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Urban water-energy-food-climate nexus in integrated wastewater and reuse systems: cyber-physical framework and innovations

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Abstract

Wastewater treatment is one of the major carriers of the water-energy-food-climate (WEFC) nexus, and although the relationship between water and energy is well recognized, there is still a lack of adequate analysis of the cyber-physical framework to address and assess urban and peri-urban WEFC nexus in an integrated approach. In this review paper, we deeply analyze and summarize the modelling tools and data that are currently used to quantify the nexus in wastewater treatment. Currently, comprehensive models and tools are missing that consider the interconnections amongst catchment, sewer network, wastewater treatment plant (WWTP), river and climatic system in a holistic approach and define relevant monitoring requirements and trustable information provision. Cyber-physical systems provide a technological ground for an efficient management of such integrated systems. The nexus approach in precision irrigation and smart agriculture is further discussed, highlighting the issue of water reuse and the engagement of different levels of stakeholders. Digital solutions and serious games addressing the nexus in urban and peri-urban water management are also presented to facilitate innovative practice aspects and to foster public involvement. Adaptable digital solutions can help to understand stakeholders' perception of water quality and its governance and to improve the levels of awareness and collaboration between utilities, authorities, farmers and citizens. Finally, recommendations on the added value of currently used models, tools and possible digital solutions are given to WWTP and reclamation managers and/or operators to bring the WEFC nexus approach on the operative environment.

Keywords: water reuse; serious game; smart peri-urban agriculture; urban water management; wastewater treatment; water-energy-food-climate nexus

1. Introduction

There is a high interconnection between water and energy. Water is needed for most stages of energy production and transmission, and energy is crucial for water provision and treatment. This fundamental resource relationship is called the water-energy (WE) nexus [1]. The WE nexus assessment approach mainly focuses on the linkages between water and energy, but also on the network with other fields such as water-energy-food (WEF), water-energy-food-climate (WEFC), water-energy-pollution (WEP) and water-energy-food-ecosystem (WEFE) [2]. In fact, the challenges facing the secure supply of each sector are highly interconnected, mostly because of the high energy and water use in food production. In addition, there is the engaged connections of these three sectors with the broader ecosystems and climatic conditions [3].

Fragmented management of interrelated sectors as well as their consideration in isolation from the natural system hide a potential risk of not achieving the desired outcomes. This is caused by underestimated or even unexplored synergies, antagonisms and ripple effects. The shift towards integrated management (WEFC approach) requires a shift towards integrated approaches for systems analysis and assessment as well. So, the aim should be at using WEFC nexus, targeting the holistic systems analysis and revealing the multiple and complex interactions and feedback loops between technical and biological cycles. A multi-sectoral system analysis framework symbiotically managing different resources (e.g. water, energy and food) is needed for modelling both socio-economic (e.g. food) and non-economic (e.g. ecosystems, climate) sectors to investigate the complex interactions and interdependencies between the sectors in order to promote synergies and reduce antagonisms between them [4].

The WEFC nexus can be defined as a systematic approach on 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 [5]. The assessment and optimization of the WEFC nexus is complex since it involves many variable factors with different consequences for the users of each resource (water, energy and land). Economic development requires energy, water, and land resources consumption. Agricultural practices for food production need considerable amounts of inputs, such as water, land, electricity, fertilizer, pesticides, as well as agricultural machinery, and cause major environmental changes, such as pollution and stresses on primary sources (**Fig. 1**). Hence, sustainable management of water, energy, primary resources and land use by balancing economic development and environmental pollution implies the characterization of WEFC nexus. A multi-objective analysis and programming is needed to better understand the interrelationships between the components of WEFC nexus, that are generally nonlinear and hard to quantify [6].

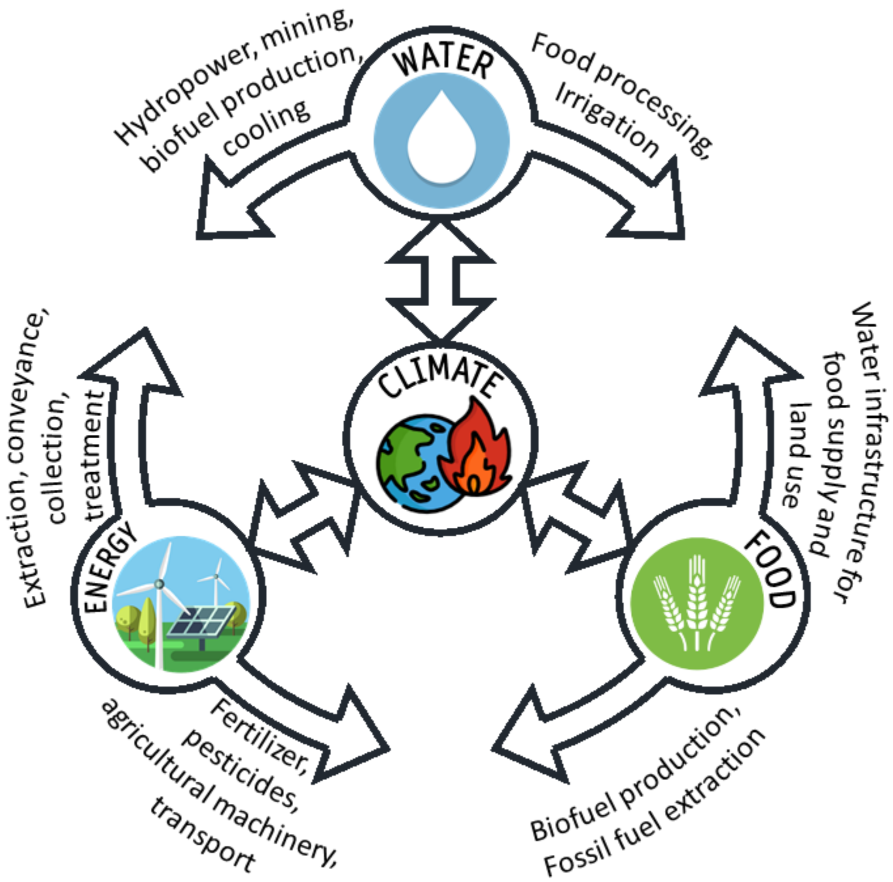

Fig. 1. Water-energy-food-climate (WEFC) nexus.

While the worldwide urbanization phenomenon is still on-going, about half of the world population still lives in rural areas. In the EU, about 30% of the population of former Central and Easter European countries (42 million people) lives in settlements of less than 2000 inhabitants, while this percentage is lower than 20% in the western part. Many other areas of the world still exhibit strong rural or peri-urban characteristics [7]. For instance, approximately 768 million people in China held rural status in 2010, corresponding to 57% of the total population. However, the domestic wastewater treated was only about 11% in provincial towns and less than 1% for rural villages [8].

In most rural areas of developing countries, the supply of water, energy and food are limited, which results in rural populations turning to natural systems for basic survival. As the nexus approach is mainly concerned with integrating these three connected resources, the approach is envisaged to provide pathways that transform rural livelihoods and ensure their resilience [9]. Given the huge differences between developed and developing countries in political structures, socio-economic conditions and financial capacities, the replication of developed country's wastewater management structure is not appropriate nor viable in developing countries. Most of the developing countries suffer from political interference in environmental decisions such as site selection and other aspects related to construction and operation [10]. While many developing countries cannot afford expensive and complex WWTPs to construct and operate, this also becomes a challenge in rural areas with low population density [11]. Despite the lack of water and funding for a proper centralized treatment, decentralised systems are often common in small communities in developing countries. The implementation of a decentralized structure provides a long-standing and effective and cost-efficient solution for these communities [11,12].

The characteristics of water treatment and reuse systems are site specific and usually very different between rural and urban areas as well as between developed and developing regions. Rural areas, where non-point agricultural runoff dominates wastewater production and sewage systems are mainly absent, may require decentralized treatment systems for small communities that are rather limited potential for intentional reuse mainly focused on agriculture. On the other hand, urban areas may rely on a combination of decentralized and centralized treatment plants, depending on the degrees of agglomeration and centralization of waterworks. Urban areas, therefore, have larger potential for intentional reuse, as smaller distances and existing sites for pipelines can more easily connect the locations for treatment and reuse. In fact, decentralised water reuse systems are attracting more interest in urban areas due to their modular design that can be implementable near the source of generation such as households, high-rise buildings, or parts of a city in response to demand [13]. In a recent study by Landa-Cansigno et al. [14], the impact of centralised and decentralised water reuse strategies was assessed in an integrated urban water system using integrated assessment framework of urban water metabolism and the WEP nexus. The authors found that decentralised water reuse strategies perform the best with respect to potable water saving, reductions of eutrophication and GHG emissions, while centralised strategies can provide the largest savings of energy use.

When addressing the water-related nexus, infrastructures are the key interfaces of urban resource use connecting production to consumption, energy to water and land use [15]. In the context of traditional management of urban water systems, all components are considered to be independent of each other in a fragmented manner. The Integrated Urban Water Management (IUWM); on the other hand, has been defined in model development, with integration of the whole system without neglecting important physical phenomena in each component and their interactions [16]. In sustainable IUWM, a significant effort needs to be undertaken to improve water and energy use efficiency, which can further help to reduce their associated environmental impacts [17]. At this point, ensuring cost- and resource-efficiency of wastewater treatment is important in order to ensure the reliability and financial sustainability of the service. WWTPs are great energy carriers and responsible for up to 26% of the GHG emissions of the whole water supply chain [18]. From an environmental and economic point of view related to climate change, any reduction in energy consumption and associated with GHG emissions is valuable [19]. Furthermore, nutrients and reuse potential of reclaimed wastewater are valuable and can be reutilized in urban agriculture as a potential strategy to provide local communities. 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. The impact of water sector is expected to gain more importance in the future due to different factors such as more stringent water quality standards, increasingly urbanized population, higher living standards, more stringent energy efficiency requirements and climate change mitigation plans. Many of these needs are already acknowledged by the European legislation, in particular within the Water Framework Directive 2000/60/EU and Energy Efficiency Directive 2012/27/EU [20]. In this regard, several methodologies are developed to quantify the nexus in urban wastewater and reuse systems using different footprinting tools and models (i.e. carbon, energy, water). In addition to individual footprinting approaches, where considerations on other system(s) are incorporated into the optimisation of a main system through footprint data, the aim of integrated footprints is to co-optimise multiple systems, considering these systems in objectives and decision variables, and incorporating similar levels of detail for their structural and/or behavioural characteristics [3].

Cyber-physical systems (CPS) can be used to respond to the needs of smart wastewater and reuse management. CPS is an emerging framework to control physical systems using digital tools (e.g., sensors) based on ICT technologies [21,22]. The implementation of digital solutions, such as innovative sensors or knowledge- and data-driven analysis, can help to support decision making based on multi-sources data platforms, including real-time quality and quantity monitoring of wastewater treatment. In a typical CPS of an IUWM, subsystems are designed as complex network of interacting elements that are usually operated by different utilities. Therefore, the interoperability of these integrated systems is a major challenge [23].

This review on the WEFC nexus discusses existing tools and models that have been used to investigate the interdependencies and interlinkages between the different sectors of the WEFC nexus but also between the sectors and the natural environment while placing wastewater treatment at the center. The added value of this paper is that it further connects the WEFC nexus with smart agriculture and digitalized solutions in a more innovative platform with upgraded perspectives. The following sections were conceptualized as follows: The nexus concept in wastewater treatment is initially addressed and followed by the footprinting tools and models that are frequently used to quantify the nexus in WWTPs within the urban scale. Then, the nexus in precision irrigation and smart agriculture is discussed focusing on the reuse of treated water from urban wastewater treatment in peri-urban areas. Digital solutions and serious games addressing the WEFC nexus are further evaluated as an alternative approach for smart management to raise awareness and to reduce the fragmentation of knowledge across the water value chain amongst relevant end-users. In the last section, possible research and application routes are recommended to bring the nexus perspective to operators. Finally, main highlights are brought together with the concluding remarks.

2. Nexus in wastewater treatment

An urban water management considers water supply, wastewater treatment and disposal as an integrated system. The increasing demand for good quality water brings higher necessity for water extraction, conveyance, treatment and discharge, which in turn demands more energy use and associated greenhouse gas (GHG) emissions. More specifically, the main processes in urban water systems that consume the major share of energy are extraction, conveyance and storage, raw water treatment and distribution to consumers, pumping and wastewater collection treatment and disposal. Urban water, in particular wastewater treatment, is often evaluated in the framework of WE nexus [17,24] or WEF nexus [25,26] as well as considering climatic effects in terms of GHG emissions [27] as discussed latter, while often neglecting the whole picture. Today, many technologies are available to recover energy and resources (e.g., water, nutrients) from wastewater. The reuse in agricultural irrigation is the most common end-use for reclaimed water [28], which is discussed in Section 4. Recovered nutrients from wastewater can be valorised as soil amendments or fertilizers. Alternatively, nutrient-rich effluents can be useful for fertigation purposes [29]. When effectively designed and operated, wastewater can generate positive externalities through by-products like fertilizer and energy [30]. For instance, Gondhalekar and Ramsauer [31] applied the urban WEF nexus for climate change adaptation in a neighbourhood 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. On the other hand, energy-intensive nature of wastewater treatment and discharge creates an important part in sustaining urban water systems [32]. WWTPs are often considered great energy consumers and a typical case of WE interactions as illustrated in **Fig. 2**. Wastewater treatment stages, such as the collection and conveyance of wastewater, physical and chemical treatment, biological treatment, disinfection, sludge treatment and disposal, require considerable amount of energy [24]. A conventional WWTP, spends approximately 25-40% of its operating costs on energy consumption [33,34]. This energy demand takes place onsite (i.e. electricity required for pumping and aeration), and offsite (production and transportation of materials/chemicals) [35]. Regional and local characteristics are also highly effective on the urban nexus. In many European countries, domestic and industrial water cycles account for 1–3% of total electric energy consumption, and can reach up to 4–5% when water management and agricultural demand are also included [35–37]. Other sources indicate 0.3–2.1 kWh/m^3 of power consumption for treated wastewater in the EU, and 0.41 to 0.87 kWh/m^3, in the U.S., depending on type of treatment, plant size and topography, etc [38].

