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Water-Energy-Food-Climate Nexus in an Integrated Peri-Urban Wastewater Treatment and Reuse System: From Theory to Practice

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Abstract: This paper develops a framework for the identification, assessment and analysis of the water reuse-carbon-energy-food-climatic (WEFC) nexus in an integrated peri-urban wastewater treatment and reuse system. This methodology was applied to the municipal wastewater treatment plant (WWTP) of Peschiera Borromeo (Milan, Italy) and its peri-urban district to define the most possible affirmations and conflicts following the EU regulations 741/2020. Results of this work showed that transferring the WEFC nexus from theory to practice can realize sustainable resource management in the operating environment by providing a reduction in greenhouse gas (GHG) emissions, overall energy savings, reduction in water stress and optimization of agricultural practices. Particularly, it was found that if the plant configuration is upgraded to reach water quality class C for water reuse, instead of wastewater discharge, energy savings are estimated to reach up to 7.1% and carbon emissions are supposed to be reduced up to 2.7%. In addition, enhancing water quality from class C to class A resulted in increments in energy and carbon footprint of 5.7% and 1.7%, respectively. Nevertheless, higher quality crops can be cultivated with reclaimed water in class A, with bigger economic revenues and high recovery of nutrients (e.g., recovery of 154,450 kg N/y for tomato cultivation).

Keywords: carbon footprint; energy assessment; greenhouse gas emission; nutrients recovery; wastewater disinfection; agricultural reuse

1. Introduction

Water is rooted and highly interlinked to natural resources and their productivity [1]. Water management is indeed one of the pillars for the efficiency of the balance and resilience of many productivity sectors such as energy production and transmission [2]. Fragmented management of interrelated sectors, as well as their separated analysis without considering the integrated system, hide a potential risk of not achieving the desired outcomes [3]. This is caused by underestimated or even unexplored synergies, antagonisms, and ripple effects. The shift of integrated management (so-called nexus approach) requires a shift towards integrated approaches for systems analysis and assessment as well [4]. Hence, the aim should be at using water-related nexus, targeting the holistic systems analysis, and revealing the multiple and complex interactions and feedback loops between technical and biological cycles [5]. A multi-sectoral system analysis framework symbiotically managing different resources (e.g., water, energy) is needed for modelling both socio-economic (e.g., food) and non-economic (e.g., climate) sectors to investigate the complex interactions and interdependencies between the sectors in order to promote synergies and reduce antagonisms between them [6,7]. The water-energy-food-climate (WEFC) nexus is a systematic approach to scientific investigation and design of coherent policy goals and instruments that focuses on synergies, conflicts and related trade-offs emerging in the interactions between water, energy, food and climate at bio-physical, cyber-physical, socio-economic, and governance level [8].

Urban water management considers water supply, wastewater treatment and disposal as an integrated system. The increasing demand for good quality water brings a higher necessity for treatment that enables water reuse, which in turn demands more energy use and associated greenhouse gas (GHG) emissions [9]. The energy-intensive nature of wastewater treatment creates an important part in sustaining urban water systems [10]. The modern thinking about urban water systems not only regards augmenting the existing water supply with new and alternative water sources but also ensuring that adaptive measures are applied for climate change mitigation by reducing energy use and GHG emissions [5,11].

Some authors discussed the nexus addressing issues through water and energy use in agriculture [7,12], while others focused on WWTP boundaries [13] or on water supply and treatment lines [10]. In most cases, the Water-Energy-Food (WEF) nexus is applied, and climate is often neglected in the nexus approach [14]. However, climate change has been considered one of the most threatening factors that put the sustainability of the WEF nexus at risk [15], especially considering water availability [16].

In the wastewater reuse-based agricultural sector, energy-carbon and water footprints are highly interconnected and exhibit a great example of the Water-Energy-Food-Climate (WEFC) nexus [17]. WWTPs are great energy carriers [18,19] and responsible for up to 26% of the GHG emissions of the whole water supply chain [20]. From an environmental and economic point of view related to climate change, any reduction in energy consumption and associated with GHG emissions is valuable [21]. Furthermore, the nutrients and reuse potential of reclaimed wastewater are valuable and can be reutilized in urban agriculture as a potential strategy to support local communities. Between 50% and 90% of the total water demand is represented by agriculture, and the reuse for agricultural irrigation is by far the most established end-use for reclaimed water and is seen as a solution to overcome global water stress [22]. Hence, integrated wastewater treatment and reuse systems are a typical case of WEFC interactions both at city and farm levels, bridging the gap between food and climate sectors. For instance, Gondhalekar and Ramsauer [11] applied the urban WEF nexus for climate change adaptation in a neighborhood of Munich, Germany. The authors provided 26% saving of current freshwater supply by wastewater recycling and reuse coupled with rainwater harvesting as well as 66% of local demand for fruit and 246% of local demand for vegetables by intensive urban agriculture.

