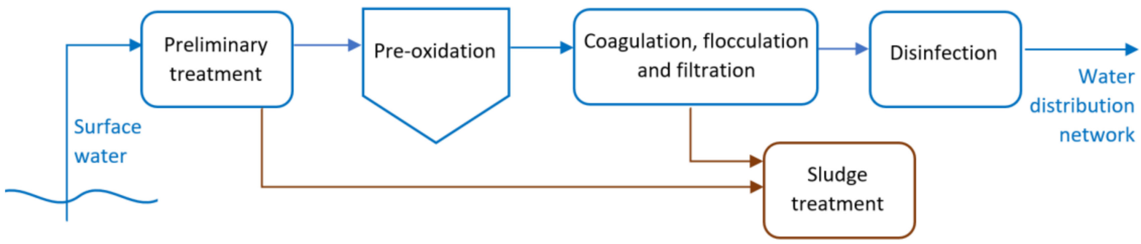

Figure 4. Schematic configuration of Lever WTP.

4. Results and Discussion

The configuration of the WtR network will depend on the end uses. It is important at this stage to analyze each possible configurations in order to understand their specifications.

At the beginning of this study, it was intended to provide WtR to the golf course, to municipal irrigation and for pavement washing. However, the city council informed that, since the beginning of 2020, the use of water for pavement washing was suspended, so it was discarded from the following phases of the study. Thus, discarding pavement washing, three scenarios were defined: (1) WtR to the golf course, (2) WtR to municipal irrigation and, finally, (3) WtR to both. The supply to the delivery points will be carried out mainly by a pressurized network, with a pumping station installed in the WWTP. The configuration of this station will vary for each scenario.

4.1. Scenario 1—Golf Course Supply

The first scenario considers the supply of WtR only to the golf course. It has a clear advantage, which is the proximity: the golf club is situated about 1.5 km northeast of Espinho WWTP (Figure 5).