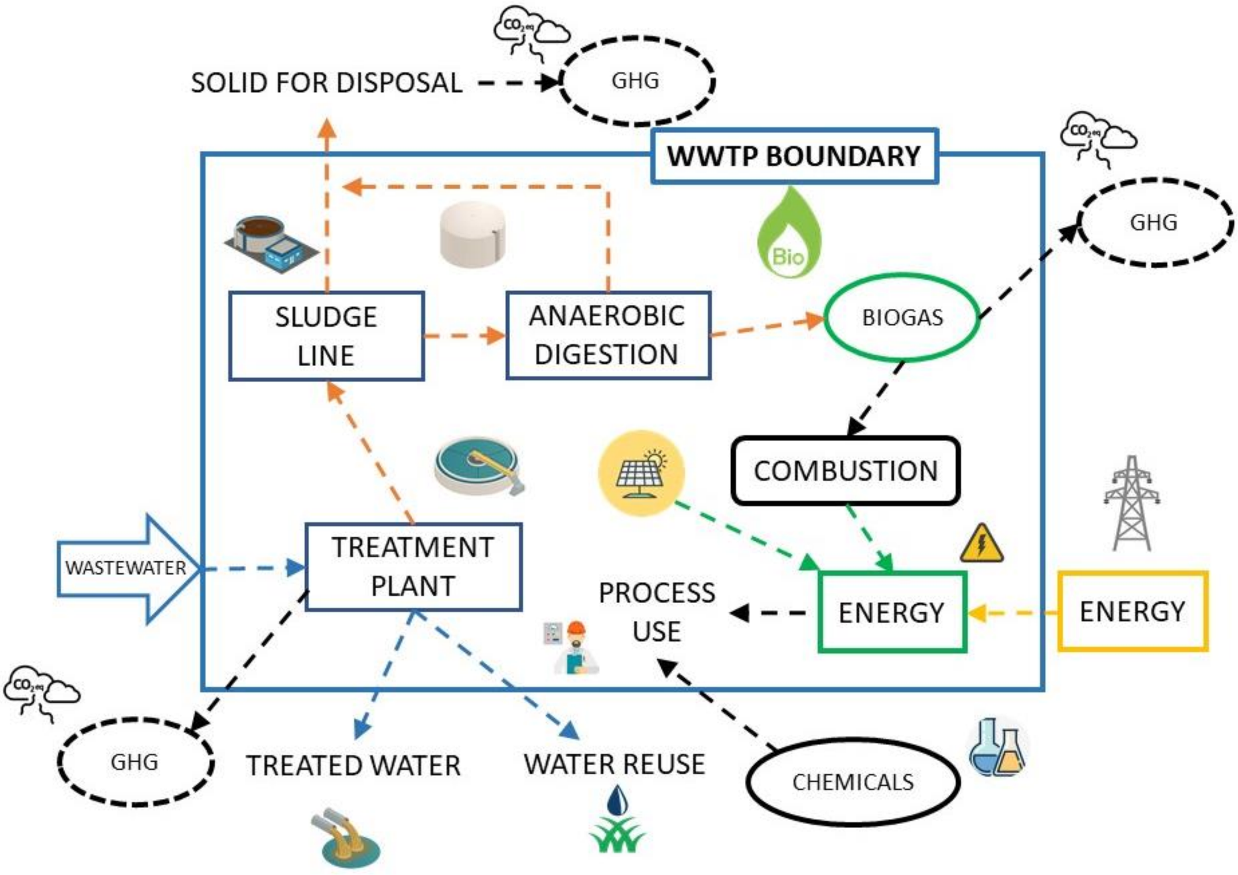

Fig. 2. A simplified scheme of the WEFC nexus in a wastewater treatment and reuse system.

Other criteria for the energy demand of a WWTP include the plant size, type of treatment process (e.g. aerobic or anaerobic), desired effluent quality, etc. [34]. The treatment scale and treatment process are key parameters influencing energy consumption in a WWTP. A conventional municipal WWTP commonly consists of primary, secondary, and tertiary (advanced) treatment stages. The wastewater collection and treatment are less energy intensive at the primary stage compared to the subsequent stages. The energy consumption for secondary treatments vary, depending on the technologies used and the geo-political context. For example, the average energy input of conventional activated sludge (CAS) treatment systems can assume values of 0.46 kWh/m^3 in Australian WWTPs, 0.269 kWh/m^3 for China, 0.33–0.60 kWh/m^3 for USA, and 0.30–1.89 kWh/m^3 for Japan [34,39]. Aeration system is the main contributor to the energy-consumption in the CAS treatment process. In the majority of medium and large WWTPs with CAS treatment, aeration is responsible for 50–60% of the total electricity consumption. In terms of other processes, sludge treatment contributes to 15–25% of the plant energy consumption, while the energy demand for secondary sedimentation is 15% including recirculation pumps [40]. Wastewater treatment with the use of membrane processes usually results the highest amount of energy consumption. Typically, the energy consumption of membrane bioreactors (MBR) are in the range of 0.37–2.5 kWh/m^3 [34].

Sludge treatment is indeed an energy-intensive process. The results from a research work conducted in 10 WWTPs in Greece, with an overall capacity of 15,000–4,000,000 population equivalents (PE), showed that sludge treatment units accounted for about 8% of the total energy consumption [40]. The final destination of treated sludge also influences the overall energy consumption. For instance, more than 14% of the sewage sludge is incinerated in many European countries, while the USA and Japan incinerate over 25% and 50% of the sewage sludge, respectively [41]. A research conducted in 985 Japanese municipal WWTPs demonstrated that the specific energy consumption of WWTP configurations applying CAS treatment coupled with sludge incineration was 0.38–1.49kWh/m^3, which could be lower in plants using CAS system without incineration. Moreover, specific energy consumption of advanced wastewater treatment was between 0.39–3.74 kWh/m^3 [42]. Although the data on advanced wastewater treatment did not consider whether incineration is adopted or not, it seems that the incineration and advanced treatment process cause a relatively higher energy consumption in municipal WWTPs. A comprehensive assessment was performed on sludge processing in reference and upgraded WWTPs [43] showing that separate processing of primary sludge (wet oxidation) and secondary sludge (intensive stabilization processes) reduced the total sludge production by 45–49%. Innovative technologies can improve sludge management, while the same authors reported that dewatered sludge decreased from 45-56 g SS/(PE×day) in conventional plants to 14–49 g SS/(PE×day) in the upgraded ones.

Power consumption depends not only on the design and technology but also on the plant size (PE, organic, or hydraulic load). In general, the smaller the facility, the higher its specific power consumption, where the unit energy consumption is in reverse proportion with wastewater inflow. In the study of [42] showed a decrease in energy consumption from 2.07 kWh/m^3 to 0.44kWh/m^3 for secondary treatment in oxidation ditch for inflow volume ranging from 100 m^3/d to 8500 m^3/d. An increase on the inflow from 600m^3/d to 283,000m^3/d, is accompanied by energy consumption varying in the range of 1.89–0.30 kWh/m^3 in a CAS process without sludge incineration [34].

Approximately 1% to 2% of the overall energy requirement is estimated to be attributed to wastewater utilities in a country level. Based on the report published by US EPA, the energy requirements for wastewater treatment in the US is expected to increase by 20% in the next years; in parallel to what is expected in other developed countries [44]. In this way, more pressure is put on the climate considering the increased demand for energy in the form of electricity that promotes GHG emissions [45,46]. In fact, the compliance with the Water Framework Directive requirements in the UK wastewater utilities is expected to result in more than 110,000 tonnes of CO_2 emissions annually only because of the increase in operational energy requirements [47]. According to the Energy Efficiency Directive, it is obligatory for large water utilities (>250 employees, income €43 million or yearly trading volume >€50 million) to perform energy audits. For instance, a water utility in the UK paid £5.9 million to the Carbon Reduction Commitment in 2012 due to carbon emissions from energy consumption in addition to the annual electricity [48]. The water utilities endeavour significantly to be able to cope with the increasing costs and climate change challenges.

In the last decade, wastewater sector started to recognise wastewater as a resource and makes effort to recover materials and energy [49]. There is an increasing number of studies on WWTPs that develops innovative technologies for efficient recovery of valuable resources, such as chemicals, nutrients, bioplastics, enzymes and water [50–52]. It is estimated that wastewater contains 1.3 MJ/person/day (6.5 MJ/L) in terms of chemical energy, 20% of the phosphorous consumed and 10%-30% of nitrogen needed in agriculture. In this regard, economic, environmental and industrial incentives take place in the circular economy concept of the water sector [53].

In recent years, great efforts have been made to promote the sustainability of WWTPs via two main approaches: improving energy efficiency and resource recovery [54]. Electricity consumption is not considered the most significant contributor to the operational carbon footprint during the wastewater treatment. Wastewater treatment processes are highly energy demanding, with high operational cost, and significant sources of GHG emissions, whose reduction has been recently mandated by the EU and other countries' policies [55] and raised as global concern [56,57]. CH_4, N_2O and CO_2 are the main GHGs emitted in WWTPs. Emissions are categorized as direct, if they are released during treatment processes, such as biologic treatment, sludge processing or biogas combustion. Emissions due to energy and chemical consumption, transport, waste disposal and treated water discharge are referred as indirect, because even if they are not emitted inside the plant boundaries, they are dependent on WWTPs activities or management decisions. In recent years, particular attention has given to N_2O emissions, as its Global Warming Potential (GWP) is 265 times higher than CO_2 [58]. The US Environmental Protection Agency (US EPA) estimated that wastewater sector was responsible for 5% of global non-CO_2 GHG emissions in 2005, with a predicted increase by 27% by 2030 [59].

N_2O is also the most significant contributor to ozone depletion [60]. The main processes that contributes to N_2O formation in a WWTP include activated sludge systems and autotrophic oxidation of ammonia to nitrite/nitrate under aerobic conditions (nitrification/nitritation). It is also an intermediate during the reduction of nitrate/nitrite to nitrogen gas (heterotrophic denitrification/denitritation) by heterotrophic denitrifying bacteria under anoxic conditions. In general, biological nutrients removal (BNR) processes applied at WWTPs have different design and operation approaches such as varying number of compartments/zones for nitrification and denitrification, recirculation flows, flow-patterns, operation mode etc. It was reported that the contribution of direct N_2O emissions during biological nutrients removal to the operational carbon footprint of WWTPs can be up to 78% [61].

Another source for significant N_2O emissions is the biological treatment of high-strength wastewater streams. The anaerobic supernatant is formed during the treatment of the primary and secondary sludge via anaerobic digestion following the sludge dewatering. This stream is small in volume (1-2% compared to the mainstream line), but very concentrated in nutrients and is conventionally recycled back to the primary treatment. In this regard, biological technologies (i.e. partial-nitritation – anammox) have been developed to treat side-stream high-strength streams in a cost and energy efficient way [62]. In these processes, favourable condition for N_2O generation can prevail (i.e. NO_2^- accumulation, elevated NH_4^+ concentrations etc.). Schaubroeck et al. reported that biological processes treating high-strength streams can contribute to the total direct N_2O emissions by over 90% compared to the mainstream BNR processes [63].

N_2O emissions originated from biological nitrogen removal in WWTPs were extensively studied [64–66]. The outcomes of these studies pointed out that environmental and operational parameters (i.e. DO, NH_4^+, NO_2^-, pH etc.) highly influence the magnitude and generation mechanisms of N_2O at WWTPs. Overall, N_2O emission dynamics vary temporally [67,68]. N_2O emission factors (EFs) estimated during monitoring campaigns in mainstream full-scale biological processes range between 0.0025% and 5.6% of the TN-load [18]. Vasilaki and colleagues [18] critically reviewed the quantified N_2O EFs in full-scale WWTPS in the last decade. Their survey showed that there is a significant variability in the monitoring strategy and sampling duration and frequency between different studies that can eventually impact the amount of the quantified N_2O EFs. For instance, discontinuous (i.e. via grab-samples) and continuous (i.e. via chambers and gas analysers) monitoring of full-scale wastewater treatment process yielded an average EF equal to 0.44% and 1.2% of the N-load, respectively. Additionally, Daelman and co-authors [61] suggested that short-term campaigns cannot accurately determine annual EF in the target system and the underestimation of actual emissions is highly possible. The relative error of the estimated annual N_2O emissions ranged between -22% and 35% (95% of the cases) by simulating a 50-days long N_2O sampling campaign.

Over the past few decades, energy recovery from wastewater has increased [69,70], and also been developed and applied in WWTPs. In fact, carbon neutrality and serious reduction in operation costs, and energy consumption can be achieved in energy self-sufficient WWTPs [34,70,71]. Up to date, many models and tools have been developed and integrated to determine the footprints of the WWTPs as discussed in the following section. These methodologies can help to take an action towards a more sustainable and energy-efficient urban wastewater management.

3. Modelling tools and data currently used to quantify the nexus

WWTPs generate significant amounts of operational data sourced from heterogenous sources such as sensors and laboratory analyses. In order to comply with regulatory discharge requirements, WWTPs have been using various monitoring techniques for so long to reduce pollution risks and control/optimise treatment processes. Several process parameters such as temperature, pressure, flowrate, DO, are conventionally monitored online in WWTPs. SCADA systems or remote-control tools are often applied to collect and manage all the data acquired online. Several studies have applied data-driven techniques to the variables conventionally monitored in WWTPs to predict latent variables and key performance metrics that cannot be quantified via sensors; more detailed overview of this topic can be found in another study [72]. Commonly-used data-driven methods for the classification and regression practices are based on i) linear methods for dimensionality reduction and regression, (e.g. principal component regression (PCR), partial least squares regression (PLS)) and

ii) non-linear supervised learning techniques (e.g. artificial neural networks, support vector machine (SVM) methods) [72,73].

The optimisation of the performance of WWTPs can be possible by using multivariable and multi-objective approaches that enables the correlation of energy consumption or operational costs with system performance [74,75]. The benchmark simulation model 2 (BSM2) was combined with Life Cycle Assessment (LCA) to evaluate the sustainability of different operating strategies [76,77]. The key features, development steps, calibration, validation, optimisation and uncertainty to develop integrated urban water models were reviewed elsewhere [16]. In addition, the data limitations in WEF nexus methodology, methods, and tools were addressed [78].

Overall, the type of data required for a holistic assessment of the WEFC are:

- fields within natural systems with very good protocols and metadata (i.e. related to weather and climate);
- fields within natural systems that are underdeveloped in terms of data requirements and reporting (i.e. ecosystem services);
- human systems in which challenges with both i) accessibility, data ownership, trust, inter-organizational competition, security and privacy issues for data-sharing and ii) lack of knowledge on which data are required and how they can be used, different philosophies in data importance, acquisition techniques prevail.

Water and carbon footprints of WWTPs are connected via energy footprints. However, there is still lack of availability of data on the long-term real-field WWTP. The study of Gu et al. [24] showed that on average 13.38 L of freshwater is required to produce 0.4 kWh of electric energy, used as input for treating 1 m^3 domestic wastewater, with a consequent emission of 0.23 kg CO_2 during the process. However, the reduction of Grey Water Footprint ΔGWF due to wastewater treatment was 6.78 m^3/m^3 of sewage treated in Chinese WWTPs. One impact of wastewater treatment is an increase in GHG emissions that results from energy use in WWTPs. Energy modeling can help to analyse different

WWTP management scenarios and choose the most suitable solution amongst various technology and operational options, before putting them into practice [24].

