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SET-UP OF WATER REUSE TECHNOLOGIES AND RISK MANAGEMENT PLANS IN MEDITERRANEAN RURAL AND URBAN AREAS

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ABSTRACT

The increasing water demand, caused mainly by rapid population growth and growing consumption, is the principal driver for water reuse. This study investigates the potentiality and drawbacks of water reclamation solutions through a Life Cycle Thinking approach. UV and peracetic acid disinfection are applied to the full-scale WWTP of Peschiera Borromeo, while UASB-AnMBR system is set-up at pilot-scale. The outcomes highlight the need to change the traditional way we see WWTP since they can be considered as a resource recovery facilities in which not only water, nutrients and energy are recovered but also economic cost and carbon footprint are minimized. The fertigation by effluent from AnMBR system reduces the fossil depletion of 31% and the global warming of 28% respect to withdraw surface water and discharge in water body the wastewater treated in CAS system. At the same time, the experimental results hightlight the significance of operation conditions: the temperature and organic loading rate are the main influencing parameters.

The safety of water reuse is also addressed. After a review of the existing guidelines on risk management applied to water reuse, this study provides a list of data to collect to lay down a Water Reuse Risk Management Plan, as requested by the new EU Regulation 2020/741. Concerning the Integrated Wastewater Reuse System (IWRS), the hazards and hazardous events may occur are analyzed, as well as the preventive measure to be adopted to reduce the risk.

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1. Introduction

The challenge to global water resources is acknowledged and well-documented. Population growth, escalating urbanisation, salinization and climate change are key factors, exacerbated by individuals' increasing water footprints fuelled by changing diets, societal aspirations and growing industry requirements. The consequences can be especially serious in the Middle East and North Africa where water demand is expected to increase due to population and economic growth. According to the FAO Aquastat data, irrigation water requirements in the Mediterranean region (North Africa, Near East and Mediterranean Europe) are around 120 billion m3 year-1. At the same time and in the same region, around 28 billion m3 year-1 of urban/domestic wastewater (almost ¼ of irrigation needs) is produced and discharged every year (after treatment or not) into water bodies, regardless to climatic conditions. This sustainable and constant source of water, suitably described as an "untapped resource" in the latest World Water Development report of the United Nations, remains an underexploited resource in Europe, despite huge potential to help tackle water scarcity. Being also nutrients-rich, is a very precious resource and should be valorised for irrigational use. Nevertheless, numerous projects and facilities operating in many parts of the world testify the success of this water supply option in improving water resources availability and reliability. Nowadays, the recognition of reclaimed (recycled) water as an essential component of integrated water resources management is entering a mature phase. Water reclamation technologies have been greatly improved and diversified, in parallel to advances in drinking water research. Reclaimed water and reclamation technologies are being increasingly evaluated taking drinking water quality as a reference, both in developing countries and particularly in developed/industrialized countries.

In this perspective, the main objective of FIT4REUSE European Project is to provide safe, locally sustainable and accepted ways of water supply for the Mediterranean agricultural sector focusing on innovative treatment technologies. It exploit the use of non-conventional water resources in agriculture and for aquifer recharge both from a technical point of view and from a regulation/assessment side by a specific holistic methodological framework, taking into account environmental, social, and economic aspects through LCA/ELCC/S-LCA/CBA tools. In this study, an innovative reclamation technology like UASB+AnMBR was experimentally set-up at a pilot-scales. It combines the energy saving and nutrients release proper of anaerobic processes with the beneficial effect of ultrafiltration system on particles and pathogens removal. The result is a safe and nutrient-rich effluent suitable for fertigation without limitations on irrigation method.

At the same time, existing guidelines on water reuse safety plans was investigated focusing on the major safety and environmental concerns of wastewater reuse in agriculture. Indeed, in spite of its advantages, there is still reluctance of users to accept reclaimed water as a valuable resource. Existing guidelines such as "WHO guidelines for the safe use of wastewater, excreta and greywater" of 2006 describe the conceptual bases to assess the risks associated with water reuse. In this sense, WHO guidelines state that strategies for risk reduction should be adjusted to the local context. The lack of adequate and adapted risks plans for the Mediterranean creates unnecessary risks to users and workers (e.g. exposure to pathogenic microbes) and the environment (e.g. eutrophication risks) reducing the confidence in reuse solutions and limiting their widespread adoption. According to the latest report of the European Commission on the implementation status of the Urban Wastewater Treatment Directive (91/271/EEC)(9), only Greece, the United Kingdom, France, Italy, Malta, Cyprus, Spain and Belgium indicated reusing treated wastewater on a regular basis, with reuse percentages varying from 0.08% in the UK to 97% in Cyprus. At an EU level, consultations have taken place on the best policy options to help expedite the uptake of water reuse. Recently an important milestone in the history of water reuse in Europe is achieved: the new Regulation on minimum requirements for water reuse for agricultural irrigation has entered into force on the 25th June 2020. The new rules will apply from 26 June 2023 and are expected to stimulate and facilitate water reuse in the EU. The Regulation sets out:

- Harmonised minimum water quality requirements for the safe reuse of treated urban wastewaters in agricultural irrigation;
- Harmonised minimum monitoring requirements, notably the frequency of monitoring for each quality parameter, and validation monitoring requirements;
- Risk management provisions to assess and address potential additional health risks and possible environmental risks;
- Permitting requirements;
- Provisions on transparency, whereby key information about any water reuse project is made available to the public.

In this context, a water quality integrated platform (WQIP) will be designed, realized and validated in the Milan Peschiera Borromeo WWTP throughout the Europen Project "DIGITAL-WATER.city - Leading urban water management to its digital future'". It aims 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. The overall treatment capacity of the Milan Peschiera Borromeo WWTP is 516,000 P.E. including 250,000 P.E. for the second treatment line which will be used for reuse purposes. An assessment of the current plant configuration was performed through a Life Cycle Thinking approach. The pathogenic load is removed in Peschiera Borromeo WWTP by chemical disinfection with peracetic acid in one treatment line and UV disinfection in the other.

Finally, these two tertiary treatments are hypothetically enhanced to reach reclaimed water quality set out by EU Regulation 2020/741. A environmental and economic assessment was conducted to compare such technologies with the emerging AnMBR system.

2. State of the Art

2.1 Water reuse regulations

The need to minimize health and environmental risks associated with water reuse practices has led to the development of guidelines and regulations on the safe use of reclaimed water. Three main types of approaches can be distinguished:

1. An approach based on limit values defined for a range of parameters of the reclaimed water. By complying with these numerical limit values, health and/or environmental risks are deemed to be minimised. The limit values may be applicable at different points, depending on the standards (e.g. at the reclaimed water delivery point or at the outlet of the WWTP). This approach is the one followed in the policy of six EU Member States that regulate water reuse (Italy, Spain, France, Cyprus, Greece and Portugal)
2. An approach based on wastewater treatment requirements and limit values. This approach is adopted in California (Title 22 of the Code of Regulations). For each potential use, a specific wastewater treatment technique is required. Californian regulation has a system for approving and certifying treatment technologies. In addition, for certain use categories, water quality criteria can be applied (numerical limit values). The USEPA guidelines also follow this kind of approach.
3. An approach based on the implementation of a risk management system for each reuse project. This approach is the one adopted by Australian and WHO guidelines. An advantage of this approach is that it involves identifying and managing risks in a more proactive way, rather than relying on post-treatment testing and reacting when problems have already arised. Itis also more flexible as it may be applied to a wide range of situations. First, the main health and environmental risks need to be identified and assessed, then measures to prevent and control the risks have to be implemented, followed by the implementation of monitoring procedures to check the risks are effectively reduced to an acceptably lower level.

Between the EU Member States, there are large disparities in the number of parameters associated with limit values (where they exist). For example, while France defines 6 water quality parameters, Italy defines 55 parameters, Greek has up to 80 parameters and Spain up to 90 parameters. In a country like Spain, monitoring costs can therefore become significant for water reuse scheme operators as well as competent authorities in charge health and environmental inspections. Moreover, because the reuse categories are not defined the same way across the different standards, it is of limited relevance to try and compare the individual numerical limit values specified by each standard. As an example, a comparison carried out by EUREAU on limit values for E. coli and faecal coliforms applicable to unrestricted irrigation is shown in Figure 2-1.

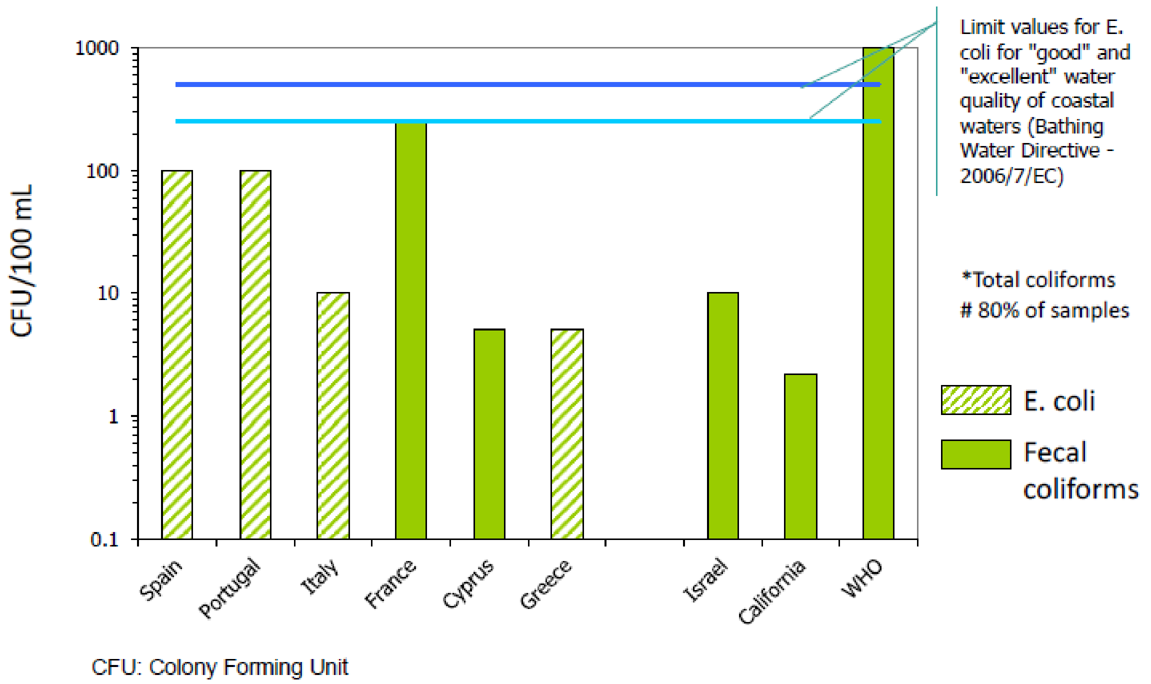


Figure 2-1. Comparison of limit values for E.coli and faecal coliforms applicable to unrestricted irrigation using reclaimed water. From (by Deloitte, 2015)

In the next subsections an overview of three standard example are provided. In particular, starting from the Guidelines laid down in 2005 by the UNEP, passing from the Italian water reuse policy, we arrive to the newly approved European Regulation 2020/741 on minimum requirements for water reuse.

2.1.1 UNEP 2005- GUIDELINES FOR MUNICIPAL WATER REUSE IN THE MEDITERRANEAN REGION

The United Nations Environment Programme (UNEP) is the leading global environmental authority that sets the global environmental agenda, promotes the coherent implementation of the environmental dimension of sustainable development within the United Nations system, and serves as an authoritative advocate for the global environment. In 2005, the UNEP produced guidelines to address public health aspects of water reuse and set out minimum requirements, which should constitute the basis of water reuse regulations in every country of the region. They were issued as a direct consequence of the absence of comprehensive international guidelines resulting in no uniformity in national reuse policy in the Mediterranean area. These inconsistencies in the existing guidelines or standards may have led to too conservative or too liberal standards.

At the heart of the project is the awareness that to be useful and efficiently contribute to the improvement of human health and the alleviation of water resource shortages, guidelines must take the local conditions into account. As a consequence, for instance, the proposed standards are focused only on the microbiological criteria since non-potable applications were and would long remain most of reclaimed water reuse projects in the Mediterranean. After all, heavy metal content in secondary treated effluents are generally within acceptable levels for most non-potable uses.

Since complete elimination of pathogens is not possible, multiple barriers between pathogens and humans that may be exposed to the reclaimed water are required to minimize public health risk. Barriers such as detention time in storage systems, selected irrigation systems, setback distances from the application site, entry restrictions, warning signs, avoiding or preventing cross-connections with potable water distribution systems/backflow prevention, and coded distribution systems, would minimize the direct contact of potentially contaminated water.

Three water quality criteria are proposed: nematode eggs, fecal coliforms or Escherichia coli, and suspended solids (SS). At the same time, four water categories based on comparable levels of risk have been distinguished:

I. urban and residential uses, landscape, and recreational impoundments,
II. unrestricted irrigation, landscape impoundments (contact with water not allowed), and industrial uses,
III. restricted agricultural irrigation,
IV. irrigation with reclaimed water application systems or methods (drip, subsurface, …) providing a high degree of protection against contamination and using water more efficiently

Such repartition underlines the importance of water reuse cost-effectiveness: a reclaimed water supply network must serve as many reuse applications as possible in the same area.

For each category, minimum water quality requirements and monitoring frequency are established. At the same time, wastewater treatments expected to meet those criteria were defined. Especially, to set out the bacterial threshold, these guidelines made extensive use of the results of the WHO guidelines assessment by Blumenthal et al., (2000).

Water category	Intestinal nematode (No. eggs per liter, arithmetic mean)		FC or E. coli (cfu/100 mL, geometric mean)		SS (mg/L)	
	Quality criteria	Sampling frequency	Quality criteria	Sampling frequency	Quality criteria	Sampling frequency
I	≤ 0.1	Fortnightly	≤ 200	2/week	≤ 10	weekly
II	≤ 0.1	Fortnightly	≤ 1000	1/week	≤ 20 ≤ 150	Weekly*
III	≤ 1	Monthly	≤ 10-5	1/month	≤ 35 ≤ 150	Monthly
IV		None required		None required		None required

*: where affordable also check BOD for efficiency o treatment reasons

About the monitoring, these guidelines set out two control points. The microbial quality should be monitored at the outlet of the treatment system (treatment plant + storage, if this storage is included in the treatment process) and at the point of use to evaluate future improvements or degradation of the water quality. Instead, the sampling frequency should be decided to take into account health risks related to the reclaimed water applications and the size of the project. Besides, periodical monitoring of the soil should also be established for irrigation and agricultural purposes.

2.1.2 Italian water reuse regulation

In Italy, the technical measures for wastewater reuse are laid down in DM 185/2003 by the Ministry of Environment, Ministry of Agriculture and Ministry of Public Health. This regulation sets out the same water quality limits for all uses of reclaimed water aside from industrial uses. Limit values for industrial reuse are set by the parties concerned depending on the requirement of the industrial process. This approach does not consider the different risks associated with each particular use, and it is not consistent with the later approach recommended by the WHO (2006). The intended uses are listed in Table 2-1, while the quality standard in Table 2-2.

Table 2-1. Intended uses for reclaimed water in Italy.

Intended uses	Description
1. Irrigation	Irrigation: for the irrigation of crops intended for the production of food for human and animal consumption in non-food purposes, as well as for the irrigation of green areas intended for recreative or sports activities.
2. Civil	Civil: for cleaning of roads, for the supply of heating and cooling systems, for the power supply of dual networks, separate from drinking water, with direct use exclusion of such water in buildings for civil use, except for the plants drain in toilets.
3. Industrial	Industrial: as fire-fighting water, process, washing and for the thermal cycles of industrial processes with the exclusion of the uses that involve contact between wastewater retrieved and foods or pharmaceutical and cosmetic products.
4. Environmental (only where there are regional regulations)	Environmental: as feed water for the restoration or improvement of the water balances of wetlands and the increase of the biodiversity of natural habitats; regulate the flow of rivers that have long dry periods during the year; food, restore or improve systems of wetlands and natural habitats; retrieve streams characterized by an inadequate quality status; recharge indirectly the bodies of groundwater.

Table 2-2. Minimum quality standards for reclaimed water in Italian regulation.

Parameter	Maximum limit values	Parameter	Maximum limit values
pH	6-9.5[a]	Active chlorine (mg/l)	0.2
SAR	10	Chlorides (mg Cl/l)	250[a]
Coarse Materials	Absent	Fluorides (mg F/l)	1.5
Total Suspended Solids (mg/l)	10	Fats and oils (mg/l)	10
BOD_5 (mg O_2/l)	20	Mineral oils (mg/l)	0.05
COD (mg O_2/l)	100	Total phenols (mg/l)	0.1
Total Phosphorus (mg P/l)	2 or 10	Pentachlorophenol (mg/l)	0.003
Total Nitrogen (mg N/l)	15 or 35	Total aldehydes (mg/l)	0.5
Ammonia Nitrogen (mg NH_4/l)	2[a]	Tetrachloroethylene (mg/l)	0.01
Electric conductivity (µS/cm)	3000	Total chlorides solvents (mg/l)	0.04
Aluminium (mg/l)	1[a]	Trihalomethanes (mg/l)	0.03
Arsenic (mg/l)	0.02	Total aromatic organic solvents (mg/l)	0.01
Barium (mg/l)	10	Benzene (mg/l)	0.001
Beryllium (mg/l)	0.1	Benzopyrene (mg/l)	0.00001
Boron (mg/l)	1	Total nitrogenous organic solvents (mg/l)	0.01
Cadmium (mg/l)	0.005	Total surfactants (mg/l)	0.5
Cobalt (mg/l)	0.05	Chlorinated pesticides (each) (mg/l)	0.0001
Total chromium (mg/l)	0.1	Phosphorus pesticides (each) (mg/l)	0.0001
Chromium 6 (mg/l)	0.005	Total other pesticides (mg/l)	0.05
Iron (mg/l)	2[a]	Escherichia coli (CFU/ml 100)	10
Manganese (mg/l)	0.2[a]	Salmonella	Absent
Mercury (mg/l)	0.001	Vanadium (mg/l)	0.1
Nickel (mg/l)	0.2	Zinc (mg/l)	0.5
Lead (mg/l)	0.1	Total cyanides (mg/l)	0.05
Copper (mg/l)	1	Sulphides (mgH_2S/l)	0.5
Selenium (mg/l)	0.01	Sulphites (mg SO_3/l)	0.5
Tin (mg/l)	3	Sulphates (mg SO_4/l)	500[a]
Thallium (mg/l)	0.001		

[a] Guide values that can be modified by regional authorities.

Finally, the policy defines the frequency of monitoring according to the plant capacity. Up to 499999 PE, the analysis must be performed once per month, while for twice per month is the minimum number of analysis required in the case of 50000 PE or more.

2.1.3 Regulation (EU) 2020/741 on minimum requirements for water reuse

Recently, the European Parliament and of the Council approved the Regulation 2020/741. It lays down minimum requirements for water quality and monitoring and provisions on risk management, for the safe use of reclaimed water in the context of integrated water management. Quality requirements are specified in Annex I for the final use of reclaimed water, under the "fit for purpose" principle. Water quality classes are defined depending on the crop category to be irrigated and the irrigation technique (Table 2-4).

Table 2-3: Classes of reclaimed water quality and permitted agricultural use and irrigation method

Quality class	Crop category*	Irrigation method
A	All food crops consumed raw where the edible part is in direct contact with reclaimed water and root crops consumed raw	All irrigation methods
B	Food crops consumed raw where the edible part is produced above ground and is not in direct contact with reclaimed water, processed food crops and non-food crops including crops used to feed milk- or meat-producing animals	All irrigation methods
C	Food crops consumed raw where the edible part is produced above ground and is not in direct contact with reclaimed water, processed food crops and non-food crops including crops used to feed milk- or meat-producing animals	Drip irrigation or other irrigation method that avoids direct contact with the edible part of the crop
D	Industrial, energy, and seeded crops	All irrigation methods**

(*) If the same type of irrigated crop falls under multiple categories of Table 1, the requirements of the most stringent category shall apply.

(**) In the case of irrigation methods which imitate rain, special attention should be paid to the protection of the health of workers or bystanders. For this purpose, appropriate preventive measures shall be applied.

Table 2-4: Reclaimed water quality requirements for agricultural irrigation

Reclaimed water quality class	Indicative technology target	Quality requirements				
		E. coli (n/100 ml)	BOD_5 (mg/l)	TSS (mg/l)	Turbidity (NTU)	Other
A	Secondary treatment, filtration, and disinfection	≤10	≤10	≤10	≤5	*Legionella* spp.: <1 000 CFU/l where there is a risk of aerosolization Intestinal nematodes (helminth eggs): ≤1 egg/l for irrigation of pastures or forage
B	Secondary treatment, and disinfection	≤100	In accordance with Directive 91/271/EEC (Annex I, Table 1)		-	
C	Secondary treatment, and disinfection	≤1 000			-	
D	Secondary treatment, and disinfection	≤10 000			-	

The indicated values for *E. coli*, *Legionella* spp. and intestinal nematodes must be met in 90 % or more of the samples; none of the values of the samples exceeds the maximum deviation limit of 1 log unit from the indicated value for *E. coli* and *Legionella* spp. and 100 % of the indicated value for intestinal nematodes. The indicated values for BOD5, TSS, and turbidity in Class A are met in 90 % or more of the samples; none of the values of the samples exceeds the maximum deviation limit of 100 % of the indicated value.

Table 2-5: Minimum frequencies for routine monitoring of reclaimed water for agricultural irrigation

Reclaimed water quality class	E. coli	BOD5	TSS	Turbidity	*Legionella* spp. (when applicable)	Intestinal nematodes (when applicable)
A	1/week	1/week In accordance with Directive 91/271/EEC (Annex I, Section D)		Continuous	2/month	Twice a month or as determined by the reclamation facility operator according to the number of eggs in wastewater entering the reclamation facility
B	1/week			-		
C	2/month			-		
D	2/month			-		

Routine monitoring shall be included in the verification procedures of the water reuse system. Validation monitoring shall be performed before a new reclamation facility is put into operation.

At least 90 % of validation samples shall reach or exceed the performance targets.

Table 2-6: Validation monitoring of reclaimed water for agricultural irrigation

Reclaimed water quality class	Indicator microorganisms(*)	Performance targets for the treatment chain (log_{10} reduction)
A	E. coli	≥ 5,0
	Total coliphages/F-specific coliphages/somatic coliphages/coliphages(**)	≥ 6,0
	Clostridium perfringens spores/spore-forming sulfate-reducing bacteria(***)	≥ 4,0 (in case of *Clostridium perfringens* spores) ≥ 5,0 (in case of spore-forming sulfate-reducing bacteria)

Of relevance, within the new EU Regulation there are provisions for risk management. Hence, this policy includes and harmonized the first and third approach defined above. According to Article 5, the competent authority shall ensure that a water reuse risk management plan is established for water reuse production, supply, and use. It shall be prepared by the reclamation facility operator, other responsible parties, and end-users, as appropriate. Aim of risk management shall comprise identifying and managing risks in a proactive way to ensure that reclaimed water is safely used and managed and that there is no risk to the environment or human or animal health. In particular, the WRRMP shall be based on all the key elements of risk management set out in Annex II. They can be summarized in:

1. Detail and critical description of the entire water reuse system, from the entry of wastewater to WWTP to the irrigation method and crop type.
2. Identification of all parties involved in the water reuse system focusing on roles and responsibilities
3. Identification of potential hazards and potential for hazardous events such as treatment failures or accidental leakages or contamination of the water reuse system
4. Identification of the environments and populations at risk and the relative exposure routes considering specific environmental factors such as hydrogeology, topology, farming and irrigation practices
5. Assessment of risks to the environment and human health including confirmation of the nature of the hazards, the assessment of the potential range of exposure or dose and the characterisation of the risks.
6. Identification of preventive measures that are already in place or that should be taken to limit risks, from access control, additional disinfection or pollutant removal measure to specific irrigation technology mitigating the risk of aerosol formation (e.g. drip irrigation) or pathogen die-off support before harvest;
7. Establishment of an adequate quality control system and procedures as well as adequate maintenance programmes for equipment.
8. Definition of an environmental monitoring system
9. Definition of an appropriate system to manage incidents and emergencies.

The risk assessment may be carried out using qualitative or semi-quantitative risk assessment. The quantitative risk assessment shall be used when there are sufficient supporting data or in projects having a potentially high risk for the environment or public health.

Furthermore, depending on the outcome of the risk assessment, additional requirements to that set out in Annex I shall be required. They may concern heavy metals, pesticides, disinfection by-products, pharmaceuticals and other substances of emerging concern, including micropollutants and microplastics, and anti-microbial resistance. In any case, risk management should consider also other aspects such as the reduction of water pollution from nitrates, protected areas, environmental objective and quality standards, groundwater and soil protection, hygiene measures, maximum levels of contaminants and pesticides and animal health. Under the definition of “preventive measure” may be also included the quality control systems and procedures, monitoring the reclaimed water for relevant parameters, maintenance programmes for equipment, environmental monitoring systems, procedures to manage incidents and emergencies, to inform all relevant parties of such events and regular update of the emergency response plan.

2.2 Water reuse technologies (UASB/AnMBR) and disinfection treatments (UV and PAA)

The main objective of wastewater treatment plants (WWTPs) is to remove suspended solids, organic matter, and, in certain areas, nutrients. These are the parameters enforced by the UWWTD about discharging treated wastewater to the environment. When treated wastewater is to be reused, there is a need for additional treatment to minimize health and environmental risks and ensure its quality and fitness for the foreseen use. The additional treatment is called reclamation treatment and is carried out in water reclamation plants (WRP) as an additional process in the WWTP. The main objective of reclamation treatment is to remove pathogens and chemical contaminants.

In addition to beneficial microorganisms, raw domestic wastewater can contain a large variety of pathogenic microorganisms that are derived principally from the feces of infected humans and primarily transmitted by the "fecal-oral" route. A pathogen is a microorganism that causes disease in its host. Most pathogens found in untreated wastewater are known as 'enteric' microorganisms; they inhabit the intestinal tract where they can cause disease, such as diarrhea. They are classified into three broad groups: bacteria, parasites (parasitic protozoa and helminths), and viruses. Concentrations of some organisms observed in the research are reported in Table 2-7 to provide a general comparison.