In recent years, EU regulations such as 2020/741 "Regulation on minimum requirements for water reuse" [23] and strategies such as "Farm to Fork" have enabled the valorization of wastewater. In the meantime, many wastewater utility managers are seeking to implement nexus-oriented projects to support their city's energy transition policy [24]. However, the nexus has remained conceptual so far and eventually many operators and/or reclamation managers do not know how this approach can bring added value to the operating environment. Currently, innovative ways such as serious games, participatory processes, and bottom-up approaches are adopted to make the nexus more tangible and usable by water utilities, policymakers and citizens [25,26]. The nexus analysis in urban development requires a common matrix to measure the carbon, energy and water efficiency of proposed scenarios and technical options. In many cases, relative carbon, energy and water footprints are calculated and evaluated to quantify environmental impacts [27]. According to the European Environmental Agency (EEA), in 2007, at least 11% of Europe's population and 17% of the territory were estimated to be affected by water scarcity, with a related cost of droughts over the past thirty years at EUR 100 billion. In the Mediterranean region, 20% of the population lives under constant water stress, which increases up to over 50% in summer. Moreover, water losses are important issues to be addressed for a more efficient distribution system. Non-conventional water resources, e.g., reclaimed wastewater reuse for irrigation, are innovating solutions to be implemented by a smart water management system. It can guarantee safe and good quality of reclaimed water for irrigation, and it will help to satisfy the high-water demand of the agriculture sector. In this paper, we therefore wanted to showcase a practical application of the WEFC nexus in an integrated peri-urban system for wastewater treatment and reuse system in Milan, Italy, to highlight the relationships between different sectors including wastewater treatment, irrigation infrastructure and agricultural district. In this regard, the nexus approach was adopted to define connections and interactions between water reuse, carbon and energy footprint, as well as food production in various water reuse scenarios and conditions.

2. Materials and Methods

2.1. Description of the WWTP and Peri-Urban Area

The peri-urban district of Peschiera Borromeo WWTP is geographically located in the Lombardy Padana Plain. The treatment capacity of the plant is 566,000 population equivalent (PE) with a total average inflow rate of 216,000 m^3/d treated in two different wastewater lines. Line 1 consists of a conventional activated sludge process followed by biological filtration to remove inorganic nitrogen and a final chemical disinfection using peracetic acid. Line 2 is designed and will be used for reuse purposes that include a two-stage upflow biological filtration (Biofor®) and two parallel lines of ultra-violet (UV) disinfection. The water demand of the peri-urban areas in the south of Milan (near Parco Agricolo Sud Milano) is mainly required for irrigation purposes. The surrounding agricultural land has an area of approximately 2500 ha and its main crop is corn, and its water demand can be widely covered by the treated effluent of Line 2 of the WWTP. Agriculture is a crucial sector for the economy of the region. The most common irrigation techniques are still traditional and rely on border irrigation, which implies a water demand of about 1.5–2 L/s/ha of over the agricultural season. The current water sources come from rivers, and it is distributed by gravity through a network of open unlined canals. The irrigation network of canals and the related water delivery systems that supply water to farmers is managed by the consortium Est Ticino Villoresi, which is one of the most important irrigation consortia in Italy. Current water distribution and irrigation systems are still characterized by poor efficiency and are affected by significant losses. In addition, a decrease in freshwater availability is observed in the territory, which makes water reuse a valid option.

2.2. Nexus Approach

For the evaluation of the WEFC nexus, single sector footprints and single subsystem' stages were initially considered, to define the significative elements that characterized each impact. Footprints were first calculated individually for each sector, from energy to carbon and water, and were determined separated for each stage of the integrated system, from the WWTP to the field. Where available, standardized methods were used.

2.3. Energy Footprint

The recently standardized ENERWATER methodology [19] was adopted to assess the energy audit of the WWTP. All the electromechanical equipment serving the treatment units was listed, defining for each the working hours, the absorbed power, and the functioning characteristics. Measured data from the energy meters installed along the treatment units were collected and elaborated, to evaluate the monitored consumptions and assign to each unit the respective energy demand. Moreover, energy bills were collected to verify effective consumption. Each electromechanical equipment was assigned to one of the 5 stages in which the plant layout was divided into. In this way, consumption could be normalized in respect to the parameter that most affected the single stage, i.e., the entering flowrates (in m^3) for the preliminary treatments (stage 1), the amount of total solids removed (kg TSS removed) for primary treatments (stage 2), the amounts of organics and nutrients removed for the biologic unit (stage 3) expressed in terms of total pollutant equivalent (kg TPE removed), the pathogen log reduction for m^3 of treated water for the disinfection unit (stage 4), and the solids load processed expressed as total solid equivalent (kg TSE processed) for sludge treatment (stage 5). In this way, key performance indicators (KPIs) were calculated according to the standard method [19]. Calculations were performed considering one year operation of the plant. Finally, a global indicator of plant performances, the "water treatment energy index" (WTEI), was calculated and a label describing the global efficiency of the plant was assigned as reported in Table 1.

Table 1. Labels for the general representation of a WWTP energy efficiency according to the WTEI (adapted by Longo et al. [19]).

ENERGY EFFICIENCY	WTEI
A	$X < 0.110$
B	$0.110 \leq X < 0.220$
C	$0.220 \leq X < 0.330$
D	$0.330 \leq X < 0.440$
E	$0.440 \leq X < 0.550$
F	$0.550 \leq X < 0.775$
G	$X \geq 0.775$

2.4. Carbon Footprint Assessment

The Italian Regulatory Authority for Energy, Networks and Environment (ARERA) introduced the additional indicator G5.3 "Carbon Footprint of the water treatment service" according to the standard ISO 14064-1, 2019. This guideline provides general information for the assessment of the carbon footprint of activity, but it does not include specifications for single sectors, such as water or wastewater service. International guidelines, such as IPCC [28], can support providing Emission Factors (EFs) groped in sectorial activities, but site-specific conditions can differ significantly from the ones assumed.

