Energy Efficiency and Greenhouse Gas Emissions Foresighting Report

Prepared for the Water Test Network

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November 2022

SW Public
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1. Introduction

The aim for this report is to set out ways in which transforming the water sector can be approached, exploited and improved upon by European SMEs with cutting edge technologies and knowledge. This report provides an overview of the impact of energy efficiency and greenhouse gas emissions (GHGs) within the water industry with the intention to guide and inspire technologies and methodologies to achieve the standards set by European and International law.

In December 2015 at the Paris meeting of the United Nations Framework Convention on Climate Change, countries around the world reached a landmark agreement to mitigate climate change and move towards a sustainable low carbon future. The output of this meeting resulted in 17 "*Sustainable Development Goals*" (SDGs), known as the "*United Nations SDGs*". One of the key targets is to limit the world temperature increase to a maximum of 1.5°C above the pre-industrial baseline (c.a. average over the years 1850-1900) by 2050. However, the annual mean global near-surface temperature for each year between 2022 and 2026 is predicted to be between 1.1 °C and 1.7 °C higher than pre-industrial levels (WMO, 2021).

The 2015 objective is ambitious within the specified timeframe, failure is simply not an option.

This statement points out the urgency of identifying and developing solutions to reduce GHG emissions and modify our behaviours whilst building a sustainable society. It's true that climate change cannot be stopped. However, the global community can focus on efforts to mitigate its impact.

Two key issues in the domain of wastewater treatment that require attention are our increasing energy need for treatment and the increase of the water discharge standard. This implies increasing the efficient use of energy in general, and, if not abandoning, at least limiting our use of fossil fuels by introducing alternative energy sources (such as wind, solar, hydro, tidal, biogas and biomass), rationalising and optimising energy intensive processes. The objective is not to stop using energy, which is key to development, but to reduce emissions of GHGs that are shown to cause climate change. Another important source of GHG emissions that received a lot of attention recently is the fugitive emissions of nitrous oxides and methane at different stage of wastewater treatment. The change in the climate results, among other factors, is an increased pressure on water resources (WMO, 2021) and imposes a critical optimisation of wastewater management. The wastewater treatment sector, due to its impact on the environment and its energy requirements, is scrutinised in detail with one SDG (*Goal 6: Clean Water and Sanitation*) to improve its environmental performance. For example, Scottish Water is one of the biggest energy consumers in the UK with 440 GWh per year (Scottish_Water, 2021). These SDGs are interrelated with *SDG 6: 'Clean Water and Sanitation'*, SDG7 '*Affordable and Clean Energy*', SDG 11 '*Sustainable Cities and Communities'*, and SDG13 '*Climate Actions*' interlinked and encompass the development of sustainable potable and wastewater systems.

This report focuses on the energy consumption of wastewater treatment with the aim of limiting the environmental impact, improving resource efficiency and developing the circular economy.

In Europe, wastewater can be split in two categories: domestic/municipal wastewater, and industrial wastewaters. Industrial wastewater management has three scenarios: direct release to water bodies, onsite treatment, or discharge to the domestic wastewater system for treatment via private sewage systems (septic tanks). Due to the heterogeneity of industrial wastewater management and the available data, the data provided in this report refers to domestic/municipal wastewaters.

The values presented in this report are extracted from scientific publications, governmental & Non-Governmental Organisation (NGO) reports and analysis of private sector reports. Reviewing the literature, it becomes apparent that there is yet no common international or EU benchmark methodology to analyze and report the efficiency, energy consumption, or carbon footprint of domestic/municipal wastewater treatment technologies. Hence, the values reported here are indicative since they must be contextualised in regards of the country they concern.

2. Political Factors

Following the Paris Agreement (COP-21, 2015) and in accordance with the 2019 IPCC objective, the EU set two frameworks to keep the global temperature increase to well below 2°C and pursue efforts to keep it to 1.5°C. These frameworks, refined during the COP26 (2021), are known as the "*2030 Climate & Energy Framework*" and the "*2050 Long-Term Strategy*" and apply to every domain, beyond wastewater treatment. In addition, the EU adopted a new circular economy action plan in 2020, to support EU competitiveness, along with a zero-pollution action plan in 2021 to introduce boundaries with which the planet and human health can cope. This latter action plan coincides with the 2023 revised version of the "*Drinking Water Directive*" and directly addresses the water and wastewater management sectors.

In September 2020, the "2030 Climate & Energy Framework" aimed at raising the 2030 greenhouse gas emission reduction target, including emissions and removals, to at least 55% compared to 1990. To reach this objective, the EU targets are to have at least 40% cuts in greenhouse gas emissions (from 1990 levels), at least 32% share for renewable energy and at least 32.5% improvement in energy efficiency. For this to occur, the EU relies on the Emissions Trading System (ETS) that was put in place in 2005 and caps the emissions and provides allowances: the monetary unit of the carbon exchange market. The ETS is considered by the EU as the cornerstone of its strategy to achieve the 40% GHG emission reduction in 2030 and reach net-zero in 2050. In 2021, it was decided that the sectors covered by the EU, ETS must reduce their emissions by 43% compared to 2005 levels. Also, the GHG emissions allowances will decrease by 2.2% each year from 2021 onward.