Table 2-7.Typical concentration of pathogen microorganisms in the raw wastewater

Pathogen	u.m.	Concentration	Ref.
Bacteria			
Total coliform	CFU/100ml	3.9E+07	Kay et al. 2007
	CFU/100ml	1.96E+07- 4.36E+07	WERF 2004
	CFU/100ml	5.15e+08	Thwaites et al 2018
	MPN/100ml	10^7 - 10^9	Metcalf & Eddy, 2014
	MPN/100ml	1.1E+08	Howard et al. 2004
Fecal coliforms	MPN/100ml	10^6 - 10^8	Metcalf & Eddy, 2014
	MPN/100ml	8.2E+06	Howard et al. 2004
	MPN/100ml	2.1E+06-5.3E+06	Oakley et al 2019 (from Rose)
	CFU/100ml	1.7E+07	Kay et al. 2007
E.coli	MPN/100ml	10^5 - 10^7	Metcalf & Eddy, 2014
	MPN/100ml	5.37E+03 - 3.47E+07	Oakley et al 2019
	logMPN/100ml	6.42±0.28 (5.99 - 7.28)	Bailey et al 2018
	CFU/100ml	3.6e+06	Marin et al 2015
	CFU/100ml	5.31e+07	Thwaites et al 2018
	N/l	10^5 - 10^10	NWQMS 2006
Salmonella	MPN/100ml	10^2 - 10^4	Metcalf & Eddy, 2014
	MPN/100ml	266.7	Howard et al. 2004
	MPN/L	3-1100	Lemarchand et al. 2002
	n/l	10^3 - 10^5	NWQMS 2006
	n/l	1-10^5	WHO 2006
Protozoa			

Cryptosporidium	MPN/100ml	10 - 10^3	Metcalf & Eddy, 2014
	n/l	1-10^4	WHO 2006
	oocysts/L	0 - 10^4	NWQMS 206
	oocysts/L	2.5 - 277	Hamilton et al 2008
	oocysts/L	4.5±0.8	E. Carraro et al. 2000
	oocysts/L	1-87.13	Lemarchand et al. 2002
	oocysts/L	96±105	Ramo et al. 2017
	oocysts/L	6–350	Montemayor et al., 2005; Castro-Hermida et al., 2008, 2010; Galván et al., 2014
	oocysts/L	22 - 456	Oakley et al 2019 (from Ramo2017)
	oocysts/L	6.5 - 37.8	Oakley et al 2019 (from Rose)
	oocysts/L	0.3 - 5e+04	Soller at al. 2017 che cita Yang et al., 2015; Crockett, 2007; Harwood et al., 2005; Nasser, 2016).
	oocysts/L	30±5	Briancesco et al. 2004
Giardia	MPN/100ml	10^3 - 10^4	Metcalf & Eddy, 2014
	N/L	10^2 - 10^5	WHO 2006
	cysts/L	10^2 - 10^5	NWQMS 2006
	cysts/L	764 - 6606	Oakley et al 2019 (from Ramo2017)
	cysts/L	3247±2039	Ramo et al. 2017
	cysts/L	61.2 - 794	Oakley et al 2019 (from Rose)
	cysts/L	89-8305	Montemayor et al., 2005; Castro-Hermida et al., 2008, 2010; Galván et al., 2014
	cysts/L	3.2 - 1.0E+04	Soller at al. 2017:
	cysts/L	7000 ± 2000	Briancesco et al. 2004
Viruses			
Enterovirus	MPN/100ml	10^3 - 10^4	Metcalf & Eddy, 2014
	N/L	10^5 - 10^6	WHO 2006
	PFU/L	10^2 - 10^6	NWQMS 2006
	MPN/L	4.6 - 93.7	Oakley et al 2019 (from Rose)
Norovirus	PFU/L	10 - 10^4	NWQMS 2006
	copies/L	10^3.76 ±10^0.93	J.A. Soller et al. 2017, Eftim et al., 2016
Norovirus gi	copies/L	1.12 E+03 - 5.75E+05	Oakley et al 2019
Norovirus gii	copies/L	6.46e+02 - 2.19e+06	Oakley et al 2019

Reclamation technologies can be classified as intensive (conventional) and extensive technologies (non-conventional) (Table 14). Intensive technologies are characterized by the need for large quantities of energy and minimum space. They are accelerated artificial processes that can be rapidly modified if needed. Besides, they need a highly specialized operation and maintenance personnel. Extensive technologies, on the contrary, require a large amount of land because they use environmental matrices and rely on natural processes for water treatment, so the processes occur at almost natural rates and the energy requirement is very low. These technologies also require low, but very important, levels of operation and maintenance.

Table 2-8. Intensive and extensive reclamation technologies. From (Alcalde-Sanz & Gawlik, 2017)

INTENSIVE TECHNOLOGIES	EXTENSIVE TECHNOLOGIES
Physical-chemical systems (coagulation-flocculation, sand filters)	Waste stabilisation ponds (maturation ponds, stabilisation reservoirs,…)
Membrane technologies (ultrafiltration, reverse osmosis, membrane bioreactor, …)	Constructed wetlands (vertical-flow, horizontal-flow,..)
Rotating biological contactors	Infiltration-percolation systems

In the following are the range of log removals for different unit process of wastewater treatment plant.

Table 2-9. Indicative log removals of indicator microorganisms and enteric pathogens during various stages of wastewater treatment. From (USEPA, 2012)

	Indicator microrganism				***Pathogenic microorganism***			
Type of microorganism	***Escherichia coli* (indicator bacteria)**	***Clostridium perfringens***	**Phage (indicator virus)**	**Enteric bacteria (e.g., *Campylobacter*)**	**Enteric viruses**	***Giardia lamblia***	***Cryptosporidium parvum***	**Helminths**
Bacteria	X	X		X				
Protozoa						X	X	X
Helminths			X		X			
Secondary treatment	1 - 3	0.5 - 1	0.5 - 2.5	1 - 3	0.5 - 2	0.5 - 1.5	0.5 - 1	0 - 2
Dual media filtration2	0 - 1	0 - 1	1 - 4	0 - 1	0.5 - 3	1 - 3	1.5 - 2.5	2 - 3
Membrane filtration (UF, NF, and RO)3	4 - >6	>6	2 - >6	>6	2 - >6	>6	4 - >6	>6
Reservoir storage	1 - 5	N/A	1 - 4	1 - 5	1 - 4	3 - 4	1 - 3.5	1.5 - >3
Ozonation	2 - 6	0 - 0.5	2 - 6	2 - 6	3 - 6	2 - 4	1 - 2	N/A
UV disinfection	2 - >6	N/A	3 - >6	2 - >6	1 ->6	3 - >6	3 - >6	N/A
Advanced oxidation	>6	N/A	>6	>6	>6	>6	>6	N/A
Chlorination	2 - >6	1 - 2	0 - 2.5	2 - >6	1 - 3	0.5 - 1.5	0 - 0.5	0 – 1

In the following are briefly described the UV and chemical disinfection through peracetic acid dosing, as well as the ultrafiltration applied to anaerobic processes (AnMBR). These technologies are the subject of further evaluation in terms of technical and environmental performances. Ultraviolet disinfection and dosing of peracetic acid are both used in the full-scale plant of Peschiera Borromeo (MI). The AnMBR are set-up in the experimental pilot-scale of Falconara Marittima (AN).

Table 2-10. Advantaged and disadvantages of reclamation solutions(Europe, 2018)

	Advantages	Disadvantages
Membranes	High effluent quality, very low SS and turbidity, high removal of organics and microorganisms; consistency in the quality of water produced; reliable and predictable; low footprint; suitable for a wide range of reuse applications, decentralised or centralised (agricultural, industrial, commerical and environmental).	High capital costs; energy consumption for high pressure operating systems; maintenance costs associated with membrane fouling management (cleaning/membrane replacement); regular maintenance (chemical cleaning of the membranes); production of concetrated wastes.
MBRs	High effluent quality, low in nutrients; high capacity to retain microbial contaminants; decoupled control of sludge and hydraulic retention times; low sludge production; low footprint; easy automation/simple process control.	Membrane fouling; capital costs associated with membranes; maintenance costs (cleaning, membrane replacement every 5-10 years); energy consumption and associated costs.
FO	Operated at a lower pressure than reverse osmosis (RO) systems, hence less energy intensive; limited fouling as opposed to RO systems; can process effluent with high level of suspended solids.	Lower fluxes than RO systems; FO permeates not directly reusable and require additional treatments which are energy intensive; uncertainties regarding the overall cost of the treatment technology; technology still in a development phase, although full-scale schemes exist[51].
Natural Systems	Simple to design and operate, robust and tolerant; recharge via percolation/soil filtration through unsaturated soils combined with underground storage provides additional water treatment*; high underground storage capacity that can buffer seasonal variations in water supply and demand*; retains microbial contaminants; low maintenance and operation**; aesthetic benefits**; passive technologies attractive for decentralised and rural applications**	Large land requirements; clogging of systems, requiring regular maintenance*; potential irreversible clogging of subsurface soils*; potential impact on physico-chemical properties of groundwater*; performance closely linked to soil properties*; potential odour issue**
AOP	No waste generation[52]; rapid reaction rates[52]; simple automation and control.	Chemicals and/or energy comsumption[52]; potential formation of hazardous by-products; high operating costs.
Analytical Online Tools and Rapid Monitoring	Automated analysis of physico-chemical, microorganisms, trace organics and emerging contaminants is possible; rapid resonse to water contamination; reduce collection of water samples and lab analysis; provide additional barrier to protect public health; support tool for optimisation of disinfection regime.	Emerging technologies; potential robustness, sensitivity and repeatability issues; potential false positive alarm; complex matrix effects can affect the results.

2.2.1.1 *UV disinfection*

UV disinfection of reclaimed water is gaining in use due to increasingly energy-efficient and lower-cost UV technologies. UV technology provides a rapid and effective inactivation of microorganisms through a physical process that causes a molecular rearrangement of the genetic material (known as DNA) of the microorganism which renders it inactive and incapable of causing infection. Due to individual cell make up, different organisms require different levels of UV energy for their destruction. This energy level is known as dosage.

The UV dose is expressed, for practical purposes, as the product of UV intensity, expressed in milliwatts per square centimeter (mW/cm^2), and the exposure time of the fluid or particle to be treated, expressed in seconds (s). The design UV dose will depend on the target microorganism and the quality of the water-supply source prior to UV disinfection. This technology has demonstrated efficacy against pathogenic organisms, including those responsible for cholera, polio, typhoid, hepatitis and other bacterial, viral and parasitic diseases (USEPA, 2012).

While designing UV systems for wastewater reuse, UV transmission of water being disinfected is an essential factor to be considered while sizing the UV system. The lower the UV transmission, the higher the UV power required, even to achieve the same dose. Indeed, disinfection of treated wastewater by UV can be complicated by several factors. Most of these factors are governed by the level of treatment the utility has implemented prior to the UV disinfection reactor. Two key water quality issues that can impact UV disinfection performance and efficiency are the presence of particle-associated microorganisms and the UV transmittance (UVT) of the wastewater. Particles can shade target microbes, shielding them from UV light; bacteria frequently become embedded in particulate matter, partially or wholly protecting them from the UV light (Paraskeva et al., 2002; Emerick et al., 1999). UV disinfection is enhanced by filtering water prior to disinfection, both by the reduction in particulates (a reduction in the number of large particles with embedded and shielded microorganisms) and by the increase in UVT (a reduction in smaller particulates that do not shield organisms but do reduce UVT and thus reduce UV efficiency). Additional safety features such as automatic cleaning of the quartz sleeve, temperature cut-offs, specially designed UV reactors for wastewater with high levels of BOD and suspended solids, assist in reliable and effective disinfection.

Besides, one challenge with UV disinfection is the possibility that some organisms may undergo photoreactivation after UV exposure; this can occur when the microorganisms repair their DNA damaged by the UV light. Photoreactivation of disinfected organisms can occur when UV-damaged cells are exposed to light in the visible wavelength spectrum (310 to 480 nm) that prompts cell-initiated repair of damaged DNA (Harris et al., 1987; Ni et al., 2002). Photoreactivation can be a function of UV dose, the concentration of organisms, UV transmittance, and suspended solids concentration.

A review of log reduction reported in literature are presented below.

Microrganismi	Log removal	References
Bacteria	2 - >4	WHO 2006
E.COLI	2 - >4	NWQMS 2006
	1.8 - 4.7	DEMOWARE D 3.3
	2.63 - 4.38	Francy et al. 2012
	0.56 - 3.30	Peschiera Borromeo WWTP
SALMONELLA		Howard et al. 2004
	5.6	Hijnen et al. 2006
		J.A. Soller et al. 2017 (Eftim et al., 2016)
CRYPTOSPORIDIUM	>3	WHO 2006
	>3	NWQMS 2006
	3	Chahal et al 2016 (Craik et al., 2001; Linden, Shin, Faubert, Cairns, & Sobsey, 2002)
	0.45 - 0.48	Liberti et al. 2002
	2 - 3.5	J.A. Soller et al. 2017. (U.S. EPA, 2003)
VIRUS	1 - >3	who 2006
	2.9 - 4.2	DEMOWARE D 3.3
	4	Chahal et al 2016
ENTEROVIRUS	>3	NWQMS 2006
NOROVIRUS	0.5 - 1.5	J.A. Soller et al. 2017

2.2.1.2 *Peracetic acid disinfection*

Peracetic acid (PAA) is a strong oxidizing organic compound with a wide spectrum of antimicrobial/biocidal properties similar to liquid chlorine or sodium hypochlorite (NaOCl). It has been widely used in the food, beverage, medical, and pharmaceutical industries for over 20 years. Because of its strong antimicrobial properties, PAA has been getting a lot of attention as a wastewater disinfectant to replace chlorine in recent years (Garg et al., 2016; Luukkonen & Pehkonen, 2017).

PAA is a clear, colorless liquid available at a concentration of 12% to 15% in an equilibrium mixture of acetic acid, hydrogen peroxide and water. When PAA decomposes its by-products are acetic acid, hydrogen peroxide, oxygen, and water:

$$CH_3COOH + H_2O_2 \leftrightarrow CH_3COOOH + H_2O$$

It has been reported that PAA and sodium hypochlorite have similar antimicrobial activities against E. coli, fecal coliform, and total coliform (Veschetti et al., 2003); however, PAA holds multiple advantages over sodium hypochlorite as disinfectant for wastewater effluent. These advantages include: need for lower doses, lower residuals, faster disintegration, and absence of disinfection by-products (DPBs) in the treated effluent (Booth and Lester, 1995; Liberti and Notarnicola, 1999; Monarca et al., 2000; Kitis 2004; Vaschetti et al., 2003; Crebelli et al., 2005; Koivunen & Heinonen-Tanski, 2005; Antonelli et al., 2013).

In Italy the use of chlorine-based disinfectants has been strongly constricted due to the risks related to Disinfection By-Products (DBPs) occurrence. Regulations on wastewater reuse set the limit for total trihalomethanes at 0.03 mg/L, which practically excludes chlorination as a main disinfection in Waste Water Treatment Plants (WWTPs), involving the need for alternative solutions. Among these, peracetic acid (PAA) is a broad-spectrum disinfectant. One of the main advantages of PAA is the possibility of an easy retrofit of sodium hypochlorite (NaOCl) disinfection equipment, which is almost always present in existing WWTPs, without expensive and structural interventions. This has particularly favoured the spread of PAA disinfection for WWTP upgrade in comparison with other disinfection technologies, such as UV irradiation, requiring the implementation of dedicated facilities and filtered effluents (Antonelli et al., 2013).

The PAA disinfection displayed a log reduction from 1 to nearly 5 of E. coli and faecal coliform bacteria, depending on initial bacterial concentration, residual PAA and contact time. For complying with the Italian standard for discharge in surface water (5,000 CFU/100 mL for E. coli), with 1 or 2 mg/L of PAA, a contact time over 18 min is necessary; at higher doses, a contact time 6 min is adequate. For complying with the more stringent standard for agricultural reuse, doses over 5 mg/L and longer contact times are required (Antonelli et al., 2013). The irreparability of the damages caused to coliform bacteria and consequently the PAA bactericidal efficiency is confirmed by Santoro et al: the log reductions observed 5 h after disinfection, without any residual PAA, were comparable to those obtained immediately after disinfection for all doses and contact times. Such absence of bacterial regrowth phenomena as long as needed for agricultural reuse, and the limited toxicity effects on the aquatic environment indicated the good sanitary safety of PAA, whose bactericidal properties were demonstrated.

Sand filtration followed by disinfection with peracetic acid (2-3 ppm) is currently employed as tertiary treatment in Milano Nosedo WWTP (1'250'000 PE) where an average of 4 m^3/s, out of 5 m^3/s influent to the plant, are reused in agricultural since 2003.

Table 2-11. Full-scale plant installation in US (PeroxyChem, n.d.).

Full-scale application	Average dose (ppm)	Average CT (min)	Limit CFU/100 ml	Indicator
Florida, St Augustin	1.5	30	200	Fecal Coliform
New Jersey, Hoboken	2.5	2*	200	Fecal Coliform
Tennessee, Memphis	1.2	45	126	E.coli
Tennessee, Tullahoma	0.75	45	126	E.coli
Illinois, Mundelein	0.5	120	200	Fecal Coliform
Oregon, Clackamas	1.5	60	126	E.coli
Kentucky, Bowling Green	1.3	20	126	E.coli

*as pretreatment of aging UV

2.2.1.3 *AnMBR technology*

In the perspective of fertigation, anaerobic processes permit to obtain an elevated release of nutrients without reaching sufficient quality level for reuse in terms of bacteriological proprieties and organic matter. Therefore, tertiary treatments are needed to increase the final effluent characteristics. The combination of anaerobic processes with advanced post-treatments could improve the final effluent quality.

Anaerobic membrane bioreactor (AnMBR) technology is focused on a more sustainable concept for sewage treatment, where sewage turns into a source of energy and nutrients (nitrogen and phosphorus) whilst producing a recyclable water resource (Pretel et al., 2016). This enables to close the loop in the water field in line with Circular Economy principles (COM 2015). Furthermore, AnMBR technology can contribute to reduce the environmental impact within the sewage treatment field since it reduces drastically the CO_2 emissions by avoiding organic matter oxidation and replacing it by the production of biogas suitable for energy recovery (Innovation Deal).

AnMBR integrates anaerobic digestion treatment with membrane filtration. During AnMBR treatment, organic substances in wastewater are biologically converted to methane-rich biogas. The produced biogas can offset the energy demand for wastewater treatment (McCarty et al., 2011). Since anaerobic treatment converts nutrients to chemically available forms (e.g. ammonia and phosphate), AnMBR can also facilitate nutrient recovery via subsequent precipitation. Coupling UASB and AnMBR, the almost total COD and TSS removals can be reached (85% COD% and 100% TSS%). Thanks to TN and TP releases (from 75% to 85%) the permeate is suitable for fertigation and agriculture application. The effluent fits the limit values for reuse according the new EU regulation on water reuse, also in terms of E.Coli, as demonstrated even in the following experimental set-up. In addition, the innovative UASB and AnMBR system removed 97% of influent microplastics, providing 1.7 MPs/L after UASB reactor up to 0.1 MPs/L (100 MPs/m^3) after ultrafiltration (Foglia et al., 2020)

The anaerobic biological process involves four integrated stages, namely hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Degradation of organic matter and their conversion to biogas depend on the symbiotic relationship among the different groups of microorganisms (e.g. fermentative bacteria, syntrophic acetogens, homoacetogens, hydrogenetrophic methanogens and aceticlastic methanogens) (Chen et al., 2016). Of these microorganism groups, methanogens play arguably the most important role for biogas production by converting intermediate products from previous stages to methane gas. However, methanogens are slow-growing microorganisms and can be easily washed out from conventional anaerobic bioreactors. By integrating membrane separation processes, commonly including microfiltration (MF) and ultrafiltration (UF), the hydraulic retention time (HRT) can be decoupled from sludge retention time (SRT). Thus, AnMBR can produce more biogas than conventional anaerobic treatment (Liao et al., 2006). It will decrease the energy demand. Furthermore, since the areation is not required, AnMBR has a significantly lower energy input to the bioreactor compared to aerobic MBR.

There are several AnMBR configurations depending on the anaerobic treatment process (Figure 2-2). Common anaerobic bioreactors for AnMBR include up-flow anaerobic sludge blanket (UASB), completely stirred tank reactor (CSTR), and anaerobic fluidized bed bioreactor (AFBR) (Figure 2-2A–C). AnMBR can be operated in either side-stream or submerged mode (Figure 2-2D–F). In the side-stream AnMBR, membrane module is integrated outside of the bioreactor. Mixed liquor in the bioreactor is transferred to the membrane unit for clean water extraction. In the submerged AnMBR, membrane unit can be directly immersed into the bioreactor (Figure 2-2E) to extract treated water through the membrane.

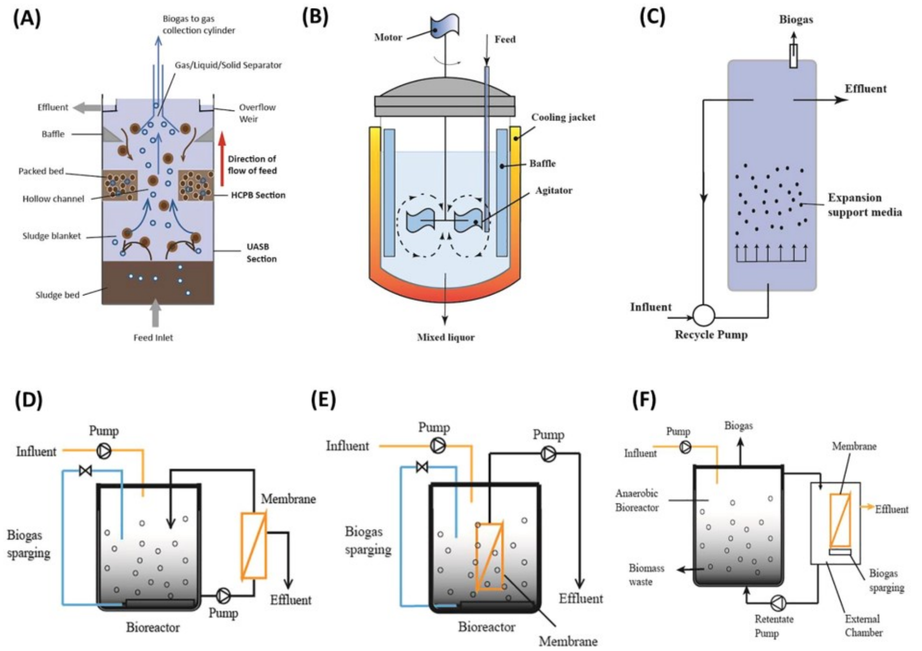


Figure 2-2

It has been well established that biogas produced by AnMBR consists of more than 80% of CH_4 (Skouteris et al., 2012). During AnMBR treatment, the CH_4 yield increases linearly with the organic loading rate (Yeo et al., 2015). Under optimized condition, AnMBR can convert up to 98% of the influent COD into biogas, which is equivalent to seven times of the energy required for system operation (Van Zyl et al., 2008). In practice, current biogas yield is considerably lower than the theoretical value, due to the high solubility of CH_4 in the effluent and process inhibition caused by inhibitory substances. Dissolved CH_4 in the permeate does not only reduce the energy efficiency of AnMBR treatment, but also contributes to global warming as the greenhouse potency of CH_4 is 25 times higher than carbon dioxide.

Nevertheless, there remain several significant challenges in the development of AnMBR for resource recovery from wastewater, particularly municipal wastewater. These include low organic and nutrient contents in municipal wastewater as well as issues associated with salinity build-up, membrane stability, membrane fouling, and the occurrence of inhibitory substances.

Membrane fouling during AnMBR treatment is governed mainly by membrane properties and operational conditions (e.g. water flux, temperature, HRT, and SRT), hydrodynamics, and sludge characteristics. Several techniques have been developed to control and clean membrane fouling during AnMBR operation. In the side-stream AnMBR, high cross-flow velocity can reduce foulant build-up on the membrane surface; while fouling control is typically accomplished through biogas sparging for the submerged configuration. Despite these strategies to control fouling, membrane cleaning is still necessary. Membrane cleaning includes physical, chemical, and biological schemes. Physical membrane cleaning can be achieved by backwashing, surface flushing, and ultrasonication (Lin et al., 2013). Chemical cleaning is necessary to further remove fouling layers using suitable agents, such as sodium hypochlorite, hydrochloric acid, nitric acid, citric acid, sodium hydroxide, and EDTA for target foulants.

AnMBR is also susceptible to the accumulation of free ammonia and sulphate, in wastewater. High sulphate concentration inhibits AnMBR performance due to the competition between sulphate reducing bacteria (approximately 2 g COD/g SO_4-Sremoved) and methanogenic microbes for available carbon (Chen et al., 2016).

2.3 Existing guidelines and regulations on risk management applied to the water sector

A range of potential risks is associated with reused water which is likely to contain pollutants (organic, microbiological, chemical, etc.). These risks differ by type of reuse and entail contamination of the environment (water resources, soil) and people (direct exposure, ingestion of food products irrigated with reclaimed water, etc.). Health risks are partially addressed by existing legislation concerning agricultural product safety, i.e. the Regulation on the Hygiene of Foodstuffs; however, this legislation does not specify the requirements for treated wastewater used for irrigation of agricultural products. Environmental risks associated with water reuse must be considered as well, e.g. chemical contaminants from inorganic salts, nutrients, heavy metals and detergents can negatively affect the environment. For heavy metals there are concerns that these substances can build-up in the soil over time. Salinity of the water is also a risk to the environment and crops (in case of irrigation). There are also growing concerns over the fate of the wide variety of compounds of emerging contaminants (CECs), e.g. pharmaceuticals, which are present in sewage, often at trace levels, and often unmonitored. Evidence remains limited as to how well treatment processes deal with these pollutants. In general, such risks can be addressed by applying suitable barriers, the most important barrier being treatment of waste water and applying a risk based approach these risks can be split into 2 categories associated with water reuse in agricultural irrigation:

1. the health risks to consumers of agricultural products irrigated with reclaimed water and placed on the Internal Market; this category of risk includes those to health of animals consuming crops irrigated with reclaimed water
2. the health risks to humans exposed to reclaimed water (workers, bystanders and residents in nearby communities) and risks to the local environment (surface waters and groundwaters, soil and depending ecosystems).

Next, the following regulations or manual are presented:

- Guidelines for the safe use of wastewater, excreta and greywater, volume II – Wastewater use in agriculture, WHO 2006
- Sanitation Safety Planning – manual for safe use and disposal of wastewater, greywater and excreta, WHO 2016
- Australian Guidelines for Water Recycling: Managing Health and Environmental Risks, 2006
- Water Reuse Safety Plans - a manual for practitioners, DEMOWARE 2017

These documents aim to provide a practical guidance to facilitate risk management development within the water reuse application. A risk management plan intends to consistently ensure the safety and acceptability of water reclamation, but it is only useful if it is implemented and revised. Finally, few case study of WRRSP implementation are reviewed.

2.3.1 Guidelines for the safe use of wastewater, excreta and greywater, volume II – Wastewater use in agriculture, WHO 2006

The Guidelines developed by WHO aims primarily at human health protection, with particular attention for workers and their families, local communities and product consumers. They provide information on the health impact of water reuse in agriculture, health hazards identification and measures to minimize the associated risks.

Those guidelines are mainly used in developing countries and technical issues rely on readily and easily available technologies, in order to encourage beneficial use of scarce resources with public health benefits. The Guidelines support policy makers, public health and water management expertise.

Hazards associated with the use of wastewater can be pathogens, such as bacteria, helminths, protozoa and viruses, skin irritants, vector-borne pathogens or chemicals, such as heavy metals, halogenated hydrocarbons and pesticides. For each one exposure routes are defined. Indicator microorganisms can be used for each category to quantify hazards.

The Guidelines provide a list of health-risks associated with the use of wastewater for irrigation for different exposure groups, that can be evaluated through microbial and chemical laboratory analysis, epidemiological studies and quantitative microbial and chemical risk assessment.

Health-based target are used to define the minimum level of health protection from each hazard, depending on the level of tolerable health risk. Disability-adjusted life years (DALYs) is a population metric of life years lost to disease due to both morbidity and mortality. 10^{-6} DALYs is the defined health target and health protection measures are evaluated considering the log_{10} pathogen reduction required to achieve 10^{-6} DALYs for different exposures.

Maximum soil concentrations for different chemicals based on health risk assessment and levels that impact agricultural productivity are both presented.

Health protection measures consider a multi-barrier approach of treatments, technical and behavioural practices. Risk management strategies considered include wastewater treatment, produce restriction, application techniques, exposure control methods and produce washing/disinfection/cooking. The Guidelines provide pathogen reductions achievable by various protection measures, including their combination to reach the health-based targets.

Monitoring activities are divided into validation, operational monitoring and verification. Validation is required to guarantee that the system is able to satisfy the designed functions and is performed for new systems or process changes; operational monitoring includes routinely practices to ensure the functionality of the single measures; verification is performed to ensure that the end product satisfies the specific targets.

Sociocultural aspects and public perception should be taken into account, considering the level of acceptance and trust in practices for water reuse. Community and stakeholder participation is encouraged through education and information activities, public meetings and workshops.