In this work, emissions were calculated according to Equation (1) in agreement with IPCC Guidelines [28].

$$Emission\left(\frac{tonCO_2e}{y}\right) = Activity\ data\left(\frac{quantity}{y}\right) \times EF\left(\frac{tonGHGs}{quantity}\right) \times GWP \quad (1)$$

where, for each greenhouse gas (*GHG*), emissions were calculated multiplying an Activity Data (*AD*), which is the representative quantity of an activity or a service that cause the emission, by an Emission Factor (*EF*), which represent the specific contribution, and a Global Warming Potential (*GWP*) to convert each GHG into CO_2 equivalents.

In general, AD represents a quantity generated or used, of energy, mass, or volume, representing the key parameter for each emission category. As concerning WWTP, the main activities are related to the amount of wastewater and pollutants treated (m^3/y, tonCOD/y, tonN/y, . . .), chemicals (ton/y) and energy consumed (MWh/y), as explained by Gustavsson and Tumlin [29]. Annual operational data were collected from the plant and elaborated to obtain the needed activity data to describe GHG emissions from a WWTP operation.

Applied EFs were collected from literature, guidelines, and national and international databases, such as IPCC guidelines [28,30–32] and ISPRA [33–35].

Emissions were grouped into categories, distinguishing between direct and indirect ones. Regarding direct emissions, the main sources were biological processes of organic oxidation, nitrification and denitrification [36]. Indirect emissions were related to energy consumption, chemical dosing and waste disposal and were considered too, even if their sources were located outside the physical boundaries of WWTPs, since they were caused by specific management strategies under the responsibility of the water utility. The main sources of direct emissions included biogas combustion, WWTP processes and fugitive emissions, while emissions for dissolved gases on the water body, energy and chemical consumption, transports and sludge disposal were considered as indirect.

Utilized GWPs were obtained by the IPCC Fifth Assessment Report, AR5 (IPCC, 2019) [37].

2.5. Water Footprint

The water footprint was addressed by distinguishing four different cases of water quality, depending on the classes foreseen in EU Regulation 741/2020. The current discharge limits satisfy the requirements of class D, which was considered as the non-reuse option. The plant has to satisfy Italian Regulation 2006/52 for effluent quality, with stricter restrictions for nitrogen and phosphorus concentrations, which must be under 10 mg/L and 1 mg/L, respectively. Moreover, *E.coli* concentrations at the effluent must be lower than 5000 CFU/100 mL.

For the irrigation of crops where the edible part is not in direct contact with reclaimed water, class C could be used in case drip irrigation is applied to furtherly reduce risks; otherwise, a minimum of class B is necessary. Class A is required for food crops consumed raw where the edible part is in direct contact with reclaimed water. In this way, the quality class reached determined the possible applications available.

2.6. Water Reuse

Single footprints were interconnected to each other. For instance, energy consumption impacted both on energy footprint and on carbon footprint, since the emissions related to energy production must be included in the carbon footprint assessment. In the same way, the use of chemicals impacted both the GHG emitted and the energy requirements for their production. Moreover, to provide a certain quantity of water of a defined quality for irrigation, WWTP efficiency must be improved, increasing the energy demand to enhance treatment performances, especially in the disinfection unit, and increasing the related GHG emissions accordingly. Footprints at WWTP level were then extended, to include the agricultural sector. For water reuse applications, the cultivated crops to be irrigated with the reclaimed water were selected according to the requirements provided by the EU 741/2020 for each class and considering the most diffused species of the integrated peri-urban system in the surroundings of Peschiera Borromeo WWTP. Data on culture productivity, nutrient demand and carbon sequestration were collected from literature and national and international guidelines. Table 2 shows the demands of different crop types selected in this study. Water quality class influence the type of crops that could be irrigated, with varying water and nutrient demand, as well as different GHG emissions and carbon sequestration. Finally, it is important to highlight that the water demand for the cultivation of the three selected crops in the surrounding agricultural lands (2500 ha) of the peri-urban of Milan can be widely covered by the treated effluent of Line 2 of the WWTP (25,929,332 m^3/y).

Table 2. Characteristics and requirements for crops cultivated in the peri-urban area of Peschiera Borromeo.

Parameter	Unit	Corn	Carrot	Tomato
Crop productivity	ton/ha	10	50	100
Nutrient demand—N	kg N/ha	135–235	150	250
Nutrient demand—P	kg P/ha	58–80	70	65
Emissions/Carbon sequestration	tonCO_2e/ha	3.52	2.27	2.11
Crop water demand	m^3/ha	5000	5200	5400
Expected revenue	€/kg	0.26	0.48	0.78

Different irrigation methods were taken into consideration to address the water demand of selected crops, varying from traditional to more technologic techniques, such as drip irrigation. Each irrigation method is characterized by a certain level of efficiency, considered as the ratio between the quantity of water that effectively reaches the crop in respect to the amount of water provided. In these terms, surface irrigation is characterized by the lowest efficiency level, equal to 0.5; sprinkler irrigation has an efficiency of 0.7; drip irrigation, which is the most efficient method, has an efficiency of 0.9.

It is evident that drip irrigation is by far the technology able to provide the highest saving of water during irrigation. Hence, drip irrigation was selected as irrigation technology to calculate water needs for crops and energy consumption during irrigation. Energy requirements for irrigation and the consequent carbon footprint were calculated, to evaluate the requirements connected to the production of each crop and define the specific relationships between irrigation method, water demand, energy and carbon footprint. Once calculated single-subsystem footprints, different combinations of WWTP treatment efficiency level and irrigated crop were considered, and their integrated cross-sectorial footprints were defined. The information was collected to provide a reliable database for the implementation of a serious game, based on the real data of the demo-case of the peri-urban area of Peschiera Borromeo WWTP.