In January 2023, the EU will revise the Drinking Water Directive (Recast). The aim is to increase the protection to human health through the implementation of more stringent standards, with a special focus on pollutants of emerging concerns (e.g. microplastic and pharmaceuticals). There will also be a review of the Urban Wastewater Treatment Directive that aims to introduce the requirement of the continuous monitoring and analysis of wastewaters, with the list of the targeted parameters yet to be defined. Similarly, the aim is to increase the nutrient and pollutant removal to enable the reuse of the treated water and the sewage sludge. This echoes the ambition to develop the circular economy and increase EU competitiveness. This includes municipal wastewater, industrial wastewater, but also waste streams from the farming industry (e.g. slurry, manure) that have high loading of organic matter and nitrogen. The objective is to meet the net-zero objective along with a zero-pollution whilst increasing energy efficiency and carbon neutrality. There is also a will to move towards a better application of the 'polluters pays' principle. These future stringent regulations are the opportunity to enhance innovative technologies and approaches.

To support the transition towards net-zero and zero-pollution, innovation funding is being made available through Horizon Europe funding, a research and innovation program (2021-2027) equipped with a budget of €95.5 billion. For SME's, Pillar II and Pillar III are of interest. Pillar II focuses on "*Global Challenges and European Industrial Competitiveness*" and Pillar III "*Innovative Europe*" is focused on the SME promoting breakthrough innovation with scale-up potential at the global level. This considers the priorities of the Horizon Europe strategic plan (a.k.a. reaching net-zero). Along with the Horizon Europe funding, the Next Generation EU offers financial support for the reduction and control of the pollution. One of the pillars of Next Generation EU is to improve the water quality of rivers and the sea and to reduce waste. Although there are other pillars that are not linked to wastewater management, the EU has agreed to invest a total of €806.9 billion.

3. Environmental Factors

Wastewater utility companies play an important role in the water cycle as they mitigate water pollution. Under the EU net-zero target, they can play an important role in the circular economy by enhancing water reuse, energy generation and water sanitation. At present, the services provided by the European water sector are amongst the most effective worldwide by removing up to 99% of all pollutants in wastewater. That said, these services would not meet net-zero objectives due to the energy intensive processes employed. Indeed, the wastewater treatment sector has an important impact through its energy requirements and the diffusive release of GHGs within the sewage network and the treatment processes. The energy required accounts for roughly 75% of the carbon footprint. (e.g. 59% electricity, 12% natural gas, 5% transport (Scottish_Water, 2021)). In most European wastewater treatment plants (WWTPs), most of the energy is consumed during biological treatment (e.g. aeration step). Any improvements of this stage would be of great interest to the wastewater treatment sector.

The IPCC (Intergovernmental Panel on Climate Change (Bartram et al., 2019)) objective is to decrease carbon footprints by 45% from 2010 levels by 2030, reaching 'net zero' around 2050. To reach this objective, most wastewater utilities companies will increase the use of renewable energy and therefore decrease their carbon footprint. This is achieved by either: buying renewable energy from energy utilities, setting up microgeneration on wastewater treatment sites or harvesting energy from wastewater.

With existing infrastructure and technologies in place, a growing population, stringent discharge consents and rising energy costs, utility companies will look for opportunities that increase the wastewater treatment process efficiency:

- Increase the amount and type of pollutant being removed (e.g. microplastic, xenobiotics)
- Improve the energy efficiency of existing processes
- Develop new processes/technologies that can be retrofitted to infrastructure
- Harness value from wastewater (e.g. nutrient recovery, energy).

Wastewater has been shown as a potential fuel and is recognised by the EU as a renewable energy source (EU Directive 2018/2001) in the form of heat and reduced organic matter. Studies have shown that in municipal sewer networks, the temperature of the wastewater is relatively constant over the year with potential to capture energy for reuse (Cipolla and Maglionico, 2014). The idea of riothermy ("extracting thermal energy from fluids") is to extract this thermal energy through heat pump and dedicated heat exchangers (Đurđević et al., 2019, Nagpal et al., 2021), which has been demonstrated in test sites in the UK (Liu et al., 2022). The objective is to extract this energy for commodities without impeding the biological wastewater treatment process during a cold period. This technology requires to identify technologies that enable heat recovery close to local demand and be flexible for adaptation to existing site infrastructure. Fortunately, there are predictive models published that can assist with selection and implementation of the technology. Wastewater contains a maximum of 1.93 $KWh.m^{-3}$ recoverable energy for a loading of 500 $mg \cdot L^{-1}$ Chemical Oxygen Demand (COD), which could entirely cover the energy cost (0.3–2.1 $KWh.m^{-3}$) of most wastewater treatment plants (Yang et al., 2020, Panepinto et al., 2016). In practice this means that wastewater treatment has the potential to be energy positive by utilising energy recovery approaches such as anaerobic bio-digestion and sludge combustion to convert the energy to either methane or heat. This combined generation of heat and power from the biogas is generally regarded as the main contributor to achieve energy self-sufficiency. However, only larger plants include anaerobic processes within existing infrastructure, less than 20% of plants have this option. This highlights the fact that there is not a standalone technology that would lead to energetic self-sufficiency, and that other solutions need further development (e.g. riothermy, bioelectrochemistry, hydropower, onsite solar/wind systems).

EU reporting of the carbon footprint of the wastewater treatment sector doesn't include CO_2 emissions, these are regrouped into the footprint of the energy sector and the transport sector. Other sources of GHG in the wastewater treatment sector include nitrous oxide (N_2O) and methane (CH_4), which are expressed as CO_2 equivalent ($CO_{2.e}$) to normalise their respective impact. This then provides some detail when the energy consumed by the wastewater sector represents roughly 75% of the carbon footprint, 23% results from process emissions created by the biological processes that occur during wastewater treatment (Zawartka et al., 2020).