Even if the main purpose is human health protection, environmental impacts are also considered. Effects of pathogens, salts, metals, toxic organic compounds, nutrients, organic matter, suspended solids and acid/bases substances are considered on soil, crops, groundwater or surface water and specific control measures are proposed.

Economic feasibility is evaluated through cost-benefit analysis and market feasibility assessment should be performed at the planning stage.

Policy aspects are considered, since the Guidelines aims to represent a reference for regulation and standards at national and international levels. Laws and regulation framework, economic measures, educational programmes and institutional authorities can support safe water reuse practices.

Planning and implementation of water reuse programmes follow progressive steps. The initial phase of requirement definition, participant roles, staff training, development of health protection measures, priorities identification and communication with local community. At the intermediate stage monitoring is enhanced, statistical analysis of data is performed, and national databases are set up. On the advanced phase, routine tests and frequencies are defined for each health-related parameters and national management framework for wastewater reuse in agriculture is improved. The activities include communication and public participation, stakeholder involvement, use of data and results dissemination.

2.3.2 Sanitation Safety Planning, WHO 2016

Sanitation Safety Planning (SSP) Manual focuses on the safe use of human waste and implements the Guidelines by providing a structure for risk assessment and management in the stepwise process.

WSPs provide a systematic approach towards assessing, managing and monitoring risks from catchments to drinking-water consumers. Similarly, SSP applies the approach from sanitation waste generation to the waste's final use and/or disposal. However, SSP typically operates in a less defined regulator environment, has multiple objectives, has more stakeholders and addresses risks to multiple exposure groups.

	Sanitation Safety Planning	Water Safety Planning
Similarities	Derived from WHO Guidelines for the Safe Use of Wastewater, Excreta and Greywater	Derived from the WHO Guidelines for Drinking-water Quality
	Uses risk management, HACCP, Stockholm Framework (see Note)	Uses risk management, HACCP, Stockholm Framework
	Core components: (1) system assessment; (2) monitoring; (3) management	Core components: (1) system assessment; (2) monitoring; (3) management
	Follows the sanitation chain	Follows the drinking-water supply chain
Differences	Considers multiple exposure groups for microbiological, physical and chemical hazards	Considers single exposure group (drinking-water consumer) for microbiological, physical, chemical and radiation hazards
	Expands from waste generation to its uses and discharges into the environment	Contracts from catchments and converges to the drinking-water delivery point
	Usually no clear regulatory framework – roles and responsibilities are shared over different sectors and levels	Usually operates in a clear regulatory framework
	Objectives – reduce negative health impacts of use of wastewater, excreta or greywater while maximizing the benefits of their use	Objectives –- to consistently ensure the safety and acceptability of a drinking-water supply and to reduce the risk of drinking-water contamination
	Implementing agency – varies depending on objectives, skills and resources	Implementing agency – water utility or a community association for small supplies

SSP process follows six main steps, called modules. The concepts of coordination and incremental improvement over time are central to the SSP approach.

Table 2-12. Schematic description of the procedure to draw up the Sanitation Safety Plan

SSP Module	Description
Module 1: PREPARE FOR SSP	
Establish priority areas or activities	identification and agreement on the focus of the SSP process, considering reported or suspected critical areas for water supply, food or recreational activities, wastewater use and vulnerable population
Set objectives	define the purpose of the SSP, staying that the main objective is the public health
Define the system boundary and lead organization	boundaries are defined by the specific objectives set, to identify and define sub-systems
Assemble the team	select expertise with health and technical skills and engage team members from a stakeholder analysis, appoint a team leader, define roles and estimate provisional costs
Module 2: DESCRIBE THE SANITATION SYSTEM	
Map the system	flow diagrams are used to schematize the system and available quantitative information on flows and waste streams are collected
Characterize the waste fractions	characterization is necessary for hazard identification and treatment performance evaluation
Identify potential exposure groups	categorize people that could be exposed and help prioritization
Gather compliance and contextual information	collect data on demographics, land use patterns, quality standards, certifications or requirements, information about system management and performances, variabilities, existing epidemiological and environmental data
Validate the system description	ensure accuracy and completeness, confirm system characteristics and performances
Module 3: IDENTIFY HAZARDS, ASSESSING EXISTING CONTROLS AND ASSESS EXPOSURE RISKS	
Identify hazards and hazardous events	at each step along the sanitation chain, hazardous events could be associated with normal operation, due to failure in the system, related to seasonal factors, due to cumulative hazards or indirect
Refine exposure groups and exposure routes	exposure groups are detailed depending on the hazardous events previously specified, the expected exposure and transmission routes can be primary if through direct contact or short-distance transmission, or secondary if through an external route such as consumption of contaminated produce

Identify and assess existing control measures	evaluate the effectiveness of already in place control measures through literature or detailed technical assessment, through expected or measured log reduction values or through analysis of operational data over a long period
Assess and prioritize the exposure risk	risk assessment can be conducted through team-based descriptive or semi-quantitative approach if undertaken by several individuals, or through a quantitative method such as QMRA. The final goal is to prioritize the interventions.
Module 4: DEVELOP AND IMPLEMENT AN INCREMENTAL IMPROVEMENT PLAN	
Consider options to control identified risks	identify improvement actions such as capital works, operational measures and/or behavioural measures. Evaluate them according to the cost-benefit of the control option, the most appropriate location, the technical effectiveness, and its acceptability in relation to local cultural and behavioural habits
Use selected options to develop an incremental improvement plan	organize the workflow for the implementation of control measures highlighting timeline and funding, roles and responsibilities of different organizations involved.
Implement the improvement plan	it requires also monitoring of the working in progress to ensure that action is taken.
Module 5: MONITOR CONTROL MEASURES AND VERIFY PERFORMANCE	
Define and implement operational monitoring	select monitoring points and simple parameters to give rapid feedback of the selected control measure so that decisions can be made in time to remedy a problem. For each point should also be identified method and frequency of monitoring, the person in charge, a critical limit, and actions to be undertaken when the critical limit is exceeded.

2.3.3 Australian Guidelines for Water Recycling: Managing Health and Environmental Risks, 2006

Australian Guidelines provide a framework for risk management to be applied in water reuse systems. The process consists in assessing, managing, monitoring and reviewing risks.

Assessing is performed through the identification of hazards and hazardous events, the estimation of their likelihood, the evaluation of impacts and the characterisation of the corresponding risks. This scheme can be replied both for health as well as for environmental risks. As concern human health protection, a particular focus is paid for microbial risks caused by pathogens, like bacteria, viruses, protozoa and helminths. On the other side, environmental risks mainly involve chemicals that may cause plant toxicity (boron, chloride, sodium, cadmium and chlorine), soil degradation (salinity, sodium) or nutrient imbalance. Even water excess is considered. DALYs are used to quantify impacts on human health and define acceptability levels and targets. The characterization distinguishes between the maximum risk and the residual risk, taking into account existing preventive measures, to define priorities.

Management considers a multiple barrier approach and focuses on critical control points. Treatment processes are combined with on-site controls and use restrictions. Multiple barriers can be used to meet performance targets for microorganisms and keep concentrations of any chemical contaminants below target values. Critical control points are preventive measures essentials to the functioning of the recycling scheme that removes a high-risk hazard or reduce it to acceptable levels, are monitored and in case of failure can be rapidly corrected.

Four types of monitoring are used with both human and environmental health risks: to obtain baseline data, to validate the system, to obtain operational data and to verify process effectiveness.

Communication activities and public consulting are encouraged to increase acceptance and trust.

2.3.4 Water Reuse Safety Plans - a manual for practitioners, DEMOWARE 2017

The report promotes the adoption of a risk management framework in water reuse and is intended to enable operators and authorities to develop viable management and safety concepts for existing water reuse systems. A dedicated Water Reuse Safety Plan (WRSP) is introduced to operationalize such a framework. It is drawn on the approaches of the WHO Guidelines and their concept of Safety Plans. However, the proposed WRSP expands the application of WSP to any type of water reuse.

Following the SSP approach, the WATER REUSE SAFETY PLAN relies on a structured analysis of the system (hazards and related risks), suggests multi-barrier approaches to control risks, and highlights the importance of communication, cooperation, and review.

Table 2-13. Schematic description of the procedure suggested by (DEMOWARE et al., 2015) *to draw up the WRSP*

WRSP steps	Description
Module 1 PREPARATION	Clearly define the objective, limitations and boundary conditions of the safety plan
1.1 Set objective	The main goal of WRSP is to assess the safe operation of water reuse schemes, but also other objectives might be targeted such as environment protection
1.2 Define system boundaries	The boundaries involve the scope of the water reuse, source of water, type of reuse application, administration boundaries, areas of use of products, specific exposure groups, or area to be considered.

1.3 Set up the team	Identify all stakeholders that should be involved, and to identify their corresponding roles and responsibilities.
Module 2 SYSTEM ASSESSMENT	Provide a stepwise description, characterization, and evaluation of the reuse system and associated risks.
2.1 System description	Elaborate a flow diagram depicting the water reuse system illustrating the interrelations between stages, inputs, and outputs. Water of different qualities crossing boundaries of sub-systems should be identified as this is often related to a transfer of responsibilities
2.2 Health risk assessment	Identify who is at risk and how the hazardous events causing risk can occur. Analyze impact in terms of the number of the affected person and the severity of health implications or environmental damage.
2.2.1 Identify hazard and hazardous events	Potential hazards in water reuse are caused by microbial pathogens, toxic and chemical compounds, and CECs. Assess the exposure groups and routes.
2.2.2 Describe and assess control measures	Assist in elaborating and assessing control measures and decide where to place them in the system. How effective these control measures are in practice as well as how effective they could be, should be evaluated based on the technical and performance information available as well as results of current monitoring or detailed technical assessment.
2.2.3 Assess and prioritize the risks	Identify and evaluate the health risks associated with water supply/a sanitation chain
2.3 Environmental impact assessment	Assess environmental impact through LCA, Water footprinting or EIA to compare different technology choices and treatment trains
2.4 Assess societal impact and response	Understand the needs and expectations of multiple stakeholders and satisfy the concerns of reclaimed water users, including the public.
2.5 Choose the system from predefined options	Require a ranking to prioritize options and could take the form of a modified cost-utility analysis.
Module 3 OPERATIONAL MONITORING	Establish the procedures to demonstrate that the control measures are working as intended. Specify corrective actions for events of non-compliance with specified values

Module 4 MANAGEMENT and COMMUNICATION	Define and describe communication programs that should include information flows, adequate reporting formats, notification procedures, stakeholder's contacts, and availability of information and consultation processes.
4.1 Engagement of stakeholders and public	Make people aware of the water cycle, of the need to reuse water, and of the associated benefits of reuse.
4.2 Surveillance	The surveillance activities are periodic external reviews
4.3 Supporting programs – staff training	Assure that clear management procedures frame the WRSP operation.

In the preparation step, the Water Reuse Safety Plan must focus on setting clear and defined objectives beyond improving the health outcomes of different user groups. The wastewater reuse is more complex than the water supply system, and thus, it requires a thoughtful selection of multiple stakeholders to be involved in the team. Even the system assessment outcomes to be trickier due to a variety of exposure pathways, risk interaction, and multiple dimensions of consequences. Throughout the 2nd module, the team must find an answer to the following questions: What can happen? How likely is it to happen? What are the consequences? Who will be affected? How do we prevent it from happening and control consequences?

Therefore, the way the risk is measured varies with the context. While DALYs can be used to measure disease burden, other targets need to be defined for environmental risks such as eutrophication, groundwater contamination and salinization etc. Also, the consequences of redirecting water from discharge to the environment into direct uses will require attention. This encompasses aspects such as minimum ecological flow. All the available risk assessment methods (Team based descriptive risk assessment, risk matrix, QMRA and QCRA) are valid to identify and evaluate the risk. Nevertheless, a more sophisticated QMRA/QCRA can be a better choice when resources are available. In general, three types of control measures can be applied that either target water quality or work on the exposure routes:

- (water)treatment
- Non-treatment but technical measures
- non-technical (behavioural) measures

The operational monitoring should include measuring parameters at control points, but also audits and visual inspections using check-lists and interviews can be beneficial as well and help operators to understand better the functionality of the system as well as the background of the risk management process. Online monitoring systems and real-time data reporting are advisable since fast response are required to detect a failure in the system early.

Finally, the communication is deemed to be more challenging than the water supply system, as water reuse is generally viewed quite critical by the public. It is important to engage with the public and other stakeholders in the planning and introduction of systems for water reuse, preferably at an early stage as possible. This helps to create transparency and allows for useful information to be gathered from stakeholders. Stakeholder (including public) involvement is a key component in creating trust and acceptance. The good practice encompasses multiple levels of public and stakeholder participation, ranging from targeted awareness-raising campaigns through to consultation and higher levels of stakeholder involvement in planning and decision-making. Making people aware of the water cycle, of the need to reuse water, and of the associated benefits of reuse needs public education and communication.

2.3.5 Case Studies of Water Reuse Risk Management Plan

A wastewater safety plan (WWSP) has been drawn up, based on multiple barriers approach, for reuse of treated wastewater in green areas in “Universidad Nacional Autonoma de Mexico (UNAM)” (campus University City) (Orta de Velasquez, et al. 2012). The proposed scheme involved eight major components and was inspired to the WSP manual provided by WHO for drinking water system. The main objective is to ensure human health protection. The health-based target was identified in the “Norma Oficial Mexicana, NOM 003 SEMARNAT 1997” which establishes the maximum contaminant limits for treated wastewater for reuse in public services. During the risk assessment, critical control points were determined considering the wastewater treatment processes, reception and storing practices, accidental or deliberated contamination, distribution system maintenance and protection practices, and variations due to weather. As a final consequence of WSSP implementation, an upgrading of the WWTP and improvement of physical conditions of storage tank were performed to ensure the safety of human health. At the same time, a monitoring and maintenance programme will be established.

As intermediate step of a Water Reuse Safety Plan, four of the DEMOWARE case-studies (El Port de la Selva, Braunschweig, Olf Ford and Sabadell) have been investigated for health risks caused by pathogens via quantitative microbial risk assessment (QMRA). This approach calculates the probability of infection combining the calculated concentration of pathogenic microorganisms with available dose-response relationships and end-use specific exposure scenarios. Final step consists in calculating the disability adjusted life years (DALYs), used as indicator of disease burden.

In the specific, two thirds of the Braunschweig WWTP effluent (ca. 15 Mio m^3 per year) is used for the irrigation of 2700 ha of agricultural area. Therefore, in Braunschweig quantitative microbial risk assessment (QMRA) was conducted in order to quantify the probability that the planned reuse system would be able to meet the WHO health-based target of 10^{-6} DALYs per person per year (Kraus, et al. 2017). The selected reference pathogens were identified in rotavirus, Campylobacter jejuni, Cryptosporidium and Giardia; while for exposure assessment three different scenarios were assessed:

a. exposure of fieldworkers,

b. exposure of local/nearby residents
c. children ingesting soil irrigated with reclaimed water.

The risk assessment shows that the current measures for risk reduction are sufficient to meet the WHO benchmark for water reuse for local residents (including children) for all pathogens. However, fieldworkers have an increased work-related risk of infection which exceeds the WHO benchmark. It can be can only be met by combining UV disinfection and irrigation on demand.

The Australian Guidelines for recycled water management reports a real case of risk management plan for agriculture reuse of treated wastewater (Conference 2006). 120 ML of raw sewage from domestic and industrial activities enter daily the WWTP that consists of secondary treatment followed by about 20 days of lagoon storage and polishing. In order to use the effluent for irrigating commercial food crops, treatment was expanded to include coagulation, dissolved air flotation and filtration (DAFF) and disinfection. From the risk assessment, it appears that human health is mainly affected by microbial hazards, while chemical aspects of recycled water (such as chloride, sodium and nutrients concentration, and salinity) produce risk to the environmental performance. To reduce the risks preventive measures are implemented and critical points are identified.

To ensure the application of best practices in water reuse, the new Portuguese policy focuses on the adoption of projects supported by a risk management framework and quality standards defined according to a fit-for-purpose approach. Rebelo and its colleagues describe the proposed methodology based on ISO standards 16075 that allows validating appropriate quality standards to be noted on water reuse permits and helps authorities on the decision-making process. At the same, the application of the risk assessment methodology was demonstrated in a case study, namely a vineyard irrigated with reclaimed water from an urban wastewater treatment plant (Rebelo, et al. 2020).

2.4 Early warning systems

Early warning systems (EWS) are generally an integrated system consisting of monitoring instrument technology, with an ability to analyze and interpret results in real-time. They are a suitable control measure to reduce and prevent the risk. The goal of an EWS is to identify low-probability/high-impact contamination events in a time period as short as to be able to safeguard public health. EWS should provide a fast and accurate system to distinguish between normal variations and anomalous events, both deliberate as well as accidental. It should be also able to detect quality changes due to biochemical and physical interactions. EWS tools need to be reliable, with few false positives and negatives, not too expensive, easily maintainable, and easily integrated into network operations (Storey et al., 2011).

Early warning systems are currently employed in the drinking water system and freshwater quality monitoring. Advances in instrument development have contributed to several reliable online/real-time monitoring systems available for the rapid detection of chemical or biological contaminants, treatment optimization, and water quality management in water systems. Their application in wastewater treatment plants WWTPs are increasing in recent years, due to technology progress. The main existing applications rely on toxic event detection. Toxic contaminants in the inflow can cause inefficiencies on the activated sludge process, especially what concern the more sensitive bacteria, as the ones responsible for nitrification, and lead to significantly exceeded total nitrogen concentration in the effluent. The existing EWS in this field differs for the monitoring location (along with the sewer collection or in the WWTP intake), the parameters investigated, and the measurement method. Chow and its colleagues demonstrated the potential usefulness of an anomaly detection system with an online scanning instrument to give early warnings of the abnormal status of water plants, in Whyalla WWTP (Australia) (Chow, et al. 2018). An online spectrophotometer measure raw wastewater characteristic and this spectral data together with other database information like rainfall and temperature, are assessed by a web-based prototype portal able to integrate, visualize and predict data with the consequent capability to detect anomalies. Similarly, in Korea, Hong and its colleagues developed a DO- and pH-based strategy to identify potential nitrification inhibition (Hong, et al. 2012). The detector can be mounted at the outlet of a primary settling tank for screening wastewater to early detect toxicity from chemicals flowing into aeration basins or a biological process. If the system detects any potential toxicity by the incoming wastewater, a WWTP operator can divert the wastewater into a reservoir and prevent the complete failure of this biological process. As well, Du and its colleagues assembled an online early-warning system to monitor the shock load from industrial wastewater, improving the performance of WWTPs (Du, et al. 2019). The system relies on the Relative Oxygen Uptake Rate. It consists of a wastewater tank, a sludge tank, a filter, an aerator, a water pump, a sludge pump, a batch reactor for DO measurement, a DO probe, and a programmable logic controller (PLC). The work of Zaho, instead, applies microbial fuel cell-based biosensor as an early warning device for real-time in situ detection of Cr(VI) in industrial wastewaters (Zaho, et al. 2018).

On the other hand, there are examples of in-sewer EWS in Lodz WWTP and Wroclaw WWTP (Poland). The advantage, in this case, is that the warning event is detected early enough for WWTP operators to react and introduce the appropriate set of corrective actions. In Wroclaw WWTP, the EWS aims to identify wastewater toxicity level through activated sludge OUR (Oxygen Uptake Rate) measurement (Jurga, Gemza and Janiak 2017). It is possible through few toxicity measurement points placed at selected locations of the sewage collection system. Similarly, Black and colleagues presented results from a pilot-scale study using an in-sewer early warning system based on detection of nitrous oxide gas emitted by nitrifying bacteria naturally present in sewer biofilm (Black, et al. 2014). In Lodz, instead, a more complex concept is involved (Sakson, Brzezinska e Kowalski 2019). The system is based on measurement data from three primary sources such as existing pluviometer system, flow measurement system in sewers next to 18 combined sewer overflows, and newly constructed four stations for qualitative monitoring of wastewater in the sewage system with online sensors measuring (pH, conductivity, organic substances, ammonium nitrogen, suspended solids/turbidity, chlorides, BTX, hydrogen sulfide). As a consequence, they can receive, well in advance, reliable information on significant quantitative and qualitative changes in inflowing sewage and the possibility of a threat to biological treatment processes, allowing controlling the treatment plant performances optimally.

A similar concept is applied in Denmark, where an integrated real-time control and warning system improved the hygienic water quality in the receiving waters in the city of Aarhus, mainly by reducing the frequency of combined sewer overflow (German Water Partnership s.d.). The system comprises data acquisition, data processing, data validation, model design, optimal strategy development, sending of control instructions and control of the infrastructure elements, triggering operational alarms, and alerting the public.

Finally, within the water reuse, the EWS is mainly developed to check the pathogen contamination. For instance, aquaBio analyzer is one of several advanced monitoring solutions tested under the scope of R3Water European project (R3WATER 2017). It provides the quantity of the Escherichia coli and total coliform in water automatically, using the technology of DST® (defined substrate technology), and a detection system for measuring fluorescence and absorbance. Consorci Costa Brava uses aquaBio to monitor the intake of the inlet of the Water Reclamation Plant and consequently improve the plant's efficiency. At the same time, another unit monitors the outlet of the WRP, providing an early warning to guarantee sanitary safety in case of reclamation plant malfunction. In a completely different scenario, the SWIM-Sustain Water MED project promoted water reuse for agricultural purposes in Tunisia (Bedoui 2014). They equipped the Médenine WWTP with adequate tertiary treatment and with a computerized system allows for regular sharing of quality data with all concerned stakeholders as well as for early warning notification via SMS in case of quality problems.

Nowadays, the current European bathing water directive (BWD) (76/160/EEC 2006) demands the implementation of reliable early warning systems for bathing waters. Therefore, Seis and its colleagues proposed a methodology for implementing EWSs based on multivariate regression modelling, which takes into account the probabilistic character of European bathing water legislation for both alert levels and model validation criteria (Seis, Zamzow, et al. 2018). The system was implemented based on information and data collected at a river bathing site in Berlin. Precipitation, river flow and the volume of the non-disinfected discharge of WWTP were used as key explanatory variables to construct the models.

Application	Sampling	Measurement/method	Location	Ref.
Influent Toxicity determination	Intake of WWTP	Online spectrophotometer	Whyalla WWTP Australia	(Chow, et al. 2018)
		DO and pH detector	Korea	(Hong, et al. 2012)
		Oxygen uptake rate	Nancao WWTP China	(Du, et al. 2019)
		Microbial fuel cell-based	Lanzhou WWTP China	(Zaho, et al. 2018)
	Sewer system	Oxygen uptake rate	Lodz WWTP Poland	(Jurga, Gemza and Janiak 2017)
		N_2O emissions	Pilot-scale UK	(Black, et al. 2014)
		pH, conductivity, organic substances, NH_4-N, TSS/NTU, Cl, BTX, H2S	Wroclaw WWTP Poland	(Sakson, Brzezinska e Kowalski 2019)
Reduction of overflow frequency			Aarhus city (Denmark)	(German Water Partnership s.d.)
Pathogen contamination	Effluent	E.coli concentration through DST technology	Consorci Costa Brava	(R3WATER 2017)
		Online multiparameter analyzer (BOD, COD, TSS, TDS, pH)	Medenine WWTP (Tunisia)	(Bedoui 2014)
Bathing water quality		Multivariate regression modelling	River Havel, Berlin	(Seis, Zamzow, et al. 2018)

2.5 Life Cycle Assessment

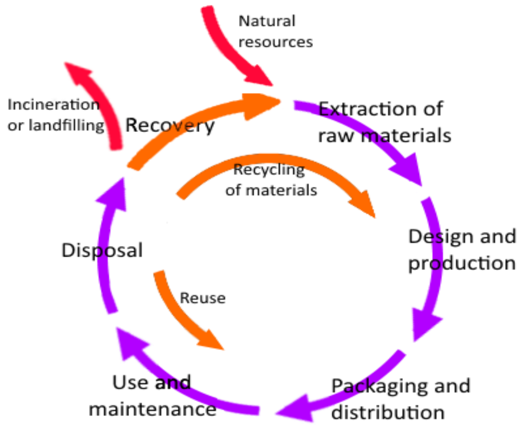


Figure 2-3. Life Cycle Thinking approach.

Sustainable development is defined as balancing the fulfillment of human needs with the protection of the natural environment. A common definition of sustainable development, set out in "Our Common Future", also known as the Brundtland Report (WCED 1987), is "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" The field of sustainable development can be conceptually broken into three constituent parts: environmental protection, economic sustainability, and social justice.

In this respect, Life Cycle Assessment is defined as "a tool to assess the potential environmental impacts and resources used throughout a product's life cycle, i.e. from raw material acquisition, via production and use stages, to waste management" (ISO 2006). This definition goes further the limited approach where only the manufacturing step was recognized as the pollution driver. Several purposes can be fulfilled with this kind of methodology: comparison of alternative products, processes or services; comparison of alternative life cycles for a certain product or service; or identification of parts of the life cycle where the greatest improvements can be made (Roy, et al. 2009)

The standard ISO 14040 establishes the framework and principles universally valid to plan and conduct an LCA. The LCA framework operates with four separate phases: Goal and scope definition, Inventory analysis, Impact assessment and Interpretation The relationship between the phases is illustrated in Figure 2-4.

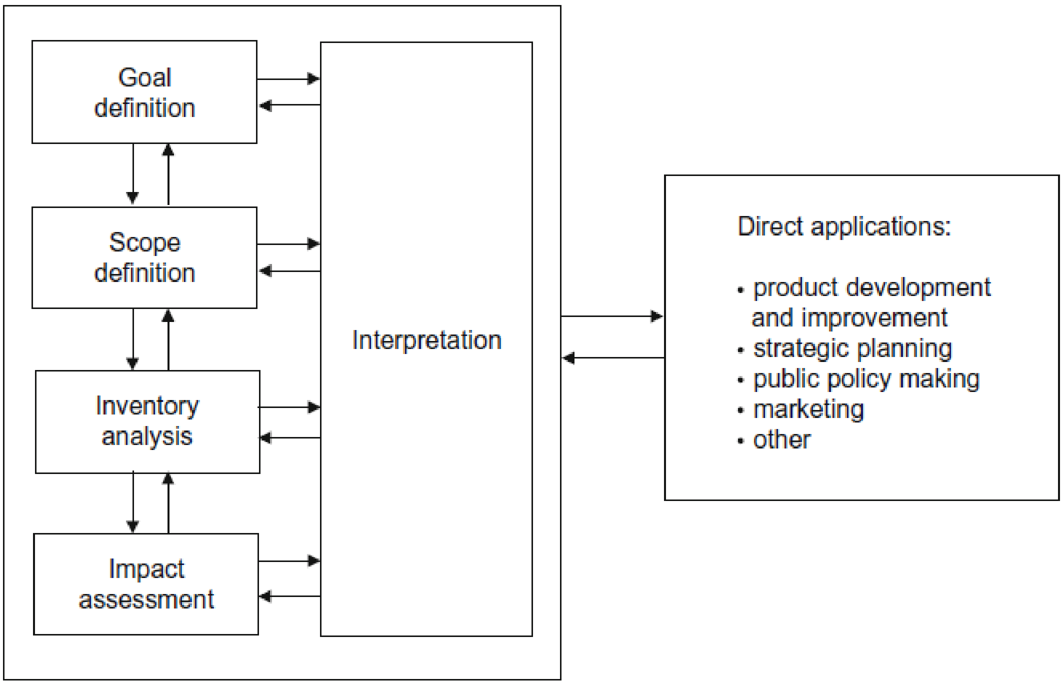


Figure 2-4. Framework of LCA modified from ISO 14040 standard

The first essential step consists in the goal definition. It sets the context of the LCA study and is the basis of the scope definition primarily in terms of:

- Defining the functional unit
- Scoping the product system, deciding which activities and processes belong to the life cycle of the product that is studied (system boundaries definition)
- Selecting the assessment parameters
- Selecting the geographical and temporal boundaries

Indeed, a life cycle assessment can be applied at a planning level where alternative management strategies, conceptual designs, and long-term scenarios are analyzed. Or, it can be applied at a design level when preliminary designs plant, unit operations, or collection/reuse systems are generated and evaluated. Third, LCA can be applied to existing plants for operation, optimization, and retrofitting, enabling decision-makers to chart pathways to improve the environmental performance of a given system. Finally, LCA can also be applied during the development of new technologies to understand how best to advance an individual system. Therefore, the main purpose of the LCA will dictate the overall methodological approach and the level of detail required (Lluís Corominas et al., 2020).