2.7. Assessment of Water Reuse Scenarios

For each scenario considered, single sector and single stage footprints were calculated and combined, linking energy requirements needed to achieve a defined water quality class, the water demand required to the cultivated crop depending also on the irrigation method used, and the related carbon footprint. Water quality impacted on energy consumptions and carbon footprint of the WWTP, but also limited the kind of crops that could be irrigated, as well as the irrigation method. On the other side, crop quality and irrigation techniques influenced the amount of water needed, as well as the energy and fuel consumption, GHG emissions and carbon sequestration. A summary of requirements needed for each scenario is provided in Table 3, where standard limits are related to the EU regulations 741/2020.

Table 3. Water reuse requirements for different scenarios according to EU Regulation 741/2020.

Parameter	Unit	Non Reuse	Reuse Class C	Reuse Class B	Reuse Class A
E.coli	CFU/100 mL	5000	1000	100	10
Biochemical Oxygen Demand (BOD_5)	mg/L	25	25	25	10
Total Suspended Solids (TSS)	mg/L	35	35	35	10
Turbidity	NTU	-	-	-	5
Irrigated crop	-	-	Corn	Corn	Corn-Tomato-Carrot
Irrigation method	-	-	Drip irrigation	All irrigation methods	All irrigation methods

2.7.1. Non-Reuse Scenario

The baseline scenario was the non-reuse case (Figure 1), where the WWTP treats wastewater to meet the minimum regulatory limits for discharge. Since in this case, the discharged wastewater is not in direct contact with cultures, no particular attention needs to be paid to toxicity issues for chemical overdosing. Considering that the conventional treatment line of Peschiera Borromeo WWTP was not designed for water reuse and was characterized by a chemical disinfection unit with peracetic acid, the same chemical was considered to simulate the non-reuse scenario. The destination for sludge disposal considered was the production of defecation gypsum, as it is one of the most common pathways in the area.

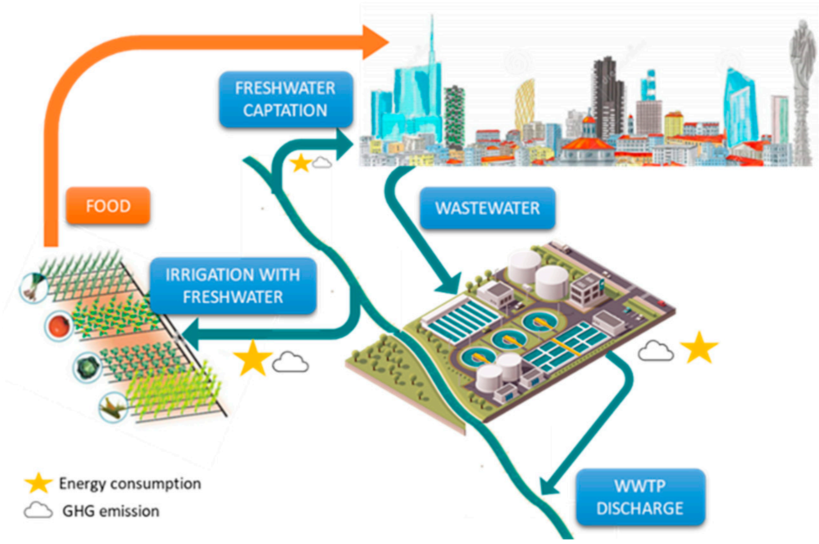

Figure 1. Scheme of the non-reuse scenario.

2.7.2. Reuse Scenarios

Different reuse scenarios were analyzed, combining water quality class, irrigation method used and cultivated crop (Figure 2). On WWTP level, the treatment configuration included UV disinfection instead of chemical dosing.

Treatment Line 2 of Peschiera-Borromeo WWTP used biological filtration as secondary treatment, and it was already able to respect standards for BOD_5 and TSS related to Reuse class A (Table 3). In any case, standard limits for BOD_5 and TSS could be easily accomplished by adding a sand-filtration unit after the biological stage. UV doses were selected to respect limits for *E. coli* provided by the EU regulations 741/2020 for the different water quality classes [32,33].

In the peri-urban district of Milan, water reuse was practiced, according to crop demand, for five months between April and August.

Figure 2. Scheme of the reuse scenarios.

<u>*Reuse class C*</u>

Class C was characterized by the lowest quality requirements for food crop irrigation but implied additional measures to guarantee an acceptable level of risk. Edible parts of crops must have no direct contact with reclaimed water and must be irrigated using more precise techniques, such as the drip method. Even if nutrient content in reclaimed water is usually not sufficient to compensate crop demand, part of the synthetic fertilizer commonly used for crop growth could be saved anyway. It is specified that in the application in the exam, nutrients concentration in wastewater were assumed to be in compliance with discharge limits of current Italian regulation 152/2006, since in case of non-acceptability for reuse, water quality is needed in any case to satisfy requirements for discharge. Further improvements could consider fertigation practices or sludge application on the cultivated fields, to optimize resources recovery and further decrease impacts due to nutrient removal from the water line or sludge disposal. However, all analyzed reuse scenarios were focused on the water line, while sludge application in the cultivated fields was not considered, since further considerations on the type of post-treatment and final product quality were needed.

Reuse class B

If reclaimed water was provided with class B standards, any irrigation method could be applied for food crops without edible parts in direct contact with water. In this way, the reclaimed water provided by the WWTP could be used for a wider range of potential users, that did not need to satisfy specific requirements of irrigation techniques applied. On the other side, the energy and carbon footprint of WWTP would increase, since more efforts were required to provide a higher quality reclaimed water, especially as concern tertiary treatments for pathogen reduction.