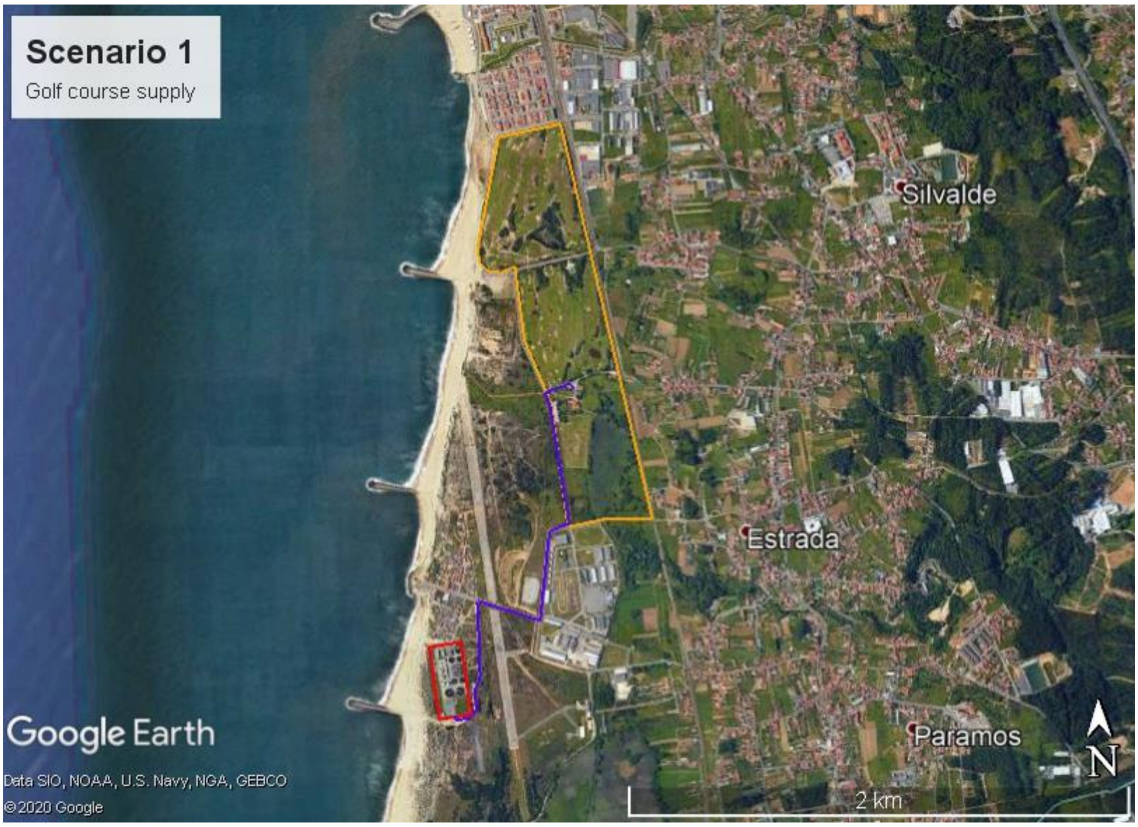

Figure 5. Scenario 1: WtR supply, provided by Espinho WWTP (in red), by pressurized network (pipe in blue) to the Oporto Golf Club bordered in orange.

According to the national legislation, for this scenario, Espinho WWTP, managed by AdCL, is the centralized system that must obtain the producer license to provide WtR. The entity that must obtain the user license is the Oporto Golf Club. Thus, AdCL must provide, at the delivery point, WtR with a quality equivalent to B-class irrigation, but the Oporto Golf Club should also install a post-disinfection unit on the irrigation network to assure the safety of the employees, who, for example, may remain on the lawn during the irrigation period.

WtR supply to the golf course could also be provided by road transport because, in this case, the need for water to irrigation only exists in the months of June to September. This could save exploration costs related to the pumping system. An economic analysis of both solutions for water supply in this scenario must be performed in the following phases of this study.

The water–energy nexus was analyzed in this scenario regarding the consumptions recorded in 2019 (about 31,840 m^3 in summer months) and the results are presented in Table 3.

Water costs for potable supply were estimated considering the price of water for commerce and industry (1.9456 EUR/m^3 in 2019) and WtR costs were estimated with the unitary costs for disinfection (0.02 EUR/m^3 [27]) and water pumping (0.15 EUR/kWh), considering the option of a pressurized network for WtR supply. No other tariffs (such as sewage or waste disposal) or charges were included in water price in order to provide a fair comparison between the two sources of water. The pumping energy was calculated considering the following pipe characteristics: extension of 1920 m, in HDPE SDR17 Ø110 mm and with a flow of 8.7 L/s, able to fulfill the reservoirs in about 8 h. Energy consumption and associated CO_2 emissions were determined with the range values presented in Section 2, considering the additional treatment needed for WtR production (filtration, pre-disinfection and post-disinfection).

Table 3. Scenario 1: Supply with drinking water and WtR to the golf course.

Consumption (m^3)	Supply with Drinking Water (from the Public Network)					Supply with WtR				
	Cost (EUR)	Energy (Range Interval) (kWh)		CO_2 Emissions (Range Interval) (kg)		Cost * (EUR)	Energy (Range Interval) (kWh)		CO_2 Emissions (Range Interval) (kg)	
Jan–May	**0**	**0**	**0**	**0**	0	0	0	0	0	0	0
Jun	4226	8222	2115	3483	781	1286	281	793	1013	293	374
Jul	17,092	33,254	8542	14,067	3154	5194	1138	3206	4094	1184	1512
Aug	4151	8076	2077	3421	767	1263	276	779	995	287	367
Sep	6371	12,395	3181	5238	1174	1934	424	1195	1526	441	563
Oct–Dec	0	0	0	0	0	0	0	0	0	0	0
TOTAL	**31,840**	**61,948**	**15,914**	**26,209**	**5876**	**9677**	**2119**	**5972**	**7627**	**2205**	**2816**

* Disinfection, pumping and post-disinfection.

4.2. Scenario 2—Municipal Irrigation Areas Supply

The second scenario considers the WtR supply only to municipal irrigation. It is not feasible to provide WtR to all green areas in the municipality, so only those with significant consumption in Espinho (see green areas in Figure 6) were considered. These areas correspond to about 2184 m^3 of water per year, according to the recorded values for 2019 provided by the city council. The supply should be provided by a pressurized WtR network, longer than the one from scenario 1. As the irrigation areas in the city are mainly not fenced, it is safer to establish also in this scenario a post-disinfection unit in the beginning of each irrigation area.