As the second step, the inventory analysis collects information about the physical flows in terms of input of resources, materials, semi-products and products and the output of emissions, waste and valuable products for the product system. Six main categories of physical flows are identified:

Input flows:	Output flows:
1. Materials	4. Products
2. Energy	5. Waste to treatment
3. Resources	6. Emissions.

Resources and emission, since not exchanged between unit processes, are referred to as elementary flows. They are defined by ILCD as “single substance or energy entering the system being studied that has been drawn from the ecosphere without previous human transformation, or single substance or energy leaving the system being studied that is released into the ecosphere without subsequent human transformation” (JRC, EU 2010).

Besides, it is useful to distinguish between unit processes belonging to the foreground and background system. The foreground system is commonly defined as comprising those processes of a product system that are specific to it. The foreground system is largely modelled using primary data, i.e. data collected first-hand by the LCA practitioner, e.g. obtained through the commissioner of the study. The background system, in contrast, is commonly defined as those processes of a system that are not specific to it. Such processes take part in numerous product systems besides the one studied. Examples are society’s electricity supply, the production of metallic copper, or the waste management systems. The background system is typically modelled using LCI databases, which contain average industry data representing the process in specific nations or regions.

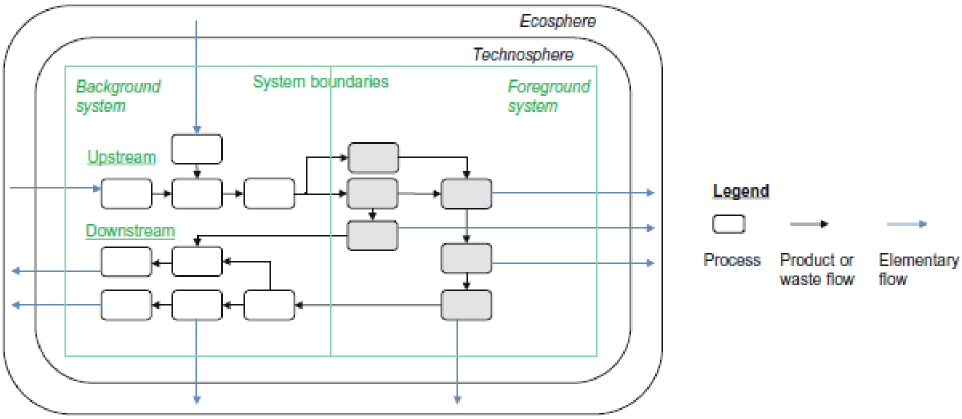


Figure 2-5. LCI model for a generic product system. (Hauschild, Rosenbaum and Olsen 2018)

The result of LCI is an inventory of the aggregated quantities of elementary flows, separated into resources and emissions, from all the unit processes within the system boundary. These elementary flow quantities must be correctly scaled to the assessed product by considering the extent to which the function of each unit process is required to deliver the studied product.

Several LCI databases are available to use in LCA software. The Ecoinvent database is published and maintained by the Ecoinvent Centre in Switzerland. It is the most renowned database for life cycle inventory (LCI) datasets. It contains approximately 4500-5000 harmonized, reviewed and validated datasets for use in Life Cycle Assessments (LCA). These datasets are all fully documented.

Once finalised the inventory, the impact assessment translates the physical flows and interventions of the product system into impacts on the environment using knowledge and models from environmental science. Impact assessment turns a Life Cycle Inventory into a Life Cycle Assessment. It consists of five elements of which the first three are mandatory according to the ISO 14040 standard:

1. Selection of impact categories representative of the assessment parameters that were chosen as part of the scope definition. Which impacts do I need to assess?
2. Classification of elementary flows from the inventory by assigning them to impact categories according to their ability to contribute by impacting the chosen indicator. Which impact(s) does each LCI result contribute to?
3. Characterisation using environmental models for the impact category to quantify the ability of each of the assigned elementary flows to impact the indicator of the category. The resulting characterised impact scores are expressed in a common metric for the impact category. How much does each LCI result contribute?

4. Normalisation, e.g expressing LCIA results relative to those of a reference system. Is that much?
5. Grouping or weighting, e.g. aggregating several impact indicator results into a group.

In practice, the Life Cycle Impact Assessment (LCIA) phase is largely automated and essentially requires the practitioner to choose an LCIA method and a few other settings for it via menus and buttons in LCA software.

Figure 2-6 shows the most common methodologies published since 2000 that all meet the requirements of ISO 14044.

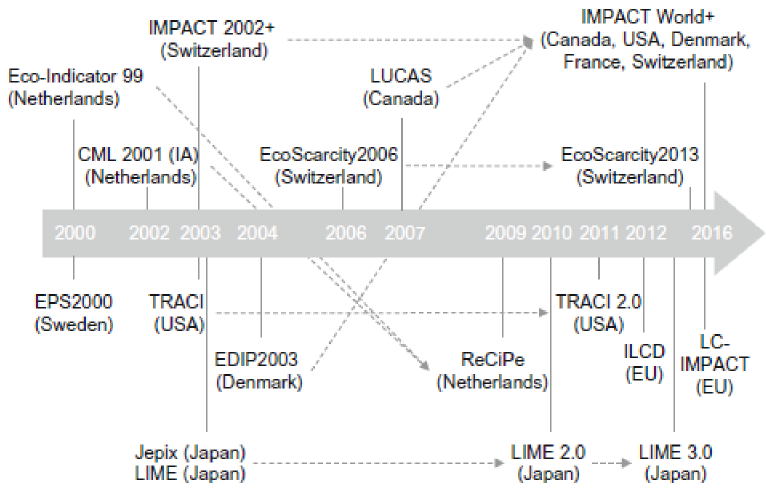


Figure 2-6. LCIA methods published since 2000 with country/region of origin. (Hauschild, Rosenbaum and Olsen 2018)

As the final step, the interpretation phase considers both outcomes of the inventory analysis and the impact assessment elements characterisation and, possibly, normalisation and weighting. The interpretation must be done with the goal and scope definition in mind and respect the restrictions that the scoping choices impose on a meaningful interpretation of the results, e.g. due to geographical, temporal or technological assumptions. The effects of the interpretation may lead to a new iteration round of the study, including a possible adjustment of the original goal.

It is worth mentioning that LCA involves many feedback loops between its different phases. Insights from the impact assessment are used in refining the inventory analysis and insights from both of these phases may feedback to the scope definition, e.g. in the setting of the boundaries of the product system, what to include and what to exclude. Sensitivity and uncertainty analysis are thus not just performed in the interpretation at the end but throughout the study as part of both inventory analysis and impact assessment to identify the key figures or key assumptions of the study and the data that are associated with the largest uncertainties (Hauschild, Rosenbaum and Olsen 2018)

2.5.1 LCA applied in the wastewater treatment field

Urban wastewater management requires large material, energy, economic and technological investments for the construction and operation of treatment plants. Energy consumption in WWT plants and the related greenhouse gas (GHG) emissions are also steadily increasing due to strict treatment requirements. Given the need to achieve long-term sustainability, the objectives of urban water systems need to go beyond the protection of public health and receiving bodies, and also focus on strategies to reduce the impacts on natural resources, to optimize the use of energy and water and reduce waste generation. Therefore, urban systems should adopt innovative approaches to wastewater management to maximize the recovery of useful materials and/or energy and minimize emissions releases (Buonocore, et al. 2018).

Life cycle assessment (LCA) has been widely used to quantify environmental impacts associated with urban water infrastructure, including wastewater treatment plants (WWTPs) (Byrne, et al. 2017). The evaluation of the LCA outcomes will help in the optimization of energy consumption and energy recovery processes, the enhancement of the efficiency of equipment and technology operation, and the good management of energy costs within WWTPs.

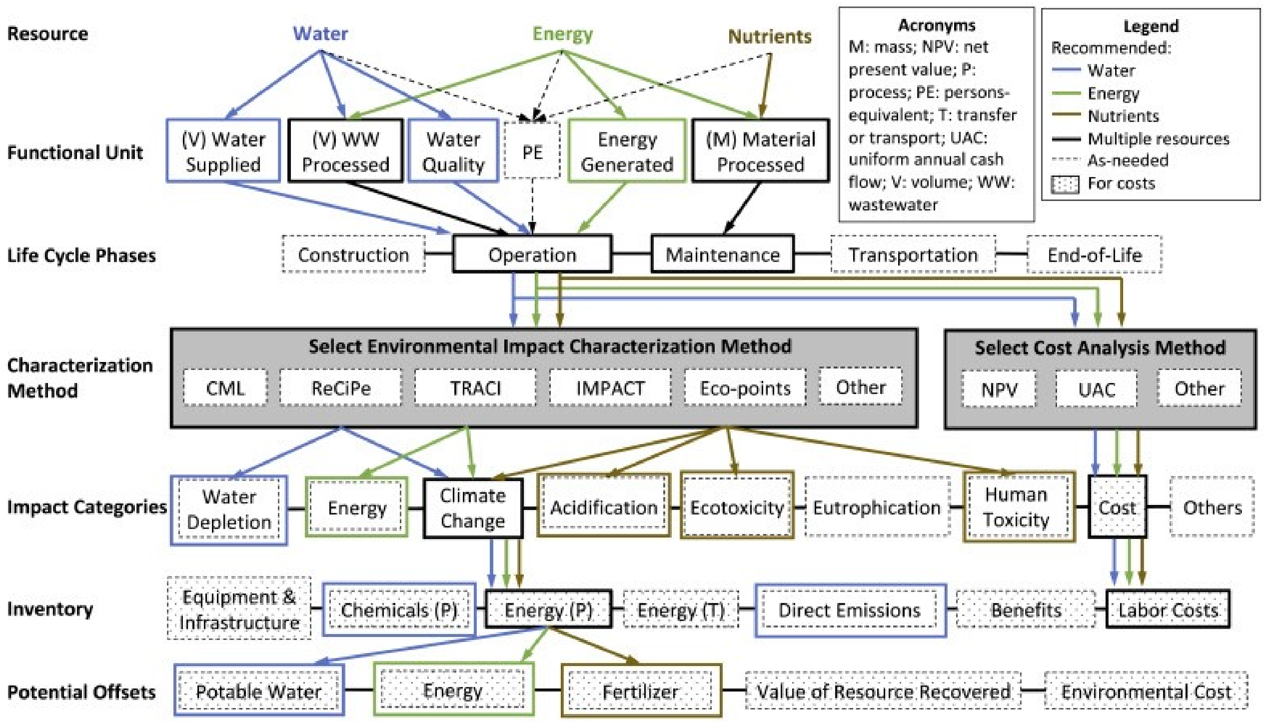


Figure 2-7. Guidelines for life cycle assessments and economic analyses of resource recovery systems (Diaz-Elsayed, et al. 2020)

Published LCA studies about WWT plants deal with the energy consumption, GHG emissions of existing plants as well as the potential energy and GHG emission benefits that can be achieved by introducing new alternative technologies (Corominas, Foley, et al. 2013). Useful reviews are listed in Table 2-14.

Table 2-14. Existing review of LCA applied in wastewater treatment.

References	Review focusing
(Lluís Corominas et al., 2020)	Systematic guidance for the application of LCA in the context of municipal wastewater management
(Diaz-Elsayed, et al. 2020)	Identification of trends in the environmental and economic impacts for the recovery of water, energy, and nutrients from wastewater.
(Lam, Zlatanović and van der Hoek 2020)	Assessing opportunities for wastewater-based nutrient recycling.
(Byrne, et al. 2017)	Analysis of preferences for functional unit basis, system boundaries, and impact assessment methodology
(Corominas, Foley, et al. 2013)	Analysis of the key challenges in applying LCA to wastewater systems
(Yoshida, Christensen and Scheutz 2013)	Analysis of using LCA to evaluate sludge treatment and disposal

The most commonly used functional unit in the case of a wastewater treatment plant is a volume unit of treated wastewater. However, this unit is not always representative, because it does not reflect the influent quality or the removal efficiency of the WWTP (Corominas et al. 2013). Nonetheless, the water quality should be explicitly stated (Diaz-Elsayed, et al. 2020). Some studies also add a temporal scope (e.g., 20 years of operation) to transparently account for the construction burden.
Depending on the goal and scope definition, the physical system boundaries have to expand beyond the fenceline of the WWTP (e.g., to include the agricultural water reuse or beneficial agricultural use of treated sludge). Figure 2-8 shows the physical system boundaries that are commonly applied in WWTP LCAs.

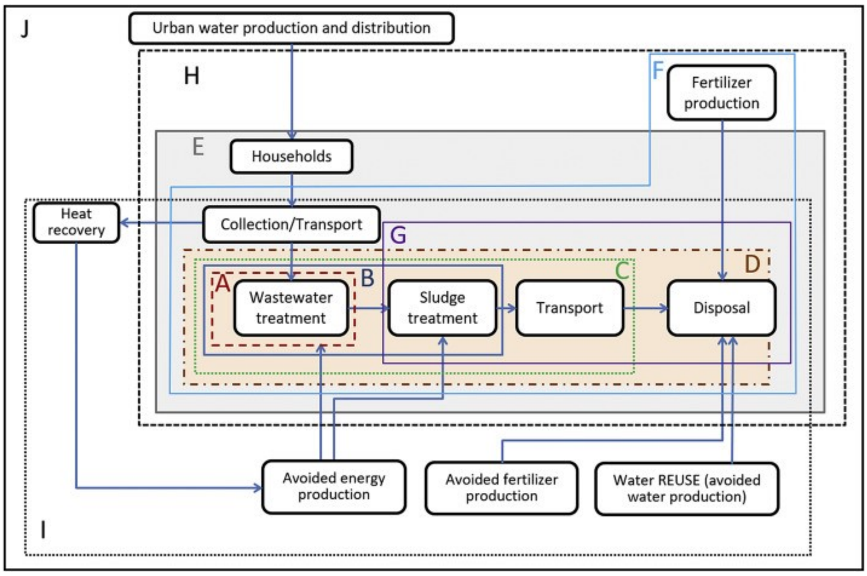


Figure 2-8. Examples of physical system boundaries for WWTP LCAs. (Corominas, Byrne, et al. 2020)

Operation and maintenance (O&M) are the leading life cycle phases considered in water reuse studies. Within the 45 papers reviewed by (Ll. Corominas et al., 2013), 23 of the studies included only the operation of the WWTP and neglected the environmental load of the construction and demolition phases. However, it is recommended to include construction inventories as part of wastewater LCA studies (Lluís Corominas et al., 2020). The smaller the size of the plant and the less energy-intensive the process, the more influential construction becomes with respect to life cycle environmental impacts.

The life cycle inventory elaboration is the most work-intensive and time-consuming phase compared to other phases in an LCA, mainly because of data collection. The foreground life cycle inventory (LCI) data is normally compiled directly from measurements, detailed design documents and vendor-supplied information. Background information (e.g. electricity generation systems, concrete and chemicals production processes) is normally provided by LCI databases, e.g. the Ecoinvent (Ll. Corominas et al., 2013; Foley et al., 2010)

With regards to the construction phase, data can be retrieved by (from higher to lower level of detail):

i.	Using project drawings and budget: Quantification of materials, equipment, and processes from construction and planning documents or information directly from material suppliers, vendors, contractors, and designers	(Buonocore et al., 2018; Morera et al., 2017; Remy et al., 2013) Morera 2020, EPA disinfection
ii.	Using multiplication factors: The detailed measurement of one construction element (e.g., the volume of reinforced concrete) is used along with a multiplier on existing detailed construction inventories for the estimation of other construction phase processes and materials.	(Foley et al., 2010; Rashidi et al., 2018; Remy et al., 2013)Larsen 2010, Remy 2010
iii.	Extrapolating from existing inventories based on the number of inhabitants.	
iv.	Using a construction inventory from literature (without running any extrapolation).	
v.	Using construction design software	

Besides the data on civil works, it is recommended that large equipment (e.g., blowers, pumps, centrifuges, dewatering belt filters) be included by accounting for their primary materials (by mass) such as steel and copper (Morera et al., 2017). The most of papers accounting for the construction phase establishes a lifespan of 30 and 10-20 years for the infrastructure and the equipment, respectively.

Within the operation inventory, the main data to include are on direct emissions (to water, to air and soil), energy, chemicals and transport. Between the emission to water, the nutrients discharged are always considered. In recent years, there has been a growing interest in including organic micropollutants (Lorenzo-Toja et al., 2016) and even microbial pathogens (Harder et al., 2017) in LCA. The direct emission to air from the water and sludge lines, instead, are not always taken into account. Besides the N_2O, CH_4 and CO_2 emissions are mostly estimated through secondary data depicting the accuracy.

Not all chemicals of interest will have corresponding LCI datasets available and in such cases, assumptions must be made. In any case, it is recommended not to exclude them, but rather identify and include suitable chemical analogues or surrogates. This can be done according to function or by identifying suitable alternate chemicals which have similar composition and/or background manufacturing processes (Lluís Corominas et al., 2020).

Nonetheless, the life cycle inventory can also include offsets of potable water, energy, or fertilizer production depending on the resource being recovered as shown in Figure 2-8. Product offsets are deemed optional because the contribution varies based on the type of resource being recovered and the scope of the study (Diaz-Elsayed et al., 2020). Additionally, for nutrients, assumptions grounded in the literature regarding efficiency on uptake and runoff for nutrient application should be used (e.g. Bouwman et al., 2009; Smil, 1999, 2000) while transportation may be excluded given a current lack of fertilizer transport data. Recovered water can be accounted for as offsets by integrating a water quantity indicator (Lluís Corominas et al., 2020).

Concerning the impact assessment phase, midpoint indicators are preferred for wastewater systems. However, they should no provide adequate clarity for decision-making. At this regard, it may be advantageous to limit the number of indicators used for impact assessment: climate change, eutrophication, and ecotoxicity are recommended as key indicators for wastewater systems (Lluís Corominas et al., 2020).

Multiple LCIA methodologies exist at both the midpoint and endpoint levels and are available within existing LCA software (e.g., Umberto LCA+). According to the reviews presented in Table 2-14, the methodologies most employed are ReCiPe, CML and TRACI. The main impact categories analyzed are:

The Global Warming Potential (GWP100) related to the climate change and greenhouse gas emissions. Characterization factors are expressed as potential impact for a time horizon of 100 years in this case.

The fossil (or abiotic resource) depletion includes depletion of nonrenewable resources, i.e. fossil fuels, metals and minerals. It is calculated as kg oil eq consumed in one year.

Eutrophication potential (EP) is defined as the potential to cause over-fertilisation of water and soil, which can lead to increased growth of biomass. It can be divided into freshwater eutrophication (expressed in kg P released in one year) and marine eutrophication (defined as kg N released in one year).

Human toxicity potential (HTP) is calculated by adding the releases, which are toxic to humans, to three different media, i.e. air, water and soil and it is calculated as kg 1,4 DCB. The organic pollutants decachlorobiphenyl (DCB) are a group of persistent synthetic substances of high risk to human and environmental health (Zenteno-Rojas A. et al, 2019).

In general, the acidification potential (AP) is based on the contributions of SO2, NOx, HCl, NH_3 and HF to the potential acid deposition, i.e. on their potential to form H^+ ions. The terrestrial acidification potential (TAP) is expressed as kg SO2 equivalent per year.

Depending on the defined goal and scope of the LCA, it may be appropriate to incorporate pathogen risk into life cycle impact assessment given the disproportionately local impact wastewater treatment has on reducing exposure to pathogens (Byrne, et al. 2017). One proposed option for this is the blending of LCA with quantitative microbial risk assessment (QMRA) (Harder et al., 2016), a decision-making tool used to quantify human health risks associated with multiple pathogens and exposure pathways. This approach typically involves using the common metric of disability-adjusted life years (DALYs) which requires the use of an endpoint methodology for LCIA and can therefore introduce additional uncertainty (Heimersson et al., 2014) In all cases, the integration of pathogen risk in LCIA should be dependent on the LCA's goal and scope definition.

2.5.2 Life Cycle Costing

Economic performance metrics can be divided into three categories based on life cycle phases:

i. project initiation and construction,
ii. operation and maintenance (O&M)
iii. end-life costs.

Project initiation and construction costs include not only capital expenditure (CAPEX) for treatment infrastructure and equipment, but also area requirements (e.g. land footprint may affect land purchase costs), energy and labour costs during construction, and external costs associated with construction. operation and maintenance (O&M) costs include chemicals and other consumables, equipment maintenance, licensing fees, administration, and training and labour requirements. Clearly, energy requirements also represent a significant operational cost; therefore, the energy data collected as an environmental performance indicator can be converted into energy cost in analyses of economic performance.

LCC is a rather consolidated methodology aimed at calculating the overall cost of a product or a service over its life span or life cycle. Despite being used for a long time by both decision-makers and businesses, LCC was standardized only regarding specific product categories. Conducting an LCC can have different purposes. It may be used as a planning tool, an optimisation tool, a tool for hotspot identification, as part of a life cycle sustainability assessment of a specific product, or to evaluate investment decisions.

Several approaches can be found in literature, mainly differing in terms of perspective, costs included, and potential application (De Menna, 2018). Hunkeler et al. (2008) provided a classification of LCC into three main approaches:

- Conventional (C-LCC),
- Environmental (E-LCC)
- Societal Life Cycle Costing (S-LCC) m

Conventional LCC assess costs occurred during the life cycle of products, services, and technologies, focusing on the life cycle in its LCA-related meaning, rather than the product, service or investment life span.

E-LCC should have the same product system, functional unit, and system boundaries as LCA, while S-LCC further enlarges the boundaries of the analysis by assessing the overall direct and indirect costs covered by the society in a larger perspective (De Menna, 2018).

Costs done by actors directly involved in the life cycle of the product are termed internal costs (internal or private costs). However, a product or system may involve other costs, borne by other actors indirectly influenced by the product life cycle. These are termed external costs. External costs are value changes caused by a business transaction, which are not included in its price, or value changes caused as side effects of the economic activity (Dodds and Galtung 1997; Hunkeler et al. 2008). For example, in the construction of a highway close to a residential area, one possible external cost that is not normally included in the life cycle costs of the highway is the value reduction of the houses close to the highway due to the increased noise levels. In conventional LCC, external costs are usually not included. If the external costs are already expressed in some monetary unit, they can be included in the environmental LCC. In societal LCC, externalities can be monetarized and included in the assessment. The figure below shows the comparison of the three different types of Life Cycle Costing.

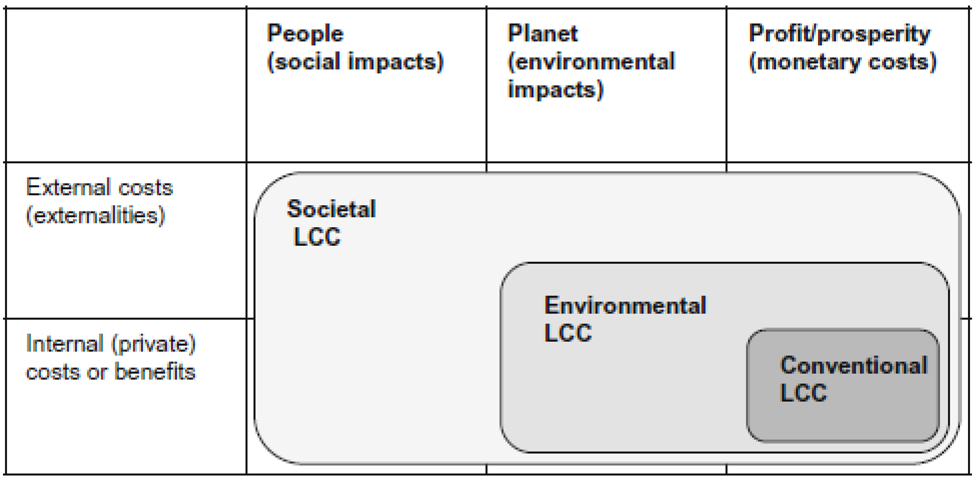


Figure 2-9. Comparison of the three different types of Life Cycle Costing

LCC of wastewater infrastructure can be a good means for minimizing environmental impacts through green public procurement while keeping costs low. Estimations of lifecycle costs suggest that often the total operational costs exceed the initial investment costs. Therefore, taking this into account is important in making the right decision for example when balancing a more expensive investment with lower operational costs or longer life-time against an alternative with lower initial investment costs but higher operational costs. Hence, in this report, it was considered that the LCC results should be accounted for in synergy with the LCA results.

So, to conduct an eLCC in a consistent way and in parallel to an LCA, I must cover the same steps of the LCA:

1. Goal and Scope definition: in addition to the functional unit that needs to be defined as a reference for results, it is necessary to define a product system value, which, depending on the objectives of the study, may be functional, qualitative or monetary. For what concerns the system boundary, if the eLCC is conducted in parallel to an LCA, system boundaries for both must be equivalent and assume the same user perspective.
2. Data collection: In the inventory analysis, costs must be quantified in one currency (e.g. euro or US dollar) and be based on a common year.
3. Interpretation

WWTPs life-cycle costs are highly constrained by operational costs and study demonstrated that annual equivalent costs linked to construction represent a minor contribution to total costs. Lorenzo-Toya (2016) fixed the monetary unit for the system value as the cost of treating 1 cubic meter of wastewater. In this way, it is possible to compare the economic and environmental impacts of the WWTPs assessed. The author, analyzing 22 WWTP, showed that, on average, 29% of the cost of operation and maintenance is related to energy consumption and 34% is due to personnel costs. Operational costs per cubic meter of treated wastewater ranged from 0.044 to 0.344 €, with an average of 0.144 ± 0.074 €.

Crucial is the definition of a lifespan. It should be noted that the lifetime of full scale WWTP has been reported to be 50 years in China (Li et al., 2013). In the United States, the US-EPA assumed that in WWTP the lifetime of the buildings and tanks is 100 years. A shorter lifetime of 25 years was estimated for the pumps and motors (US-EPA, 2014). Furthermore, according to the "Guide to Cost-Benefit Analysis of Major Projects'' a time horizon of 30 years has been used for the financial and economic analyses in the EC "GUIDE TO COST-BENEFIT ANALYSIS OF INVESTMENT PROJECTS" (EC, 2014) for water and wastewater infrastructure. Moreover, according to the ''EVALUATION of the Council Directive 91/271/EEC of 21 May 1991'', concerning urban waste-water treatment (EU, December 2019) a lifetime of 25 years for WWTPs should be considered. Therefore, our assumptions about lifetime were conservative.

3. Materials and Methods

3.1 Case study: Peschiera Borromeo WWTP

Water reuse is intended to be applied to the full-scale plant of Peschiera Borromeo WWTP. In this study the environmental performances are investigated in the current configuration and in the future one where reclaimed water will be reused in the surrounding agricultural area. The final aim is to identify and quantify the benefit or burdens of plant upgrading. The comparison is mainly carried out through a Life Cycle Thinking approach, but it requires preliminary static evaluation such as mass and energy balances and carbon footprint analyses. Moreover, the ENERWATER methodology is applied to Peschiera Borromeo WWTP to perform energy audit and benchmark today's plant efficiency

3.1.1 Description

The Peschiera Borromeo UWWTP consists of two distinct water lines and a single sludge line with biogas recovery and final sludge disposal as fertilizer. The overall treatment capacity is 516,000 PE, of which 250,000 PE are served by the second treatment line intended to be used for reuse purposes.