Reuse class A

Reclaimed water in class A had the strictest quality standards. All food crops consumed raw where the edible part is in direct contact with reclaimed water and root crops consumed raw could be irrigated and all irrigation methods could be used. WWTPs must increase the efficiencies of their tertiary and disinfection treatments, to guarantee concentration of *E. coli* as low as 10 CFU/100 mL. Where UV disinfection units were applied, higher energy consumptions for lamps and consequently higher carbon footprint were foreseen; meanwhile, for chemical units, the higher dosage of reagents was necessary, which implied an increase in energy and carbon footprint related to their production. Moreover, overdosage must not impact health and environmental risk for water reuse [38].

3. Results

Benefits and Applications from Reuse Scenarios

Considering only at the WWTP level, delivering a lower quality effluent seems to imply fewer impacts, since the plant consumes less energy and thus produces fewer carbon emissions. However, it is also characterized by less efficient configuration. In the same way, on the agriculture side, when the treated wastewater is discharged, high-quality fresh water is consumed for irrigation purposes and a greater quantity of synthetic fertilizers is required for crop growth.

Footprint assessments showed the interconnections between water, energy and carbon in an application of water reuse for agricultural irrigation. Carbon emissions and energy consumptions varied depending on the water quality required to be delivered (Table 4). For example, upgrading plant performances to reach higher quality classes of treated wastewater implied an increase in the energy and in the carbon footprint of the plant, but higher quality crops could be cultivated with the reclaimed wastewater. In Table 4 calculations have also taken into account the energy consumption (1160 MWh/y) and GHGs emission (515 tonCO_2eq/y) for drip irrigation of the investigated district.

If the WWTP is upgraded to reach water quality class C, instead of wastewater discharge, energy savings were estimated to reach 7.1%, in agreement with results of previous studies [39,40], and carbon emissions were supposed to be reduced up to 2.7%. When the water quality was aimed to reach class B, then 5.8% energy footprint reduction was achieved, while the carbon footprint was reduced by 2.0%. However, enhancing water quality from class C to class A implied the additional WWTP increments on energy and carbon footprint of 5.7% and 1.7%, respectively. On a more global and complex view, however, lower quality effluent wastewater means more contamination and bigger impacts on health and the environment. Moreover, higher quality crops can be cultivated with reclaimed water in class A, with bigger economic revenues for farmers. To provide the readers with additional information on carbon footprint calculation, details of GHG emissions grouped for categories and related to the operation of Peschiera-Borromeo WWTP are reported in Table 5.

Table 4. Footprints for reuse and non-reuse scenarios.

Category	Unit	Non-Reuse	Reuse Class C	Reuse Class B	Reuse Class A
Energy footprint	MWh/y	16,374	15,196	15,427	16,121
Carbon footprint	tonCO_2eq/y	24,505	23,849	23,952	24,260
Treated wastewater	millions of m^3/y	25.9			
Nutrients in the wastewater effluent	mgN/L	7.8			
	mgP/L	0.6			

Table 5. GHGs emissions at Peschiera-Borromeo WWTP grouped by categories.

GHG Emission Category	Unit	Value			
Biogenic emission due to WWTP operation	tonCO2eq/y	7278			
Transport	tonCO2eq/y	66			
Use of chemicals	tonCO2e/y	2787			
Dissolved gases in the effluent	tonCO2eq/y	6937			
Waste management (production of defecation gypsum from sludge)	tonCO2eq/y	753			
Energy consumption for WWTP operation	tonCO2eq/y	4718			
Disinfection	tonCO2eq/y	Chemical 1451	UV-Class C 795	UV-Class B 898	UV-Class A 1206

In a similar way, information about energy consumptions of the different units of Peschiera-Borromeo WWTP are reported in Table 6 in terms of KPI and WTEI in agreement with the standardized ENERWATER methodology [19]. Particularly, it is interesting to observe that the upgrade of the disinfection units did not determine changes in the classification of the energy efficiency of the plant, which remained in class F.

Finally, in Table 7 are resumed data on saved energy, reduced GHG emission, recovered water and nutrients for the irrigation of corn, carrot and tomato with reclaimed water compared to the non-reuse scenario. During drip irrigation, the edible part of corn is not in direct contact with reclaimed water. Hence, this crop can be irrigated by class C water. On the contrary, tomato and carrot need to be irrigated by class A water. Particularly, the lowest energy consumption and GHG emission were obtained during corn irrigation, due to the smallest energy need for UV disinfection (Table 4). On the contrary, during irrigation of carrots and tomatoes, which have a higher water demand (Table 2), it was possible to have a higher recovery of nutrients and water. In addition, these two crops can have a higher economic revenue (Table 1).

Table 6. KPIs for energy consumptions at Peschiera-Borromeo WWTP grouped by treatment stages and WTEI related to one year of operation.

Stage	Treatment Unit	Unit	Value			
Stage 1	Pre-treatments	kWh/m^3	0.101			
Stage 2	Primary treatment	kWh/kg TSS rem	0.646			
Stage 3	Secondary treatment	kWh/kg TPE	0.535			
Stage 4	Disinfection	kWh/(m^3 logred)	Chemical 0.025	UV-Class C 0.011	UV-Class B 0.012	UV-Class A 0.013
Stage 5	Sludge treatment	kWh/kg TSE	0.223			
WWTP	WTEI	-	0.719	0.686	0.686	0.691
	Global efficiency	-	F	F	F	F

Table 7. Saved energy, reduced GHG emission, and recovered water and nutrients during water reuse.