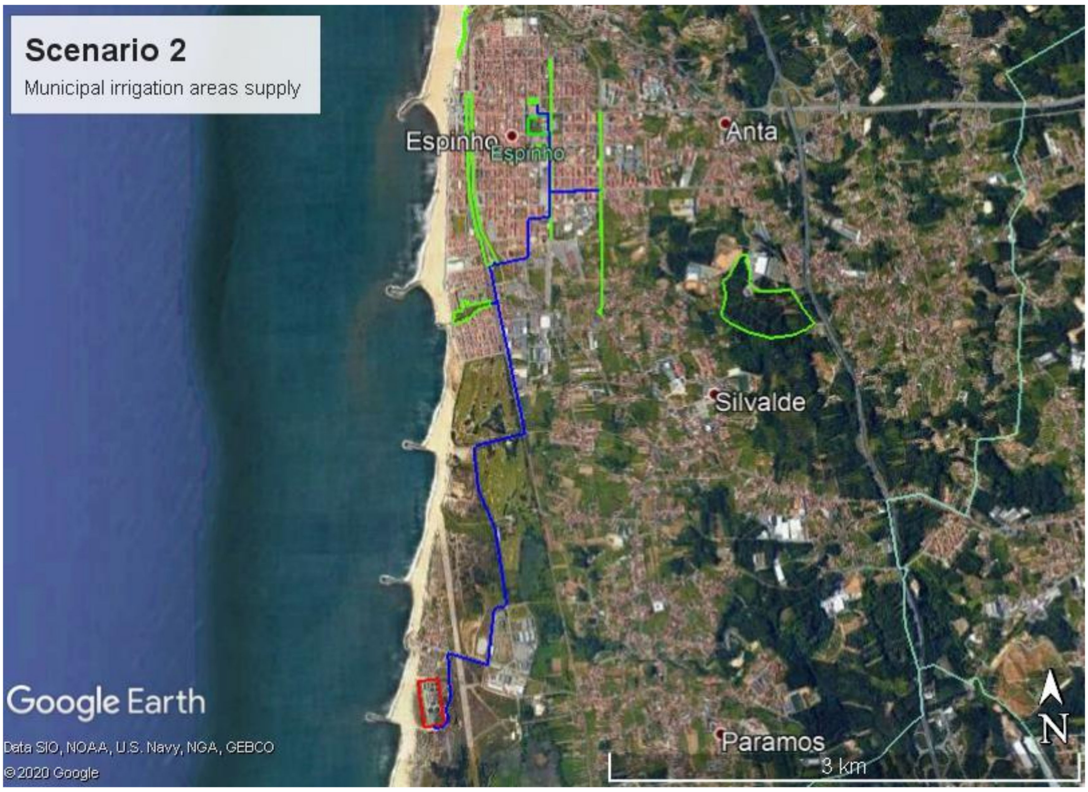

Figure 6. Scenario 2: WtR supply, provided by Espinho WWTP (in red), by pressurized network (pipe in blue) to the municipal irrigation areas marked in green.

For this scenario, and according to the national legislation, the centralized system that must obtain the producer license to provide WtR is the Espinho WWTP, managed by AdCL, and the final user that must obtain the user license is the Espinho city council. AdCL must provide, at the delivery point, WtR with a quality equivalent to B-class irrigation, but the city council must also apply a barrier equivalent to a post-disinfection unit, taking into account the nonexistence of fences in the irrigation areas.

The water–energy nexus was analyzed in a similar way to the previous scenario, also comparing the supply with drinking water (with a cost for municipal uses of 0.4259 EUR/m^3) and the supply with WtR, using the same unitary costs for disinfection and pumping (Table 4). The pumping energy was calculated considering the following pipe characteristics: extension of 5927 m, in HDPE SDR17 Ø63 mm and with a flow of 2.4 L/s considering a maximum of 2 h irrigation. Energy consumption and associated CO_2 emissions were determined with the methodology indicated in Section 2.

Table 4. Scenario 2: Supply with drinking water and WtR to municipal irrigation areas.

Consumption (m^3)		Supply with Drinking Water (from the Public Network)					Supply with WtR				
		Cost (EUR)	**Energy (Range Interval) (kWh)**		**CO_2 Emissions (Range Interval) (kg)**		**Cost * (EUR)**	**Energy (Range Interval) (kWh)**		**CO_2 Emissions (Range Interval) (kg)**	
Jan	**791**	**337**	**395**	**651**	146	240	117	393	434	145	160
Feb	189	80	95	157	35	58	28	95	105	35	39
Mar	189	80	95	156	35	57	28	94	104	35	38
Apr	1275	543	638	1050	235	388	189	634	701	234	259
May	254	108	127	209	47	77	38	126	140	47	52
Jun	1646	701	824	1356	304	501	244	819	905	303	334
Jul	745	317	372	613	137	226	111	370	409	137	151
Aug	280	119	140	230	52	85	42	139	153	51	57
Sep	143	61	72	119	27	44	21	72	79	26	29
Oct	167	71	84	138	31	51	25	83	92	31	34
Nov	143	61	72	119	27	44	21	72	79	26	29
Dec	434	185	217	357	80	132	64	216	238	80	88
TOTAL	**2814**	**2664**	**1407**	**2317**	**520**	**856**	**928**	**1400**	**1546**	**517**	**571**

* Disinfection, pumping and post-disinfection.