In 2019, the European wastewater treatment and discharge sector produced a total of 24.9 million tons of $CO_{2.e}$, through the combined release of CH_4 and N_2O, which represent a 13.5% decrease from 2010 (Figure 1). Although many disparities exist between each member state, 72.2% (median; average= 63.9%) of the GHG are released as CH_4 whilst 27.8% is emitted as N_2O (median; average= 36.1%).

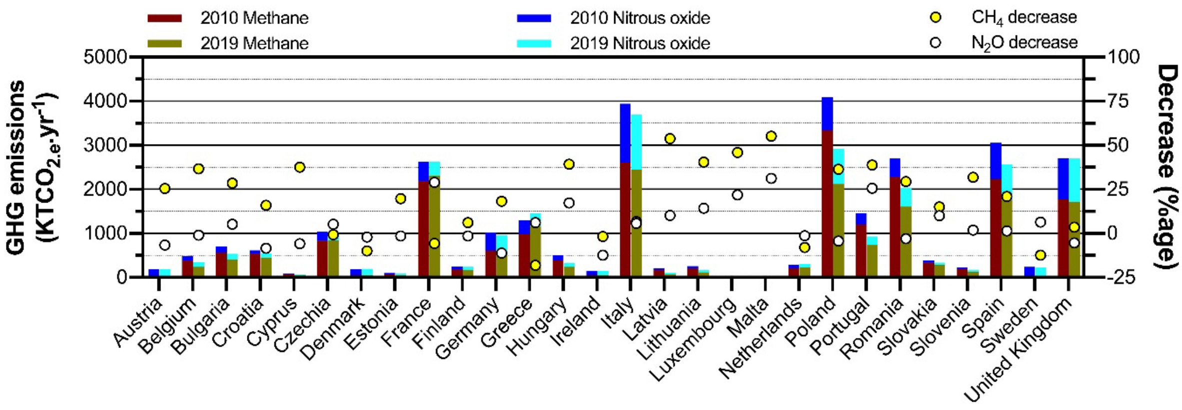

Figure 1 Breakdown of the GHG emissions from European wastewater treatment and discharge sector and comparison between the 2010 benchmark year and the data collected in 2019 (Eurostat data-set: [env_air_gge] updated on the 10-06-2022). The circles indicate the decrease of both GHG in $KTCO_2$.e from 2010.

Nitrous oxide emissions by the wastewater treatment sector have constantly increased over the past two decades, however, these emissions have been underestimated due to the measurement and reporting methodologies that were not effective in recording observations. Estimations of countrywide N_2O emissions are based on assumed emission factors (EFs) that are a percentage of emission in relation to the volumetric loading. In the IPCC 2006 guidelines, the EFs were around 0.03-0.14% when the IPCC methodology was refined in 2019, the EFs reported had increased to 0.01-2.9% (Bartram et al., 2019). Recent results (Gruber et al., 2021) have shown that when long-term, full-scale measurements are performed, there is variability in the yearly EFs (EFs: 0.1-8.0%). Hence, new countrywide EFs have been proposed depending on the nutrient removal category (carbon removal, 0.1–8%; nitrification only, 1.8%; full nitrogen removal, 0.9%), which again are higher than the figures reported using the IPCC 2019 guidelines (Figure 1). The consequence of this is that real N_2O emissions are worse than previously thought, and secondly any improvement is going to require to have a greater impact than envisaged (c.a. GHG decrease). This highlights the crucial need for continuous onsite N_2O monitoring, with the need for the development of appropriate sensing systems to avoid having to rely on EFs that are somewhat specific to the location and conditions.

4. Economic Factors

Wastewater treatment is performed through a series of processes that varies in function of the setting. For example, municipal wastewater treatment combines a series of interlinked processes whilst rural dwellings are often connected to septic tanks. Roughly, the energetic cost and associated greenhouse gas emission can be associated with the daily volume of treated wastewater and the subsequent retention time. The higher the volume and the shorter the hydraulic retention time, the higher the energy requirement for treatment. In a conventional plant about 25–40% of the operating costs can be attributed to energy consumption (Panepinto et al., 2016). The cost varies in the range of approximately 0.3–2.1 $kWh.m^{-3}$ of treated wastewater.

Another factor to consider is the effluent standards of the country where the treatment takes place, with the strictest effluent standards placing a higher energy demand and therefore cost on operators. Within the EU, wastewater treatment processes have some of the largest energy demands on average with 1.18 $kWh.m^{-3}$, which correlates to the robust wastewater effluent standards of the region (Walker et al., 2021). Future effluent standards will become more stringent as the global population focuses on sustainability. These higher standards will inevitably result in higher energy requirements for wastewater treatment. In 2019, the overall electricity uses in Europe by wastewater treatment plants (plants with more than 2000 population equivalent (PE)) is approximatively 24,747 $GWh.yr^{-1}$ which account for 0.8% of the electricity consumption in the EU-28 (Ganora et al., 2019). Table 1 shows the energy consumption of the three member states that contribute to nearly half of the energy consumption of the EU.