The International Water Association (IWA) developed the Activated Sludge Models (ASM) to simulate WWTP processes. During years, models have been upgraded and different versions are now available. Activated Sludge Model No. 1 (ASM1) describes the biological process of carbon and nitrogen removal and provides the concentrations of pollutants and solids in the biological reactors and in the effluent. Activated Sludge Model No. 2 (ASM2) includes the chemical precipitation of phosphorus, while Activated Sludge Model No. 2d (ASM2d) describes also the denitrification due to phosphorus accumulating organisms (PAOs) [79]. Activated Sludge Model No. 3 (ASM3) was developed based on ASM1 and distinguishes the decay processes of heterotrophic and autotrophic bacteria, includes a death-endogenous respiration process and considers the linkage between heterotrophs and nitrifiers. ASM3-BioP model was further upgraded to include phosphorus processes. Anaerobic Digestion Model No. 1 (ADM1) was developed to describe biological and physical-chemical processes in anaerobic digesters [80].

To integrate models with operative controls of WWTP and foster a plant-wide analysis, benchmarking tools were developed by combining process models (e.g., ASMs) with instrumentation, control and automation (ICA) equipment [81]. IWA developed Benchmark Simulation Models, creating a simulation environment in a defined plant layout, providing a generator of influent flows and loads, testing procedures and evaluation criteria. BSM1 [82] represents a virtual plant integrating biological process modelled with ASM1 coupled with a secondary settler and can evaluate different control strategies in a period of 14 days in different weather conditions. BSM1LT is a modification of BSM1, with a longer evaluation period (609 days), and simulates toxic events or problems on sensors and actuators [83]. BSM2 [84] has a more complete layout, adding to BSM1 a primary clarifier and a sludge treatment line, consisting of a thickener, an anaerobic digester modelled with ADM1, and a dewatering unit. Dynamic behaviour of sensors and actuators is modelled considering the response time, noise and measuring interval of each instrumentation. The objectives for the monitoring strategies are to maintain the NO_3-N concentration in the second compartment of biologic reactor at a set point of 1 g/m^3 and the dissolved oxygen concentration in the fifth compartment at 2 g COD/m^3. For N-NO_3 control, the manipulated variable is the internal recycle flow rate (Qa), while for DO regulation the manipulated variable is the oxygen transfer coefficient in the fifth compartment (KLa,5). BSMs can evaluate performances of different scenarios considering two indices, describing treatment efficiency and costs. In particular, the Effluent Quality Index (EQI) represents the pollution removal efficiency in terms of TSS, COD, BOD_5, TKN and NO_X; while the Operational Cost Index (OCI) includes operating costs in a plant, such as energy for aeration, pumping and mixing, additional carbon source, sludge production, methane generation and the net heating energy required for anaerobic digestion [45].

ASMs generally require inputs of flows characterization, such as flow rates, concentrations and pollutant loads, operating parameters values, such as retention times or dissolved oxygen settings in aerated tanks, environmental conditions and volumetric and surface dimensions of the different treatment units. Models contain assumptions on kinetic variables and process parameters default values. BSMs integrate those data with typical parameters measured by online sensors. Regarding Carbon and Energy footprints, additional data are required, such as energy consumptions, chemical dosage, transports and the final destination of sludge and wastes. Integrated models are able to simulate influent flows from catchment and sewer network; however, open-access models, such as SWMM developed by EPA, can be used to obtain sewage water characterization from morphologic data, demographic information, land-use factors, rain flows, pipeline and furniture characteristics.

3.1.Carbon footprint

Carbon footprint is an evaluation of GHG emissions due to WWTPs activities. General guidelines on Carbon footprint inventory are provided by ISO 14064-1:2018*[1]. However, we still miss a unified methodology to assess carbon footprint from WWTPs [58,85]. One of the simplest ways to evaluate carbon footprint is using EFs that normalize the emissions with respect to a process parameter. Depending on the category, there are many databases that collect and update EFs. IPCC Guidelines provide EFs specific to different processes or activities and developed an online database, the EFDB*[2], that can be freely consulted. On the other hand, more specific EFs can be evaluated at national level. For instance, ISPRA and SINANET developed national databases for the main activities in Italy [86], while the Swiss national GHG inventory has been updated under the UNFCCC in 2020, covering the years 1990-2018 [87].

According to IPCC an EF of 1.6% for of the total N-load is suggested [88]; to increase reliability of the EF estimates in large WWTPs, a country-specific EF is also proposed. Reliable EFs estimates require long-term sampling campaigns to capture the seasonal variability of N_2O emissions, however, this is rarely applied in practice due to the associated costs and labour demands.

Many Excel tools have been proposed, such as the Carbon Footprint Calculation Tool [89] developed in the project entitled “Calculation of the CF from Swedish WWTPs” (SVU 12-120). More sophisticated tools use models to simulate treatment processes. First, steady-state process models were developed to assess GHG emissions. In recent years, dynamic models are also applied to evaluate strategies for GHG emissions mitigation [81].

3.1.1. Carbon footprinting models

Procedures and equations to estimate GHG emissions from different sources or activities are reported in the IPCC Guidelines for National Greenhouse Gas Inventories. At national level, UKWIR developed a standardised workbook, the Carbon Accounting Workbook (CAW) [90], that can be followed for estimating operational GHG emissions.

Models can be used to integrate calculation in an automatic way. An example of steady-state model is represented by the diffusive emissions estimation model (DEEM), that uses ASM1 framework and includes the estimation of CO_2 and N_2O emissions due to nitrification process. Rodriguez-Garcia et al. [91] applied the steady state DEEM to Spanish WWTPs and implemented its results for LCA.

The Horizon2020 (H2020) project “CF-FOOT-CTRL” *[3] developed a model in the same name of a software tool to evaluate the carbon footprint in WWTP. Simulations are performed using sub-models for the main stages of the treatment line. Primary treatments, as the primary clarifier, the gravity and mechanical thickeners and the dewatering unit, are estimated using mass balances based on the efficiency of each unit; the biological reactor is simulated using ASM1 and the secondary settler is schematized using a one-dimensional model. An anaerobic digestion sub-model was developed for the sludge line. For instance, in a C-FOOT-CTRL and H2020 SMART-Plant*[4] combined approach: The software tool has three components, the online measurements, the database and the dynamic model for carbon footprint estimation. The integrated mathematical model for the simulation of a WWTP consists of several sub-models, one for each treatment unit. The different sub-models were developed in order to simulate the processes in the all stages, the energy consumption and the GHG emissions. More specifically, for the processes taking place in the bioreactor, the developed mathematical model is based on the activated sludge model no.1 (ASM1), while for the secondary settler a one-dimensional model was used. For anaerobic digestion, an anaerobic digestion sub-model was developed and in cases of pre-treatment, mass balances were used with respect to the efficiency of each unit such as primary clarifier, gravity and mechanical thickeners and dewatering unit. Besides the simulation of the processes within the plant units and the assessment of the effluent quality, the mathematical model is able to estimate biogas production of the anaerobic digestion of sludge, oxygen consumption of the aerated compartments of the bioreactor, energy consumption of each unit of the WWTP and direct and/or indirect GHG emissions.

The Activated Sludge Models for Nitrogen (ASMN) is a modified version of ASM1, in which the nitrification process is described in two steps and the denitrification in four steps. Porro et al. [92] modified the BSM2 model substituting ASM1 with ASMN and including the model proposed by Guisasola and co-authors [93] to predict CH_4 emission in the sewer system. The combined models were applied to a sewer system and to a WWTP, finding that N_2O emissions from WWTP were responsible for approximately 25% of the total system GHG emissions, while CH_4 emissions from the sewer system accounted for 8%. In terms of WWTP performance optimization, low dissolved oxygen (DO) results in CO_2 emissions reduction due to the aeration system, but increase of the N_2O emissions from the biological process [81].

The BSM2G model was developed by Flores-Alsina et al. [45] to implement the BSM2 in order to analyse GHG emissions from WWTPs. Model simulations are evaluated using the EQI and OCI indicators included in BSM2, in order to assess pollutant removal efficiency and related costs. [45] used the BSM2G to evaluate GHG emissions under different operative conditions in WWTPs. The BSM-e model developed by Sweetapple et al. [94] implements the BSM2, dividing the denitrification process in four steps, including N_2O stripping and CO_2 emissions. BSM2-e was used to evaluate strategies to reduce GHG emissions, adopting multi-objective optimization criteria. They found that the variance in total GHG emissions is mainly related to the changes in direct N_2O emissions.

In most cases, WWTPs performance are conditioned by economic aspects and oriented to the reduction of energy consumption, operating strategies to decrease sludge production and increase biogas generation. In addition to operational costs, it is also crucial to consider environmental impacts when realizing these aspects since it allows to reduce direct and indirect GHG emissions [95–97]. Operating parameters (such as DO, temperature, influent C/N ratio, sludge retention time, nitrite concentrations in nitrification and denitrification stages) may have a high influence on the N_2O emission. The treatment of GHGs in WWTPs can be another possible solution to reduce emissions. Industrial gaseous streams such as N_2O, CH_4, and CO_2 can be annihilated by various technologies available, while these technologies are still quite expensive and there is still a need to develop efficient low-cost technologies [98].

3.1.2. Carbon footprinting tools

Tools have been developed to facilitate Carbon footprint estimation, with different levels of complexity depending on the type of the model applied. The choice of the complexity level, from the simplest, that consider steady-state scenarios, to the more complex ones, that perform dynamic simulations, is strictly related to the availability and the affordability of the input data, other than the quality of the requested output.

A ready-to-use tool for carbon footprint calculation consists in a MS Excel spreadsheet, The Carbon Footprint Calculation Tool (CFCT) dedicated for WWTPs, uses EFs provided by literature studies and IPCC Guidelines, together with Global Warming Potentials (GWPs), to evaluate the total CO_2 equivalent emissions related to wastewater treatment [89]. The tool requires input data for influent and effluent characterization, energy consumption, chemical dosage and supply, sludge and waste production and final disposal destination.

In addition, CF-TOOL-CTRL evaluates on-site and off-site emissions [99]. The tool estimates the direct emissions due to biological, biogas production and consumption of chemicals, and includes the indirect emissions due to energy consumption and sludge disposal.

3.2.Energy footprint

Energy Footprint allows the evaluation of the energetic efficiency of wastewater treatment plants and the individuation of the most consuming categories, considering that 25 – 40% of operating costs are attributed to energy consumption in conventional WWTPs [34]. Energy footprint is performed through the evaluation of consumptions, related to specific parameters that indicate the quantity of energy required to treat a certain amount of water or pollutant load. Energy footprint needs a common and shared methodology in order obtain benchmarks to compare different plants with different treatment capacity and operating in different conditions of loads, environment or regulatory context, in order to evaluate relative performances. Specific energy consumptions are generally used that refer to a process parameter.

ENERWATER*[6] methodology for Energy Footprint was developed under a project founded by H2020. Two different levels of analysis are applied: Rapid Audit (RA), that is a general evaluation of the plant; and Decision Support (DS), that specifies each stage of the treatment process. Different levels of detail can be performed in the DS analysis, depending on the quantity and the quality of the available data, from Bronze to Platinum scenario. Different energetic vectors are included and energy requirement for chemical production are also included. Net energy consumption is calculated considering the energy production and recovery that may be applied in the plant. Key Performance Indicators (KPIs) are calculated, normalized into EPIs and weighted with literature values, provided by the ENERWATER database. Finally, labels are attributed for each stage of the treatment process and EPIs are aggregated into a unique indicator, the WTEI, that characterizes the energy label of the whole plant.

According to Rosso et al. [100], different models can be used to assess Energy Footprint of WWTPs, depending on the kind of data available as inputs, from a cumulative analysis when only energy bills and historical information are achievable, to a dynamic energy footprint modelling, where it is possible to consider unit operations separately and detailed characterizations are available. WWTP model was set up using ASM1 and ADM1 in the SIMBA*[5] simulator. Applying their model to different plants they found that activated sludge process was the most impacting unit for energy consumptions. Moreover, modelling could support the optimization of the aeration system, improving effluent quality and reducing energy wastage. Optimization strategy was developed considering the F:M ratio, varying influent load and temperature.

3.2.1. Energy footprinting tools

The H2020 project ENERWATER provides a tool to perform Energy Footprint of a WWTP. Calculations are set into an online free application from the website. Depending on the type of WWTP selected and the different level of analysis (RA or DS), different data are required by the tool. For RA assessment are needed: treated volume; energy and chemical consumptions along the plant; routine data from influent and effluent characterization in terms of COD, Ntot and Ptot, TS produced by the sludge line, and, in case of plants focused on water reuse, the log reduction of *E. coli*. For DS level, energy consumptions shall be measured in situ with specific meters installed in order to cover at least 90% of the total consumptions reported in the energy bill. Different energy vectors use, chemical dosage and energy production must be provided. For pre-treatments, treated volume is required; the primary stage needs TSS removal; biological treatments require a weighted indicator of load removal in terms of COD, N and P, called TPE; tertiary treatments are compared with E.coli log reduction; while sludge line is evaluated with a composite indicator, TSE. Data should be measured directly in the plant with a required frequency, in order to assess the maximum level of analysis (Platinum).

Energy consumption and carbon footprint of different stages in a conventional WWTP is illustrated in **Fig. 3**.