4.3. Scenario 3—Golf Course and Municipal Irrigation Areas Supply

Finally, in the last scenario, both golf course and municipal irrigation were considered. The goal was to supply WtR (about 34,654 m^3/year) to these two non-potables uses (Figure 7). The supply was also considered to be provided by a pressurized network from the WWTP to the municipal irrigation areas, with a derivation to the golf course. Post-disinfection units must be considered for all the supply areas in this scenario, due to the reasons explained above.

The centralized system for this scenario was still the Espinho WWTP, managed by AdCL, and there would be two final users—Oporto Golf Club and the Espinho city council—that should obtain their user licenses. AdCL must provide, at the delivery point, WtR with a quality equivalent to B-class irrigation, and both end users must also apply barriers equivalent to post-disinfection units.

The water–energy nexus was analyzed in a way similar to the previous scenarios, by comparing the supply with potable water and with WtR and using the same unitary costs for disinfection and pumping. Energy consumption and associated CO_2 emissions were determined using the methodologies indicated in Section 2. Results are presented in Table 5 and the pumping energy was calculated considering the following pipe characteristics:

- Pipe 1, from WWTP to golf course—extension of 1920 m, in HDPE SDR17 Ø110 mm and a with a flow of 11.1 L/s, considering both golf and municipal irrigation during 2 h/day. For the other 6 h of supply to the golf course, the considered flow was 8.7 L/s;
- Pipe 2, from golf course to municipal irrigation areas—extension of 4007 m, in HDPE SDR17 Ø63 mm and with a flow of 2.4 L/s.