Table 1 Annual electric energy consumption for wastewater treatment and related cost in Europe. These values are a rough indication of the average energetic cost of wastewaters treatment in Europe. The date when data are published indicated as a subscript

	Energetic cost ($KWh.m^{-3}$)	Volume treated ($Gm^{-3}.yr^{-1}$)	Annual energy consumption ($GWh.yr^{-1}$)	Electricity Prices ($€.KWh^{-1}$)	Annual cost ($M€.yr^{-1}$)
UK	0.80 [2021, a]	4.52 [2021, b]	3,616	0.1065 [2020-S1, f]	385.10
Germany	1.40	3.00 [2015, c]	4,200 [2015, c]	0.0967 [2020-S2, f]	406.14
France	1.18±0.50 [2017, d]	5.00 [2017, d]	5,900	0.0810 [2020-S2, f]	477.90
EU	1.18 [2021, a]	-	24,747 [2019, e]	0.1032 [2020-S2, f]	2,553.89

[a] Pitfalls in international benchmarking of energy intensity across wastewater treatment utilities (Walker et al., 2021)
[b] Sum of wastewater volume treated daily by water utilities in the United Kingdom and reported in their respective Annual reports: Thames Water (2021 , pg 11) ; Severn Trent Water (2021, pg 2); Scottish Water (2020, pg 5); Yorkshire Water (2021, pg 8); Anglian Water (2021, pg 144); Southern Water (2021, pg 8); Wessex Water (2021, pg 65.).
[c] ENERWATER – Deliverable 2.1 Study of published energy data (Ref. Ares (2015)4042615 - 01/10/2015)
[d] Consommation énergétique du traitement intensif des eaux usées en France: état des lieux et facteurs de variation (Stricker et al., 2017)
[e] Opportunities to improve energy use in urban wastewater treatment: a European-scale analysis (Ganora et al., 2019).
[f] Eurostat: Electricity prices for non-household consumers - bi-annual data (NRG_PC_205)

Reducing energy consumption within wastewater management is designed to improve resource efficiency and reduce GHG emissions. The main GHGs reported in literature are CO_2, N_2O and CH_4, with the latter two the most potent. The global warming potentials of these gases are estimated to be 265 and 28 times higher, respectively than CO_2 over a 100-year period (Skea et al., 2022). It should be noted that the CO_2 emissions from wastewater are not considered because these are generally derived from organic matter in human excreta or food. A carbon that was previously fixed through photosynthesis and is part of the biological carbon cycle. For a better evaluation of GHG emission, values are always given as ton per CO_2 equivalent ($TCO_{2.e}$). The emissions domain is split into operational and capital (embedded) emissions. The operational emissions cover electrical consumption (e.g. pumping), process emissions (e.g. CH_4), transport (e.g. vehicle fuel), and gas and oil consumption (e.g. heating). The embedded emissions cover electricity (e.g. delivery of infrastructure), concrete (e.g. sewer systems), metal (e.g. mining to transformation), and fuels (e.g. construction vehicles).

The emissions of $TCO_{2.e}$ have a market price, with a value estimated as shown in Figure 2. This data is a rough indication of the potential value of the GHG emissions on the carbon market. It should be noted that these GHG emissions are low because they only take into account the CH_4 and the N_2O emissions. The GHG process emissions (24,471 $KT.yr^{-1}$) average value can be estimated at roughly €70 million per year per member states, for a total of €1,957.67 million.

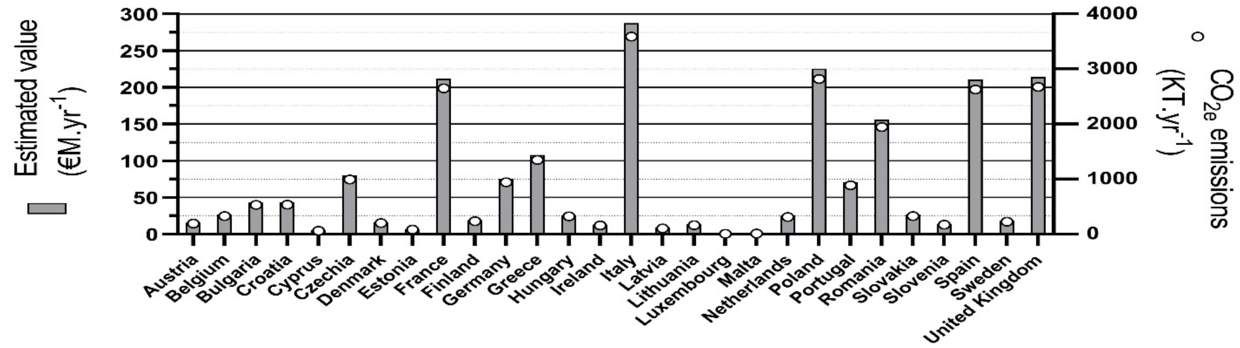

Figure 2 Illustration of the potential economic value of GHG. On the left, the estimated value, in million euro per year, of the GHG emitted by the EU member states in 2020 assuming the 2022 average cost of €80 per ton of carbon dioxide equivalent. On the right, the annual GHG process emissions, in thousand ton of carbon dioxide equivalent, from the wastewater treatment and discharge sector in 2020 (Eurostat date set:[env_ir_ggd] updated 10/0622.

The major source of GHG emissions in the sector comes from energy consumption (e.g. 59%, Scottish Water annual report 2021) with water companies focusing on decreasing the energy demand to decrease GHG emissions associated with wastewater treatment. Three main options are considered: employing renewable energy within the treatment process, generate part of the energy required onsite from wastewater, improve the energy efficiency of equipment (e.g. pumps, electrical vehicles etc.).

Water UK has estimated that delivering the transition to Net Zero by 2030 will cost in the region of £2-£4bn (2021). The EU had an ambition to invest €15 billion in water management (under the "*Water Framework Directive*") with European Regional Development Fund (ERDF) (2014-2020) investment running until 2023 (Scarpa, 2020).The largest share (€9.9 billion) is dedicated to wastewater collection and treatment, which not only includes construction or upgrading of wastewater treatment plans and sewerage networks, but also sewage sludge management. By the end of 2020, substantial contribution of the resource was yet to be invested (Figure 3).