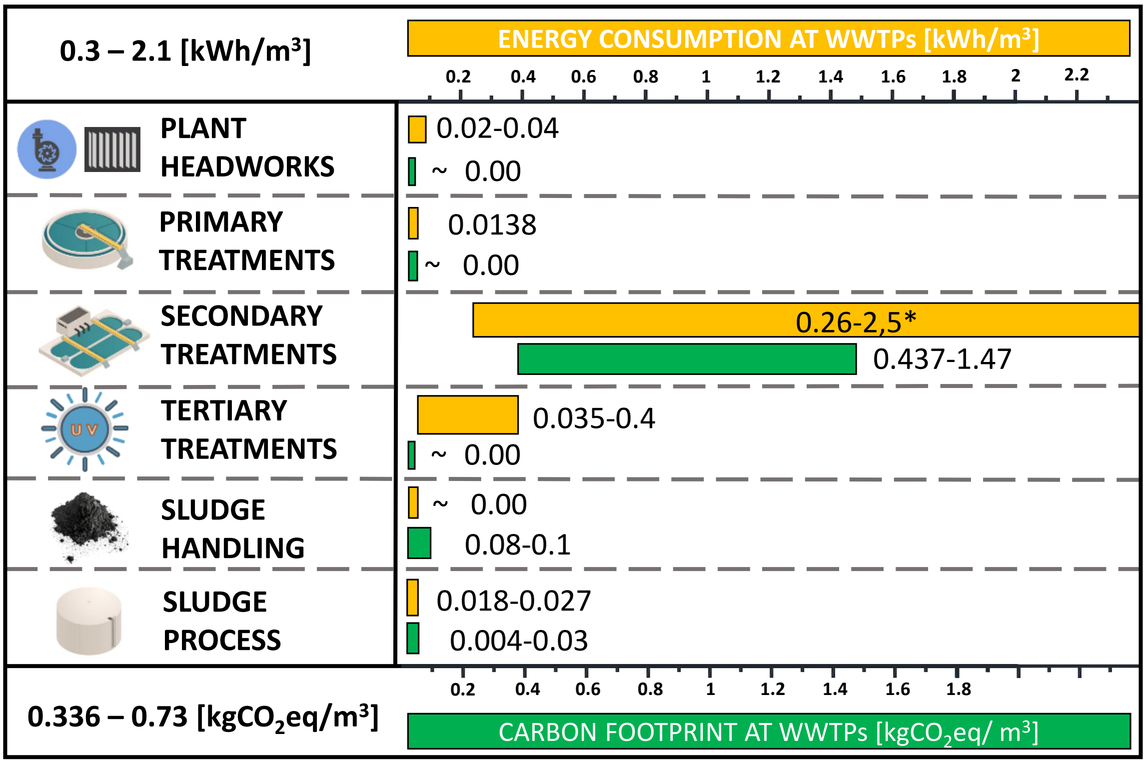

Fig. 3. Energy and carbon footprints at different stages in a WWTP (Based on the data taken from [35,101–104]).

3.3.Water footprint

Literature suggests two main approaches that have been developed for the calculation of the Water Footprint of a product [105]. The first one follows a volumetric approach and was developed by the Water Footprint Network (WFN) [106], whereas the second one is based on a LCA approach as introduced by the LCA community [107].

According to the WFN, the water footprint of a product is an important spatial and temporal indicator of freshwater use that looks into both direct and indirect water use of the product through the whole supply chain [108,109]. The WFA approach aims to identify the availability of freshwater resources identifying three types of different water-use sources, the blue water (WF_{blue}), that refers to the freshwater consumed for the production of a service or a product and not returned to the initial catchment, the green water (WF_{green}) that is defined as the precipitation water consumed instead of becoming a run-off and the grey water (WF_{gray}) that indicates the pollution of the freshwater resources. The methodology consists of four stages: the goal definition, the assessment of the Water Footprint, the evaluation of sustainability and the formulation of the response scheme [106]. This approach has been focused on identifying the water-relating hotspots of a product's life cycle and proposing actions towards improved integrated water management schemes, better resource allocations and use of more water efficient processes and products [110]. Recently, the water use-related environmental, social and economic dimensions have been integrated in this approach towards a water sustainability assessment; relevant studies, though, are still limited [111].

On the contrary, the LCA-based Water Footprint approach of a product intends to assess water-based impacts through the whole supply chain and implement Life Cycle Inventory methods [107]. This approach has been extensively used for the assessment of different alternatives towards the minimisation of products' environmental impacts [112]. However, most of the widely accepted LCA methods disregarded water-based impacts and water use [113]. Hence, the UNEP-SETAC WULCA project [107] aims to introduce a framework towards an LCA-based Water Footprint assessment. In that direction, a new ISO standard on water footprint (BS ISO 14046, 2014) has been published proposing guidelines and requirements for LCA-based Water Footprint assessment.

Generally, the LCA approach targets the quantification of potential impacts on humans and climate connected with water deprivation and even water contamination and focuses on the assessment of environmental indicators such as eutrophication, ecotoxicity, human toxicity and water scarcity [114]. The methodology comprises four steps including goal and scope definition, Life Cycle Inventory (LCI) accounting and impact assessment and interpretation. Even though both methodologies aim to contribute towards water preservation, the different approaches that they follow result in non-comparable quantitative indicators. However, as Boulay and colleagues have suggested [115], the quantitative indicators of the blue water footprint can be potentially used as inventory flows in the LCA methodology.

The Water Footprint Assessment methodology was developed by the WFN and is divided in four steps: First, goals and scope are defined; then the water footprint (WF) is calculated, using the following equation:

$$\mathrm{WF} = WF_{blue} + WF_{green} + WF_{gray} \tag{1}$$

Once WF has been calculated, the sustainability is evaluated considering environmental, economic and social aspects. Finally, strategies to improve the water footprint are provided.

Regarding the evaluation of WF_{gray}, Morera and others [116] proposed a method based on a mass balance of the pollutants (p) at the discharge points of WWTPs:

$$Q_{eff}C_{eff,p} + WF_{gray}C_{nat,p} = (Q_{eff} + WF_{gray,p})C_{max,p} \tag{2}$$

Where Q_{eff} is the effluent flow, $C_{eff,p}$ is the concentration of the pollutant p in the effluent water, $C_{nat,p}$ is the concentration of the pollutant p in the water body, $WF_{gray,p}$ is the grey water footprint calculated for each pollutant (p) and $C_{max,p}$ is the maximum level of concentration admitted for the pollutant p. The total grey water footprint WF_{gray}represents the maximum of the diluting freshwater required for each pollutant p, as shown in the equation below.

$$WF_{gray} = \max(Q_{eff}\frac{C_{eff,p}-C_{max,p}}{C_{max,p}-C_{nat,p}}) \tag{3}$$

WF_{gray} depends on local regulatory requirements for water quality; thus, this indicator cannot be used to compare WWTPs that discharge in water bodies with different quality characteristics. The indicator “Water Footprint Reduction” (ΔGWF) was then proposed by Gu et al. (2016) to represent the reduction in freshwater volume required to assimilate the pollutants due to WWTP, independently from water quality standards. ΔGWF is calculated as follows:

$$\Delta\mathrm{GWF} = \frac{(C_{in}-C_{out})}{C_{out}}V_{treated} \tag{4}$$

Where C_{in} and C_{out} represent respectively pollutant concentrations in the influent and in the effluent, while $V_{treated}$ is the water volume treated in the time period under analysis.

The eGWF indicator has been introduced to evaluate the nexus between energy consumptions ($E_{consumed}$) and water footprint, considering the energy consumed to reduce the WF_{gray} in WWTPs:

$$\mathrm{eGWF} = \frac{\Delta \mathrm{GWF}}{E_{consumed}} \tag{5}$$

A greater eGWF corresponds to higher ΔGWF for a unit energy input into the wastewater treatment process.

3.4.Integrated models and tools

WWTPs management implies a series of impacts on different sectors, connected into the WEFC nexus. Catchment, sewer network, WWTP and water bodies receptors are highly interconnected. Characteristics, efficiencies or variations in each stage of the urban water cycle can affect the other stages. In order to quantify the WEFC nexus, all the steps that involve wastewater production, transportation, treatment and reuse should be considered. Integrated Urban Wastewater Systems (IUWS) have been developed to assess those linkages. Integrated models can help providing a wider panorama of all the interconnections that implies the urban wastewater cycle, from its catchment to the final destination.

Urban Wastewater System (UWS) modelling was developed to consider the interconnections amongst catchment, sewer network, WWTP and river system following a holistic approach. Benchmark Simulation Model BSM-UWS is an open-source system-wide model developed in Matlab, used to simulate, predict and evaluate different strategies in UWS. BSM-UWS is applied to provide an integrated system assessment. The toolbox uses different sub-models for each UWS stage, connected through interfaces in which mass-balances are verified. The BSM2 dynamic influent pollutant disturbance scenario generator (DIPDSG) is used to simulate the catchment model is simulated using, in order to obtain flow and concentration of pollutants in different wastewater sources: domestic, industrial, stormwater and infiltration to sewer. Sewer network sub-model considers the transport of wastewater and first flush loads from the catchment to WWTP, considering the presence of storage tanks and pumping stations. WWTP is modelled through ASM2d, while river water system is simulated using the IWA River Water Quality Model (RWQM).

Performances of each sector are assessed using evaluation indexes. For the sewer network overflow duration, frequency, volume and overflow quality index (OQI, kg pollutant units/day) are considered. WWTP efficiency is evaluated considering influent quality index (IQI, kg pollutant units/day) and effluent quality index (EQI, kg pollutant units/day). River water system is evaluated considering dissolved oxygen (DO) and unionized ammonia (NH_3) concentrations. Three main control strategies were used by Saagi and others [117]. Sewer network system efficiency is evaluated considering the flowrate at WWTP inlet, manipulated by varying the flows from the storage tanks. Concerning the WWTP, the DO concentration in the aeration tanks is measured, modulating the oxygen transfer coefficients k_La. River water system is evaluated through the concentration of ammonia, controlled by the thresholds set up for the by-pass flows in the WWTP.

BSM-UWS is applied on different tools. WESTforIUWS, developed by Dansk Hydraulisk Institut in 2016, developed water quality-based indicators, including uncertainty and sensitivity analysis. SIMBA# water, developed by the German Institut für Automation und Kommunikation in 2016, uses hydrological and hydrodynamic models for the sewer network, biochemical and physical processes to simulate the WWTP and modules for biochemical processes in the river. CITY DRAIN [118] is an open-source Matlab based toolbox that uses hydrological models for sewers and river systems as well as a simplified model for WWTP [118]. It allows the users to create new blocks in addition to the existing model library [119]. The models and tools that are commonly used to measure carbon, energy and footprints in WWTPs are summarized in **Table 1**.

Table 1. A summary of some of the models and tools used to measure carbon, energy and water footprints in WWTPs and to quantify the nexus.

Footprint	Model/method	Tool	Reference	Advantages	Disadvantages
Carbon footprint	EF, IPCC Guidelines	Carbon Footprint Calculation Tool (CFCT, 2014)	[89]	Easy to use, based on simple calculations; EF database available	Uncertainty of EFs; representativeness of EF to site-specific conditions

	Mass balances, ASM1, sub-models for secondary settler and AD	CF TOOL CTRL	[120]	Implemented sub-models to simulate different operations of WWTPs	CH_4 direct emissions from biologic unit not included
	Diffusive Emissions Estimation Model DEEM		[81,91]	Easy application for Life Cycle Assessment	CH_4 direct emissions from biologic unit not included
	Activated Sludge Models for Nitrogen ASMN		[81,121]	Implemented N_2O formation in nitrification and denitrification processes and CH_4 production and emissions in the sewer system	Model complexity
	BSM2G		[45,81]	Implemented indexes for strategy control	Over-parametrization, calibration required
	BSM-e		[81,94]	Included N_2O and CO_2 stripping	Overparameterization, calibration required
Energy footprint	ENERWATER	On-line tool	[122]	Estimation of WWTPs energy efficiency	Measured data required for Decision Support
Water footprint	Water Footprint Network (WFN)		[106]	Evaluation of the impact in water resource of a product or activity	Limited studies in the urban water cycle and in water and wastewater infrastructures
Integrated footprint	BSM-UWS	WESTforIUWS	[117,119]	Implemented water quality-based objectives, uncertainty and sensitivity analysis	Model complexity
		SIMBA# water	[117,119]	Controller programming with industry standard languages	Model complexity
		CITY DRAIN	[117–119]	Open-source toolbox	Simplified models

3.5.What is missing?

In recent years modelling development gave a great contribution for the estimation of WWTP footprints, providing support tools for decision-making processes. WEFC nexus models can be used to evaluate designed solutions or scenarios, and support decision making. Even if more specific models are being constructed to fit WWTP conditions, still not all the footprint assessments can rely on specific tools for WWTP modelling. Different models are based on different hypothesis for process simulation or are focused on different parameters. A comprehensive tool that considers all the sectors of the WEFC nexus is still missing.

In addition, besides several Nexus studies at wide scale, ranging from global to regional to national, but with very coarse resolution, local specificities must be addressed when designing effective management plans because international and regional decisions have a direct effect at the local level. Nexus quantification depends on accurate, open access information. Decision-makers are often hindered to compare management options, make informed decisions balancing economic, social and environmental interests, and subsequently evaluate and prioritize potential sustainability solutions. To overcome this bottleneck, a mechanism is needed for data and monitoring requirements and trustable information provision.

4. The nexus approach in reclaimed water reuse for precision irrigation and smart agriculture in peri-urban areas

There is a great share of water and energy resources in agriculture for food production. In a most common sense, water and energy are required for irrigation, food production/processing and energy production, while food production can also count for biofuel feedstock [6,123,124]. Approximately 70% of the total water demand is represented by irrigation in agricultural production. In the Mediterranean region, which faces severe problems on water availability due to climate change, this demand is projected to increase up to 18% until the end of this century [125]. In fact, it is estimated that the Mediterranean region could save 35% of water by implementing more efficient irrigation and conveyance systems [126]. Therefore, the optimal use of limited water, energy, and land resources should be well considered for a sustainable agricultural system.

Although, urban and rural areas are geographically dispersed, their functioning is tightly interconnected [127]. As urbanization and industrialization have increased especially in developed countries, some developing countries have experienced pressure from the decline in both quality and quantity of farmland resources, which further witnessed remarkable transitions in rural livelihoods. Some common livelihood strategies during these transitions include rural-urban migration, off-farm employment, adjusted cropping patterns, land transfer, and changes in production inputs [128]. The complexity in the nexus approach is utmost important for areas where agricultural activities are the primary source of income, such as peri-urban areas [129].

The concept of wastewater reuse in agriculture refers to further use of “treated” wastewater for crop irrigation. This is essential for managing water resources, especially in arid areas that face water stress due the irregular availability of water sources throughout the hydrological year [130]. Recycle and re-utilization of nutrients and water from urban wastewater to urban agriculture can be a remarkable strategy to efficiently address the WEFC nexus. Although these cycles may still use energy and increase GHG emissions, there are advantages of water reuse and nutrient recovery [131]. Some of the environmental benefits associated with the agricultural reuse of advanced treated wastewater include reduced pressure on aquifers, successful groundwater recharge, reduction in synthetic fertilizer demand and expenses due to nutrients presence in reclaimed water, and higher crop yields for some crop types that are grown with reused water [132]. When water reuse implementations are coupled with advanced, water-saving, drip irrigation technologies, e.g., sensor-based systems (see Section 5), the impacts on water conservation and overall crop production can be remarkable. Besides the advantages, health issues should be considered and risks should be addressed when urban wastewater is used for irrigation [133]. Food safety and environmental pollution (i.e. soil and aquifers) are the main critical points in these practices. A new method called wastewater reuse effectiveness index (WREI) was developed [134] from the concept of the nexus approach by elaborating the concepts of trade-offs and thresholds, which measures the effectiveness of wastewater reuse and assesses environmental risks.