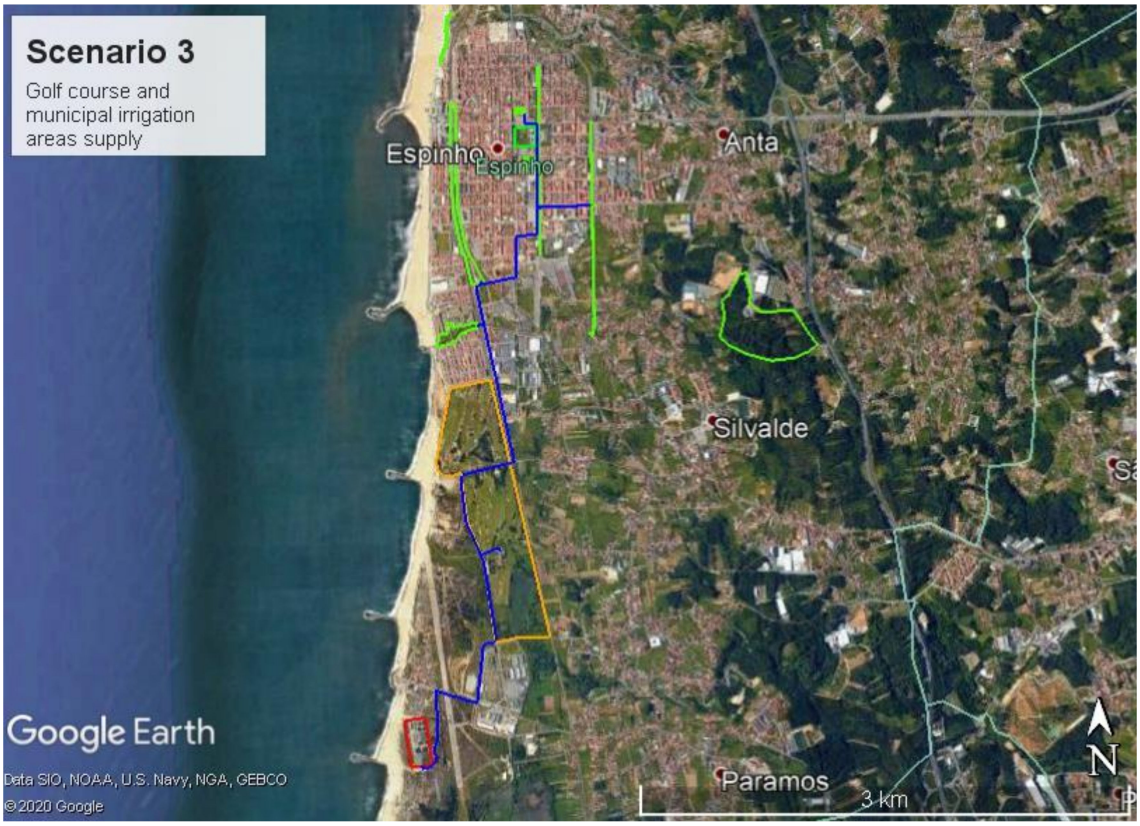

Figure 7. Scenario 3: WtR supply, provided by Espinho WWTP (in red), by pressurized network (pipe in blue) to the Oporto Golf Club bordered in orange and to the municipal irrigation areas marked in green.

Table 5. Scenario 3: Supply with drinking water and WtR to the golf course and municipal irrigation areas.

Consumption (m^3)		**Supply with Drinking Water (from the Public Network)**					**Supply with WtR**				
		Cost (EUR)	**Energy (Range Interval) (kWh)**		**CO_2 Emissions (Range Interval) (kg)**		**Cost * (EUR)**	**Energy (Range Interval) (kWh)**		**CO_2 Emissions (Range Interval) (kg)**	
Jan	791	337	395	651	146	240	435	393	434	145	160
Feb	189	80	95	157	35	58	28	95	105	35	39
Mar	189	80	95	156	35	57	28	94	104	35	38
Apr	1275	543	638	1050	235	388	189	634	701	234	259
May	254	108	127	209	47	77	38	126	140	47	52
Jun	5872	8923	2936	4835	1084	1785	403	1717	2081	634	768
Jul	17,837	33,571	8919	14,689	3293	5424	1126	4447	5614	1642	2073
Aug	4431	8195	2215	3648	818	1347	279	1686	1975	623	729
Sep	6514	12,456	3257	5364	1202	1980	398	2368	2795	874	874
Oct	167	71	84	138	31	51	25	83	92	31	34
Nov	143	61	72	119	27	44	21	72	79	26	29
Dec	434	185	217	357	80	132	64	216	238	80	88
TOTAL	**34,654**	**64,612**	**17,327**	**28,536**	**6397**	**10,536**	**3036**	**10,218**	**12,466**	**3773**	**4445**

* Disinfection, pumping and post-disinfection.

4.4. Qualitative Analysis

The quality requirements for a B-class WtR and for a WtR suitable for pavement washing is presented in Table 6, where, for comparison purposes, the quality records of the discharged water from Espinho WWTP (provided by AdCL) are also presented. It is possible to see that treated wastewater from Espinho WWTP meet the BOD, TSS and pH requirements for B-class irrigation and pavement washing. However, further specific analysis of *E. coli* should be carried out to assure safe reuse. According to the legislation, ammoniacal and total nitrogen, as well as total phosphorus, are facultative parameters, relevant in some irrigation projects to minimize the development of biofilms and the obstruction of the irrigation system. Nevertheless, their analysis is important, and the secondary treatment should be improved in order to make them fulfill the legal recommendations.

Table 6. Quality requirements for the suggested purposes and quality records of the discharged water from Espinho WWTP.

	Irrigation: B-Class	Pavement Washing [(1)]	Quality Records from Espinho WWTP in the Summer of 2019							
			13 Jun	25 Jun	2 Jul	23 Jul	13 Aug	29 Aug	4 Sep	17 Sep
BOD mgO_2/L	**≤25**	**≤25**	15	10	22	21	22	10	19	13
QOD mgO_2/L	-	-	123	38	117	112	117	40	77	45
TSS mg/L	**≤35 mg/L**	-	10	10	30	20	20	5	15	<10
pH -	-	**6 to 9**	7.47	7.38	7.36	7.38	7.79	7.3	7.01	7.6
Temp °C	-	-	18.9	19.7	19.9	21.1	21.85	21.87	21.6	-
***E. coli* CFU/100 mL**	**≤100**	-	-	-	-	-	-	-	-	-
Ammoniacal nitrogen [(2)] mg/L	**≤10 mg/L**	-	-	-	-	-	-	-	-	-
Total nitrogen [(2)] mg/L	**≤15 mg/L**	-	17	18	39	13	32	12	24	31
Total Phosphorus [(2)] mg/L	**≤5 mg/L**	-	1.5	0.2	2.9	4.4	5.2	<0.5	2.1	5.8

[(1)] These values do not apply to manual pressurized washing systems. In that case, limits are lower, leading to a better WtR quality (similar to A-class irrigation). [(2)] Facultative parameters that may be applied in some irrigation projects to minimize the risk of biofilm production and obstructions in irrigation systems.