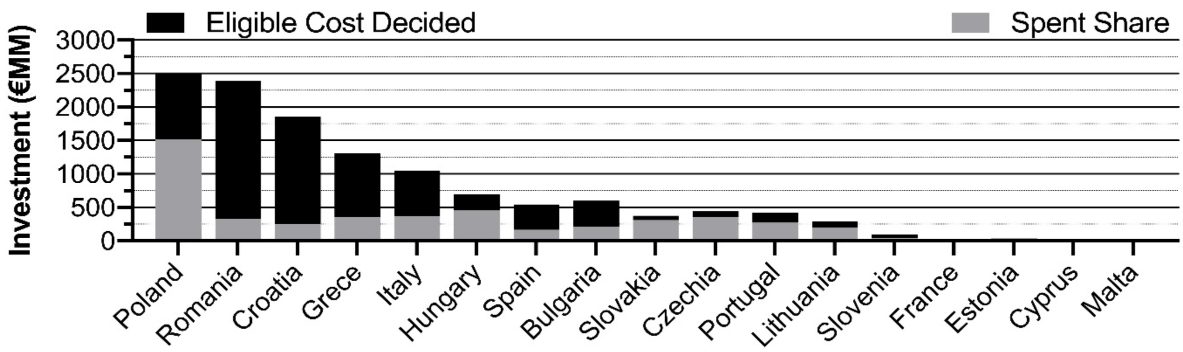

Figure 3 Snapshot of the European investments progress in November 2020. These investments were made through the Cohesion Fund and the European Regional Development Fund for the 2014-2020 period.

ERDF (2021-2027) investments will focus on the following priorities: to make Europe and its regions "smarter", "greener" (low-carbon and resilient), "more connected" (enhancing mobility), "more social" and "closer" to its citizens (locally led development and sustainable urban development).

5. Social Factors

An increasing population brings a need for stricter discharge levels to mitigate against further damage to the progressively degraded water environment. To reach these stricter standards implies extending tertiary treatment to all wastewaters. Using the retention of microplastic as a function of the treatment level: primary treatment retains 80.5% of microplastic, cumulated with secondary treatment gives 97.5% retention which is further increased to 99.2% after tertiary treatment (European_Commission, 2020). Comparing the percentage of EU population connected to tertiary treatment to the whole population connected, it appears that although secondary and tertiary treatments are implemented in most EU states, a fair amount (approximatively 12% pf the EU average) have not developed the associated infrastructure (Figure 4).

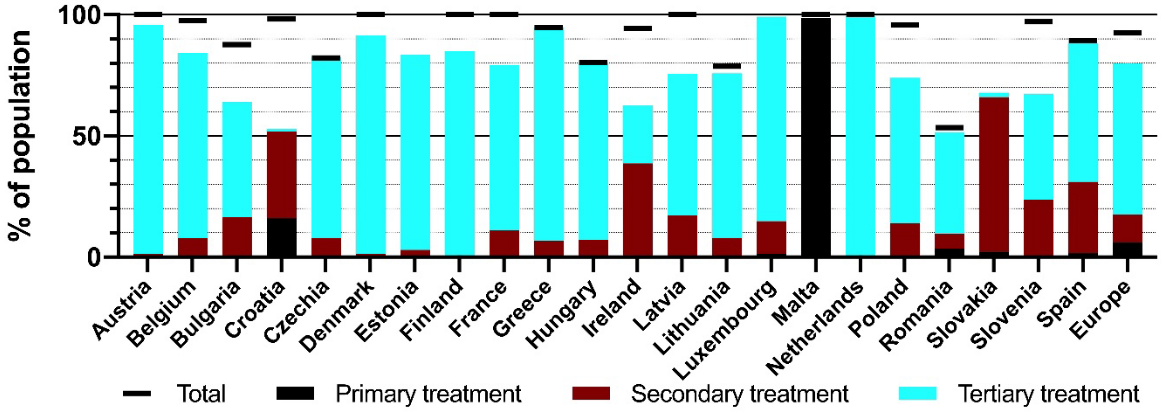

Figure 4 Proportion of the population connected to a wastewater system in 2018. Are only present the countries that have reported their data for this specific year (Eurostat data-set: [env_ww_con] updated on the 02-03-2022).

Some of the EU population do not live in large cities, therefore, all of the wastewater produced cannot be treated in large WWTP equipped to deliver tertiary treatment. Therefore, 12% of the EU population that do not have primary, secondary or tertiary treatment live in small communities (<2000 PE) or isolated housing not connected to domestic sewers and rely on off-grid Private Sewer Systems including septic tanks. The effectiveness of these systems is variable and depends on maintenance, site conditions such as receiving soils/geology as influenced by draining and topographic features and population distribution. For example, agricultural infrastructure and rural dwellings cannot be connected to municipal sewer systems and requires their own wastewater treatment such as Private Sewer Systems including septic tanks.

The heterogeneous distribution of both the population and WWTPs, combined with a variety of size and technological capabilities to treat wastewater, directly impacts their treatment efficiency and subsequently their energy efficiency and GHG emissions (Akoumianaki and Ibiyemi, 2022). A study by Ganora *et al.* stated that in Europe 88.4% of wastewater treatment plants connect 31.2% of the population whilst consuming 42.7% of the energy consumption of the sector (Table 2). This results in an energy consumption that is roughly 3 times higher for small communities (2,000 < PE < 50,000) with an average of 111 $KWh.yr^{-1}.PE$. It is difficult to evaluate which proportion of these plants provide tertiary treatment, this situation indicates that such plants are the least energy efficient.