As already addressed and summarized by Fernández García et al. [135], the concerns about optimizing WEFC nexus in irrigated areas have led to the development of different strategies aimed at reducing the use of energy and water resources. These strategies can be grouped into: (i) measures based on energy audits and benchmarking analysis, (ii) measures with respect to water distribution network management, (iii) strategies to optimize the performance of pumping station, (iv) solutions to minimize overall operational costs, (v) actions towards water distribution design, and (vi) smart irrigation. In smart irrigation, sensors are developed to adopt precision irrigation and smart agriculture and to support the decision making for applying the right amount of water at the right time and at the right place [136–138]. Sensors can estimate the volumetric water content and according to evo-transpiration crop models the right quantity of water could be determined to avoid water stress [139]. Considering the system management of water service, the issue of water reuse involves different levels of stakeholders in many national and local applications. For instance, a great part of water for agriculture is managed by irrigation and reclamation consortia in Italy, which are responsible for providing the farmers water for irrigation and for draining water from the fields. The activity of the irrigation and reclamation consortia is under the supervision of the Regional Authority, but it receives the inputs also by municipalities and farmers association. A simplified scheme for the involvement of stakeholders for a smart irrigation is depicted in **Fig. 4**. In this scenario, the engagement of end-users and next generation of irrigation channels/distribution network equipped with interconnected meters could make possible to implement a match-making tool to maximize the reuse of water from WWTP.

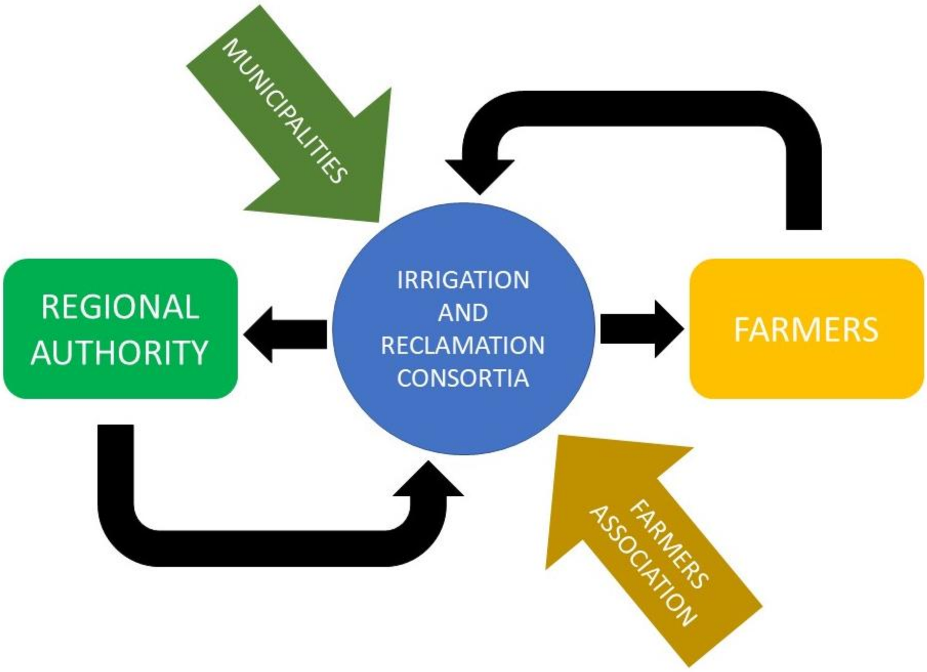

Fig. 4. Involved stakeholders for a digitalized irrigation architecture.

5. Digital solutions and serious games addressing the nexus

Many cities are currently initiating public-private partnerships and/or special financing to adopt the “smart city” model with respect to sustainable urban development. The basic idea behind the smart city concept is to increase the effectiveness of city governance by creating positive feedbacks between end users and innovative technologies, building a communication paradigm in which the objects of everyday life are equipped with digital solutions [140]. The main goal of the smart city model is to reduce costs, improve efficiencies, and ease the life of citizens by providing urban planners with definitive tools [141]. Hence, smart cities are believed to be a promising solution to environmental challenges of urban life in the near future where resources and processes can be managed in a closed system [142]. The integration of smart cities with digital solutions offers the chance to reorganize urban infrastructures, likewise transportation or food and water supply, in much smarter ways [143,144]. When developing a smart city with proposed possible digital solutions, the nexus approach must be placed at the heart of the plan. Recently, the digital and ecological transition which is permeating the global (e.g. The Agenda 2030 for Sustainable Development) and European policies and initiatives (e.g. New European Green Deal) has integrated the “smart” with the “circular” approach to cities and regions. This approach is being highly applied in the water management, and not only for the urban life but also should be taken into account for rural areas that was highlighted by Hosseini and colleagues [143]. Despite the afore-mentioned points of motivation, some critical concerns and gaps regarding the concept of smart city were also addressed elsewhere [140].

Nevertheless, many public and private water service providers have been reclaiming their conventional supply-oriented strategies toward a more sustainable urban water management. On the other hand, this transmission requires heavy work originated from accurate, adequate and reliable data that can be thoroughly and cost-effectively interpreted to help utilities improve their services, reduce water and energy losses and manage demand [145].

Intelligent metering (or smart metering) has high potential to evolve customer engagement and management of urban water by utilities into technologies that encourages sustainable urban water management. In general, intelligent metering is a blend of components and procedures designed for the continuous and remote monitoring and assessment of water use (also electricity and gas) to inform strategic planning processes and aid decision making. These systems include four key processes: the (i) measurement; (ii) transfer of the data; (iii) data process and analysis; and (iv) feedback. Through these steps, the determination of water consumption, in real-time or near real-time, is enabled and the possibility to read consumption both locally and remotely is provided [145]. However, one of the main challenges stands as the vast volume of continuously accumulating information is used to ensure that digital technology enhances urban water, electricity and gas management [146].

In urban water cycle, functional subsystems, e.g., drinking water treatment and distribution, wastewater and stormwater collection, wastewater treatment and discharge, are all interconnected and managed by computing and control systems through physical domain sensors [21]. In a CPS framework, monitoring and controlling processes for digital representations work in real time, with interactions between virtual and physical spaces of systems [22]. The application of CPS in the water sector can bring high added value to the IUWM. Online monitoring and warning systems, so-called (bio)sensors, has received considerable attention in recent years in the integrated assessment of water networks such as WWTPs, combined sewer overflows (CSOs) as well as receiving water bodies [147,148]. Sensors allow the physical infrastructures to be monitored and controlled, and provide high sensitivity, selectivity, reliability, simplicity, low-cost and real-time response. There is also an increasing interest in operating WWTPs with advanced digital control systems to minimize energy consumption by utilizing the energy (biogas) potential. For this purpose, digital solutions are often used to optimize performances across sectors, e.g. wet-weather control of WWTPs aimed at temporarily increasing their capacity to avoid CSO and bypass during rain [149].

Biosensor-based strategies for wastewater monitoring can be classified into three main categories for the detection of (i) organic materials (ii) heavy metals and (iii) microorganisms [148]. Currently, the on-going (2019–2022) H2020 Innovation Action Digital.Water-City (DWC*[7]) deploys digital solutions with the aid of sensors for water services at the communities in five European urban and peri-urban areas in Berlin, Milan, Copenhagen, Paris and Sofia. These solutions are expected to minimize health-related-risks in water reuse and bathing water by improved decision support and added-value from on-line data and advanced modelling. In addition, based on scientifically sound and field validated wastewater treatment and crop growth models, a web-based serious game is being developed for near real-time assessment of the WEFC nexus, engaging public to overcome social and economic barriers to water reuse, as summarized in **Fig. 5**.

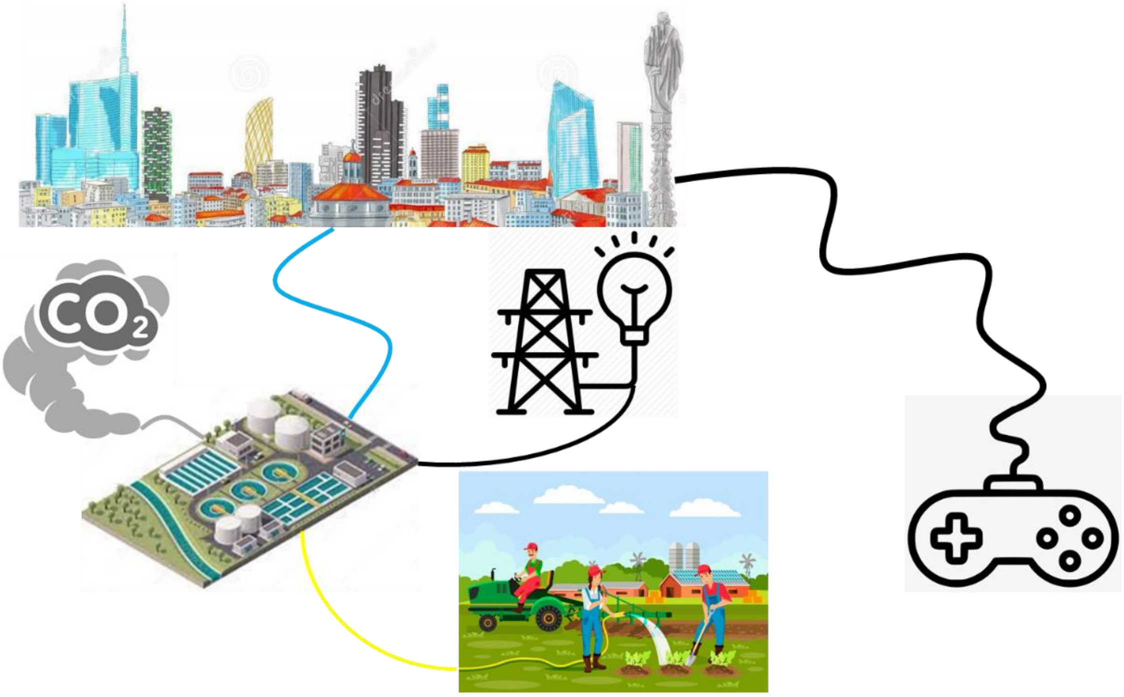

Fig. 5. Schematic of the data-driven serious game on the water reuse, carbon, energy, food and climatic nexus under development in H2020 DWC (from www.digital-water.city).

Serious games have presented an alternative way to didactic tools from an innovative strand for raising awareness on sustainable water management in the last years [150]. Serious games are often described as the games that are not intended only for amusement and entertainment but also have a specific aim with an explicit educational purpose [151,152] and for these reason a rational design is mandatory [153]. A serious game approach brings a learning objective with a fun activity that aims to increase the potential for learning uptake, self-learning and knowledge retention [154]. These games help to (i) create a realistic learning environment (ii) elevate the potential for interactive visualization (iii) improve social learning and decision making skills and (iv) enable the involvement of stakeholders from the beginning of the planning process [152,154].

While serious games have been widely used in education and training, especially in military or flight simulators [154], in the last decade, such games combining computer simulation and role playing games have been developed also in water-related issues such as water management [155–157], wastewater infrastructures management [158], water governance and policy [159], as well as land management [150] and optimal sensor placement to localize leaks in water distribution systems [160]. As the understanding of the WEFC nexus has become a more important approach in a holistic way, a few serious games have been demonstrated in recent years to address the nexus from regional to global scales. These games allow to investigate the trade-offs and synergies between sectors and enable the stakeholders to better understand nexus-related policies. For instance, Sušnik et al. [154] developed a serious game within the EU H2020 project SIM4NEXUS*[8] and investigated the potential cross-nexus implications and synergies due to policy interferences for several case studies at different scales as well as at different time horizons. The authors provided a frame for complex systems that depict the interactions between the water, energy, food, land and climate sectors within the nexus that can be modelled against future climate scenarios.

The water industry of the future is expected to be digital, smart and resource efficient. At this point, benefits provided by digital solutions can reduce the fragmentation of knowledge across the water value chain and among stakeholders by facilitating information exchange through increased interoperability of data and digital systems.

6. Further recommendations for research and application to bring nexus perspective to operators

Water, energy and food are interlinked resources managed by separate institutions and operators to facilitate decision-making and optimization, which overlooks the interdependences and interconnectivity of the resources. To implement the Nexus concept, development of multilevel governance systems, investment into human and social infrastructure, encouraging innovations across water-using industries, and leveraging public–private partnerships, while involving local citizens in co-creation and decision-making processes, must be supported. Solutions should come from all stages of supply chains, from development to consumption, to provide water, food, and energy protection to a growing and urbanizing global population under high climate challenges to face. The phrase "more crop per drop" is commonly used to describe increased water productivity, whereas the phrase "more biomass per decrease" is more fitting to the Nexus concept [161]. Unless agricultural policies can guarantee revenues for small and medium size farming systems which includes payment for these resources, public regulation, and subsidization of the energy costs of non-conventional water resources appear to be the only way forward. Explicit Nexus strategies across governance levels are therefore required if non-conventional water resources are to contribute to the sustainable management of water resources. It is obvious that the provision of water, energy, and food protection for citizens within a geographical area is concerned with the consumption side of the region rather than the development side. As a result, trade between regions is essential to safeguard these three sources. However, we must not forget that sustainability does not mean self-sufficiency. So far, only few projects have considered the Nexus concept in practise for efficient and sustainable use of resources in the water sector in practise. For instance, H2020 SIM4NEXUS*[10] applies the Nexus concept in 12 case studies at different scales to better understand interlinkages of decision making across spatial scales, and support decision making in the short-, medium- and long-term. H2020 MAGIC-NEXUS*[11] created a set of relationships between identified factors to explore the complexity between water, soil, energy, and climate while integrating social challenges, stakeholders and citizens perceptions related to the Nexus into the analysis. Finally, demographic change, urbanisation, climate change, digitalisation as well as the circular economy are all tightly interconnected with water, energy, and food, offering both challenges and opportunities for Europe to lead the way towards a sustainable future. In order to fit to the digital age, we must give serious efforts to move towards a greener Europe supported by an integrated approach to the establishment of WEFE-smart communities and society, even by implementing effective strategies and policymaking with the participation of citizens to achieve sustainable development by complying with the Sustainable Development Goals (SDGs) by 2030.