The catchment that collects wastewater to Peschiera Borromeo WWTP covers the peri-urban area of Milan and collects the municipalities of Brugherio, Carugate, Cassina de' Pecchi, Cernusco sul Naviglio, Cologno Monzese, Peschiera Borromeo, Pioltello, Segrate, Vimodrone, served by a dedicated line (Line 1) in the layout of Peschiera Borromeo WWTP, and the eastern districts of Milan, served by the other separate configuration (Line 2) of the plant. The estimation of the industrial contribution is about 23%. On the industrial fluxes, specific measures are set up periodically to verify the total amount discharged and the contaminant loads influent to the WWTP and ensure compliance with the limits established in Table 3, Annex 5 of D.Lgs n. 152/2006, which regulates wastewater discharges.

The sewer network that collects urban wastewater to Peschiera Borromeo WWTP is divided into two sectors, that serve separated areas of Peschiera Borromeo catchment and are managed by different utilities. One is controlled by Metropolitana Milanese and the other is directly managed by CAP Holding and serves the municipality of Milan and Linate district of Peschiera Borromeo. On the fraction of sewer under CAP control, stormwater overflows are managed using 8 equalization ponds, controlled and remotely activated based on pumping status, influent and effluent flowrate, tank level and rain measurements. Hence, from the remote control in Peschiera Borromeo WWTP is possible to activate or stop manually pumping, to modulate meteoric flows to avoid overflows or excessive dilution of the plant influent.

The sewage flow coming from the area managed by Metropolitana Milanese is then treated in a conventional configuration, called Line 1, while the sewer fraction controlled by CAP has a dedicated layout, called Line 2.

The treatment chain of the plant is schematically described in Table 3-1, while an aerial view is provided in Figure 3-1. The non-conventional units operating along the waterline are briefly described below.

Figure 3-1. Aerial view of Peschiera Borromeo WWTP

Table 3-1. Processes involved in the Peschiera Borromeo WWTP

Line 1:	**Line 2:**
- Coarse screening, intermediate pumping station, fine screening - Grit and oil removal system - Primary sedimentation through two circular settlers - Activated sludge oxidation with 15 days SRT - Secondary clarification through 4 circular settlers - Chemical Phosphorous removal by $FeCl_3$ or PAC addition on the return sludge flow - Tertiary treatment with 2 stages up-flow biological filtration (Biofor®) where denitrification/nitrification takes place. Denitrification is ensured by adding an external carbon source. - Final disinfection with peracetic acid.	- Coarse screening, pumping, fine screening, and deodorization - Degritting, degreasing and primary lamellar settlers (Sedipac™) - Chemical Phosphorous removal through Al2O3 addition in the internal backflush sent back to the Sedipac™ - Denitrification/Nitrification through 2 stages up-flow biological filtration (Biofor®) - Final disinfection by UV.

Sludge treatment line:
- Pre-thickening of primary sludge by gravity - Dynamic thickening of waste activated sludge with polymer addition - Primary anaerobic digestion - Secondary anaerobic digestion - Post-thickening by gravity - Dewatering through centrifuges with polymer addition - Defecation lime production
Biogas valorization[a]
- 2 CHP units - 6 boilers - 2 gasometers - 2 emergency torches
Deodorization system
- Biofilters - Scrubbers with sodium hypochlorite dosage

a: the electricity from CHP units (Combined heat and power) is self-consumed while the thermal energy is used to heat the digesters. An amount of biogas is also used directly in boilers to cover the digester heating demand.

The Sedipac™ 3D combines 3 pretreatment functions – grit removal, grease removal and settling – into one single work using separate dedicated areas. Air is injected into raw water to separate the organic particles from grit and then the water to be treated moves into a calm area where the grit settles. It then joins the degreasing zone, where fine bubbles are injected that accelerate grease flotation. The suspended solids are subsequently separated from the clear water optimally in the lamellar modules. Finally, the settled sludge is scraped and extracted to be sent to the sludge treatment line.

Indeed, the Biofor® allows an advanced treatment of suspended solids (SS) and carbon and /or nitrogen pollution with no odour. The effluent to be treated is continuously fed into a biological reactor called a "biofilter", passing through materials that retain the suspended solids. Carbon and/or nitrogen pollution is eliminated due to the development of natural bacteria into a fixed biofilm (purifying biomass) on mineral support that is also natural, the BIOLITE®. It is a high-performance treatment complying with regulations for all types of effluents (low-temperature effluent, variation of flow and/or load, diluted effluent, industrial effluent such as oil, paper pulp, etc…) and it has a limited footprint due to its compactness that favour even an easier covering.

Biofor® reactor in L1 is divided into 8 modules, 4 for denitro and 4 for nitrification. While in L2 are installed 10 Biofor® modules, 5 dedicated to pre-denitrification and 5 voted to organic removal and nitrification.

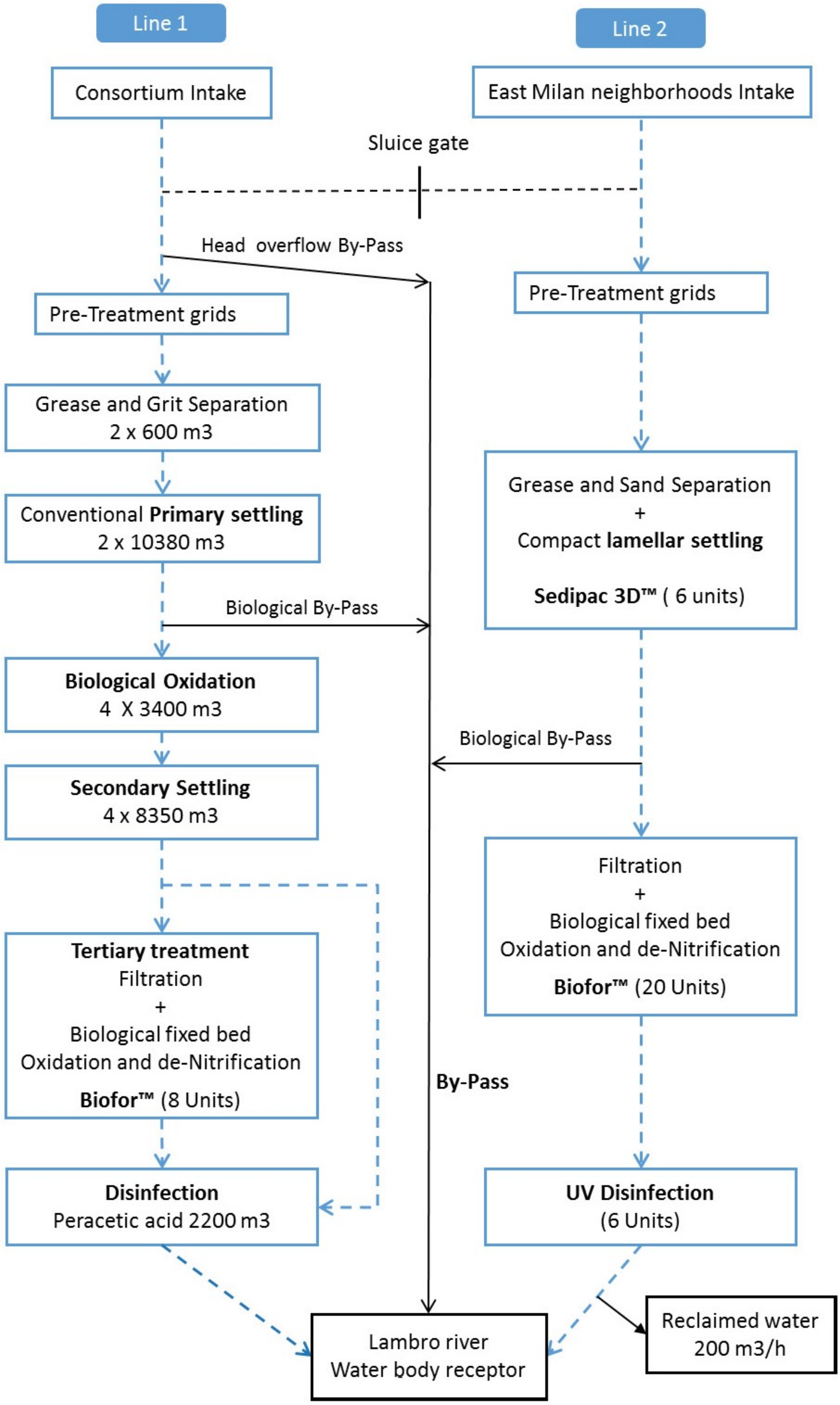


Figure 3-2. Block Flow diagram of Peschiera Borromeo WWTP

3.1.2 Collection and organization of real data

For the further assessment step, it is essential to collect and validate data about quantity and quality influent and effluent flow, energy and chemical consumption, process performances like removal and log reduction, and waste management.

In Peschiera Borromeo WWTP, laboratory analyses on 24-hour composite samples are performed once per week to characterize the influent and effluent, as well as to control specific processes. The influent is sampled downstream of the degritting process. Flowrate is monitored continuously in the inlet of the two waterlines. While offline data about cumulative energy consumptions from bills, chemicals supply, sludge and waste production and transportation to final disposal are stored in internal management systems. Moreover, energy meters are installed to monitor electricity demand.

Table 3-2. Data available from Peschiera Borromeo WWTP

Type	Source
Design / process parameters	Internal procedures / SCADA
Laboratory analysis registered in RGFI*	Internal software (WATERLIMS)
Maintainance program and reports	Internal procedures
Absorbed power and working time of electromechanical equipment	Internal register
Energy bills	Internal register
Waste production	Internal register
Dosage solutions / chemicals	Internal register
Transports	Internal procedures

**registro giornaliero di funzionamento impianto - plant operational daily registry*

Energy information is also retrieved by internal energy audit of WWTP carried out by the energy-team of CAP Holding complying with D.Lgs 102/2014. They consist in a detailed list of energy-consuming machinery with data of installed power, working time, utilization factor and diversity factor that if multiplied give us the energy consumption (kWh/d). These data are analyzed and managed to perform the energy balance. Each equipment is allocated to the proper unit to evaluate the specific production of different processes. For the thermal energy, we rely on natural gas bills and measurement of biogas produced in loco. These are coupled with the efficiencies of boilers and CHP, obtained by the technical sheet, to calculate the heat demand.

Concerning the mass balances, the lab results and the flowrate measurements are managed in a spreadsheet file to elaborate statistical analysis. The average value and standard deviation are calculated on a daily, monthly and annual basis, as well as minimum and maximum value. The monitored parameters are flow rate, pH, COD, BOD5, total nitrogen TN, ammonia nitrogen NH_4-N, total phosphorus TP, total suspended solids TSS, chloride Cl, sulphates SO_4, some heavy metals and E.coli. The loading mass as the product of concentration and flowrate is also calculated and statistically elaborated both for the influent and the effluent. Hence, the overall removal of each line was monitored.

Next step is the collection of design and process parameters like reactor volume, HRT, SRT, MLSS concentration and chemicals dosing. They help us to estimate the process removal in absence of punctual data before and after the unit. As a general rule, the removal of the unit process is calculated through the outlet and inlet loading mass, when available.

In the following are briefly described the assumptions made. If real data miss, we obtain literature value mainly from (Longo et al., 2019).

First, the influent wastewater is considered to have a typical characteristic ratio TP/PO_4-P of 1.6. The preliminary treatment (screening and degritting) are considered only in terms of waste production and data are obtained by the internal report of WWTP as total quantity produced within the plant. The single quantities produced by each line are calculated based on the flowrate proportion.

The removal of TSS and organic matter into the primary sedimentation of line L1 is calculated through the empirical formulation by (Longo et al., 2019): $R = \frac{t}{a+bt}$ where R is the expected removal efficiency, the t nominal detention time and a and b are empirical constants. At the same time, the nitrogen and phosphorus content of primary sludge is assumed: 4% and 1 %, respectively.

The Conventional Activated Sludge process is considered to operate at specific ammonia utilization rate of 0.02gNH_4/gMLVSS/d with a MLVSS/MLSS ratio of 0.75. The secondary sedimentation tank doubles the MLSS concentration in the return flow and the resulting wasted activated sludge has 1.2 % of dry solids. The overflow, instead, reaches a TSS concentration of 10 mg/l. The amount of orthophosphate removed through the addition of $FeCl_3$ is based on the kg of reagents dosed and metal to initial soluble phosphate ratio of 1.5 Fe: 1 P.

For the second line L2, there are available some measurements of the Sedipac™ effluent and the Biofor® effluent. There are used to estimate the removal efficiency of primary and secondary treatment.

The disinfection units only affect the pathogens load and the efficiency is expressed as log reduction. From the data provided by CAP there also lab analysis on the influent and effluent of both UV and PAA disinfection. They refer to a few months, but the calculated log reduction is used in the final mass balance.

Concerning the sludge line, the available data are the volume of sludge that enters to the digestion and that exits, as well as the volume sent to dewatering and final volume and weight of the dewatered sludge. Characterization of the centrate is also provided. We need to assumed solids capture of the single units. Thickener overflow, supernatant and centrate are returned upstream of Biofor ® modules in L1.

3.2 Carbon footprint parametric calculation

It is estimated that the waste and wastewater industry holds a 3% share in total global greenhouse gas (GHG) emissions (Xu 2013). WWTPs produce a considerable amount of GHGs directly within biological treatment (Xu et al. 2017). Furthermore, indirect GHG emissions, such as those related to energy consumption, cannot be ignored (Figure 1). The CF of WWTPs is strongly related to the source of electricity used at the plant (depending on the share of green energies), wastewater treatment technologies, additional amount of fossil carbon source (either for denitrification or co-digestion), and influent and effluent characteristics (Wang et al. 2016). Therefore, CF analysis becomes an important tool in WWTPs to recognize which sections emit more GHGs and discover the potential solutions to reduce CF.

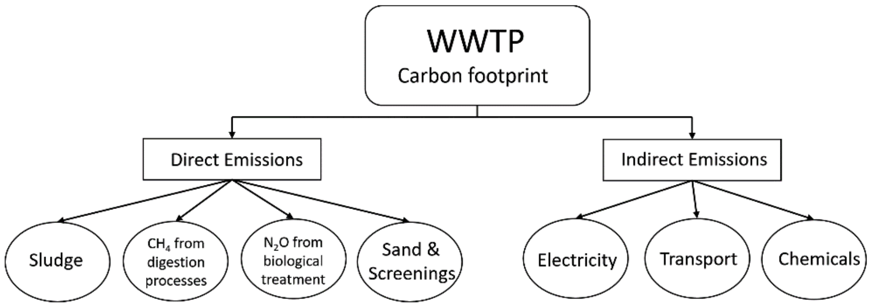


Figure 3-3. Direct and indirect emissions discharged from WWTPs

The tool for calculating the CF of WWTPs was a customized version of the MS Excel spreadsheet (CFCT, 2014), developed in the project entitled 'Calculation of the CF from Swedish WWTPs' (SVU 12-120) (Gustavsson & Tumlin 2013).

The CF calculation follows the indications provided by Part 1 of the standard ISO 14064 "Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals." It addresses conducting greenhouse gas emission inventories of organizations using a bottom up approach to data collection, consolidation and emissions quantification. It not specifically refers to the integrated water system.

Within the primary text, the standard identifies three key aspects for developing a greenhouse gas inventory. These aspects include setting inventory boundaries, quantifying GHGs, and reporting GHGs.

Boundaries for a GHG inventory include both the organizational boundaries and the operational boundaries. Organizational boundaries refer to defining which facilities are recognized as part of organization conducting the inventory and should be included within this inventory. In the specific case, the facilities investigated is Peschiera Borromeo WWTP.

Two approaches to defining organizational boundaries are possible by control or according to equity share:

- Under the control approach, an organization looks at facilities where it has authority to implement either financial or operational policies, then accounts for all GHG emissions from facilities where it does have control.

Under the equity share approach, the organization accounts for emissions from all facilities in which it has some equity interest (even a minority), but accounts for only a percentage of the total emissions equal to the share it has in the particular facility or sub-entity.

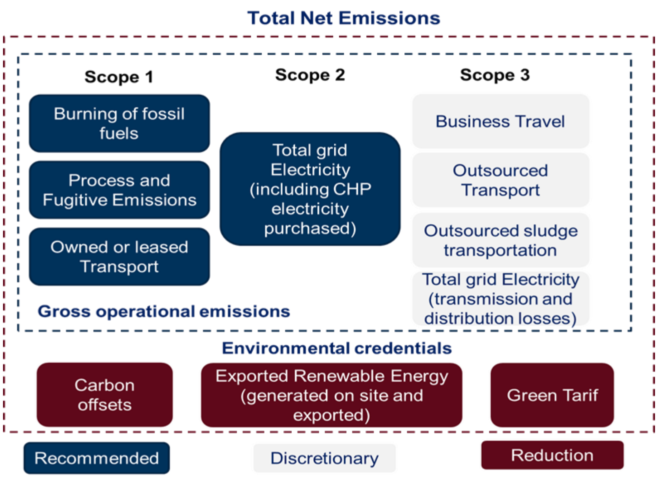
The GHG emissions may be classified in two categories:

- DIRECT EMISSIONS AND REMOVALS: involves the direct emissions from the plant like burning of fossil flues, process and fugitive emissions
- INDIRECT EMISSIONS: includes the Indirect emissions from electricity generation andall other indirect emissions that result from organization activities but are generated outside the boundaries of the organization’s direct control.

So, the procedure followed for quantifying GHG emissions for the inventory consists in:

i. Identification of organizational and the operational boundaries according to the control approach.
ii. identification of specific emission sources within the operational boundaries and classification in SCOPE.
iii. selection of an emissions quantification methodology applicable for the sources identified.
iv. collection of data required for each source.
v. the identification of established emission factors for the data collected.
vi. quantify emissions from individual emission sources.

The emissions quantified for each source are then consolidated with the other sources within the operational boundaries, but ensuring that direct and indirect sources are kept separate.



The calculation of the carbon footprint carried out in this report was based on the identification of a characteristic data ($Acitivity\ data$), specific for single SCOPE. The Activity Data was multiplied by the relevant emission factors (EF), in accordance with the 2006 IPCC Guidelines and based on data from the technical/scientific literature. Finally, the quantified emission data were reported in CO_2 equivalent based on the Global Warming Potential (GWP) factors derived from the FIFTH ASSESSMENT REPORT (AR5) 2014 and equal to 1 for CO_2, 28 for CH_4 and 265 for N_2O. Hence:

$$GHG\ emission = Activity\ data * EF * GWP$$

The activity data for the WWTP are obtained mainly by O&M reports and they consist in:

- flow rates, mass loads of influent and effluent pollutants;
- electricity consumption, distribution and consumption of other energy carriers;
- treatment of external liquid waste;
- biogas production and destination;
- consumption and composition of external reagents;
- waste produced and intended disposal (grit and screening);
- the number of journeys, km travelled and means used relating to the transport of external reagents and to the transport of waste produced in the installation;
- produced sewage sludge and its characterisation, possible storage, disposal or reuse;
- travel for employees.

The emission factors considered and distinguished by single Scope are summarised in Table 2-1.

Table 3-3. Emission factors related to the activity data collected

	Activity data	**EF**
Scope 1-Direct emission		
Direct emissions from stationary combustion	Total quantity of each fuel reported from the reading of energy meters	+Kg CH_4/kg CH_4 consumed +Kg N_2O/kg CH_4 consumed
Direct process emission – sludge line	Quantity of sludge produced for average storage time in the plant.	+%N_2O emitted/Ntot suldge Nm^3 CH_4/ton VS, h
Direct process emission – water line	Inlet COD mass load per CH_4 Mass load COD removed for CO_2 Denitrified nitrogen load per N_2O	+kg CO_2/kg COD removed +kg CH_4/kg COD influent +kg N_2O/kg N removed
Direct fugitive emission	Volume of biogas (Nm^3) produced in the reference year for cogeneration, combustion in boiler or flare.	+% CH_4 fugitive/total biogas produced
Scope 2- INDIRECT EMISSION		

Indirect emissions from imported electricity consumption	Actual annual electricity bill consumption	+tonCO_2/GWh
Scope 3- Other emission		
Indirect emissions to receiving water body	Mass loads of nitrogen and influent COD/effluent N_2O and CH_4	+kg N_2O/kg N effluent +kg CH_4/KgCOD effluent +kg CO_2/KgCOD in ingresso
Waste produced	Quantity of sludge on annual basis	+% CH_4 produced/Kg managed sludge +% N_2O relase/Kg managed sludge
Chemicals	Specific consumption of all reagents (PAC, $FeCl_3$, NaOH, methanol, peracetic acid, polyelectrolyte,) as tonnes consumed in the reference year.	+Kg CO_2 eq/ton consumed chemical
Trasports	Number of journeys multiplied by the kilometres of each journey considered for: -screening and grit disposal -transfer of sludge to the final disposal -domestic travel by ordinary management	+g CO_2/km +g CH_4/km +g N_2O/km
Removal		
Carbon Sequestration	Quantity of treated sludge applied to soil	-KgCO_2eq saved/Kg C applied to soil

3.3 Energy audit calculation

An energy audit of the plant was assessed through the ENERWATER methodology (Longo et al., 2019) that is here described. The methodology developed in the framework of the ENERWATER project aims to systematically determine the energy efficiency of a particular WWTP expressed by the WTEI (water treatment energy index). To sum up the procedures, first, the type of WWTP is established according to its functions; then, energy consumption and other measurements (flowrate, pollutant concentrations, etc.) are combined to obtain the relevant KPIs, which are then normalised and weighted to obtain the WTEI. Finally, the WTEI is presented as an energy label to provide all stakeholders with standardized information and facilitate dissemination of WWTPs' the energy efficiency.

The methodology can be applied in two different ways according to the following goals:

– The **Rapid Audit (RA)** method leads to a quick estimation of the WTEI based on existing information, such as historical energy use data along with influent and effluent quality values obtained by routine analyses. By doing so, the aim is to obtain a WWTP energy benchmark, a rapid tool to compare a given WWTP performance with other plants and ascertain the need for a detailed monitoring campaign.

– The **Decision Support (DS)** method requires intensive monitoring of energy use and water quality parameters to provide an accurate and detailed calculation of the WTEI for each WWTP stage as well as its overall value for the plant. By doing so, the aim is to serve as a diagnosis of the functions/equipment to individuate the origin of inefficiency and develop targeted energy-saving strategies.

The following typologies of WWTP are identified according to the wastewater effluent discharges:

- Type 1: Discharge to a non-sensitive area. This includes WWTPs focused on the removal of total suspended solids (TSS), biochemical oxygen demand (BOD), COD and NH_4.
- Type 2: Discharge to a sensitive area. This includes WWTPs focused on removing TSS, BOD, COD, total nitrogen (TN) and total phosphorus (TP).
- Type 3: Discharge for re-use. This includes WWTPs focused on removing TSS, BOD, COD, TN, TP and pathogens removal (e.g. coliforms log reduction).

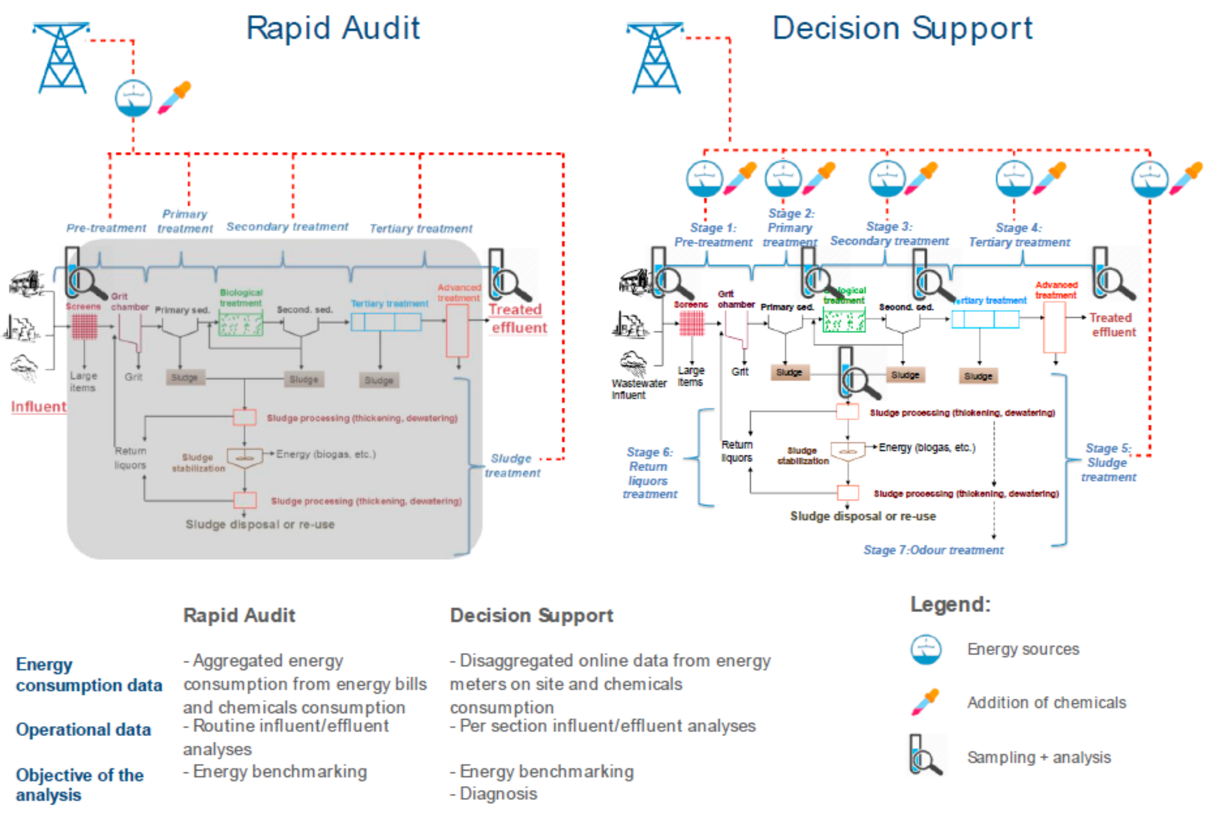


Figure 3-4. Schematic comparison of Rapid Audit and Decision Support ENERWATER methodology. From (Longo et al., 2019)

Wastewater treatment plants (WWTPs) can be composed of a very wide variety of processes designed for removing pollutants from wastewater. Independently of the processes implemented at the WWTPs, these facilities are normally organised in 7 main stages according to their respective functions:

Stage 1: Preliminary treatment includes all pumping required to discharge the wastewater to the WWTP (i.e.: pumping stations that can be found within the boundaries of the WWTP), the equipment involved in screening, grit removal, oil separation and flow equalisation. Storage of wastewater in storm tanks and respective pumps, as well as effluent pumping (e.g. treated wastewater), is also included in Stage 1.

Stage 2: Primary treatment includes all the equipment involved on primary sedimentation/clarification, as well as the elements required for desludging the primary sedimentation and dose of chemicals (e.g. iron dosing for phosphorus removal or coagulant dosing for enhanced solids removal) that takes place before or during primary sedimentation/clarification. Specific control and instrumentation tools that are required to operate Stage 2 should also be considered here.

Stage 3: Secondary treatment includes all processes and their auxiliary equipment required for biological wastewater treatment after primary sedimentation (if present). Common processes used in secondary treatment include biofilm processes (e.g. trickling filters) and flocculent processes (e.g.: activated sludge and biological nutrient removal) and their respective humus tank or secondary clarifier. Equipment required to operate the biological wastewater treatment pumping (recirculation), aeration and secondary clarification, should also be considered in Stage 3. Equipment required for desludging the secondary clarifier and dose of chemicals (e.g. iron dosing for phosphorus removal that takes place before or during secondary clarification), should also be considered in Stage 3. Specific control and instrumentation tools that are required to operate Stage 3 should also be considered.