Crop	Water Quality Class	Saved Energy (MWh/y)	Reduced GHG Emission (ton-CO_{2eq}/y)	Recovered Water (Millions of m^3/y)	Recovered Nitrogen (kg N/y)	Recovered Phosphorus (kg P/y)
Corn	C	1178	656	17.8	139,140	10,703
Carrot	A	253	245	19.1	149,026	11,464
Tomato	A	253	245	19.8	154,450	11,881

4. Discussion

Stricter environmental regulations, the requirements for wastewater and for higher efficiency in the removal of pollutants at a lower cost, as well as the generation of energy from wastewater treatment clarify the need for attention to the new methods and technologies [41]. The description and the quantification of the water reuse-based WEFC nexus in an integrated peri-urban wastewater treatment and reuse system includes cross-sectorial analysis, linking energy, carbon and water footprints, as well as cross-stage assessments of all the sub-systems involved. More energy and carbon emissions must be considered to improve wastewater quality to satisfy reuse requirements. Different crops and different irrigation methods can be combined, always keeping regulatory requirements and technological level achievable in mind. Once defined all the interlinkages that construct the nexus, those relationships can be used to develop applications to show and evaluate all the inter-related outcomes, explaining and communicating the efforts and the benefits for the sustainable development of a peri-urban system.

Based on our assessment of the agricultural water reuse scenarios for Peschiera Borromeo WWTP, remarkable reduction in carbon and energy footprints were obtained. Within the reuse scenarios, energy footprint increased as the water quality (reuse class) increased due to required high standards and associated treatment technologies/methods. On the other hand, carbon footprint remained almost the same in all reuse scenarios. Similarly, Lahlou and co-authors [42] used the WEF nexus approach to identify the optimal allocation of 13 sources of treated wastewater to be used in cultivating alfalfa, achieving reductions in greywater footprint, energy and carbon footprints in Qatar that faces severe food insecurity due to its limited water resources. The authors found greywater footprint, energy for transportation, and carbon footprint associated with the growth of 1 ton of alfalfa as −917 m^3, 70 kWh and −34 kg-CO_2eq for Erakhiya farm, and −1770 m^3, 68 kWh and −18 kg-CO_2eq for Wadi Al Araig farm.

Considering the major resource savings (including water and energy) and reduction in GHG emissions, farmers, policymakers, reclamation managers and agronomists recognize the necessity for WEFC nexus in integrated wastewater and reuse systems, and propose and implement innovative solutions based on this concept especially in the local dimension [43]. This approach can help to measure and monitor the indicators of the complex interactions between water treatment/reuse, carbon emission, energy consumption, smart agriculture and climate variability [17]. Furthermore, digitalization can improve the collection of the data required for the footprint assessments, providing a common space for their storage and elaboration. Standardized offline data from periodic lab analyses or other traditional management practices can be supported and improved with real-time signals from the monitoring network of sensors in the WWTP and in the field, improving the frequency and the level of control. Moreover, coupling inputs from the field and from WWTP can optimize water and resources management.

5. Conclusions

The evaluation of complex and multi-sectorial practices, such as water reuse for agricultural irrigation, must be performed considering the WEFC nexus of the integrated system. Single audits or partial sub-stage considerations may not be representative of the whole system, since they may not include significative aspects or counterbalances. In this paper, the nexus approach was used to evaluate water reuse practices in a peri-urban integrated system, analyzing different sectorial footprints, from energy to water and carbon, for different sub-stages that constituted the integrated system, from WWTP to the irrigated field. Only by using a nexus approach and considering all the integrated systems can a comprehensive assessment be performed, and the benefits of water reuse (i.e., energy and carbon footprints) can be clearly highlighted. The nexus approach is fundamental for a better understanding of all the connections that interlink water, energy, carbon, food and climate sectors and allows evaluating all the impacts and consequences of different strategies on water reuse practices. The nexus approach can be used to increase awareness of all the efforts required for the application of sustainable practices and the benefits that can be apported, improving the acceptability and willingness to pay for more sustainable water and resource management actions.

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References

1. Miralles-Wilhelm, F. Development and application of integrative modeling tools in support of food-energy-water nexus planning—A research agenda. *J. Environ. Stud. Sci.* **2016**, *6*, 3–10. [CrossRef]
2. Klein, B.; Koenig, R.; Schmitt, G. Managing Urban Resilience: Stream Processing Platform for Responsive Cities. *Inform.-Spektrum* **2017**, *40*, 35–45. [CrossRef]