In order to contribute to the achievement of SDGs, even many urban wastewater utilities are willing to implement nexus-oriented management to support their city's energy transition policy in the last years. However, serious difficulties are faced by the water and wastewater utility managers/operators often originated from legislative and regulatory framework that is not considering the nexus for sustainable urban integrated wastewater management and reuse. The regulations governing how wastewater utilities should operate and how open energy markets should function are proving currently highly restrictive to the utilities' aspirations to provide flexibility for energy networks [15]. According to the conclusion achieved in the workshop "H2020 Water Innovations for Sustainable Impacts in Industries and Utilities"*[9], digitalization can help to increase water sector operators' awareness concerning the nexus and longer-term impact of their day-by-day activity. Demonstrating the nexus can provide water utilities with opportunities to decrease energy consumption, improve performance and link better with the water tariffing system. In this nexus, the whole water supply chain needs to be considered from water acquisition up to wastewater treatment and disposal or reuse. Awareness of water utility operators and value chain actors can be raised by generally addressing and promoting the nexus in regulatory framework, initially without any obligation or target to be achieved. There is a need of widely validating integrated models and tools that are addressing and assessing the WEFC nexus, and smart urban infrastructure with peri-urban agriculture can be the best testbed where field data can be used to support knowledge-based regulatory, legislative and operational decisions. Data mining should be applied to public sources (e.g. Copernicus, EUROSTAT) and integrate social and economic drivers into data assessment. Locally, energy, water, carbon footprint need to be measured in case studies, also through citizen science, and relevant key performance indicators including social and economic drivers/factors need to be derived.

7. Final remarks and conclusion

Significant energy and resource recovery can be achieved in wastewater treatment and recycling as well as in sludge management using innovative technologies. However, the challenge here is to integrate WEFC nexus in the urban and peri-urban context considering all their key components as a whole. Although some remarkable efforts have been given to develop a large variety of models and tools to assess climate change impacts and ecosystem services and to provide relevant information to policy makers at a range of different levels, there is also a need for tools that focus on the holistic and integrated assessment of all sectors in the nexus. The nexus concept is indeed critical for achieving adequate water, energy and food securities which are naturally interconnected, but currently still regulated and governed by traditional sectorial approaches [161]. In fact, the nexus approach should be adopted to determine system trade-offs and synergies to provide a stronger evidence base for policy-makers to ensure sustainable use of natural resources [162].

Unless water and agricultural policies can guarantee revenues for reuse-based farming systems which include payment for recovered resources, public regulation, and subsidization of the energy costs of reclaimed water appear to be the only way forward, even considering the impacts on regional water and carbon footprint. This approach can help to better understand, measure, and monitor the indicators of the complex interactions between water treatment/reuse, carbon emission, energy consumption, smart agriculture and climate variability. The models and tools can be used to demonstrate decision support systems based on multi-sources data platforms, including quality and quantity monitoring, interconnected smart sensor networks, advanced predictive analytics and big data solutions. Digital solutions bring high relevance to address current and future water-related issues, namely the protection of human health, the technical, environmental and economic performance and return on investment of water infrastructures as well as the public and end-user awareness on water reuse management. Given the importance of these tools and models and digital solutions for decision makers, water utilities must upgrade their strategies based on best available technologies and practices. This way, multiple actors - water utilities, reclamation managers, farmers, policy makers and even citizens – can benefit from real data-driven decision making and better coordinate for informed decisions. Social acceptance and incentives to apply nexus-oriented practices also confirm the need to integrate social dimension into integrated nexus models and tools through a participatory approach and explicit representation.

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References

[1] Longo S, Mauricio-Iglesias M, Soares A, Campo P, Fatone F, Eusebi AL, et al. ENERWATER – A standard method for assessing and improving the energy efficiency of wastewater treatment plants. Appl Energy 2019;242:897–910. https://doi.org/10.1016/j.apenergy.2019.03.130.

[2] Landa-Cansigno O, Behzadian K, Davila-Cano DI, Campos LC. Performance assessment of water reuse strategies using integrated framework of urban water metabolism and water-energy-pollution nexus. Environ Sci Pollut Res 2020;27:4582–97. https://doi.org/10.1007/s11356-019-05465-8.

[3] Veldhuis AJ, Yang A. Integrated approaches to the optimisation of regional and local food–energy–water systems. Curr Opin Chem Eng 2017;18:38–44. https://doi.org/10.1016/j.coche.2017.09.001.

[4] Hülsmann S, Sušnik J, Rinke K, Langan S, van Wijk D, Janssen AB, et al. Integrated modelling and management of water resources: the ecosystem perspective on the nexus approach. Curr Opin Environ Sustain 2019;40:14–20. https://doi.org/10.1016/j.cosust.2019.07.003.

[5] 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. https://doi.org/10.1016/j.ecoser.2020.101141.

[6] Li M, Fu Q, Singh VP, Ji Y, Liu D, Zhang C, et al. An optimal modelling approach for managing agricultural water-Tenergy-food nexus under uncertainty. Sci Total Environ 2019;651:1416–34. https://doi.org/10.1016/j.scitotenv.2018.09.291.

[7] Capodaglio AG. Integrated, decentralized wastewater management for resource recovery in rural and peri-urban areas. Resources 2017;6. https://doi.org/10.3390/resources6020022.

[8] Wu S, Austin D, Liu L, Dong R. Performance of integrated household constructed wetland for domestic wastewater treatment in rural areas. Ecol Eng 2011;37:948–54. https://doi.org/10.1016/j.ecoleng.2011.02.002.

[9] Mabhaudhi T, Nhamo L, Mpandeli S, Nhemachena C, Senzanje A, Sobratee N, et al. The water–energy–food nexus as a tool to transform rural livelihoods and well-being in Southern Africa. Int J Environ Res Public Health 2019;16. https://doi.org/10.3390/ijerph16162970.

[10] Massoud MA, Tarhini A, Nasr JA. Decentralized approaches to wastewater treatment and management: Applicability in developing countries. J Environ Manage 2009;90:652–9. https://doi.org/10.1016/j.jenvman.2008.07.001.

[11] Priya AK, Pachaiappan R, Kumar PS, Jalil AA, Vo D-VN, Rajendran S. The war using microbes: A sustainable approach for wastewater management. Environ Pollut 2021;275:116598. https://doi.org/10.1016/j.envpol.2021.116598.

[12] Cipolletta G, Ozbayram EG, Eusebi AL, Akyol Ç, Malamis S, Mino E, et al. Policy and legislative barriers to close water-related loops in innovative small water and wastewater systems in Europe: A critical analysis. J Clean Prod 2021;288. https://doi.org/10.1016/j.jclepro.2020.125604.

[13] Novotny V. Water-energy nexus: Retrofitting urban areas to achieve zero pollution. Build Res Inf 2013;41:589–604. https://doi.org/10.1080/09613218.2013.804764.

[14] Landa-Cansigno O, Behzadian K, Davila-Cano DI, Campos LC. Performance assessment of

water reuse strategies using integrated framework of urban water metabolism and water-energy-pollution nexus. Environ Sci Pollut Res 2020;27:4582–97. https://doi.org/10.1007/s11356-019-05465-8.

[15] Moss T, Hüesker F. Politicised nexus thinking in practice: Integrating urban wastewater utilities into regional energy markets. Urban Stud 2019;56:2225–41. https://doi.org/10.1177/0042098017735229.

[16] Bach PM, Rauch W, Mikkelsen PS, McCarthy DT, Deletic A. A critical review of integrated urban water modelling - Urban drainage and beyond. Environ Model Softw 2014;54:88–107. https://doi.org/10.1016/j.envsoft.2013.12.018.

[17] Lee M, Keller AA, Chiang PC, Den W, Wang H, Hou CH, et al. Water-energy nexus for urban water systems: A comparative review on energy intensity and environmental impacts in relation to global water risks. Appl Energy 2017;205:589–601. https://doi.org/10.1016/j.apenergy.2017.08.002.

[18] Vasilaki V, Massara TM, 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. https://doi.org/10.1016/j.watres.2019.04.022.

[19] 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;75:153–66. https://doi.org/10.1016/j.energy.2014.06.111.

[20] Ganora D, Hospido A, Husemann J, Krampe J, Loderer C, Longo S, et al. Opportunities to improve energy use in urban wastewater treatment: A European-scale analysis. Environ Res Lett 2019;14:44028. https://doi.org/10.1088/1748-9326/ab0b54.

[21] Sun C, Puig V, Cembrano G. Real-time control of urban water cycle under cyber-physical systems framework. Water (Switzerland) 2020;12. https://doi.org/10.3390/w12020406.

[22] Wang Z, Song H, Watkins DW, Ong KG, Xue P, Yang Q, et al. Cyber-physical systems for water sustainability: Challenges and opportunities. IEEE Commun Mag 2015;53:216–22.

https://doi.org/10.1109/MCOM.2015.7105668.

[23] Wang Y, Vuran MC, Goddard S. Cyber-physical systems in industrial process control. Univ Nebraska-Lincoln Lincoln, NE, USA 2008. https://doi.org/10.1145/1366283.1366295.

[24] Gu Y, Dong YN, Wang H, Keller A, Xu J, Chiramba T, et al. Quantification of the water, energy and carbon footprints of wastewater treatment plants in China considering a water-energy nexus perspective. Ecol Indic 2016;60:402–9. https://doi.org/10.1016/j.ecolind.2015.07.012.

[25] Zhang P, Zhang L, Chang Y, Xu M, Hao Y, Liang S, et al. Food-energy-water (FEW) nexus for urban sustainability: A comprehensive review. Resour Conserv Recycl 2019;142:215–24. https://doi.org/10.1016/j.resconrec.2018.11.018.

[26] Heard BR, Miller SA, Liang S, Xu M. Emerging challenges and opportunities for the food–energy–water nexus in urban systems. Curr Opin Chem Eng 2017;17:48–53. https://doi.org/10.1016/j.coche.2017.06.006.

[27] Wang XC, Klemeš JJ, Wang Y, Dong X, Wei H, Xu Z, et al. Water-Energy-Carbon Emissions nexus analysis of China: An environmental input-output model-based approach. Appl Energy 2020;261. https://doi.org/10.1016/j.apenergy.2019.114431.

[28] Foglia A, Andreola C, Cipolletta G, Radini S, Akyol Ç, Eusebi AL, et al. 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. https://doi.org/10.1016/j.jclepro.2021.126201.

[29] Foglia A, Akyol Ç, Frison N, Katsou E, Eusebi AL, Fatone F. Long-term operation of a pilot-scale anaerobic membrane bioreactor (AnMBR) treating high salinity low loaded municipal wastewater in real environment. Sep Purif Technol 2020;236:116279. https://doi.org/10.1016/j.seppur.2019.116279.

[30] Reddy VR, Cunha DGF, Kurian M. A water-energy-food nexus perspective on the challenge of eutrophication. Water (Switzerland) 2018;10:1–13. https://doi.org/10.3390/w10020101.

[31] 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. https://doi.org/10.1016/j.uclim.2016.11.004.

[32] Nair S, George B, Malano HM, 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. https://doi.org/10.1016/j.resconrec.2014.05.007.

[33] Panepinto D, Fiore S, Zappone M, Genon G, Meucci L. Evaluation of the energy efficiency of a large wastewater treatment plant in Italy. Appl Energy 2016;161:404–11. https://doi.org/10.1016/j.apenergy.2015.10.027.

[34] Gu Y, Li Y, Li X, Luo P, Wang H, Robinson ZP, et al. The feasibility and challenges of energy self-sufficient wastewater treatment plants. Appl Energy 2017;204:1463–75. https://doi.org/10.1016/J.APENERGY.2017.02.069.

[35] Longo S, d’Antoni BM, Bongards M, Chaparro A, Cronrath A, Fatone F, et al. Monitoring and diagnosis of energy consumption in wastewater treatment plants. A state of the art and proposals for improvement. Appl Energy 2016;179:1251–68. https://doi.org/10.1016/j.apenergy.2016.07.043.

[36] FundaciónOPTI. Estudio de Prospectiva Consumo Energético en el sector del agua. 2012.

[37] Foladori P, Vaccari M, Vitali F. Energy audit in small wastewater treatment plants: Methodology, energy consumption indicators, and lessons learned. Water Sci Technol 2015;72:1007–15. https://doi.org/10.2166/wst.2015.306.

[38] Gandiglio M, Lanzini A, Soto A, Leone P, Santarelli M. Enhancing the energy efficiency of wastewater treatment plants through co-digestion and fuel cell systems. Front Environ Sci 2017;5:1–21. https://doi.org/10.3389/fenvs.2017.00070.

[39] Bodík I, Kubaská M. Energy and sustainability of operation of a wastewater treatment plant. Environ Prot Eng 2013;39:15–24. https://doi.org/10.5277/EPE130202.

[40] Mamais D, Noutsopoulos C, Dimopoulou A, Stasinakis A, Lekkas TD. Wastewater treatment

process impact on energy savings and greenhouse gas emissions. Water Sci Technol 2015;71:303–8. https://doi.org/10.2166/wst.2014.521.

[41] Arnold ME, Merta ES. Towards energy self-sufficiency in wastewater treatment by optimized sludge treatment. Water Pract Technol 2011;6. https://doi.org/10.2166/wpt.2011.069.

[42] Mizuta K, Shimada M. Benchmarking energy consumption in municipal wastewater treatment plants in Japan. Water Sci Technol 2010;62:2256–62. https://doi.org/10.2166/wst.2010.510.

[43] Mininni G, Laera G, Bertanza G, Canato M, Sbrilli A. Mass and energy balances of sludge processing in reference and upgraded wastewater treatment plants. Environ Sci Pollut Res 2015;22:7203–15. https://doi.org/10.1007/s11356-014-4013-2.

[44] Gurung K, Tang WZ, Sillanpää M. Correction to: Unit Energy Consumption as Benchmark to Select Energy Positive Retrofitting Strategies for Finnish Wastewater Treatment Plants (WWTPs): a Case Study of Mikkeli WWTP (Environmental Processes, (2018), 5, 3, (667-681), 10.1007/s40710-018-0310-. Environ Process 2018;5:931. https://doi.org/10.1007/s40710-018-0340-5.

[45] Flores-Alsina X, Arnell M, Amerlinck Y, Corominas L, Gernaey K V, Guo LS. A dynamic modelling approach to evaluate GHG emissions from wastewater treatment plants. Proc. World Congr. Water, Clim. Energy, Dublin, Ireland: 2012, p. 1–8.

[46] Maktabifard M, Zaborowska E, Makinia J. Achieving energy neutrality in wastewater treatment plants through energy savings and enhancing renewable energy production. vol. 17. Springer Netherlands; 2018. https://doi.org/10.1007/s11157-018-9478-x.

[47] EnvironmentAgency. Evidence: Transforming wastewater treatment to reduce carbon emissions. Bristol, UK: 2009.

[48] SevernTrentPlc. Annual Report and Accounts 2012. 2012. https://doi.org/10.1007/s00355-016-0977-9.