Stage 4: Tertiary and advanced treatment can be completed by a wide variety of processes including chemical (e.g. chlorination or ozonation), physical (e.g. sand filters, UV disinfection) and biological (e.g.: reed-beds; submerged aerated filters, tertiary nitrification) processes. For simplicity, the ENERWATER methodology defines as Stage 4 any process that takes place between secondary treatment and effluent discharge and their respective equipment. Pumping required for effluent discharge should be included as part of Stage 4. Specific control and instrumentation tools that are required to operate Stage 4 should also be considered.

Stage 5: Sludge treatment consists in any processes that handle concentrated streams derived from primary, secondary and physical-chemical treatment, that are traditionally above 0.5% total solids and their respective equipment. Stage 5 can be divided into two sub-stages based on the different functions carried out in this section of the plant, that is a) concentration of sludge and b) reduction of sludge. Stage 5a often includes two range of steps such as i) thickening (e.g.: gravity thickeners), and dewatering (e.g. centrifuges, belt presses etc.). Stage 5b includes sludge stabilisation technologies that range from alkalinity dosing, anaerobic digestion to thermal processes such as incineration, gasification and pyrolysis. If the WWTP receives import sludge this should be also accounted as in the energy monitoring exercise. Nevertheless, if the WWTP receives other waste to complete co-digestion then processing of these wastes should be excluded from the exercise. Also relevant is the fact that many sludge stabilisation technologies are energy producers, not consumers. Energy production on-site should be considered either by accounting for the biogas production on-site, or if possible measuring the kWh produced by these processes. Specific control and instrumentation tools that are required to operate Stage 5 should also be considered.

Stage 6: Return liquors treatment can include processes for treatment of return liquors (reject water) that are usually focused on nitrogen removal and phosphorus removal through processes such as Anammox or struvite precipitation, respectively, just give some examples. Specific control and instrumentation tools that are required to operate Stage 6 should also be considered.

Stage 7: Odour treatment often includes recovering of extraction the air of air extracted from sludge processing technologies (Stage 5) or even pumping stations. Odour treatment technologies can be classified into physical/chemical (chemical scrubbers, incinerators, adsorption systems, and so forth) and biological (bio-filters, bio-trickling filters, bio-scrubbers, and activated sludge diffusion reactors).

Auxiliaries. Many WWTPs will have exterior lighting, offices and labs. Other possible auxiliaries include pumping of water for garden irrigation, servers for data storage and transfer etc. The energy consumption from these auxiliary facilities should be measured and considered for calculating the energy index.

3.3.1 ENERWATER procedure

WTEI was defined as a composite indicator for a particular WWTP. A composite indicator measures multidimensional concepts (e.g. energy consumption for different functions of the WWTP) that could not be expressed by a single indicator. The procedure for the WTEI calculation is drawn in Figure 3-5 and summarised in the next sub-sections.

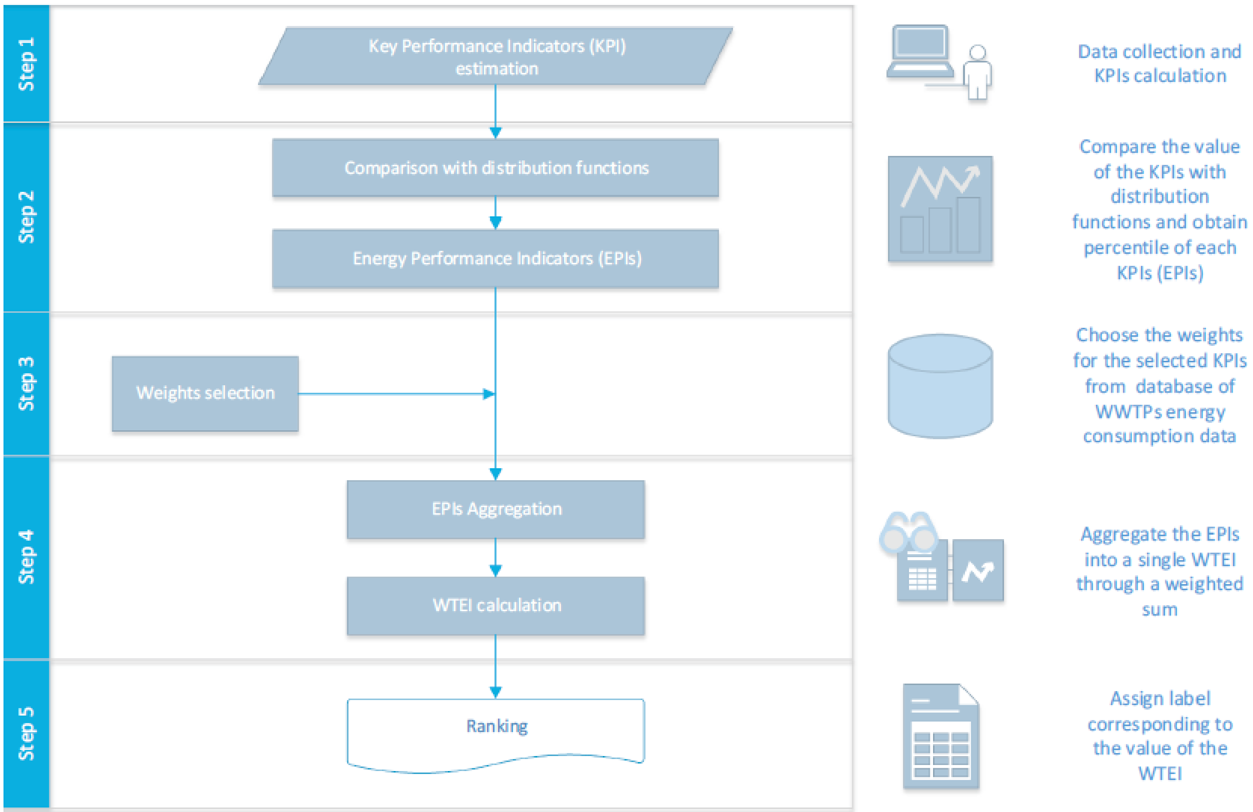


Figure 3-5. Workflow for the Water treatment Energy Index Calculation. From (Longo et al., 2019)

3.3.1.1 *Step 1. Estimation*

Gross and net energy consumption

Energy consumed at WWTP in each stage needs to be available, including electricity and other fuels such as diesel, natural gas etc. Electricity consumption in each stage can be obtained by on-line meters or disaggregated electricity consumption can be estimated combining the rated power of the electrical motor in kilowatt (kW) and the working hours in a year to provide an estimation of kWh used in each stage per unit of time. If other fuels are used, for example, to drive generators to produce electricity, the fuel consumption (i.e. in litres or tons), these also need to be quantified and converted to kWh per unit of time using conversion factors to calculate the total energy consumption (Equation 1).

$$E1: Energy\ consumption\ at\ stage\ = Ep\_V1 + Ep\_V2 + Ep\_V3 + Ep\_V4 \quad (1)$$

where Ep_Vi is the energy consumed as electric energy (V1), diesel (V2), natural gas (V3) and biogas (V4).

Some WWTPs also use chemicals, as well as energy to drive wastewater treatment and produce clean effluents. the use of chemicals and respective amounts can impact on the pollutants removal efficiency of WWTPs and replace, to a certain extent, the use of other sources of energy. To account for the use of chemicals on the ENERWATER methodology, the embedded energy in chemicals should also be estimated. This can be done using the Cumulative Energy Demand (CED) method. It is used to indicate the equivalent of primary energy consumption in the chain of a product or the energy consumed in a certain system over its entire lifecycle, from the extraction of raw materials to the end of life of the product or system. Eq. (2) represents the formula used for estimating the chemical energy consumption due to the chemicals.

$$E2: Chemical\ energy\ consumption\ = \sum_{i=A}^{L} cec_i \times M_i \left[\frac{kWh}{year}\right] \quad (2)$$

where *A* to *L* are the chemicals used in the WWTP, *Mi* is the mass (in kg) consumed of each chemical and cec_i is the specific chemical energy consumption (in kWh/kg) for all chemicals used in the WWTP. cec_i are obtained from the Ecoinvent database**.**

Wastewater treatment plants can have a range of technologies that produce energy/electricity on site.

The generation of electricity on the WWTP can offset the energy requirements to produce a high effluent quality. The energy self-produced that is used on-site can be estimated taking in consideration Equation 3.

$$E3: Energy\ produced\ = \sum_{i=A}^{L} i \left[\frac{kWh}{year}\right] \quad (3)$$

where, *A* to *L* are the types of energy produced in the WWTP, *A* – energy from biogas (kWh/year); *B* - hydraulic-power (kWh/year); *C* - wind turbines (kWh/year); *D* - solar panels (kWh/year); *E* – fuel-cells (kWh/year); *F-L* – other (kWh/year).

Many WWTPs with anaerobic digesters act as sludge treatment centres receiving sludge from nearby sites. Sludge imports can be very significant in some WWTPs (up to 2 fold the sludge produced on-site). As such, the volume of sludge imports, respective total suspended solids, as well as an estimation of the energy consumed and produced for its treatment, needs to be taken into consideration (E4).

The gross and net energy consumed can be estimated by combining the results from previous equations. Gross and net energy consumptions are used as input to estimate each KPI.

$$Gross\ energy\ consumption = E_1 + E_2 \left[\frac{kWh}{year}\right] \quad (4)$$

Gross energy consumption is defined as the total amount of energy that is consumed by the plant regardless of its source and it reflects the plant energy efficiency. Net energy consumption is defined as the amount of energy that is consumed by the plant excluded the amount of renewable energy created on-site. It reflects the plant self-sufficiency in the use of energy.

$$Net\ energy\ \ consumption = E_1 +\ E_2 - E_3 +\ E_4\ \left[\frac{kWh}{year}\right] \qquad (5)$$

Identification of KPIs and calculation of its reference values

In the DS, different KPIs are considered using composite or grab samples to account for the key pollutants removed at the different stages of the process (i.e. by detailed sampling campaign is required). The KPIs proposed are listed in Table 3-4 and they must be calculated using the specific portion of the energy consumed within the stage under analysis. They refer only to 5 stage since stage 6 and stage 7 and auxiliary are not combined into the WTEI due to lack of data.

Table 3-4. KPI proposed by (Longo et al., 2019)

STAGE	TREATMENT	KPI
1	preliminary	kWh/m^3
2	primary	kWh/kgTSS removed
3	Secondary	kWh/kg TPE_removed
4	Tertiary	kWh/Log reduction
5	Sludge	kWh/kg TSE

TPE is for Total Pollution Equivalent, a weighted sum of COD, total nitrogen (TN) and total phosphorus (TP) aims to estimate the performance of secondary treatment.

$$TPE\ =\ COD\ (kgCOD) + 20TN(kgTN) + 100TP\ (kgTP) \qquad (6)$$

Using a similar approach, TSE means Total Solid Equivalent and weight the two functions of the stage5: dewatering and sludge removal.

$$TSE\ =\ TSremoved\ (kgTS)\ + 2TSdewatered(kgTS) \qquad (7)$$

3.3.1.2 *Step 2: Normalization*

The KPIs are expressed in a variety of units. Hence, there is a need to express them on a common basis. Normalization is done here by comparison with a distribution function so that the percentiles for each KPI are normalised indicators of performance, here called energy performance indicators (EPI). Each KPI can be normalized by using Eq. (8), which corresponds to Gumbel's cumulative distribution function with parameters estimated for the population of WWTPs in the benchmark database

$$EPI_i = Percentile\ (\%) = exp\ \left(-\exp\ (-(\frac{KPI_i-\mu_i}{\sigma_i}\right) \qquad (7)$$

Table 3-5. Parameters of Gumbel's cumulative distribution functions (Longo et al., 2019)

		Stage 1	Stage 2	Stage 3	Stage 4	Stage 5
Rapid Audit	μ	0.327	-	0.324	0.057	1.997
	σ	0.242	-	0.189	0.037	1.334
Decision	μ	0.032	0.018	0.2	0.0166	0.1773
Support	σ	0.0319	0.0179	0.201	0.0172	0.1819

3.3.1.3 *Step 3: Weights selection*

Weighting emphasizes the contribution of a given KPI over others in terms of energy consumption. If not all the KPIs are applicable, i.e. in the absence of one stage, weights should be normalised by the weights to sum unity.

Table 3-6. weight of different KPIs to the overall energy consumption of a WWTP. From (Association, 2005)

STAGE	S1	S2	S3	S4	S5
RA	0.119	-	0.535	0.11	0.225
DS	0.119	0.015	0.520	0.121	0.225

3.3.1.4 *Step 4: Aggregation*

Finally, aggregation consists in the combination of the weighted KPIs at either the stage or the whole plant level so that the corresponding WTEI can be computed and results compared based on a ranking.

3.3.1.5 *Step 5: Rank and label assignation*

The final step consists of labelling. It is equivalent to assigning percentile intervals (bands) to energy classes. The median performance index is the upper boundary of class D and it is used as a criterion to fix the boundaries between labels. This labelling strategy allows good discrimination power at high efficiency, serving as an incentive for innovation.

Table 3-7. Label definition according to the WTEI value. From (ISO, 2006)

	EPI1	EPI2	EPI3	EPI4	EPI5	WTEI
A	X <0.11	X <0.14	X <0.11	X <0.06	X <0.16	X <0.11
B	<0.11<X <0.22	<0.14<X <0.28	<0.11<X <0.22	<0.06<X <0.12	<0.16<X <0.32	<0.11<X <0.22
C	0.22<X <0.33	0.28<X <0.43	0.22<X <0.33	0.12<X <0.18	0.32<X <0.48	0.22<X <0.33
D	0.33<X <0.44	0.43<X <0.56	0.33<X <0.44	0.18<X <0.24	0.48<X <0.64	0.33<X <0.44
E	0.44<X <0.55	0.56<X <0.7	0.44<X <0.55	0.24<X <0.3	0.64<X <0.8	0.44<X <0.55
F	0.55<X <0.775	0.7<X <0.85	0.55<X <0.775	0.3<X <0.65	0.8<X <0.9	0.55<X <0.775
G	X >0.775	X >0.85	X >0.775	X >0.65	X >0.9	X >0.775

The decision support methodology was followed in the Peschiera energy audit. It refers to 2018 data both for energy consumption and removal efficiencies.

3.4 Set-up of a pilot-scale AnMBR

3.4.1 Description

Experimental work with real wastewater influent was conducted from June to September to evaluate the performance of the UASB/AnMBR system. A schematic view of the experimental set-up is shown in Figure 3-6. The full- and pilot-scale plants are located in the WWTP of Falconara Marittima (Italy) that has a design treatment capacity of 80,000 PE with a nominal influent flowrate of 30,000 m^3/d.

Following the preliminary treatment (screening, degritting and grease removal), pretreated influent from Falconara WWTP was sent to a pilot-scale UASB coupled with an anaerobic ultrafiltration membrane working in the submerged-sidestream configuration. In a second step, the pretreated flow is further filtered through a dynamic filter and then used to feed the UASB reactor.

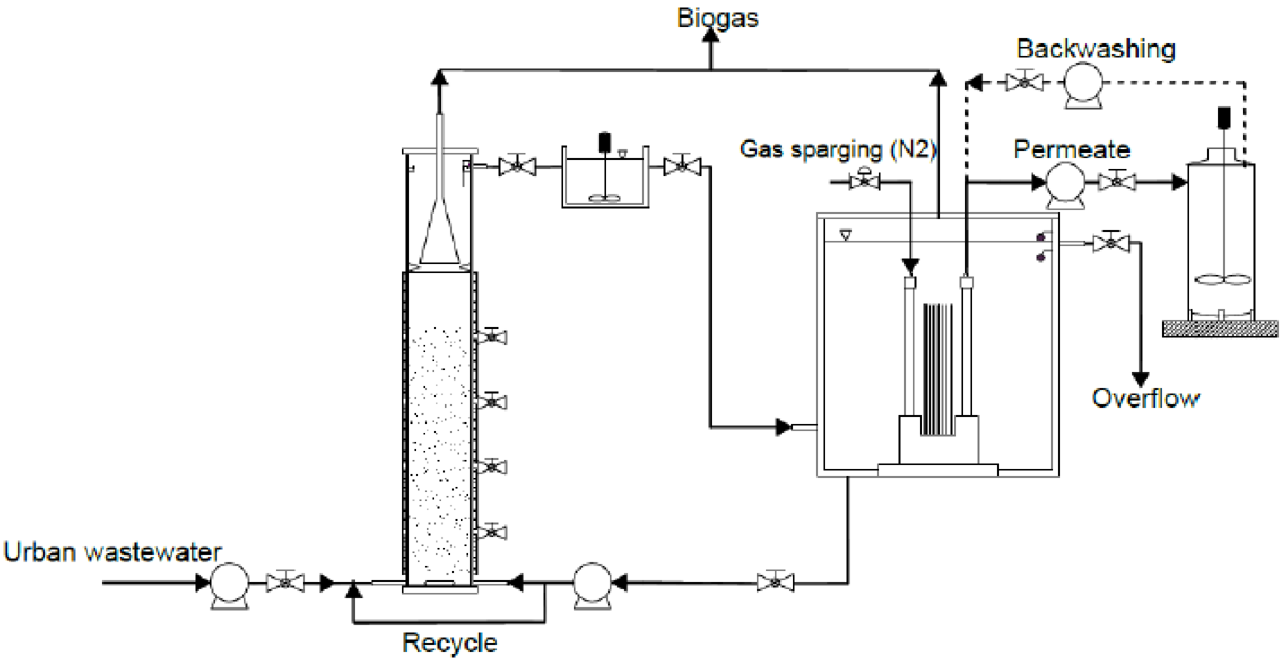


Figure 3-6. Scheme of the UASB pilot plant coupled with anaerobic ultrafiltration membranes

The UASB was a cylindrical Plexiglas reactor (16 L) with an internal diameter of 15 cm and a total height of 136 cm containing no packing or any other type of biomass support material. The reactor was divided into two compartments: the first was the real reaction chamber at the bottom (85 cm, 12.4 L), while the second, on the top, was a tri-phase separator (GLS) with 34.4 cm height and was connected to a hydraulic guard which created the appropriate backpressure for the biogas release.

Table 3-8. Geometrical characteristic of pilot-scale UASB reactor

Total volume of the reactor	L	16
Height of the reactor	cm	136
Effective height of the reactor	cm	85

Effective diameter of the reactor	cm	15
Diameter of the reactor at top	cm	15
Diameter of the GLS	cm	15
Total height of the GLS	cm	34.4
Sample 1 height from bottom	cm	19.5
Sample 2 height from bottom	cm	62
Sample 3 height from bottom	cm	76
Height of the inlet from bottom level	cm	7
N° of sample ports	-	3

The influent is fed in at the bottom of the reactor in an upstream flow by a peristaltic pump. The influent move upwards and get contact with the biomass in sludge bed, then continue to move upwards and the rest substrates act with the biomass again in the sludge blanket which has a less concentration of biomass compared with the sludge bed below. The copper coils of a heat exchanger were placed in the bottom part (Figure 3-8). In this way, we regulated the temperature inside the reactor making sure we worked at mesophilic conditions (30-40 °C). The hot water was produced from domestic electric water heaters. The UASB reactor was inoculated with the sludge obtained from a paper mill WWTP in Castelfranco Veneto (Italy).

The 3 phases (Gas-Liquid-Solid or GLS) separator located above the sludge blanket is to separate the solid particles from the mixture (gas, liquid, and solid) after treatment and hence allowing liquid and gas to leave the UASB reactor. It provides a quiescent zone in the upper part of the reactor, where suspended solids will settle and return to the sludge blanket. Any gas being produced will flow through the GLS, to be trapped by a conical gas collector whose edges are immersed in the liquid above the GSS. The solution flowing through the GLS leaves the reactor through an outlet pipe at the top (Figure 3-7). The produced biogas, after passing through the desulphurization unit to capture H2S gas, was continuously measured by a milligas counter (Ritter, Germany). The gas to be measured flows through the gas inlet nozzle and microcapillary tube within the base plate into the casing of the MGC which is filled with a packing liquid. The gas rises as small bubbles through the packing liquid and is collected in the measurement cell. The measurement cell consists of two measuring chambers, which are filled successively by the rising gas bubbles. When a measuring chamber is filled, the buoyancy of the filled chamber causes the measurement cell to tip over abruptly. The second measuring chamber then begins to fill and the first one is emptied at the same time. The tipping of the measurement cell triggers a pulse by means of the permanent magnet and the reed contact which is registered by the counter unit.

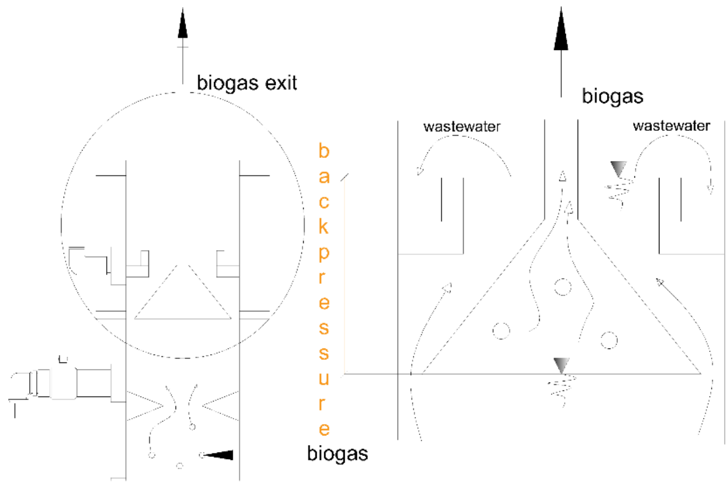


Figure 3-7. Construction details of GLS unit.

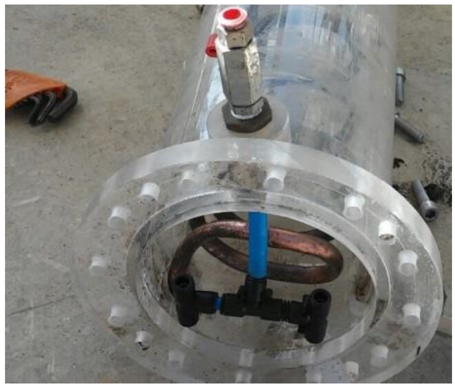


Figure 3-8. View of heat exchanger in UASB reactor

The UASB effluent was sent to the second unit by gravity. It consists in the anaerobic hollow-fibre ultrafiltration membrane (PURON® Koch membrane system, with 0.03 µm of nominal pore-size, a total nominal surface 0.5m^2, 0.25m height) installed in a Plexiglas reactor (0.29m×0.7m×0.39 m). The permeation mode runs for 9 minutes, so stops for one minute in which part of the permeate is backflushed. The membrane reactor is equipped with:

- piston pumps for the permeation and backwashing operation
- on/off control valves that determine the direction of the flow in order to control the different membrane operating stages (filtration and backflush)
- one liquid pressure indicator transmitter in order to control the TMP connected to the online data acquisition system.
- Two level indicator transmitters (maximum and minimum) to ensure membrane always submerged preventing aerobic conditions
- overflow bypass
- two outlet ports on the bottom side used to partially recirculate the flow into the UASB reactor assuring the design up-flow velocity and to empty the membrane reactor during the cleaning phase.
- a flowmeter to set the nitrogen gas supply within the optimal range of 1-2 Nm^3/h. The gas sparging operates intermittently thanks to a temporized valve installed on the nitrogen gas line.

Biogas sparging is the most common method of controlling membrane fouling in AnMBRs. The uprising gas bubbles introduced at the downside of membrane module create turbulence in the liquid which scours the membrane surface by increasing back transport of foulants from the membrane surface. The intensity of gas sparging is generally expressed as a specific gas demand per unit membrane area (SGDm).

In this case, the production rate of biogas is not sufficient to cover the gas sparging rate. To ensure anaerobic conditions, a gas-sparging method used Nitrogen gas (N_2) by alternating 10 seconds of gas off and 120 seconds of gas on with a specific flow rate value of 2- 3 $m^3/m^2/h$.

Table 3-9. Technical characteristic of the membrane module

Description	Item	Unit of measure	Values
nominal membrane surface area	A	m^2	0,5
nominal pore size	D	µm	0,03
specific gas demand	SGD_m	m^3/m^2h	1-2
filtration time	t_f	s	600
backflush time	t_{bf}	s	30

Figure 3-9. Anaerobic Membrane Reactor during operation phase (left) and after maintenance cleaning (right)

To reduce the cake layer formation, the influent wastewater to the pilot hall is further pretreated. To perform primary solids separation, the Salsnes Filter's patented rotating belt filter technology is used. Therefore, the before accumulated water pass through the filter and it is accumulated in a continuously mixed tank to then feed the UASB reactor. The operation is carried out under the supervision of a technician and takes about 15 min. The filtered effluent leads to lower solid content and COD concentration with the consequence of lower OLR for the anaerobic process. In a first step, the filtration process was performed twice a week (each Monday and Friday) and so the influent to UASB was accumulated up to four days. In a second moment, instead, to avoid COD degradation with the accumulation tank, the filter was switch on every other day.

Figure 3-10. Salsnes Filter used as primary treatment in the second and third configuration.

A steady feed loading rate of about 3 L/h of wastewater was achieved by peristaltic pumps (Watson-Marlow, UK). The hydraulic retention time (HRT) was maintained at 5–6 h. The up-flow velocity of the UASB reactor was maintained at 1 m/h thanks to the recycling flow (16 L/h) from the MBR reactor. When the sludge blanket exceeded the 65-70 m, the excess sludge was manually removed through the upper port on the UASB reactor side. For all the experimental period membrane flux was maintained below the critical flux (12-14 Lm^2h-1).

The gas-sparging method adopted in these tests uses nitrogen gas (N_2) for 120 s off (gas off) and 10 s on (gas on), with a specific flow rate value of 1-1.5 m.h−1. Operative conditions are evaluated under different operation temperature and gas sparging rate.

3.4.2 Monitoring campaign

The experimental period lasted for 17 weeks. Standard analyses were conducted in the influent flow to anaerobic process, the UASB effluent and the membrane permeate once a week. When the primary treatment was performed, even the filtered influent to UASB (or effluent from Salsnes Filter) was sampled both from the accumulation tank and as soon as be filtrate.

Therefore, all the samples were analyzed in terms of pH, alkalinity (mgCaCO3/l), chemical oxygen demand (COD), biological oxygen demand (BOD), soluble COD (sCOD), total Kjeldahl nitrogen (TKN), ammonia nitrogen (NH_4-N), nitrate-nitrogen (NO_3-N) and nitrate-nitrogen (NO_2-N), total phosphorus (TP), phosphate phosphorus (PO_4-P) and total suspended solids (TSS) according to Standard Methods (Muñoz et al., 2009).

Table 3-10. Lab test performed on the water samples collected once a week.

Parameter	Sample	Analytical method	Ref.
pH	No filtrate	Electrode potential	4500-H B
Alkalinity[a]	No filtrate	potentiometric titration	2320 B
TSS	No filtrate	Dry at 103-105 °C	2340 B

COD	No filtrate	Closed Reflux, Titrimetric Method	5220 C
BOD	No filtrate	5-day test	5210 C
sCOD	filtrate[b]	Closed Reflux, Titrimetric Method	5220 C
TKN	No filtrate	potentiometric titration	4500-Norg + 4500-NH_3 C
NH_4-N	filtrate[b]	potentiometric titration with preliminary distillation step	4500-NH_3 C
NO_3-, NO_2-	filtrate[b]	chromatography (Dionex DX120)	4110 C
TP	No filtrate	Vanadomolybdophosphoric Acid Colorimetric Method	4500-P C
PO_4-P	filtrate[b]	chromatography (Dionex DX120)	4110 C
Cl-, $SO_4$2-)	filtrate[b]	chromatography (Dionex DX120)	4110 C
Na+, K, P; Ca2+)	filtrate[b]	chromatography (ICS1000)	

a: both partial and total alkalinity is measured for the UASB effluent sample

b: through 0.45 μm Whatman membrane filters.