Table 2 Energy consumption of wastewater treatment plants in EU-28 depending on size (adapted from Ganora et al. 2019)(Ganora et al., 2019)

Size	Served PE	N. Plant	$GWh.yr^{-1}$	$KWh.yr^{-1}$ / PE
2 k < PE < 50 k	182,690,141 (31.2%)	16,870 (88.4%)	10,577 (42.7%)	111.3
50 k < PE < 500 k	257,649,774 (45.2%)	2,079 (10.9%)	9,757 (39.4%)	37.9
500 k < PE	128,847,853 (22.6%)	125 (0.7%)	4,424 (17.9%)	34.3

In Scotland, 168,635 Private Sewage Systems (PSS) serve 172,805 properties whilst 200 large scale WWTPs manage the wastewater of most of the Scottish population. This implies that the monitoring of the GHG emissions is focused on these large plants. By contrast, at the small scale WWTPs distributed across Scotland, emissions are likely relatively low at individual sites, thereby limiting the potential for water re-use, and present a significant but diffuse source of pollution across sites that must be mitigated. Most technological developments are focused on the large and centralised WWTPs that serves most of the population (67.8% PE, Table 2) whereas the most numerous systems are small ones (88.4%, Table 2) . However, decentralised systems should also be considered as an option for the development of sustainable wastewater treatment systems, using agricultural activities as an example, certain activities cannot be connected to a modern sewer system in the near future, as would be needed to reach net-zero by 2050.

6. Technological Factors

Wastewater treatment plants are designed according to standard processes (e.g. grit filtration, settling tank, pumping, recirculation), but differ by the biological treatment employed. These biological processes can be categorised into two kinds: free-cultures and fixed-cultures. Free culture systems are reactors whereby the cells are in suspension (planktonic) or floating in the medium. Fixed-cultures system are characterised by the growth of microorganism on a substratum (e.g. plastic pellets, sand). Three main kinds of free-cultures can be found, activated sludge, sequencing batch reactor and membrane bioreactors. There are two types of fixed-culture reactors: biofiltration (e.g. trickling filters) and moving bed biofilm reactors. Without considering anammox processes, all these bioremediation processes require active aeration, apart from some biofilters that are under passive aeration. These types of processes are the expression of the same principles, aeration of the wastewater to enable the biological reduction of both the organic and the nitrogen loading, separation of the microorganisms (sludge) from the treated wastewater (e.g. sedimentation, membrane), recirculation of part of the sludge to maintain the culture and evacuation of the remaining sludge (e.g. anaerobic digestion or incineration). Such aerated zones have been identified as the major contributing factor in a wastewater treatment plant to the GHG emissions (Delre et al., 2019, Nguyen et al., 2019).

The IRSTEA - a French national research institute - carried out a survey on the energy consumption of the intensive wastewater treatments plants in France (Stricker et al., 2017). This study included data from 330 sites, complemented with data from 59 publications that included 213 observations from 1118 sites. This report identified the parameters for each main process that affects the energy consumption of a WWTP and also compared the French energy consumption to the WWTP of other countries. Although specific to the French context, this report is a rare and detailed insight in the energy consumption of the sector. The main factors affecting the energy consumption are the treatment process implemented, organic loading rate, the inlet volume per day and the size of WWTP (in person equivalent). Overall, the energy consumption from three types of biological treatment are summarised in Table 3. The difference between the average energy consumption per process comparing France and other countries reside in how the WWTP are constructed in relation to the population they serve, the loading rates which are lower in France, and the fact that French WWTP are unlikely to have anaerobic digesters available and therefore, recover less energy from waste (Stricker et al., 2017).

Table 3: Energy consumption (KWh.m^{-3}) of three types of biotreatment processes to serve as an indication of their general energetic intensity in Europe. Data extracted from (Stricker et al., 2017).

	Country	Average	Median
Activated sludge	Others	0.46±0.25	0.39
	France	0.70±0.29	0.63
Sequencing Batch Reactor	Others	0.75±0.36	0.75
	France	1.07±0.45	0.98
Membrane Bioreactors	Others	1.70±1.29	1.40
	France	1.66±0.40	1.66

The EU considers wastewater as a resource (EU Directive 2018/2001) since it contains energy and nutrients mixed with other unwanted and sometimes harmful components (e.g. antibiotic, hormones, microplastic). As explained above, bioenergy recovery is not yet a standard in WWTP, although, as stated in section 3, wastewater can contain up to 1.93 KWh.m^{-3} recoverable energy for a loading of 500 mg·L^{-1} COD (Yang et al., 2020, Panepinto et al., 2016). Despite the activated sludge process being the less energy intensive, it still represents 51-56% of the energy required by a WWTP, through provision of the aeration process (Caffoor, 2008, Stricker et al., 2017). This illustrates that if solutions are found to balance this energy consumption, they would have a major impact on the carbon footprint of WWTPs. There have been attempts to homogenise the methodology for evaluating the energy efficiency of WWTPs across Europe (Longo et al., 2018), published literature on the energy-water nexus continues to increase with much of the supporting data, particularly regarding energy-for-water, remaining obscure or inaccessible (Chini et al., 2021).