[49] Puchongkawarin C, Gomez-Mont C, Stuckey DC, Chachuat B. Optimization-based methodology for the development of wastewater facilities for energy and nutrient recovery. Chemosphere 2015;140:150–8. https://doi.org/10.1016/j.chemosphere.2014.08.061.

[50] Batstone DJ, Hülsen T, Mehta CM, Keller J. Platforms for energy and nutrient recovery from domestic wastewater: A review. Chemosphere 2015;140:2–11. https://doi.org/10.1016/j.chemosphere.2014.10.021.

[51] Frison N, Katsou E, Malamis S, Oehmen A, Fatone F. Nutrient removal via nitrite from reject water and polyhydroxyalkanoate (PHA) storage during nitrifying conditions. J Chem Technol Biotechnol 2015;90:1802–10. https://doi.org/10.1002/jctb.4487.

[52] Akyol Ç, Foglia A, Ozbayram EG, Frison N, Katsou E, Eusebi AL, et al. Validated innovative approaches for energy-efficient resource recovery and re-use from municipal wastewater: From anaerobic treatment systems to a biorefinery concept. Crit Rev Environ Sci Technol 2020;50:869–902. https://doi.org/10.1080/10643389.2019.1634456.

[53] Puyol D, Batstone DJ, Hülsen T, Astals S, Peces M, Krömer JO. Resource recovery from wastewater by biological technologies: Opportunities, challenges, and prospects. Front Microbiol 2017;7:1–23. https://doi.org/10.3389/fmicb.2016.02106.

[54] Mo W, Zhang Q. Can municipal wastewater treatment systems be carbon neutral? J Environ Manage 2012;112:360–7. https://doi.org/10.1016/j.jenvman.2012.08.014.

[55] Capodaglio AG, Olsson G. Energy issues in sustainable urban wastewater management: Use, demand reduction and recovery in the urban water cycle. Sustain 2020;12. https://doi.org/10.3390/su12010266.

[56] Ashrafi O, Yerushalmi L, Haghighat F. Greenhouse gas emission and energy consumption in wastewater treatment plants: Impact of operating parameters. Clean - Soil, Air, Water 2014;42:207–20. https://doi.org/10.1002/clen.201200158.

[57] Bani Shahabadi M, Yerushalmi L, Haghighat F. Estimation of greenhouse gas generation in wastewater treatment plants - Model development and application. Chemosphere

2010;78:1085–92. https://doi.org/10.1016/j.chemosphere.2009.12.044.

[58] IPCC. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia,. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2013.

[59] Caniani D, Caivano M, Pascale R, Bianco G, Mancini IM, Masi S, et al. CO2 and N2O from water resource recovery facilities: Evaluation of emissions from biological treatment, settling, disinfection, and receiving water body. Sci Total Environ 2019;648:1130–40. https://doi.org/10.1016/j.scitotenv.2018.08.150.

[60] Daniel JS, Fleming EL, Portmann RW, Velders GJM, Jackman CH, Ravishankara AR. Options to accelerate ozone recovery: Ozone and climate benefits. Atmos Chem Phys 2010;10:7697–707. https://doi.org/10.5194/acp-10-7697-2010.

[61] Daelman MRJ, Van Voorthuizen EM, Van Dongen LGJM, Volcke EIP, Van Loosdrecht MCM. Methane and nitrous oxide emissions from municipal wastewater treatment - Results from a long-term study. Water Sci Technol 2013;67:2350–5. https://doi.org/10.2166/wst.2013.109.

[62] Lackner S, Gilbert EM, Vlaeminck SE, Joss A, Horn H, van Loosdrecht MCM. Full-scale partial nitritation/anammox experiences - An application survey. Water Res 2014;55:292–303. https://doi.org/10.1016/j.watres.2014.02.032.

[63] Schaubroeck T, De Clippeleir H, Weissenbacher N, Dewulf J, Boeckx P, Vlaeminck SE, et al. Environmental sustainability of an energy self-sufficient sewage treatment plant: Improvements through DEMON and co-digestion. Water Res 2015;74:166–79. https://doi.org/10.1016/j.watres.2015.02.013.

[64] Desloover J, Vlaeminck SE, Clauwaert P, Verstraete W, Boon N. Strategies to mitigate N 2O emissions from biological nitrogen removal systems. Curr Opin Biotechnol 2012;23:474–82. https://doi.org/10.1016/j.copbio.2011.12.030.

[65] Law Y, Ye L, Pan Y, Yuan Z. Nitrous oxide emissions from wastewater treatment processes. Philos Trans R Soc B Biol Sci 2012;367:1265–77. https://doi.org/10.1098/rstb.2011.0317.

[66] Massara TM, Malamis S, Guisasola A, Baeza JA, Noutsopoulos C, Katsou E. A review on nitrous oxide (N2O) emissions during biological nutrient removal from municipal wastewater and sludge reject water. Sci Total Environ 2017;596–597:106–23. https://doi.org/10.1016/j.scitotenv.2017.03.191.

[67] Kosonen H, Heinonen M, Mikola A, Haimi H, Mulas M, Corona F, et al. Nitrous Oxide Production at a Fully Covered Wastewater Treatment Plant: Results of a Long-Term Online Monitoring Campaign. Environ Sci Technol 2016;50:5547–54. https://doi.org/10.1021/acs.est.5b04466.

[68] Daelman MRJ, van Voorthuizen EM, van Dongen UGJM, Volcke EIP, van Loosdrecht MCM. Seasonal and diurnal variability of N2O emissions from a full-scale municipal wastewater treatment plant. Sci Total Environ 2015;536:1–11. https://doi.org/10.1016/j.scitotenv.2015.06.122.

[69] Stillwell AS, Hoppock DC, Webber ME. Energy recovery from wastewater treatment plants in the United States: A case study of the energy-water nexus. Sustainability 2010;2:945–62. https://doi.org/10.3390/su2040945.

[70] Hao X, Li J, van Loosdrecht MCM, Jiang H, Liu R. Energy recovery from wastewater: Heat over organics. Water Res 2019;161:74–7. https://doi.org/10.1016/j.watres.2019.05.106.

[71] Jenicek P, Kutil J, Benes O, Todt V, Zabranska J, Dohanyos M. Energy self-sufficient sewage wastewater treatment plants: Is optimized anaerobic sludge digestion the key? Water Sci Technol 2013;68:1739–43. https://doi.org/10.2166/wst.2013.423.

[72] Haimi H, Mulas M, Corona F, Vahala R. Data-derived soft-sensors for biological wastewater treatment plants: An overview. Environ Model Softw 2013;47:88–107. https://doi.org/10.1016/j.envsoft.2013.05.009.

[73] Corominas L, Garrido-Baserba M, Villez K, Olsson G, Cortés U, Poch M. Transforming data

into knowledge for improved wastewater treatment operation: A critical review of techniques. Environ Model Softw 2018;106:89–103. https://doi.org/10.1016/j.envsoft.2017.11.023.

[74] Zhang R, Xie WM, Yu HQ, Li WW. Optimizing municipal wastewater treatment plants using an improved multi-objective optimization method. Bioresour Technol 2014;157:161–5. https://doi.org/10.1016/j.biortech.2014.01.103.

[75] Qiao J, Zhang W. Dynamic multi-objective optimization control for wastewater treatment process. Neural Comput Appl 2018;29:1261–71. https://doi.org/10.1007/s00521-016-2642-8.

[76] Arnell M, Rahmberg M, Oliveira F, Jeppsson U. Multi-objective performance assessment of wastewater treatment plants combining plant-wide process models and life cycle assessment. J Water Clim Chang 2017;8:715–29. https://doi.org/10.2166/wcc.2017.179.

[77] Flores-Alsina X, Gallego A, Feijoo G, Rodriguez-Roda I. Multiple-objective evaluation of wastewater treatment plant control alternatives. J Environ Manage 2010;91:1193–201. https://doi.org/10.1016/j.jenvman.2010.01.009.

[78] Endo A, Yamada M, Miyashita Y, Sugimoto R, Ishii A, Nishijima J, et al. Dynamics of water–energy–food nexus methodology, methods, and tools. Curr Opin Environ Sci Heal 2020;13:46–60. https://doi.org/10.1016/j.coesh.2019.10.004.

[79] Massara TM, Solís B, Guisasola A, Katsou E, Baeza JA. Development of an ASM2d-N2O model to describe nitrous oxide emissions in municipal WWTPs under dynamic conditions. Chem Eng J 2018;335:185–96. https://doi.org/10.1016/j.cej.2017.10.119.

[80] Henze M, Gujer W, Mino T, van Loosdrecht M. Activated Sludge Models ASM1, ASM2, ASM2d and ASM3. London, UK: IWA Publishing; 2000. https://doi.org/https://doi.org/10.2166/9781780402369.

[81] Mannina G, Ekama G, Caniani D, Cosenza A, Esposito G, Gori R, et al. Greenhouse gases from wastewater treatment - A review of modelling tools. Sci Total Environ 2016;551–552:254–70. https://doi.org/10.1016/j.scitotenv.2016.01.163.

[82] Alex J, Benedetti L, Copp J, Gernaey K V, Jeppsson U, Nopens I, et al. Benchmark Simulation Model no . 1 (BSM1). Control 2008;1.

[83] IWA. BSM1. IWA Model Integr Assess 2020.

[84] Jeppsson U, Pons M-N, Nopens I, Alex J, Copp JB, Gernaey KV, et al. Benchmark Simulation Model no . 2 (BSM2). Water Sci Technol 2018;1:99. https://doi.org/10.1016/0005-7967(76)90069-3.

[85] Mannina G, Rebouças TF, Cosenza A, Chandran K. A plant-wide wastewater treatment plant model for carbon and energy footprint: Model application and scenario analysis. J Clean Prod 2019;217:244–56. https://doi.org/10.1016/j.jclepro.2019.01.255.

[86] ISPRA. Italian Greenhouse Gas Inventory 1990-2018. Roma: 2020.

[87] Federal Office for the Environment FOEN. Switzerland's Greenhouse Gas Inventory 1990-2018. Bern: 2020.

[88] IPCC. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. 2019.

[89] Gustavsson DJI, Tumlin S. Carbon footprints of Scandinavian wastewater treatment plants. Water Sci Technol 2013;68:887–93. https://doi.org/10.2166/wst.2013.318.

[90] Behling Ian, Bonifazi E, Hinton S. Workbook For Estimating Operational GHG Emissions, Version 10. UK Water Industry Research Limited; 2016.

[91] Rodriguez-Garcia G, Hospido A, Bagley DM, Moreira MT, Feijoo G. A methodology to estimate greenhouse gases emissions in Life Cycle Inventories of wastewater treatment plants. Environ Impact Assess Rev 2012;37:37–46. https://doi.org/10.1016/j.eiar.2012.06.010.

[92] Guo L, Porro J, Sharma KR, Amerlinck Y, Benedetti L, Nopens I, et al. Towards a benchmarking tool for minimizing wastewater utility greenhouse gas footprints. Water Sci Technol 2012;66:2483–95. https://doi.org/10.2166/wst.2012.495.

[93] Guisasola A, Sharma KR, Keller J, Yuan Z. Development of a model for assessing methane

formation in rising main sewers. Water Res 2009;43:2874–84. https://doi.org/10.1016/j.watres.2009.03.040.

[94] Sweetapple C, Fu G, Butler D. Identifying key sources of uncertainty in the modelling of greenhouse gas emissions from wastewater treatment. Water Res 2013;47:4652–65. https://doi.org/10.1016/j.watres.2013.05.021.

[95] Larsen TA. CO2-neutral wastewater treatment plants or robust, climate-friendly wastewater management? A systems perspective. Water Res 2015;87:513–21. https://doi.org/10.1016/j.watres.2015.06.006.

[96] Gao H, Scherson YD, Wells GF. Towards energy neutral wastewater treatment: methodology and state of the art. Environ Sci Process Impacts 2014;16:1223–46. https://doi.org/10.1039/c4em00069b.

[97] Kim D, Bowen JD, Ozelkan EC. Optimization of wastewater treatment plant operation for greenhouse gas mitigation. J Environ Manage 2015;163:39–48. https://doi.org/10.1016/j.jenvman.2015.07.005.

[98] Chou MS, Cheng WH. Gaseous emissions and control in wastewater treatment plants. Environ Eng Sci 2005;22:591–600. https://doi.org/10.1089/ees.2005.22.591.

[99] C-FOOT-CTRL. Developing on line tools to monitor, control and mitigate GHG emissions in WWTPs - Deliverable 3.1 Development of the dynamic software tool. 2016.

[100] Rosso D, Jiang LM, Sobhani R, Wett B. Energy Footprint Modelling: A tool for process optimisation in Large Wastewater Treatment Plants. Water Pract Technol 2012;7. https://doi.org/10.2166/wpt.2012.018.

[101] Haas D De, Foley J, Lant P. Energy and Greenhouse Footprints of Wastewater Treatment Plants in South-East Queensland. Adv Water Manag Centre, Univ Queensland, St Lucia, Brisbane, QLD 4072 2008.

[102] Masuda S, Sano I, Hojo T, Li YY, Nishimura O. The comparison of greenhouse gas emissions in sewage treatment plants with different treatment processes. Chemosphere

2018;193:581–90. https://doi.org/10.1016/j.chemosphere.2017.11.018.

[103] Khan MA, Ngo HH, Guo W, Liu Y, Nghiem LD, Chang SW, et al. Optimization of hydraulic retention time and organic loading rate for volatile fatty acid production from low strength wastewater in an anaerobic membrane bioreactor. Bioresour Technol 2019;271:100–8. https://doi.org/10.1016/j.biortech.2018.09.075.

[104] Lazarova V, Choo K-H, Cornel P. Water-Energy Interactions in Water Reuse. vol. 11. London, UK: IWA Publishing; 2012. https://doi.org/10.2166/9781780400662.

[105] McGlade J, Werner B, Young M, Matlock M, Jefferies D, Sonnemann G, et al. Measuring Water Use in a Green Economy. 2012.

[106] Hoekstra AY, Chapagain AK, Aldaya MM, Mekonnen MM. The Water Footprint Assessment Manual: Setting the Global Standard. London, UK: Earthscan; 2011. https://doi.org/10.1080/0969160x.2011.593864.

[107] Kounina A, Margni M, Bayart JB, Boulay AM, Berger M, Bulle C, et al. Review of methods addressing freshwater use in life cycle inventory and impact assessment. Int J Life Cycle Assess 2013;18:707–21. https://doi.org/10.1007/s11367-012-0519-3.

[108] Hoekstra AY. Water Footprint Assessment: Evolvement of a New Research Field. Water Resour Manag 2017;31:3061–81. https://doi.org/10.1007/s11269-017-1618-5.