Microbiological parameters are not included in the periodic records from the WWTP monitoring plan. Nevertheless, it is necessary to include a disinfection unit in the WWTP to reuse its water because, as stated previously, B-class irrigation and pavement washing requires a level of treatment higher than the secondary one. The disinfection unit must provide WtR with a maximum of 100 CFU/100 mL at the delivery point.

4.5. Discussion

The reuse of wastewater after specific treatment is an auspicious procedure with clear advantages. However, it is important to analyze three aspects before installation:

1. Is WtR safe for humans, soil, plants and animals? Is it reliable in time? Does it need a specific license? How is the management carried out?
2. Is the public opinion favorable to this procedure?
3. What are the costs and the savings related to this procedure?

The recent publication of a specific regulation in the European Union and a decree-law in Portugal, both about reuse of treated wastewater, brought the answer to the inquiries presented in question 1. In this case study, the recommendations about the configuration of the supply system and about some adjustments in the secondary treatment of the WWTP, as well as the monitoring plan demanded in the license, are the most important guarantees to the safe use of the supplied WtR. Besides, for this specific case study, in quantitative terms, the reliability of the reuse system is assured because in the month with higher consumptions of scenario 3 (Table 5), June, treated wastewater produced in the WWTP is 23 times higher (Table 1).

The use of wastewater can encounter strong public resistance due to a lack of awareness and trust regarding human health risks and other factors such as different cultural and religious perceptions about water in general and/or using treated wastewater [28]. The way to reduce negative public perception is to give to people all the information related to the processes, to the guarantee of its safety and to the environmental advantages that are associated. In further developments of this study, a specific inquiry to the population in the municipally should be performed, as they are the target public of this installation.

Results from Tables 3–5 can answer part of question 3: Table 7 resumes the expected savings for the three scenarios, in terms of exploitation costs and in terms of the associated energy consumption and CO_2 emissions.

Table 7. Balance between the use of potable water and WtR, for the three scenarios, estimated with data from 2019.

		Using Drinking Water	Using WtR	Balance
Scenario 1	Costs (EUR/year)	61,948	2119	**−59,829**
	Energy * (kWh/year)	21,062	6576	**−14,485**
	CO_2 emissions * (kg/year)	7777	2510	**−5266**
Scenario 2	Costs (EUR/year)	2664	928	**−1736**
	Energy * (kWh/year)	1862	1473	**−389**
	CO_2 emissions * (kg/year)	688	544	**−144**
Scenario 3	Costs (EUR/year)	64,612	3036	**−61,577**
	Energy * (kWh/year)	22,931	11,342	**−11,589**
	CO_2 emissions * (kg/year)	8467	4109	**−4358**

* Average values from the range presented in Tables 3–5.

As explained above, the tariff of WtR was estimated considering unitary costs of disinfection from Portuguese previous studies and the cost of the energy spent in water pumping for each scenario. However, additional costs may be included by the managing entity, AdCL, to produce WtR (related to investment amortization, human resources and analytic monitoring programs, for example), which can lead to a higher WtR tariff. Nevertheless, the analysis presented in this study reveals that all three scenarios present significant annual savings from using WtR instead of drinking water from the public network, especially scenarios 1 and 3, which consider golf course irrigation. In these scenarios, the operation cost of using drinking water is approx. EUR 62.000,00 and EUR 64.600,00 per year, respectively, and if WtR would be used, those costs would be EUR 2.100,00 and EUR 3.000,00 per year, respectively. The difference is of about EUR 60.000,00 in those scenarios, which may be high enough to sustain the advantage of using WtR even if it has a higher tariff.

Scenario 2 (supply with WtR only for municipal irrigation areas) presents lower savings because of the lower volumes of water consumed, lower water price for municipal uses and higher pumping costs for the supply with WtR.