The parameters listed in Table 3-10 are to monitor the performance of the anaerobic process:

- Analysis of pH, total alkalinity and partial alkalinity gives us indications on the equilibrium of anaerobic digestion. The pH should be kept near to the neutrality and alkalinity drops must be prevented, otherwise favourable conditions for acidogenesis bacteria take place. The indicator α equal to the ratio between intermediate alkalinity and partial alkalinity is monitored throughout the experimental period.
- The TSS concentration of UASB effluent reflects the capability of the anaerobic reactor to work as UASB instead of a common biofilter reactor.
- Nitrogen and phosphorus are completely characterized to verify if the expected release of soluble forms occurs.
- Anion and cations are analyzed to assess the quality of the final permeate and verify the presence of biological process inhibition.
- COD concentration defines the operative organic loading rate (OLR) influencing the biogas yield production and methane content.

A measure of temperature, blanket depth, inflow rate and recycled flowrate to UASB reactor, biogas cumulative volume, permeate and back-flush flowrate was also performed daily to monitor the operation parameters like up-flow speed or biogas production. The data of TMP were exported and then analysed once a week, while daily the instantaneous value was monitored on the display of TMP transducers to early detect failures in the system.

If the sampling day, an excess of sludge was withdrawn from the UASB reactor to keep the sludge blanket within the optimal level, a sample was collected. The dry solid contents (DS%) and the volatile to total solids ratio were measured each time, while the nitrogen and phosphorus content of dry solids was tested once in the entire experimental period.

Additionally, grab samples of produced biogas and stripped gas flow form the AnMBR headspace were collected once a week. The CH_4 content was analyzed by a Bruel and Kjaer Multi-gas Monitor Type 1302, based on photoacoustic spectroscopy. The same instrumentation is used to analyze the dissolved methane and carbon dioxide concentration in the UASB effluent and in the permeate. A liquid sample is sonicated for 15 minutes per cycle within an ultrasonic bath (SONOREX PLUS) in order to strip the dissolved gases in the vessel headspace. So, a gas sample is collected from the headspace and analyzed by photoacoustic spectroscopy.

Finally, to assess the pathogen removal of the system and the consequent reliability for water reclamation, grab samples of all stream were collected filling ad-hoc sample container to be then analyzed by an external laboratory once per month. The count of E. coli bacteria was performed through the APAT CNR IRSA 7030F Man 29 2003 methodology.

The following parameters are calculated based on the sampling campaign and data availability frequency:

SALSNES FILTER		UASB		AnMBR	
Removal efficiencies	%	HRT	H	Working time	
		Up-flow velocity	m^3/h	Effective flux at op. T	$l/h/m^2$
		OLR	$KgCOD/m^3/d$	Permeability at 20 °C	$l/h/m^2/bar$
		BIOGAS FLOW	l/d	dTMP/dt	mbar/d
		CH_4 flow	l/d	Removal efficiencies	%
		Specific gas production SGP	L $biogas/m^3/d$		
		Removal efficiencies	%		

3.4.3 System configurations

The UASB reactor was inoculated with anaerobic sludge (granular sludge TS=2.72%, VS/TS=74%; flocculent sludge TS=1.42%, VS/ TS=60%) taken from a paper mill WWTP in Castelfranco Veneto at the end of May. Then, the entire experiment was divided into three phases corresponding to three operating configurations.

In the first phase, the UASB reactor was directly fed with pre-treated effluent from Falconara Marittima WWTP and operated for 41 days at around 31±1.7°C at OLR of 1.7±0.82 kg $COD/m^3/d$. The influent flow rate was maintained between 3.04±0.45 L/h, while the recycled flow between 14.33±0.38L /h obtaining an up-flow velocity of 1 m/h as recommended by literature. Meanwhile, α was between 0.25 and 0.35, which indicated a stable biological process.

The average operative flux at process temperature was equal to 6.2±0.8 L/h/m^2 and operating TMP of 49.42±12.15 mbar was detected. The gas sparging rate is fixed to 1 m^3/h, with 10 s of gas flow and 120 s of interrupted flow.

Table 3-11. Operating parameter of three configurations

		Conf 1	Conf 2	Conf 3	Literature
Configuration		UASB AnMBR	SALSNES UASB AnMBR	SALSNES UASB AnMBR	
type of influent		wastewater	filtered ww	filtered ww	
Operation time	D	41	27	36	
Operating Temperature	°C	31	30	37	30-35
HRT	h	6	5	5	5-12
Organic loading rate OLR	kgCOD/m^3/d	1.70±0.82	0.78±0.46	0.54±0.15	1-20
upflow velocity	m/h	1	1	1	1
J flux at 20°C	l/m^2/h	7.9	8.9	10.7	
N_2 flowrate	m^3/h	1.00	1.00	1.50	
Average TMP	mbar				

During the second period, the pretreated effluent from Falconara WWTP was pumped to an accumulation tank that fed the Salsnes Filter for 15 min twice a week. This interval time was needed to fill a second accumulation tank from which an average flow of 3.24±0.16 L/h was pumped to the UASB reactor. The rotating belt filter removed partially the solid and COD loading mass and therefore it lowers the operating OLR. In detail, the second configurations operated for 27 days at 30±1 °C at OLR of 0.78±0.5 kgCOD/m^3/d. This reduction was also induced by the accumulation procedure followed within this second phase. In fact, filtrate water was accumulated within a CSTR like reactor up to four days. The mixing process acted as a sort of aeration system and COD oxidation, as well as nitrification, occurred within the accumulation tank. It was favoured by the high ambient temperature. Besides, the up-flow velocity was kept at 1 m/h. Hence, the first configuration and the second one differs only for the quality of feeding influent.

At the end of the second period, membrane cleaning was carried out using sodium hypochlorite solution (400 ppm) to remove organic fouling and to recover the initial permeability of the membrane.

Figure 3-11. Hollow-fiber membrane module before (left) and after (right) the chemical cleaning.

The last configuration operated for 36 days at 37±3.7°C and 0.54±0.15 kgCOD/m^3/d. The UASB reactor was fed with filtrate wastewater but the accumulation tank was filled with new wastewater every other day. The lower value of OLR than the second period is probably influenced by the rainy conditions interesting this last experimental phase. The inflow and recycled rata as well as the up-flow velocity were kept constant with the previous configurations. Within the membrane reactor, instead, the gas sparging was raised to 1.5 m^3/h to monitor how the methane stripping would behave.

In conclusion, during the entire experimental period the following operational parameter did not change: the inflow rate and recycled flow, the time ON-OFF of feeding pump, gas sparging and permeate/backflush cycle. The second configuration operated at lower OLR due to influent prefiltration, but same temperature and nitrogen flow rate of the first period. The third configurations instead operated at comparable OLR, but higher temperature and gas sparging than the second period.

Table 3-12. Comparative summary of different operating conditions.

Configuration 1	Configuration 2	
- Same operating temperature T=30°C; - Same gas sparging N_2 flow=1.0 m^3/h; - different organic loading rate OLR_{conf1}>OLR_{conf2}		
	Configuration 2	**Configuration 3**
	- Same organic loading rate OLR=0.7 kgCOD/m^3/d; - different operating temperature T_{conf1}<$T_{conf2;}$ - Different gas sparging N_2 flow (conf1)< N_2 flow (conf2);	

The performance in terms of macro pollutants and bacteria removal efficiencies and biogas production were investigated in the different scenarios.

3.5 Life Cycle Assessment

This section aims to assess the environmental impacts of Peschiera Borromeo UWWTP, where we expect future agriculture reuse for the treated wastewater, so far discharged to the Lambro river.

First, we perform a detailed analysis of the current environmental performances of the plant, as it is. This should outline the more impacting stages, with a focus on possible differences between waterline L1 and the L2. For each line the analysis will be carried out through Life Cycle Assessment (LCA), according to ISO14044 (Lundie et al., 2004) considering both the aspects directly related to the treatment system (foreground system) and the processes involved for the supply of energy, chemicals or auxiliary (back-ground systems).

Then, the LCA approach can be used to investigate the impact of future wastewater reuse in agriculture. The reuse could be addressed in a direct way if the reclaimed water is directly pumped to the irrigation system or in an indirect way if it is discharged first to the waterbody and then withdrawn from the irrigation channel. In the first case, the physicochemical characteristics of the reclaimed water must comply with specific regulations for wastewater reuse and it is the soil compartment to be mainly affected by the direct emissions of the WWTP.

Therefore, we conducted this study to answer the following research questions:

- Which are the environmental impacts of the current configuration of Peschiera Borromeo WWTP?
- In the two water lines, the designer made different technological choices: conventional activated sludge process VS biofiltration or compact VS extensive footprinting system, for instance. How does it affect the overall environmental impact? Are there significant disparities between the two lines contributions?
- How do environmental impacts change when irrigation systems use wastewater?

The first two questions are addressed within section 4.4.1, while the last one in section 4.4.2 In section 4.4.1 the results of a first implementation is reported.

3.5.1 OpenLCA application

The open-source and free software OpenLCA was used to start to get familiar with the Life Cycle Assessment methodology. It is used to organize inventory data and perform an impact assessment. At the same time, mass balances are employed to estimate the water flows, as well as data about annual chemical and energy consumption derived from the facility shared information. The available for free European Life Cycle Database (ELCD version 3.2) provides the background data on upstream and downstream processes.

In this research phase, both the CML 2001 and the EDIP 2003 are used as characterization methods. The impact categories analyzed are resource depletion, eutrophication, global warming potential, ecotoxicity, and human health.

3.5.1.1 *Goal and scope definition*

As the first attempt, the LCA is focused on the waterline performances omitting the sludge line processes. Figure 3-12 is a schematic view of the system boundaries.

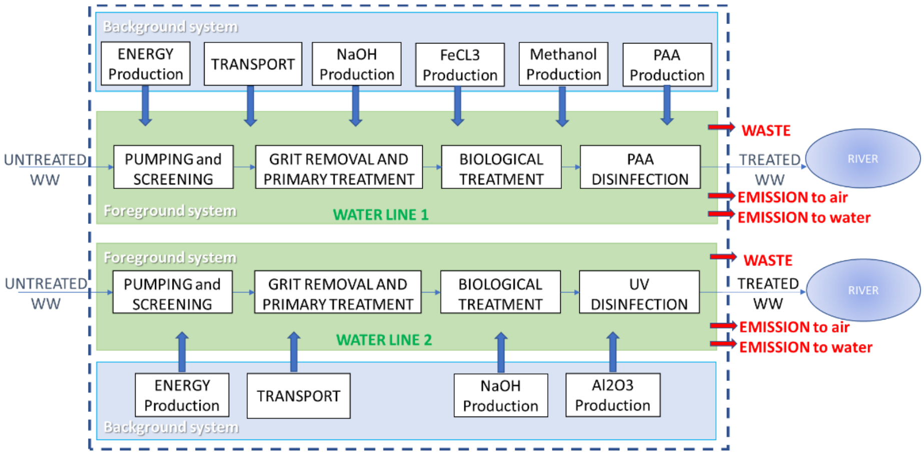


Figure 3-12. System boundaries of STATE OF THE ART scenario

When the treated wastewater is discharged to the river/irrigation channel, the output emissions will impact on the waterbody. On the other hand, it will affect the soil environment if agricultural applications directly use the treated wastewater.

The functional unit (FU) used in the assessment of any product or process will influence the outcomes of the study. Therefore, its selection entails a pivotal step in the goal and scope definition. In the present study, the volumetric option is selected. Thus, the treatment of 1 m^3 of wastewater is used as the functional unit.

3.5.1.2 *Life cycle inventory*

Each water line was modelled as a single unit process in the first round. An example of the data inventory is presented in Table 3-13, referred to the "STATE OF THE ART" scenario.

Table 3-13. Data inventory for the STATE OF THE ART scenario

Input		Unit	L1 STATE OF ART	L2 STATE OF ART
INFLUENT	Wastewater	m^3	1.00	1.00
ENERGY	Consumed electricity (no UV)	kWh/m^3	0.2381	0.2299
	UV energy consumption	kWh/m^3	-	0.0002
CHEMICALS	Sodium hydroxide	kg/m^3	0.0001	0.0001
	External carbon source	kg/m^3	0.0829	-
	Al2O3 for P removal	kg/m^3	0.0000	0.0748
	$FeCl_3$ for P removal	kg/m^3	0.0105	-
	Peracetic acid	kg/m^3	0.0032	-
TRANSPORT (operative phase)	Sodium hydroxide	km/d	0.45	0.50
	External carbon source	km/d	91.81	-
	Al2O3 for P removal	km/d	0.00	4.19

	$FeCl_3$ for P removal	km/d	0.40	-
	Peracetic acid	km/d	4.60	-

Output			Unit	L1 STATE OF ART	L2 STATE OF ART
EFFLUENT	Effluent to river		m^3/d	1.0000	1.0000
WASTE	Screenings		kg/m^3	0.0054	0.0054
	Grit		kg/m^3	0.0032	0.0032
By-PRODUCT	Sludge cake for fertilizer production		kg/m^3	13.000	6.2200
EMISSION	to air	non-biogenic CO_2 (air emission)	kg/m^3	-	-
		biogenic CO_2	kg/m^3	0.0337	0.0326
		Methane (air emission)	kg/m^3	0.0001	0.0001
		N_2O (air emission)	kg/m^3	0.0000	0.0000
	to water	COD	kg/m^3	0.0193	0.0179
		BOD	kg/m^3	0.0067	0.0060
		TP	kg/m^3	0.0005	0.0007
		PO_4	kg/m^3	0.0005	0.0006
		TN	kg/m^3	0.0103	0.0080
		NH_4	kg/m^3	0.0031	0.0009
		NO_3	kg/m^3	0.0075	0.0066
		Chlorides	kg/m^3	0.0580	0.0510
		Sulphates	kg/m^3	0.0410	0.0410
		Iron	kg/m^3	1.90E-04	3.10E-04
		Aluminium	kg/m^3	1.90E-04	1.20E-04
		Cadmium	kg/m^3	1.00E-05	1.00E-05
		Chromium	kg/m^3	1.00E-04	9.00E-05

The chemical transport is then expressed in the calculations software as kg*km, according to the FU.

Within the OpenLCA modelling, the ECLD 3.2 database implements only some back-ground processes: electricity and sodium hydroxide production and chemical transport. In particular, for the ELECTRICITY, the "Electricity grid mix 1kV-60kV, consumption mix, at consumer, AC, 1kV - 60kV, IT" process was updated with more recent data from the annual report of ISPRA. At the same time, we assumed to use "Small lorry transport, Euro 0, 1, 2, 3, 4 mix, 7,5 t total weight, 3,3 t max payload" for the transportation of the chemicals.

In terms of geographical coverage, foreground data refer to the area directly involved by the investigated process. On the other hand, back-ground data refer to European and Italian case-studies (whenever possible) or geographical areas with similar climatic conditions.

Figure 3-13 shows the model graph resulting from the product system constructed in OpenLCA. It refers to the STATE OF THE ART scenario where both lines of UWWTP discharge to the Lambro river.

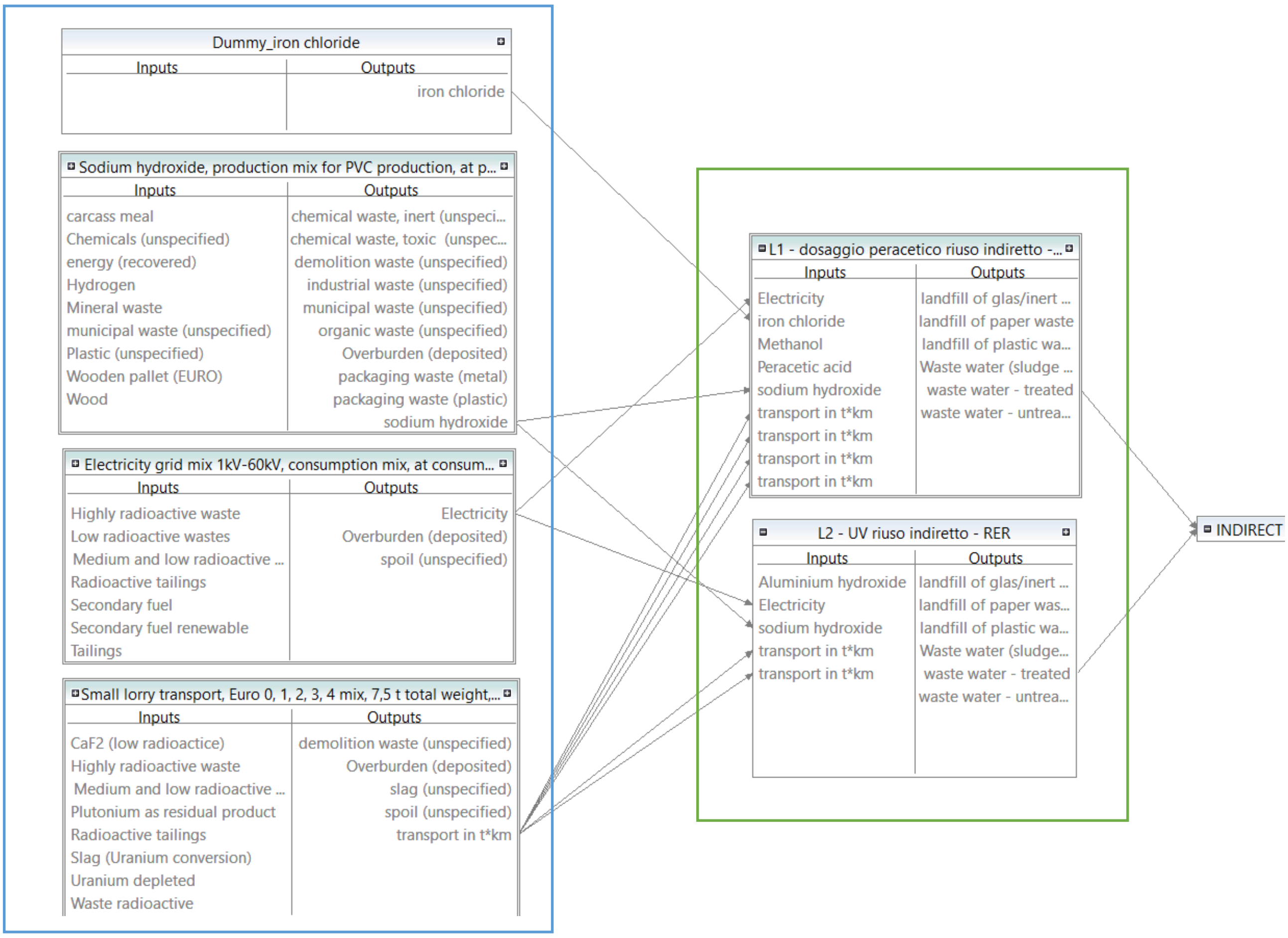


Figure 3-13. Model graph of AS IT IS scenario. From OpenLCA

3.5.1.3 *Life cycle impact assessment*

Life cycle impact assessment (LCIA) phase is conducted using characterization factors from CML 2001 Methodology, included in the free available OpenLCIA methods package, as an attempt. Table 3-14 lists the impact categories investigated.

Table 3-14. Impact categories investigated through the CML 2001 method.

Abiotic depletion	kg Sb eq	Contribution of the various emissions to the resource extraction, including their availability, energy content, concentration, and use rate.
Eutrophication	kg PO_4 eq	Contribution of the various emissions to the accumulation of nutrients in the environment. When nutrients accumulate in aquatic ecosystems, plant growth increases, and deplete oxygen levels.
Global warming (GWP100a)	kg CO_2 eq	Contribution of the various emissions to the increase in global warming. The most critical substances are CO_2, CH_4, N_2O, and halogenated hydrocarbons.
Human toxicity	kg 1,4-DB eq	Effects of toxic substances on the human environment. The Human Toxicity Potentials (HTP) are calculated with USES-LCA, describing fate,

		exposure, and effects of toxic substances. Tot 1.4-DB eq/kg emission expresses the HTP of each toxic substance.
Freshwater aquatic ecotoxicity	kg 1,4-DB eq	Impact on freshwater ecosystems as a result of emissions of toxic substances to air, water, and soil. Ecotoxicity Potential are calculated with USES-LCA, describing fate, exposure, and effects of toxic substances. Characterization factors are expressed as 1,4-dichlorobenzene equivalents/kg emission.
Marine aquatic ecotoxicity	kg 1,4-DB eq	Impacts of toxic substances on marine ecosystems
Terrestrial ecotoxicity	kg 1,4-DB eq	Impacts of toxic substances on terrestrial ecosystems

Toxicity on both humans and ecosystems has been assessed in Life Cycle Impact Assessment (LCIA) with two different characterization models, namely USES-LCA and EDIP 97. USES-LCA is an integrated multimedia fate, exposure, and effects model; potential toxicity of chemicals is measured as equivalents of a reference substance, namely 1,4 dichlorobenzene (DCB). The CML 2001 applies USES-LCA methodology for the toxicity related impact categories. However, it is worth mentioning that the heavy metals included in the data inventory (Al, Cr, and Fe) had no existing characterization factors included by-default for ecotoxicity and human health impacts in the current version. Consequently, back-ground processes play the most significant role in the toxicity assessment (Figure 3-14)

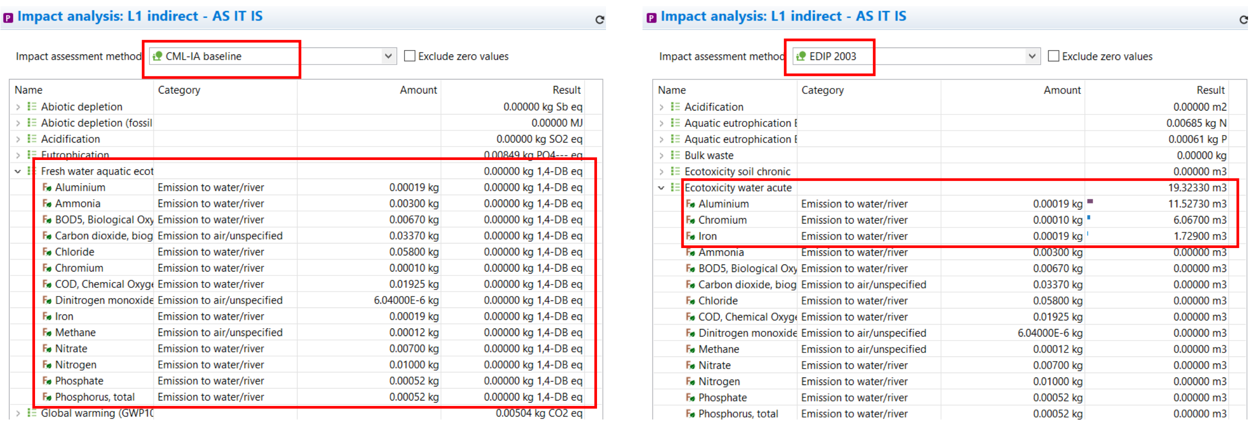


Figure 3-14. Different characterization factors for ecotoxicity assessment, with CML 2001 method (left) and EDIP 2003 method (right)

This CML version is not suitable to understand how ecotoxicity and human health is affected by direct agricultural reuse rather than no reuse case. It should be updated with CFs extracted by previous literature cases such as Alfonsin et al. 2014 or (Zhang et al., 2020).

For practice, we also decided to use the EDIP 2003 assessment as a characterization method. Toxicity of chemical substances, there, is based on independent key properties of substances, which are used to model in a simple way fate, exposure, and effects, instead of using an integrated, quantitative model like USES-LCA. EDIP97 gives the possibility of including up to three impact categories, corresponding to the three main exposure routes to humans: air, water, and soil. Instead of using a reference unit, EDIP97 measures toxicity as a dilution volume of water or soil, depending on the environmental compartment of relevance. It can be interpreted as the volume of water or soil required to dilute the pollutants so that the resulting environmental concentration to remain below the predicted no-effect concentration. Table 3-15 represents the impact categories investigated in this case.

Table 3-15. Impact categories investigated through the EDIP 2003 method.

Resources (all)	PR2004	Global warming 100a	kg CO_2 eq
Aquatic eutrophication EP(N)	kg N	Ecotoxicity water acute	m^3
Aquatic eutrophication EP(P)	kg P	Ecotoxicity water chronic	m^3
Terrestrial eutrophication	m^2	Human toxicity air	person
		Human toxicity water	m^3

Then, following the same methodology, three REUSE scenarios are implemented in OpenLCA to be compared.

The first scenario represents the AS IT IS configuration: both two water lines discharge into the Lambro river. In the second scenario, called INDIRECT/DIRECT REUSE, the L1 effluent is released in the waterbody while an irrigation system directly reuses the L2 effluent. It complies with the minimum requirements set for class C water reuse. The treatment scheme does not need any modifications.

Finally, a third scenario explores the possibility to directly use both effluent wastewaters for agricultural purposes according to the values set out in the Italian DM 185/2003. It requires to increase the PAA dosage to 5 mg/l of PAA in the L1 and the UV dose to 80 mWs/cm^2 meaning that all the 6 UV banks available in the L2 Peschiera Borromeo UWWTP should be employed.

3.5.2 Peschiera Borromeo current state

3.5.2.1 *Definition of goal and scope*

As before mentioned, an LCA is performed to assess the environmental impacts of Peschiera Borromeo UWWTP with a focus on possible differences between waterline L1 and the L2.

The system boundaries of this study included all processes (Figure 3-15), from the input flow to the WWTP to the effluent and wastes generated throughout the operation of the plant (gas fugitive emissions and management of the produced wastes). Regarding the sludge, defecation lime production and application to agricultural soil were also included within the system boundaries. The provisioning of chemicals, fuel and electricity in the upstream processes, as well as the transport associated with chemical consumption and waste management, were also included. Even though it is well known that the main environmental impacts of a WWTP are linked to the operational phase (Buonocore et al., 2018), data concerning the construction phase were also included for an accurate assessment. The CONSTRUCTION phase is also evaluated, considering the amount of material (concrete, steel, plastic) used within the civil works and in electrical motors and pumps. However, end-of-life phase for the WWTP is not included. Studies related to WWTPs (Foley et al., 2010) have reported that end-of-life phases contribute relatively little to overall impacts compared to the construction and operation phases.