[109] Paterson W, Rushforth R, Ruddell BL, Konar M, Ahams IC, Gironás J, et al. Water footprint of cities: A review and suggestions for future research. Sustain 2015;7:8461–90. https://doi.org/10.3390/su7078461.

[110] Morillo JG, Martín M, Camacho E, Díaz JAR, Montesinos P. Toward precision irrigation for intensive strawberry cultivation. Agric Water Manag 2015;151:43–51. https://doi.org/10.1016/j.agwat.2014.09.021.

[111] Jefferies D, Muñoz I, Hodges J, King VJ, Aldaya M, Ercin AE, et al. Water footprint and life cycle assessment as approaches to assess potential impacts of products on water consumption. Key learning points from pilot studies on tea and margarine. J Clean Prod

2012;33:155–66. https://doi.org/10.1016/j.jclepro.2012.04.015.

[112] Feng K, Hubacek K, Pfister S, Yu Y, Sun L. Virtual scarce water in China. Environ Sci Technol 2014;48:7704–13. https://doi.org/10.1021/es500502q.

[113] Milà I Canals L, Chenoweth J, Chapagain A, Orr S, Antón A, Clift R. Assessing freshwater use impacts in LCA: Part I - Inventory modelling and characterisation factors for the main impact pathways. Int J Life Cycle Assess 2009;14:28–42. https://doi.org/10.1007/s11367-008-0030-z.

[114] Kounina A, Margni M, Shaked S, Bulle C, Jolliet O. Spatial analysis of toxic emissions in LCA: A sub-continental nested USEtox model with freshwater archetypes. Environ Int 2014;69:67–89. https://doi.org/10.1016/j.envint.2014.04.004.

[115] Boulay AM, Hoekstra AY, Vionnet S. Complementarities of water-focused life cycle assessment and water footprint assessment. Environ Sci Technol 2013;47:11926–7. https://doi.org/10.1021/es403928f.

[116] Morera S, Corominas L, Poch M, Aldaya MM, Comas J. Water footprint assessment in wastewater treatment plants. J Clean Prod 2016;112:4741–8. https://doi.org/10.1016/j.jclepro.2015.05.102.

[117] Saagi R, Flores-Alsina X, Kroll S, Gernaey K V., Jeppsson U. A model library for simulation and benchmarking of integrated urban wastewater systems. Environ Model Softw 2017;93:282–95. https://doi.org/10.1016/j.envsoft.2017.03.026.

[118] Achleitner S, Möderl M, Rauch W. CITY DRAIN © - An open source approach for simulation of integrated urban drainage systems. Environ Model Softw 2007;22:1184–95. https://doi.org/10.1016/j.envsoft.2006.06.013.

[119] Saagi R. Benchmark Simulation Model for Integrated Urban Wastewater Systems : Model Development and Control Strategy Evaluation. 2017.

[120] Baeza J, Gabriel D, Guisasola A, Lafuente J, Katsou E, Massara T, et al. On-line monitoring, control and mitigation of greenhouse gases emissions in WWTPs. 7th Int. Conf. Biotech. Air

Pollut. Control Bioenergy, La Coruña, Spain: 2017.

[121] Porro J, Guo L, Sharma KR, Amerlinck Y, Benedetti L, Shaw A, et al. Towards a benchmarking tool for minimizing wastewater utility greenhouse gas footprints. 8th IWA Symp. Syst. Anal. Integr. Assess., vol. 66, 2012, p. 2483–95. https://doi.org/10.2166/wst.2012.495.

[122] Longo S, Mauricio-Iglesias M, Soares A, Campo P, Fatone F, Eusebi AL, et al. ENERWATER – A standard method for assessing and improving the energy efficiency of wastewater treatment plants. Appl Energy 2019;242:897–910. https://doi.org/10.1016/j.apenergy.2019.03.130.

[123] Tian H, Lu C, Pan S, Yang J, Miao R, Ren W, 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;33:104–13. https://doi.org/10.1016/j.cosust.2018.04.003.

[124] Daccache A, Ciurana JS, Rodriguez Diaz JA, Knox JW. Water and energy footprint of irrigated agriculture in the Mediterranean region. Environ Res Lett 2014;9. https://doi.org/10.1088/1748-9326/9/12/124014.

[125] UNEP/MAP Plan Bleu. State of the environment and development in the Mediterranean. Technical Report. Athens: 2019.

[126] Fader M, Shi S, Von Bloh W, Bondeau A, Cramer W. Mediterranean irrigation under climate change: More efficient irrigation needed to compensate for increases in irrigation water requirements. Hydrol Earth Syst Sci 2016;20:953–73. https://doi.org/10.5194/hess-20-953-2016.

[127] Sukhwani V, Shaw R, Mitra BK, Yan W. Optimizing Food-Energy-Water (FEW) nexus to foster collective resilience in urban-rural systems. Prog Disaster Sci 2019;1:100005. https://doi.org/10.1016/j.pdisas.2019.100005.

[128] Qi X, Li J, Yuan W, Wang RY. Coordinating the food-energy-water nexus in grain

production in the context of rural livelihood transitions and farmland resource constraints. Resour Conserv Recycl 2021;164:105148. https://doi.org/10.1016/j.resconrec.2020.105148.

[129] Medina-Santana AA, Flores-Tlacuahuac A, Cárdenas-Barrón LE, Fuentes-Cortés LF. Optimal design of the water-energy-food nexus for rural communities. Comput Chem Eng 2020;143:107120. https://doi.org/10.1016/j.compchemeng.2020.107120.

[130] Jaramillo MF, Restrepo I. Wastewater reuse in agriculture: A review about its limitations and benefits. Sustain 2017;9. https://doi.org/10.3390/su9101734.

[131] Miller-Robbie L, Ramaswami A, Amerasinghe P. Wastewater treatment and reuse in urban agriculture: Exploring the food, energy, water, and health nexus in Hyderabad, India. Environ Res Lett 2017;12. https://doi.org/10.1088/1748-9326/aa6bfe.

[132] Sapkota AR. Water reuse, food production and public health: Adopting transdisciplinary, systems-based approaches to achieve water and food security in a changing climate. Environ Res 2019;171:576–80. https://doi.org/10.1016/j.envres.2018.11.003.

[133] Weckenbrock P, Alabaster G. Designing Sustainable Wastewater Reuse Systems: Towards an Agroecology of Wastewater Irrigation. Gov. Nexus Water, Soil Waste Resour. Considering Glob. Chang., Switzerland: Springer International Publishing; 2015, p. 1–230. https://doi.org/10.1007/978-3-319-05747-7_8.

[134] Kurian M. The water-energy-food nexus: Trade-offs, thresholds and transdisciplinary approaches to sustainable development. Environ Sci Policy 2017;68:97–106. https://doi.org/10.1016/j.envsci.2016.11.006.

[135] Fernández García I, Mérida García A, Rodríguez Díaz JA, Barrios PM, Poyato EC. Water-energy nexus in irrigated areas. Lessons from real case studies. Water Scarcity Sustain. Agric. Semiarid Environ. Tools, Strateg. Challenges Woody Crop., Elsevier; 2018, p. 41–59. https://doi.org/10.1016/B978-0-12-813164-0.00002-8.

[136] Smith R, Baillie J, McCarthy A, Raine SR, Baillie CP. Review of precision irrigation technologies and their application. Natl Cent … 2010.

[137] Kamienski C, Soininen JP, Taumberger M, Dantas R, Toscano A, Cinotti TS, et al. Smart water management platform: IoT-based precision irrigation for agriculture. Sensors (Switzerland) 2019;19. https://doi.org/10.3390/s19020276.

[138] Abioye EA, Abidin MSZ, Mahmud MSA, Buyamin S, Ishak MHI, Rahman MKIA, et al. A review on monitoring and advanced control strategies for precision irrigation. Comput Electron Agric 2020;173:105441. https://doi.org/10.1016/j.compag.2020.105441.

[139] Allen RG, Pereira LS, Raes D, Smith M. FAO Irrigation and Drainage Paper No.56. Food Agric Organ United Nations 1998;56:e156. https://doi.org/10.1016/S0141-1187(05)80058-6.

[140] Colding J, Barthel S. An urban ecology critique on the “Smart City” model. J Clean Prod 2017;164:95–101. https://doi.org/10.1016/j.jclepro.2017.06.191.

[141] Naphade M, Banavar G, Harrison C, Paraszczak J, Morris R. Smarter cities and their innovation challenges. Computer (Long Beach Calif) 2011;44:32–9.

[142] Klein B, Koenig R, Schmitt G. Managing Urban Resilience: Stream Processing Platform for Responsive Cities. Informatik-Spektrum 2017;40:35–45. https://doi.org/10.1007/s00287-016-1005-2.

[143] Hosseini S, Frank L, Fridgen G, Heger S. Do Not Forget About Smart Towns: How to Bring Customized Digital Innovation to Rural Areas. Bus Inf Syst Eng 2018;60:243–57. https://doi.org/10.1007/s12599-018-0536-2.

[144] Ramaswami A, Russell AG, Culligan PJ, Rahul Sharma K, Kumar E. Meta-principles for developing smart, sustainable, and healthy cities. Science (80-) 2016;352:940–3. https://doi.org/10.1126/science.aaf7160.

[145] Boyle T, Giurco D, Mukheibir P, Liu A, Moy C, White S, et al. Intelligent metering for urban water: A review. Water (Switzerland) 2013;5:1052–81. https://doi.org/10.3390/w5031052.

[146] Stewart RA, Nguyen K, Beal C, Zhang H, Sahin O, Bertone E, et al. Integrated intelligent water-energy metering systems and informatics: Visioning a digital multi-utility service

provider. Environ Model Softw 2018;105:94–117. https://doi.org/10.1016/j.envsoft.2018.03.006.

[147] Sitzenfrei R, Rauch W. From Water Networks to a “Digital City”: a Shift of Paradigm in Assessment of Urban Water Systems. 12th Int Conf Urban Drain 2011:9.

[148] Ejeian F, Etedali P, Mansouri-Tehrani HA, Soozanipour A, Low ZX, Asadnia M, et al. Biosensors for wastewater monitoring: A review. Biosens Bioelectron 2018;118:66–79. https://doi.org/10.1016/j.bios.2018.07.019.

[149] Mikkelsen PS. Water solutions for smart cities – Smart water systems make cities more liveable, resilient and sustainable. In: Smart Cities - creating liveable, sustainable and prosperous societies, State of Green; 2018, p. 14–14.

[150] Schulze J, Martin R, Finger A, Henzen C, Lindner M, Pietzsch K, et al. Design, implementation and test of a serious online game for exploring complex relationships of sustainable land management and human well-being. Environ Model Softw 2015;65:58–66. https://doi.org/10.1016/j.envsoft.2014.11.029.

[151] Mendler de Suarez J, Bachofen C, Fortugno N, Goentzel J, Gonçalves P, Grist N, et al. Games for a new climate : Experiencing the complexity of future risks. In: Report, P.C.T.F. (Ed.), The Frederick S.Pardee Center for the Study of the Longer-range Future. Boston: 2012.

[152] Aubert AH, Bauer R, Lienert J. A review of water-related serious games to specify use in environmental Multi-Criteria Decision Analysis. Environ Model Softw 2018;105:64–78. https://doi.org/10.1016/j.envsoft.2018.03.023.

[153] Mildner P, `Floyd’ Mueller F. Design of Serious Games. In: Dörner R, Göbel S, Effelsberg W, Wiemeyer J, editors. Serious Games Found. Concepts Pract., Cham: Springer International Publishing; 2016, p. 57–82. https://doi.org/10.1007/978-3-319-40612-1_3.

[154] Sušnik J, Chew C, Domingo X, Mereu S, Trabucco A, Evans B, et al. Multi-stakeholder development of a serious game to explore the water-energy-food-land-climate nexus: The

SIM4NEXUS approach. Water (Switzerland) 2018;10. https://doi.org/10.3390/w10020139.

[155] Medema W, Furber A, Adamowski J, Zhou Q, Mayer I. Exploring the potential impact of serious games on social learning and stakeholder collaborations for transboundary watershed management of the St. Lawrence river basin. Water (Switzerland) 2016;8. https://doi.org/10.3390/w8050175.

[156] Savic DA, Morley MS, Khoury M. Serious gaming for water systems planning and management. Water (Switzerland) 2016;8:1–17. https://doi.org/10.3390/w8100456.

[157] Van der Wal MM, de Kraker J, Kroeze C, Kirschner PA, Valkering P. Can computer models be used for social learning? A serious game in water management. Environ Model Softw 2016;75:119–32. https://doi.org/10.1016/j.envsoft.2015.10.008.

[158] Prat P, Aulinas M, Turon C, Comas J, Poch M. Role playing games: A methodology to acquire knowledge for integrated wastewater infrastructures management in a river basin scale. Water Sci Technol 2009;59:1809–16. https://doi.org/10.2166/wst.2009.212.

[159] Douven W, Mul ML, Son L, Bakker N, Radosevich G, Hendriks A. Games to Create Awareness and Design Policies for Transboundary Cooperation in River Basins: Lessons from the Shariva Game of the Mekong River Commission. Water Resour Manag 2014;28:1431–47. https://doi.org/10.1007/s11269-014-0562-x.

[160] Arbesser-Rastburg G, Fuchs-Hanusch D. Serious sensor placement-optimal sensor placement as a serious game. Water (Switzerland) 2020;12. https://doi.org/10.3390/w12010068.

[161] Bidoglio G, Vanham D, Bouraoui F, Barchiesi S. The water-energy-food-ecosystems (WEFE) nexus. Encycl Ecol 2018;4:459–66. https://doi.org/10.1016/B978-0-12-409548-9.11036-X.

[162] Biggs EM, Bruce E, Boruff B, Duncan JMA, Horsley J, Pauli N, et al. Sustainable development and the water-energy-food nexus: A perspective on livelihoods. Environ Sci Policy 2015;54:389–97. https://doi.org/10.1016/j.envsci.2015.08.002.

Footnotes

*[1]: https://www.iso.org/standard/66453.html

*[2] https://www.ipcc-nggip.iges.or.jp/EFDB/find_ef.php?root=

*[3] http://www.cfootcontrol.gr/

*[4]: https://www.smart-plant.eu/

*[5]: https://simba.ifak.eu/

*[6]: https://enerwater-h2020.wtelecom.es/

*[7]: www.digital-water.city

*[8]: www.sim4nexus.eu

*[9]:https://ec.europa.eu/easme/en/news/horizon-2020-water-innovations-sustainable-impacts-industries-and-utilities-new-report

*[10] https://www.sim4nexus.eu/

*[11] http://www.magic-nexus.eu/