3. Brouwer, F.; Avgerinopoulos, G.; Fazekas, D.; Laspidou, C.; Mercure, J.F.; Pollitt, H.; Ramos, E.P.; Howells, M. Energy modelling and the Nexus concept. *Energy Strateg. Rev.* **2018**, *19*, 1–6. [CrossRef]
4. Dargin, J.; Daher, B.; Mohtar, R.H. Complexity versus simplicity in water energy food nexus (WEF) assessment tools. *Sci. Total Environ.* **2019**, *650*, 1566–1575. [CrossRef] [PubMed]
5. Nair, S.; George, B.; Malano, H.M.; Arora, M.; Nawarathna, B. Water-energy-greenhouse gas nexus of urban water systems: Review of concepts, state-of-art and methods. *Resour. Conserv. Recycl.* **2014**, *89*, 1–10. [CrossRef]
6. Hülsmann, S.; Sušnik, J.; Rinke, K.; Langan, S.; van Wijk, D.; Janssen, A.B.; Mooij, W.M. Integrated modelling and management of water resources: The ecosystem perspective on the nexus approach. *Curr. Opin. Environ. Sustain.* **2019**, *40*, 14–20. [CrossRef]
7. Li, M.; Fu, Q.; Singh, V.P.; Ji, Y.; Liu, D.; Zhang, C.; Li, T. An optimal modelling approach for managing agricultural water-Tenergy-food nexus under uncertainty. *Sci. Total Environ.* **2019**, *651*, 1416–1434. [CrossRef]
8. Van den Heuvel, L.; Blicharska, M.; Masia, S.; Sušnik, J.; Teutschbein, C. Ecosystem services in the Swedish water-energy-food-land-climate nexus: Anthropogenic pressures and physical interactions. *Ecosyst. Serv.* **2020**, *44*, 101141. [CrossRef]
9. Bassano, C.; Deiana, P.; Vilardi, G.; Verdone, N. Modeling and economic evaluation of carbon capture and storage technologies integrated into synthetic natural gas and power-to-gas plants. *Appl. Energy* **2020**, *263*, 114590. [CrossRef]
10. Meng, F.; Liu, G.; Liang, S.; Su, M.; Yang, Z. Critical review of the energy-water-carbon nexus in cities. *Energy* **2019**, *171*, 1017–1032. [CrossRef]
11. Gondhalekar, D.; Ramsauer, T. Nexus City: Operationalizing the urban Water-Energy-Food Nexus for climate change adaptation in Munich, Germany. *Urban Clim.* **2017**, *19*, 28–40. [CrossRef]
12. Tian, H.; Lu, C.; Pan, S.; Yang, J.; Miao, R.; Ren, W.; Yu, Q.; Fu, B.; Jin, F.F.; Lu, Y.; et al. Optimizing resource use efficiencies in the food–energy–water nexus for sustainable agriculture: From conceptual model to decision support system. *Curr. Opin. Environ. Sustain.* **2018**, *33*, 104–113. [CrossRef]
13. Gu, Y.; Dong, Y.N.; Wang, H.; Keller, A.; Xu, J.; Chiramba, T.; Li, F. Quantification of the water, energy and carbon footprints of wastewater treatment plants in China considering a water-energy nexus perspective. *Ecol. Indic.* **2016**, *60*, 402–409. [CrossRef]
14. González-Bravo, R.; Sauceda-Valenzuela, M.; Mahlknecht, J.; Rubio-Castro, E.; Ponce-Ortega, J.M. Optimization of Water Grid at Macroscopic Level Analyzing Water-Energy-Food Nexus. *ACS Sustain. Chem. Eng.* **2018**, *6*, 12140–12152. [CrossRef]
15. Zeng, X.T.; Zhang, J.L.; Yu, L.; Zhu, J.X.; Li, Z.; Tang, L. A sustainable water-food-energy plan to confront climatic and socioeconomic changes using simulation-optimization approach. *Appl. Energy* **2019**, *236*, 743–759. [CrossRef]
16. Cansino-Loeza, B.; Ponce-Ortega, J.M. Sustainable assessment of Water-Energy-Food Nexus at regional level through a multi-stakeholder optimization approach. *J. Clean. Prod.* **2021**, *290*, 125194. [CrossRef]
17. Radini, S.; Marinelli, E.; Akyol, Ç.; Eusebi, A.L.; Vasilaki, V.; Mancini, A.; Frontoni, E.; Bischetti, G.B.; Gandolfi, C.; Katsou, E.; et al. Urban water-energy-food-climate nexus in integrated wastewater and reuse systems: Cyber-physical framework and innovations. *Appl. Energy* **2021**, *298*, 117268. [CrossRef]
18. Capodaglio, A.G.; Olsson, G. Energy issues in sustainable urban wastewater management: Use, demand reduction and recovery in the urban water cycle. *Sustainability* **2020**, *12*, 266. [CrossRef]
19. Longo, S.; Mauricio-Iglesias, M.; Soares, A.; Campo, P.; Fatone, F.; Eusebi, A.L.; Akkersdijk, E.; Stefani, L.; Hospido, A. ENERWATER–A standard method for assessing and improving the energy efficiency of wastewater treatment plants. *Appl. Energy* **2019**, *242*, 897–910. [CrossRef]
20. Vasilaki, V.; Massara, T.M.; Stanchev, P.; Fatone, F.; Katsou, E. A decade of nitrous oxide (N2O) monitoring in full-scale wastewater treatment processes: A critical review. *Water Res.* **2019**, *161*, 392–412. [CrossRef]
21. Venkatesh, G.; Chan, A.; Brattebø, H. Understanding the water-energy-carbon nexus in urban water utilities: Comparison of four city case studies and the relevant influencing factors. *Energy* **2014**, *75*, 153–166. [CrossRef]
22. Foglia, A.; Andreola, C.; Cipolletta, G.; Radini, S.; Akyol, Ç.; Eusebi, A.L.; Stanchev, P.; Katsou, E.; Fatone, F. Comparative life cycle environmental and economic assessment of anaerobic membrane bioreactor and disinfection for reclaimed water reuse in agricultural irrigation: A case study in Italy. *J. Clean. Prod.* **2021**, *293*, 126201. [CrossRef]
23. EU Regulation. *REGULATION (EU) 2020/741 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 25 May 2020 on Minimum Requirements for Water Reuse*; EU: Luxembourg, 2020; Volume 2019.
24. Moss, T.; Hüesker, F. Politicised nexus thinking in practice: Integrating urban wastewater utilities into regional energy markets. *Urban Stud.* **2019**, *56*, 2225–2241. [CrossRef]
25. Laspidou, C.S.; Mellios, N.; Kofinas, D. Towards ranking the water-energy-food-land use-climate nexus interlinkages for building a nexus conceptual model with a Heuristic Algorithm. *Water* **2019**, *11*, 306. (In Switzerland) [CrossRef]
26. Sušnik, J.; Chew, C.; Domingo, X.; Mereu, S.; Trabucco, A.; Evans, B.; Vamvakeridou-Lyroudia, L.; Savić, D.A.; Laspidou, C.; Brouwer, F. Multi-stakeholder development of a serious game to explore the water-energy-food-land-climate nexus: The SIM4NEXUS approach. *Water* **2018**, *10*, 139. (In Switzerland) [CrossRef]
27. Yang, Y.J.; Goodrich, J.A. Toward quantitative analysis of water-energy-urban-climate nexus for urban adaptation planning. *Curr. Opin. Chem. Eng.* **2014**, *5*, 22–28. [CrossRef]
28. Bartram, D.; Short, M.D.; Ebie, Y.; Farkas, J.; Gueguen, C.; Peters, G.M.; Zanzottera, N.M.; Karthik, M. Guidelines for National Greenhouse Gas Inventories-Wastewater Treatment and Discharge. 2019. Available online: https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/5_Volume5/V5_6_Ch6_Wastewater.pdf (accessed on 30 September 2021).