The water–energy nexus analyzed for both sources of water reveals the advantages of using WtR instead of drinking water, as WtR spends less energy during production and produces fewer CO_2 emissions. The energy savings of scenarios 1 and 3 can reach an average value of about 14,500 kWh/year and 11,500 kWh/year, respectively, and 5300 and 4300 fewer kg of CO_2, respectively, would be emitted.

Comparing the three scenarios using WtR, as presented in Figure 8, it is possible to perceive that scenario 1 present lower costs associated with WtR use than scenario 3; however, it also presents less energy consumption and lower CO_2 emissions.

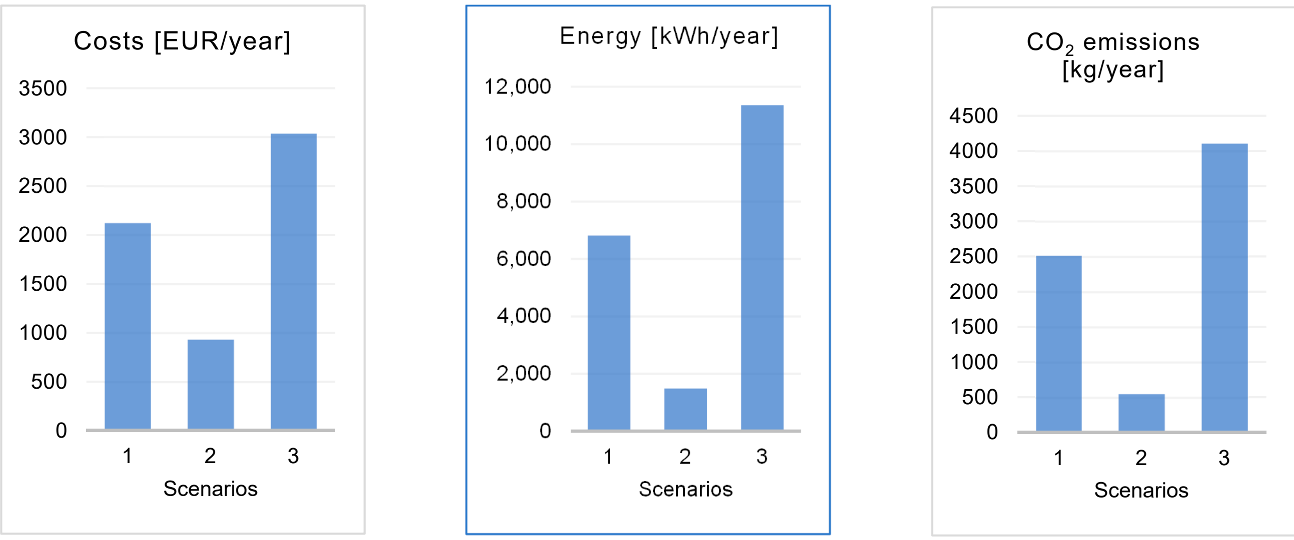

Figure 8. Average exploitation costs, energy and CO_2 emissions associated with WtR consumption.

An analysis of the unitary costs, energy and CO_2 emissions was also conducted, and the results are presented in Figure 9. The unitary cost associated with the supply with WtR is considerably lower than the traditional supply with drinking water, especially in the scenarios with golf course irrigation (1 and 3), due to the low transportation cost. The unitary energy consumption and CO_2 emissions are also lower when using WtR, which can be explained by the lower need for additional treatment applied to this solution.