At present, most utility companies try to offset the carbon footprint of their energy needs by buying energy from green sources or even by introducing renewable sources on their site. For example, Scottish Water generated 40 GWh of green energy through its own assets, host around 830GWh of wind power infrastructure from energy companies on their land, as well as planting trees to offset their carbon footprint (Scottish_Water, 2021). Scottish Water can achieve this due to its specific setting and geography. Eliminating the need for aeration to decrease the energy requirements of WWTP is the main focus of R & D efforts in the wastewater industry with the objective to become energy-positive which is achieved by tapping into the energy content of wastewater (Vindel et al., 2021, Gikas, 2017). Part of the wastewater treatment is sludge management which roughly consists of suspended solids and microbial biomass. Sludge contains some of the pollutants (e.g. heavy metals, microplastic, antibiotics) removed from the wastewater and its environmental dispersion has been severely limited to prevent spreading such pollution. Although solutions are required to enable trapping pollutants and produce a harmless sludge for reuse, recent advances try to use sludge onsite as an energy source after a partial dewatering process. A common approach is to introduce physical processing (e.g. rotating fabric belt screening) and limit biological processes to key steps (e.g. denitrification) (Gikas, 2017). For example, a study has shown that it is possible to bring the energy requirements down to 0.057 $KWh.m^{-3}$ (Gikas, 2017), which represent a 88% decrease compared to an average of 0.46 $KWh.m^{-3}$ for the activated sludge process (Table 3). When using the collected biosolids for the co-production of thermal and electrical energy, through syngas combustion in a co-generation engine, it was calculated that a WWTP could produce up to 0.172 $KWh.m^{-3}$. A more recent initiative, the LIFE Water Factory, is in preparation near Wilp in the Netherland, which aimed to investigate the use of biosolids as an energy source to power the treatment and produce clear water for reuse (https://www.youtube.com/watch?v=Tb4fzjCTdsU&feature=youtu.be). The most common challenges in these new hybrid systems are the biofouling of the active surfaces (e.g. filtering membrane, electrodes), and optimising pollutant removal both in an energy efficient and in an economical manner.

Process optimization can also be achieved by nutrient recovery with adding value to part of the waste to significantly offset the carbon footprint. For example, the Haber-Bosch process produces 70% of the nitrogen used in agriculture and represent 1%-2% of the world energy consumption, whilst phosphorus and potassium are expensively extracted from geographically unequally distributed mines. The recent price increase of fertilizers has made them unaffordable for small farmers who require cheaper alternatives. Most of the nutrients present in wastewater originates from urine (79% N; 47% P; 71% K) and could represent up to 19% of the worldwide inorganic nitrogen inputs. Indeed, fresh urine has an average concentration ranging between 8.8-9.2 $g.l^{-1}$ nitrogen, 0.7-2.0 $g.l^{-1}$ phosphorus, 2.2-2.7 $g.l^{-1}$ potassium, and 6-9 $g.l^{-1}$ COD, whilst also containing many of the micronutrients needed for plant growth. Due to the increasing pressure on phosphate fertiliser, increasing R&D focus on recovering such element from wastewater (Martin et al., 2022).

Passive treatment systems are amongst the proposed solutions to replace energy demanding systems such as activated sludge. Removing the energy consumption, when the site conditions and infrastructure allows (e.g. constructed wetland), are in principle a very efficient way to decrease the carbon footprint. When developing new processes, the energy aspect should be considered in addition to the GHG process emissions. By doing so, certain processes were shown not only to be more energy efficient than the process they replace, but also to release less GHG (e.g. constructed wetland) (Flores et al., 2021).

Independently from the type of process, most process GHG emissions are often variable and relatively difficult to measure, due a complex combination of biological and physicochemical processes. This implies that in addition to the estimated emissions, there is an unknown proportion of emissions that are not considered. At the present time, measurements are based on direct detection with highly specific instrumentation which incurs a high cost if continuous monitoring is required, especially in the case of decentralised systems. Therefore GHG emission monitoring relies on estimations based on the IPCC 2019 guidelines with constant revaluation and modelling from published data (de Haas and Andrews, 2022) making appropriate estimations a challenge. This highlights the urgent need for detection systems that enable real-time monitoring and produce precise evaluation of the emissions. Also, such detection system could be the basis of smart platforms (IoT) supporting direct mitigation action by the utilities companies through localised adjustment of the treatment conditions.

7. Opportunities for wastewater treatment technology

Wastewater management and treatment infrastructure in Europe has evolved as the sewer networks and WWTPs have grown in response to changing demand. Therefore, any new technology designed to achieve net-zero by 2050 needs to accommodate existing infrastructures of large agglomeration as rebuilding new networks or WWTPs will take time. New solutions for decentralised areas have great potential as they are usually independent from any network, thus, are not constrained by existing infrastructure. Here, the report focuses on some innovation routes that could support Europe's wastewater treatment sector reaching net-zero by 2050. Again, any developed solution should be able to demonstrate a carbon footprint improvement over the entirety of its life cycle and at the scale of the treatment plant and not only the process itself. The solutions need to be integrated both within existing infrastructure and with other processes with key areas where innovations are needed identified in the list below:

- **Increase the understanding of GHG emissions during each step of the treatment process**
  - Adopt a homogenised evaluation method to report N_2O and CH_4 emissions for a precise monitoring (and reporting?) at the European level.
  - Develop sensors to enable real-time monitoring at several locations within a wastewater treatment plant: as an example, the process emissions flow to detect can range between 0.1-50 mg m^{-2} day^{-1} for N_2O, and between for 3-2000 mg m^{-2} day^{-1} for CH_4 (Flores et al., 2021). Such sensing methods should be reliable, independent from weather conditions and easy to operate for cost-effective implementation. A widespread sensing system would enable the direct evaluation of the emissions without relying on estimations and thus, support policy development.
  - Develop software and potential sensors for extracting data from satellite observations and to enable detecting seasonal variations of site of interest.