29. Gustavsson, D.J.I.; Tumlin, S. Carbon footprints of Scandinavian wastewater treatment plants. *Water Sci. Technol.* **2013**, *68*, 887–893. [CrossRef]
30. Guendehou, G.H.S.; Koch, M.; Hockstad, L.; Pipatti, R.; Yamada, M. Incineration and Open Burning of Waste. *2006 IPCC Guidel. Natl. Greenh. Gas Invent. Waste* **2006**, *5*, 1–26.
31. IPCC. Chapter 5: Incineration and Open Burning. IPCC, 2019. Available online: https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/5_Volume5/19R_V5_5_Ch05_IOB.pdf (accessed on 30 September 2021).
32. IPCC. Chapter 3: Solid Waste Disposal. IPCC, 2019. Available online: https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/5_Volume5/19R_V5_3_Ch03_SWDS.pdf (accessed on 30 September 2021).
33. SINANET. Fattori di Emissione del Trasporto su Strada, Rete del Sistema Informativo Nazionale Ambientale. ISPRA, 2018. Available online: http://www.sinanet.isprambiente.it/it/sia-ispra/fetransp/fattori-emissione-trasporto-stradale/view (accessed on 30 September 2021).
34. ISPRA. Fattori di Emissione Atmosferica di CO_2 e Altri Gas a Effetto Serra Nel Settore Elettrico. ISPRA, 2017; ISBN 9788844808129. Available online: https://www.isprambiente.gov.it/it/pubblicazioni/rapporti/fattori-di-emissione-atmosferica-di-co2-e-altri-gas-a-effetto-serra-nel-settore-elettrico (accessed on 30 September 2021).
35. Romano, D.; Arcarese, C.; Bernetti, A.; Caputo, A.; Contaldi, M.; Cordella, M.; De Lauretis, R.; Di Cristofaro, E.; Gagna, A.; Gonella, B.; et al. Italian Greenhouse Gas Inventori 1990–2018. *National Inventory Report*. 2020. Available online: http://www.sinanet.isprambiente.it/it/sia-ispra/serie-storiche-emissioni/national-inventory-report/view (accessed on 30 September 2021).
36. Zhan, X.; Hu, Z.; Wu, G. *Greenhouse Gas Emission and Mitigation in Municipal Wastewater Treatment Plants*; IWA Publishing: London, UK, 2017; Volume 16, ISBN 9781780406312.
37. Meyer, R.K.; Pachauri, L.A. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. 2014. Available online: https://epic.awi.de/id/eprint/37530/ (accessed on 30 September 2021).
38. Hochstrat, R.; Peter, M.; Wintgens, T.; Kraus, F.; Seis, W.; Miehe, U.; Frijns, J. Water Reuse Safety Plans-a manual for practitioners. *Deliv. D3.4 Demoware* **2017**, *1*, 43.
39. Tak, S.; Kumar, A. Chlorination disinfection by-products and comparative cost analysis of chlorination and UV disinfection in sewage treatment plants: Indian scenario. *Environ. Sci. Pollut. Res.* **2017**, *24*, 26269–26278. [CrossRef]
40. Cotton, C.A.; Owen, D.M.; Ćline, G.C.; Brodeur, T.P. UV disinfection costs for inactivating cryptosporidium. *J. Am. Water Work. Assoc.* **2001**, *93*, 82–94. [CrossRef]
41. Fetanat, A.; Tayebi, M.; Mofid, H. Water-energy-food security nexus based selection of energy recovery from wastewater treatment technologies: An extended decision making framework under intuitionistic fuzzy environment. *Sustain. Energy Technol. Assess.* **2021**, *43*, 100937. [CrossRef]
42. Lahlou, F.Z.; Mackey, H.R.; McKay, G.; Onwusogh, U.; Al-Ansari, T. Water planning framework for alfalfa fields using treated wastewater fertigation in Qatar: An energy-water-food nexus approach. *Comput. Chem. Eng.* **2020**, *141*, 106999. [CrossRef]
43. Rodias, E.; Aivazidou, E.; Achillas, C.; Aidonis, D.; Bochtis, D. Water-energy-nutrients synergies in the agrifood sector: A circular economy framework. *Energies* **2021**, *14*, 159. [CrossRef]