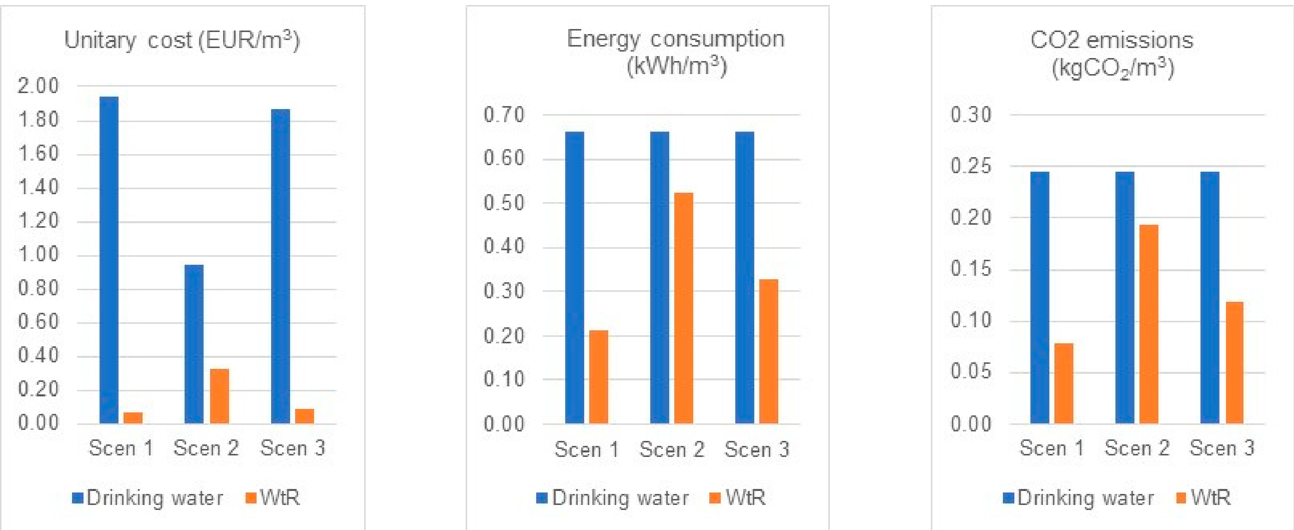

Figure 9. Unitary cost, energy and CO_2 emissions considering a supply with drinking water and with WtR.

It is now possible to see the implications of using WtR instead of drinking water in the water–energy nexus perspective but, to complete question 3, investment and maintenance costs should be calculated in further developments of this study. Together with the savings calculated in this article, they can provide the economic evaluation needed to assess the feasibility of the investment. In this stage, scenario 1 seems to be the most feasible one, with lower exploitation costs but savings provided by scenario 3 (which will certainly have higher investment costs) are about EUR 2.000,00 higher (Table 6). An economic study is necessary to validate this assumption.

It is also important to carry out further analyses to the conductivity of the WWTP discharged water, as coastal networks are very exposed to saline intrusions. Those results should meet the tolerance of the lawns that will be irrigated and, if not, an adjustment to the WWTP treatment process must be made. In terms of microbiological parameters, it is expected that the suggested disinfection processes will be effective, according to Lubello et al. [4], and the monitoring program associated with the user and producer licenses assures its continuous reliability.

5. Conclusions

The reuse of treated wastewater is strategic for Portugal to relieve the pressure on water resources and make the country more resilient to climate change. This interest is demonstrated by the recent publication of a specific regulation in the European Union and a decree-law in Portugal concerning this practice, covering all the aspects needed to a safe and reliable reuse. Based on the Portuguese decree-law, a study considering a real case (Espinho municipality) was carried out. The goal was to analyze and compare the water–energy nexus associated with the consumption of WtR as an alternative to drinking water supply to non-potable purposes.

Three specific scenarios were defined: one considering the supply of WtR to the golf course, another with the same supply to municipal irrigation areas and a last one with both end-uses.

It was possible to conclude that scenarios 1 and 3 (which included the golf course irrigation) will have savings of about EUR 60.000,00 per year by using WtR instead of drinking water. This value will probably be lower in reality if the managing entity applies additional costs for the production and supply of WtR (investment amortization, monitoring costs and human resources were not considered in this estimation).

The water–energy nexus analyzed for both sources of water reveals the advantages of using WtR instead of drinking water: WtR spends less energy on its production and supply, and also produces fewer CO_2 emissions. The energy savings of scenarios 1 and 3 can reach an average value of about 14,500 kWh/year and 11,500 kWh/year, respectively, and 5300 and 4300 fewer kg of CO_2, respectively, would be emitted.

Scenario 2, which considered only the irrigation to municipal areas, has smaller savings due to lower consumptions. The investment costs are expected to be higher than scenario 1, so it is likely the less feasible one.

Further developments of this study were also identified. Electrical conductivity analysis will be necessary, because it is a parameter that is not defined in the legislation but can destroy the lawns if it is not kept under adequate values. Otherwise, the coastal location of the drainage network, upstream the WWTP, makes it very vulnerable to saltwater intrusions. Another important aspect to develop in further steps of this work is to estimate the investment and maintenance costs for each scenario, to conduct an economic analysis and determine the best installation option.

A project of reuse treated wastewater in non-potable purposes like this will involve high investment costs. Therefore, it is very important to highlight the savings that will occur and the environmental advantages that are associated with it. The volume of WtR that will be used will also be the freshwater that is extracted from natural water sources. Thus, more detailed analysis must be carried out in order to review all the technical and economic aspects and make this a safe, feasible and widespread process.

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