- **Increasing the energetic efficiency of equipment and processes**
  - Modernisation of existing equipment: e.g. energy efficient aeration pump.
  - Improve existing process efficiency to limit GHG emissions (e.g. N_2O, CH_4).
  - Develop management software (A.I) using GHG sensors and deep learning approaches to create automated control loops that enable a fine and localised control of the biological processes along the treatment process. Developing the internet of things is not only key in controlling/mitigating GHG emissions, but is also key in energy management and reduction (e.g. localise application of mitigation solution).

- **Increase the energy and resources recovery from wastewater**
  - Wastewater contains energy under the form of reduced organic matter, thermal energy and kinetic energy. Although solutions for energy recovery (e.g. anaerobic digestion, dark fermentation) are implemented in some large centralised system, they are not widespread and the treatment plants are not energy-neutral. Certain physio-chemical processes are of interest for large and centralised wastewater networks, either as a replacing process (e.g. hydrothermal carbonisation (Tasca et al., 2019)) or as a complementary process (e.g. riothermy for heat to supporting anaerobic digestion (Nagpal et al., 2021)). The utilisation of concentrated waste streams for hydrogen production is also a route of interest due to the lower energy requirements. Combining this process to the onsite production of oxygen for the aeration would not only be beneficial for limiting N_2O emissions but also offset the carbon footprint associated production and transport.
  - Developing solutions or a set of solutions for an optimal treatment that enables local wastewater reuse/recovery (e.g. LIFE Water Factory initiative).
  - Developing solutions for nutrients recovery from the wastewater (e.g. membrane system, chemical precipitation, (bio)electrochemical systems, photobioreactors).

- **Develop alternative processes with lower energy requirements and reduced greenhouse gas emissions**
  - Constructed wetlands are a good example of a wastewater treatment technology that can replace certain type of processes due to its low energy requirements (maintenance), but attention should be focussed on limiting GHG. However, due to the surface area it requires, it is difficult to retrofit the technology to existing infrastructure. A potential development route would be to combine this technology with vertical farming technology to identify potential retrofitting solutions in urban settings.
  - Hydrothermal carbonisation is another route of interest due to its capacity to neutralise pollutants, including pollutant of emerging concerns (e.g. antibiotics, microplastics), whilst producing "biological coal" as an energy source. This technology has the potential to transform wastewater treatment plants into be energy positive infrastructure. However, to maximise the integration of such a technology, the liquid phase of the output needs to be combined with other technology to ensure a complete treatment (e.g. ammonium-rich effluent from anaerobic digester).

- **Target innovations towards decentralised systems**
  - Developing sustainable decentralised wastewater treatment solutions could include a series of modular subsystems that deliver efficient treatment that can adapt to a variety of local conditions. Nature base solutions are the preferred to compensate for the low end-user training by implementing self-sustainable systems (e.g. INNOQUA project (Tompkins et al., 2019); Berambadi system, India).

This research and development can only succeed when carried out in collaboration with SMEs. To maximise chances of success, it would be advised for SMEs to contact the academic institutes financed by the Pillar I fundings to identify project of interests (Horizon Europe portal). This would enable an SME to identify the results that are compatible with its own expertise and build a collaboration with a targeted research structure to access Pillar II fundings. This funding will enable a company and an academic partner to develop an innovation and assess its economic viability. If the innovation has a market niche and the results demonstrate the environmental benefits, then both partners, under the direction of the SME, would have access to the Horizon Europe Pilar III fundings. This later funding will enable the scale up of the innovation and validate the technology as worthwhile for commercialization with the SMEs gaining the expertise to develop the production and commercialisation steps required. This funding avenue allows SMEs to have research and development carried out at a minimal cost with the benefit of having the results validated by a scientific institute. Validation is available for innovative technologies to be reviewed by an inspection body for Environmental Technology Verification (ISO 14034) to obtain the accreditations to operate across a global marketplace. It is important to note that academic research groups are regularly seeking industrial partners to access the above funds and demonstrate the validity of technology developed by them.

As mentioned, it is crucial to decrease of the carbon footprint (energy + GHG emissions) in the wastewater sector. The innovations that will enable such decrease are three-fold (see above list): actual process improvement; improve monitoring and management tools; and combine innovations to have overall neutral processes. These innovations will take place under two contexts, in centralized urban systems or in decentralised and often rural systems. Urban settings have the advantage of allowing for the interactions of several technological solutions resulting an overall optimised sustainability. There are challenges of having to develop, test and deploy innovations in existing networks, which are somewhat inflexible. The amount of wastewater treated in decentralised systems is limited, the measurable impact on the carbon-footprint is going to be lower than that for urban settings. The disconnected nature of decentralised areas limits the complexity of interactions between innovations, however, the number of potential technological solutions will be higher, delivering independent systems tailored to specific conditions. Therefore, in summary the factors discussed above should be considered when SMEs are developing technologies suitable for the water sector as a whole.

8. Conclusion

The report has highlighted the political, environmental, economic, social, and technological context of the energy and carbon footprint within the water and wastewater sector. The aim is to concentrate the information to enable innovation toward increasing the efficiency of the sector and driving it towards sustainability. There is great potential for the sector not only to become energy neutral/positive, but also to be a source of development for the circular economy. The main challenge is to develop retro-fitting solutions in order to support EU's aim of reaching net-zero by 2050. Indeed, the EU objective is to reach this target whilst developing its competitiveness. A path that relies on bringing scientific results from the laboratory to the society through a tight collaboration between an already funded research structure and innovative SMEs.

9. Acknowledgments

The WTN team wish to thank the Scottish Centre of Expertise for Water (CREW) for their constructive suggestions on how to increase the pertinence of report, with a particular gratitude to Dr Rachel Helliwell for the thorough review she provided.

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