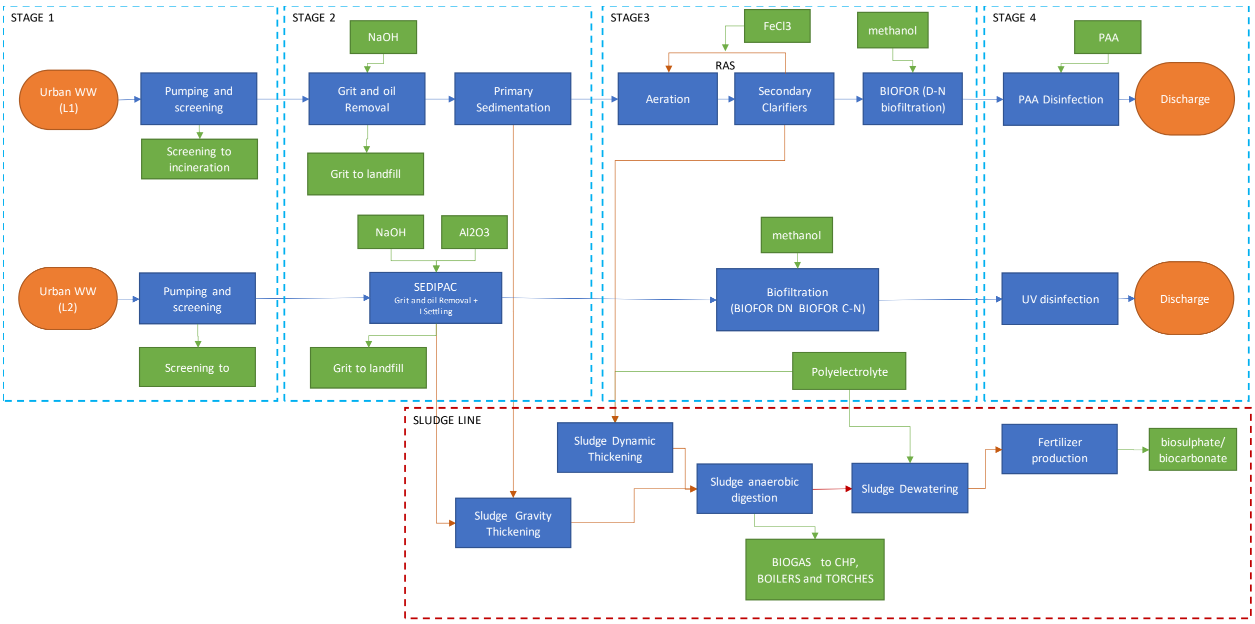


Figure 3-15. System boundary SAREBBE DA INCLUDERE ANCHE GLI OFFSET (FERTILIZZANTE E ENERGIA)

The functional unit (FU) used in the assessment of any product or process will influence the outcomes of the study. In the present study, the volumetric option should be suitable according to the LCA goal. The treatment of 1 m^3 of wastewater will be used as the functional unit.

3.5.2.2 *Life Cycle inventory*

Operation inventory

In general, empirical data collected by mass and energy balances of the WWTP, project reports, and O&M schedules provided by the staff characterize the foreground system. The material flows that are exchanged between one process and another within the plant are not considered as they have no impact on the environment. This is also underlined by the fact that these flows do not come from the database but can be created manually and entered for the convenience of the user of the software. Indeed, these are flows in which any type of assessment factor is absent.

Concerning the operation phase, full-scale data of Peschiera Borromeo WWTP is used for the electricity demand, consumption and transportation of chemicals, the flow and quality of influent and effluent, the amount of waste to be transported and disposed of (section 4.2.1). Direct GHG emissions are retrieved by the parametric Carbon footprint analysis of the plant (section 4.2.2)

The back-ground processes involved in the Peschiera Borromeo UWWTP are modelled through the Ecoinvent v3 database. Nevertheless, some assumptions should be made according to previous literature experiences:

- The peracetic acid production (PAA), since no available data are present in the Ecoinvent database, is modelled through the production processes of acetic acid (CH3COOH) and hydrogen peroxide (H2O2) assuming that the production of 1 kg of PAA requires 0.45 kg of CH3COOH, 0.79 kg of H2O2 and 0.28 kg of water (Buonocore, et al. 2018)
- The polyelectrolyte is implemented as polyacrylamide, which is a kind of polymer used for sludge coagulation (Buonocore et al., 2018; Lorenzo-Toja et al., 2016).
- Trucks 16–32 t EURO 4 were selected as transport vehicles for sludge and wastes produced in the facility. In the case of chemicals, vans less than 3.5 t were the preferred option due to the small amount transported.
- The processes “disposal, plastics, mixture, 15,3% water, to municipal incineration” and “disposal, paper, 11,2% water, to municipal incineration” is used to estimate the environmental burdens caused by the disposal of screening waste, assuming that such waste is only composed by paper and plastic (Flores-Alsina et al., 2010; Pasqualino et al., 2011; Pintilie et al., 2016; Yoshida et al., 2018)
- The process “disposal, inert waste, 5% water, to inert material landfill” can be considered for the grit disposal (Yoshida et al., 2018)
- Energy consumption and direct emissions of defecation lime production were modelled according to the detailed inventory provide by (Tinello 2018). The data are obtained through measurement campaigns in Italian facilities.
- The mineral fertilizer considered to be replaced is TSP (triple superphosphate) and CAN (calcium ammonium nitrate), in line with other LCA including fertilizer offset (Morera et al., 2017). The

defecation lime also raises soil pH, avoiding separate lime addition but it is not considered as system expansion in this study.

- The amount of avoided fertilizers were estimated according to plant availability of 30 % for N as suggested by the datasheet, while 70% of P is considered to be available for the crops (Bengtsson et al., 1997). The avoided derived emissions from their application were estimated according to (Foley et al., 2010)
- The emissions associated with the physical application of sludge-based or mineral fertiliser are mainly from the combustion of diesel used by machines. The application of defecation lime is modelled through the process "solid manure loading and spreading, by hydraulic loader and spreader, CH, [kg]". At the same, it avoids the application of mineral fertiliser on land, which is accounted for by using the process "fertilising, by broadcaster, CH, [ha]". The equivalent hectares are calculated considering a fertiliser rate for extensive crops of 3000-5000 kg/ha as suggested by the producers.
- Emission to air (N_2O and NH_3) and water (NO_3) from defecation lime application to agricultural soil were also considered and modelled following the inventory factors established by (Bruun, et al. 2016), as well as the carbon sequestration.

Electricity production was based on the consumption of Italian specific electricity mix. Lists background processes included in the system product through the Ecoinvent v3.6 database.

Table 3-16. Related dataset of Ecoinvent database for the operational phase

Energy	
electricity	market for electricity, low voltage [IT]
Chemicals	
NaOH	market for sodium hydroxide, without water, in 50% solution state [GLO]
PAC	polyaluminium chloride production [GLO]
$FeCl_3$	iron (III) chloride production, product in 40% solution state [CH]
External carbon	methanol production [GLO]
Poly	polyacrylamide production [GLO]
Lime	quicklime production, milled, loose [CA-QC]
$H2SO_4$	sulfuric acid production [RER]
UV lamps	market for ultraviolet lamp [GLO]
Waste disposal	
Grit	treatment of inert waste, inert material landfill [CH]
Screening	treatment of waste packaging paper, municipal incineration [CH]
	treatment of waste plastic, mixture, municipal incineration [CH]
Fertiliser	

P fertiliser	triple superphosphate production [RER]
N fertiliser	calcium ammonium nitrate production [RER]
Land application	solid manure loading and spreading, by hydraulic loader and spreader [CH]
	fertilising, by broadcaster [CH]

The detailed inventory for the operation phase of Peschiera Borromeo UWWTP is reported in ANNEX I. The data are reported without being normalized to the FU and they are mainly retrieved as annual average values (2019) from the O&M reports. The software Umberto LCA+ was used for the computational implementation of the inventories.

Construction phase

It is included in the inventory the amount of concrete, reinforcing steel, GFRP and excavation required for the civil works and the materials that electrical motors and pumps are made of. Since the construction budget for the WWTP is no more available, we did not follow the procedure suggested by (Doka, 2003) to obtain a detailed construction inventory. In our case, the geometrical information of tanks, building and piping are measured from the layout of the plant and design reports.

The buildings will be modelled through the product “building, hall [m^2]” present in the Ecoinvent v3 database, so only surface data are needed. The same goes for the glass fibre reinforced plastic used in the tank covers for which a weight per square meter is assumed based on the product datasheet. For reactor tanks, instead, the volume of concrete is roughly estimated, and it was then used as a multiplier for the consumption of other materials and processes in the construction phase. A similar approach was followed by (Morera et al., 2017) based on (Igos et al., 2014) inventory. In this study, due to the similarity with Girona WWTP, the ratio between concrete and other material are assumed to be the same of (Remy et al., 2013) and are presented in Table 3-17 Multiplier factor considered in the construction phase inventory (mass of reinforcing steel per volume of concrete). The disinfection step is missing in Girona therefore data from (Morera et al., 2017) and from (Morera et al., 2017) are considered for chemical and UV disinfection, respectively.

It is assumed the lifetime of the WWTP to be 20 years (Renou et al., 2008) whereas the lifetime of the equipment was 15 years (Lundin et al., 2000). The influence of the lifetime of the WWTP on the LCA assessment is addressed in a sensitivity analysis in (Morera et al., 2017). Finally, for the equipment, the type and mass of materials in each electric motor and pump was calculated using parameterisation expressions, based on rated kW obtained by the Environmental Product Declarations (EPD) used even in (Remy et al., 2013)

Table 3-17 Multiplier factor considered in the construction phase inventory (mass of reinforcing steel per volume of concrete)

CIVIL WORKS	kg/m^3	References

Pumping and pretreatment	71.28	
Primary treatment	69.53	
Secondary treatment	90.71	(Igos et al., 2014)
sludge line	137.92	
others*	27.18	
UV disinfection	103	(Goedkoop et al., 2009)
Chemical disinfection	110	(Remy et al., 2013)

Data collected are listed in Table 3-18 and Table 3-19.

Table 3-18. Inventory of civil works

Material		Reinforcing steel	GRP (glass fiber)	Concrete	Building	Earthworks
u.m		*kg*	*Kg*	*m^3*	*m^2*	*m^3*
TOTAL		1766436	124807	18896	4562	5399
L2	Phase 1	8094	2850	114	575	32
L2	Phase 2	110393	44460	1588	0	454
L2	Phase 3	282566	35955	3115	1505	890
L2	Phase 4	8783	2869	85	0	24
L1	Phase 1	11107	3675	156	486	45
L1	Phase 2	158158	10470	2275	0	650
L1	Phase 3	754646	7517	8319	1164	2377
L1	Phase 4	58658	0	533	0	152
SL	Phase 5	374032	17012	2712	832.65	775

Table 3-19. Inventory of equipment.

		Motors					Pumps	
Material		Electrical Steel	Other Steel	Cast Iron	Aluminium	Copper	Cast Iron	Stainless Steel
u.m		*kg*	*kg*	*kg*	*kg*	*kg*	*kg*	*kg*
TOTAL		8619	1474	4933	260	987	16940	1089
L2	phase 1	611	104	350	18	70	3783	243
L2	phase 2	152	26	87	5	17	227	15
L2	phase 3	2203	377	1261	67	252	4150	267
L2	phase 4	152	26	87	5	17	0	0
L1	phase 1	1101	188	630	33	126	3400	219
L1	phase 2	130	22	75	4	15	336	22
L1	phase 3	3290	563	1883	99	377	1828	118
L1	phase 4	0	0	0	0	0	3	0

3.5.2.1 *Life cycle impact assessment*

This LCA uses a midpoint oriented approach for impact assessment, mainly based on the indicator models described in the Dutch LCIA method ReCiPe 2008 (Jiménez-Benítez et al., 2020), reporting the impacts on the physical effect level of the respective category of environmental concern. The use of midpoint indicators gives a detailed picture of all relevant fields of environmental impact without further aggregation of the results along the causa-effect chain (ISO, 2006)

In detail, seven categories of environmental concern are selected for the impact assessment in this LCA, described by seven midpoint indicators (**Table 3-20**). Other environmental indicators are neglected in this LCA, mainly because they are not expected to be relevant for the scope of this study.

Table 3-20. Investigated impact categories through ReCiPe 2008 Midpoint.

Impact category	Acronym	u.m.
fossil depletion	FDP	kg oil-Eq
freshwater eutrophication	FEP	kg P-Eq
freshwater ecotoxicity	FETPinf	kg 1,4-DCB-Eq
climate change	GWP100	kg CO_2-Eq
human toxicity	HTPinf	kg 1,4-DCB-Eq
terrestrial acidification	TAP100	kg SO2-Eq
terrestrial ecotoxicity	TETPinf	kg 1,4-DCB-Eq

The assessment has been conducted using UMBERTO LCA+.

3.5.3 Comparison of reclamation solutions

One water line of Peschiera Borromeo WWTP is intended to be reused to face the water scarcity of surrounding agricultural land. It covers an area of approximately 1,500 ha and the main crop is tomato. The average water requirement is 7.318 m^3/ha from April to September. It means that almost half of the L2 effluent flow shall be reclaimed. Additionally, the nutrient needs (N and P) of tomato in drip irrigation systems are 160 kg N/ha/y and 20 kg P/ha/y (DEMOWARE et al., 2015).

However, reclaimed water must comply with reuse regulation. In Italy, the wastewater reuse is still regulated by the D.M. 185/2003, and it sets out an effluent limit of 10 CFU/100ml for E. coli. 80% or more of the samples have to meet this value. But recently the European Parliament and the Council of the European Union approved the new Regulation 2020/417 on minimum requirements for water reuse. It defines four minimum reclaimed water quality classes (from A to D), each one related to an allowed agriculture use and irrigation methods. More detailed in section 2.1.

Anyway, a tertiary process is required to reach the discharge limits set out by the regulations. Economic and environmental evaluation of such processes are compared in the following section.

3.5.3.1 *Definition of goal and scope*

LCA approach is applied to provide a holistic environmental and economic assessment of advanced tertiary treatment and further analyse the agricultural water reuse option. The final aim is to define the sustainability of the different water reclamation techniques, such as peracetic acid (PAA) and UV-disinfection and AnMBR configuration. The study was assessed according to ISO 14044 (Antonelli et al., 2013), operating with four separate phases: goal and scope definition, inventory analysis, impact assessment and interpretation.

First, the Baseline scenario is investigated. It represents the current configuration where water is discharged to the Lambro river after UV disinfection. At the same time, farmers irrigate crops with surface water withdrawn upstream of the WWTP discharge point.

The reclamation technologies, which are compared, consist in UV disinfection (Scenario 1) and chemical disinfection by peracetic acid (Scenario 2), both applied to the L2 water line. Besides, we have analysed an alternative scenario with the conversion of the current treatment chain (BIOFOR © plus UV) into an AnMBR system composed by an anaerobic reactor coupled with an anaerobic hollow-fibre ultrafiltration membrane (267,842 m^2, 0.03 µm of nominal pore-size) equipped with level and transmembrane pressure (TMP) sensors and works at the specific flux of 10 LMH (Scenario 3).

The current quality of L2 final effluent falls under the Class C water quality of the new EU Regulation 2020/741 EC. On the other hand, the ultrafiltration technology of Scenario 3 shall provide pathogen-free effluent.

Table 3-21 – Effluent concentrations and wastewater reuse limits

Parameters	unit	Effluent L1	Effluent L2	DM183/2005	Class A	Class B	Class C
E.coli	CFU/100ml	284	847		<10	<100	<1000
COD	mg/l	19.3	17.9	<100	-	-	-
BOD_5	mg/l	6.7	6	<20	<10	<25	<25
TN	mg/l	10.3	8.4	<15	*	*	*
NH_4	mg/l	3.9	1.1	<2	*	*	*
TP	mg/l	0.5	0.7	<2	*	*	*
TSS	mg/l	7.2	6.5	<10	<10	<35	<35
Al	mg/l	0.19	0.12	<1	*	*	*
Fe	mg/l	0.19	0.31	<2	*	*	*

*defined according to a site-specific risk assessment to be carried out

That is the reason why all the proposed reuse scenarios are modelled to reach the effluent quality of Class A. It requires upgrading in the waterline (Table 2-3). (Pretel et al., 2013) suggests a UV dose of 80 mJ/cm^2 to achieve 3.5 log reduction. At the same time, experiments carried out at pilot scale using wastewater from

WWTPs located in Milan urban area demonstrated that 5 mg PAA/L and a contact time from 35 to 50 min allow a 4-log reduction of E. coli (Jiménez-Benítez et al., 2020).

Table 3-22. Operative conditions of different scenarios

Scenario	E.coli in*	E.coli out*	Log reduction	Operation parameter
Baseline	29000	847	1.5	40 mJ/cm^2
Scenario 1	29000	<10	3.5	80 mJ/cm^2
Scenario 2	29000	<10	3.5	5 mgPAA/l
Scenario	n.a.	0	n.m.	0.03 µm pore size

*concentration of E.coli in the influent and effluent of UV disinfection, expressed as CFU/100 ml

The energy and chemical requirements of Scenario 3 are modelled following (Diaz-Elsayed et al., 2020) suggestions. It is assumed to add an external carbon source to achieve the same organic loading rate (0.85 kg COD/m^3/d) employed in the reference paper so that the performances are comparable.

Table 3-23. Anaerobic reactor parameters.

COD daily load	Influent flow	HRT	Anaerobic reactor	OLR	Addition
kg/d	m^3/d	h	m^3	kgCOD/m^3/d	kgCOD/d
15'842	64'282	9	24'106	0.7	4'521.40

The nutrient removal of the anaerobic process is calculated according to the data delivered by the Innovation Deal approved by the European Commission in 2016. At that time, Peschiera Borromeo WWTP was analysed as a case study to assess the economic and environmental feasibility of AnMBR system. Results of the study are presented in (Suh & Rousseaux, 2001)

The treatment of 1 m^3 of wastewater is used as functional unit to measure performance and provide a reference for the inputs and outputs of the analysed system based on the LCA. It aligns with what has been most commonly used in the literature: LCAs that evaluated alternative wastewater treatment or water reuse schemes, primarily considered a volume-based functional unit (Foley et al., 2010; Pan et al., 2019). The volume of treated wastewater per unit time has been also suggested by (Harder et al., 2015; Heimersson et al., 2014) to be the most appropriate choice as it is based on realistic data.

Physical boundaries are defined according to the goal of the study, i.e. the comparison of different tertiary treatment schemes. The system boundary includes as a first step the pumping of wastewater to the plant and as the last step the release of wastewater effluent in surface water (Baseline) or the fertigation with reclaimed water (Scenario 1, 2 and 3). It covers only the waterline, including the operation and maintenance (O&M) phase, the treatment performed within the WWTP, the transportation and final disposal of grit and screening waste. The plant construction and decommissioning were excluded owing to their negligible effects in comparison to the long-term operations (Harclerode et al., 2020). It is also included the irrigation field where according to Scenario the water and nutrient demand is covered by reclaimed freshwater plus required mineral fertilizer. The excess of reclaimed water not required by the crops is discharged to the Lambro river.

The inventory includes primary data of energy demand and production, chemicals and fertilizers consumption, direct emissions to air, to soil and water. The Ecoinvent 3.6 database is used for background data like electricity and chemicals production process, transport and waste disposal.
The environmental and human health impacts of the scenarios were characterized using the LCIA Method "ReCiPe 2008 Midpoint (H) V1.13 no LT". The impact categories investigated are climate change, fossil depletion, freshwater ecotoxicity, freshwater eutrophication, human toxicity, terrestrial acidification, terrestrial ecotoxicity and water depletion. Impacts of pathogens are not included in current impact assessment methods. There were some recent attempts to include pathogenic risk in life cycle assessment (Cotton et al., 2001)

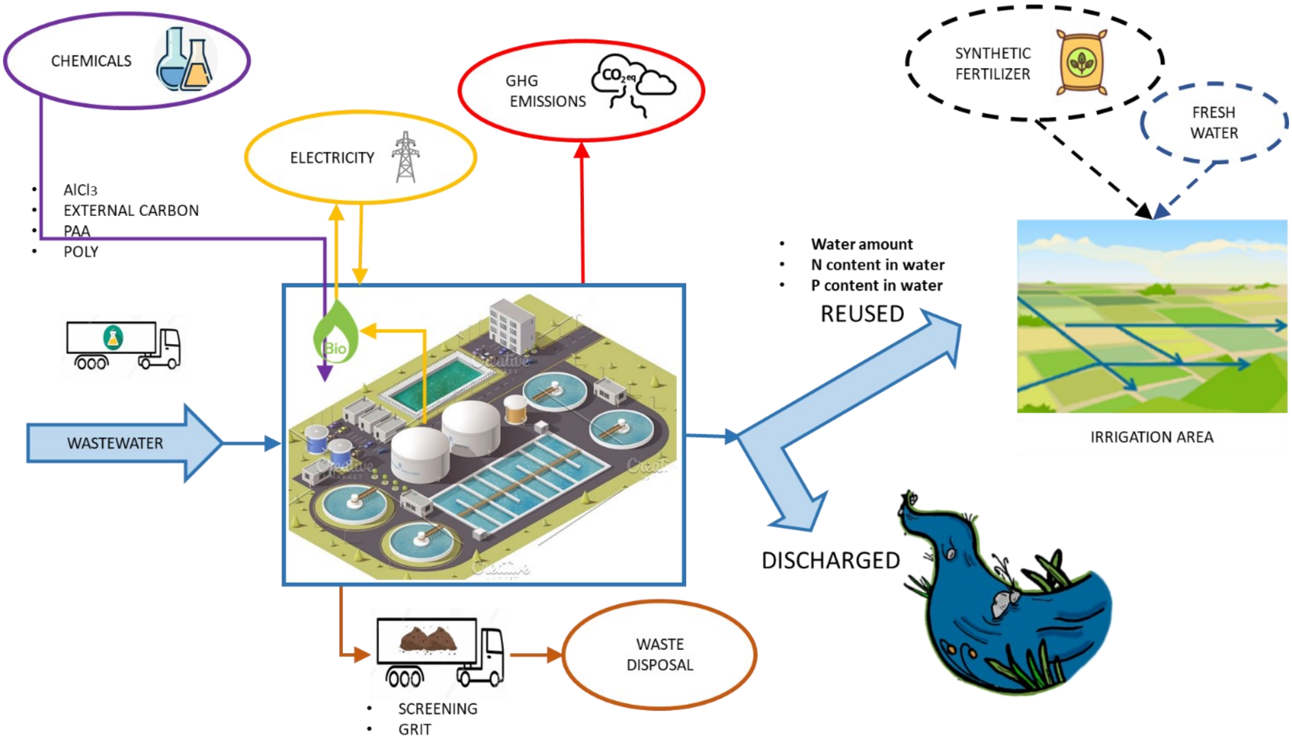


Figure 3-16. System boundaries of comparative LCA on water reuse.

3.5.3.2 *Life Cycle Inventory*

A summary of the Life cycle inventory developed for the reclaimed water reuse scenarios is given in Table 3-24. For the Baseline scenario, the main data source is O&M reports provided by the water utility of Peschiera Borromeo WWTP. The water quality, energy and chemicals consumption, waste production and related transport to disposal site are referred to 2019 data. For alternative scenarios, literature values are mainly considered. Direct greenhouse gases (GHG) emissions include the biogenic CO_2 produced by biological reactions. Where reclaimed water is used for crop irrigation, the nutrients N and P contained in such water are assumed to offset mineral fertilizer application and production. In this study, both N and P substitutability is assumed as 100% similarly to (Fang, et al. 2016) It is further assumed that reclaimed water would result in zero runoff and leaching, and would perform similarly to mineral fertilizer in terms of ammonia volatilization, and soil mineralization.

The BIOFOR © technology ensures nutrient removal to comply with the Italian discharge limits. Therefore, in Scenario 1 and Scenario 2, the amount of nutrients provided to crops with the reclaimed water does not match the demand and additional mineral fertilizer must be spread. In the other hand, the AnMBR effluent is characterized by N content higher than the crop demand (excess N), so there is no need to consider additional mineral N fertilizer, while for P, the required addition is equal to 18.13 kg/d. The excess of nitrogen is modelled as NO_3 emission to water. Scenario 3 requires also a system expansion for the electricity and thermal energy produced by using biogas in CHP unit (1349.92 kWh/ and 4236 MJ/d, respectively). The software Umberto LCA+ was used for the computational implementation of the inventories.

Table 3-24. Comparative Life Cycle Inventory

		Baseline	Scenario 1	Scenario 2	Scenario 3
		class C	class A reclaimed water		
Parameters	Units	UV	High dosage UV	PAA	AnMBR
V treated	m^3/d	64282	64282	64282	64282
V discharged	m^3/d	64282	31323	31323	31323
V water reused	m^3/d	0	32959	32959	32959
V surface water for irrigation	m^3/d	32959	0	0	0
V required by crop	m^3/d	32959	32959	32959	32959
TN effluent	g/m^3	8.34	8	8	24
TN required by crop	kg/d	657.53	658	658	658
TN added by water	kg/d	0.00	275	275	791
TN added by mineral fertilizers	kg/d	657.53	383	383	-
excess TN to soil	kg/d	-	-	-	133.45
TN discharged to surface water	kg/d	536.35	261.35	261.35	751.73
TP required by crop	kg/d	82.19	82.19	82.19	82.19
TP effluent	g/m^3	1.04	1.04	1.04	1.94
TP added by water	kg/d	-	34	34	64
TP added by mineral fertilizers	kg/d	82.19	47.78	47.78	18.13
excess TP to soil	kg/d	0.00	0.00	0.00	0.00
TP discharged to surface water	kg/d	67.12	32.71	32.71	60.88
consumed electricity (tot)	kWh/d	20318	23273	17844	21290

consumed electricity (pretr.)	kWh/d	8009	8009	8009	8009
consumed electricity (biolog)	kWh/d	9792	9792	9792	900
consumed electricity (disinf)	kWh/d	2517	5472	43	12381
produced electricity	kWh/d	0	0	0	1350
self-produced heat	MJ/d	0	0	0	4236
PAA at 16% w/w used	kgSOL/d	0	0	2009	0
PAC for P removal used	kgSOL/d	2419	2419	2419	0
external carbon source	kgSOL/d	2268	2268	2268	13188
NaOCl for MBR cleaning	kg/d	-	-	-	93
citric acid for MBR clieaning	kg/d	-	-	-	93

Regarding the background processes, the same assumptions made in section 3.5.2.2 are considered. Additionally, the freshwater required in the Baseline scenario is modelled assigning an impact characterization factor equal to 1 m^3 of water to a custom elementary flow. Therefore, it will impact only the water depletion potential. At the same time, the quality of that freshwater will impact the soil compartment once it is used to irrigate crops. So, the characterization of the Lambro river is obtained by the local environmental agency and managed as done for the reclaimed water quality in the inventory. Arsenic, cadmium and lead are included in the analysis to identify the impact of heavy metals when reclaimed water is applied in agriculture. So far, the AnMBR performances in removing heavy metals are neglected. The resulting elementary flows to soil are listed in Table 3-25

Table 3-25. Emission to the soil in different scenarios

Elementary flow	u.m	Baseline	Scenario 1	Scenario 2	Scenario 3
Total phosphorous	mg/l P	0.294	8.34	8.34	24
Total nitrogen	mg/l N	4.32	1.04	1.04	1.94
Arsenic	µg/l	1.59	50	50	50
Cadmium	µg/l	0.05	10	10	10
Lead	µg/l	2.64	10	10	10

3.5.3.3 *Life Cycle Cost inventory*

The economic evaluation is done considering both the capex and opex of the plant, in a lifetime of 25 years. The investment cost of civil works and equipment are retrieved by literature. The same cost estimated by (Harclerode et al., 2020) are scaled down to the Peschiera Borromeo capacity and average flow. The UV disinfection unit refers to (Goedkoop et al., 2009) The unitary cost (€/kg) for energy, chemical and waste disposal comes from WWTP reports. While the price of material input not involved in the baseline scenario are obtained from the Ecoinvent database. The membrane modules are assumed to be replaced every 10 years and operation cost is retrieved by (Remy et al., 2013). Ultraviolet lamps instead have a lifetime of 10000 hours that means a replacement every 1.14 years. Finally, the farmers pay 115€ /ha/y to withdraw the irrigation water from surface water. It is considered the same cost even in the case, reclaimed water is used to irrigate crops.

Table 3-26 and

Table 3-27 show respectively the capital and the operative costs evaluated for the three scenario and expressed as annual cost.

Table 3-26. CAPEX for the three scenarios

		Baseline	Scenario 1	Scenario 2	Scenario 3
Preliminary and Primary Treatment	€	353'453	353'453	353'453	353'453
CAS Secondary Treatment	€	895'840	895'840	895'840	-
AnMBR Secondary Treatment	€	-	-	-	1'457'992
Biogas Conditioning and CHP	€	-	-	-	470'883
Disinfection	€	65'123	65'123	180'214	-
Overall WWTP	€	1'314'415	1'314'415	1'429'507	2'282'327

Table 3-27. OPEX for the three scenarios

			Baseline	Scenario 1	Scenario 2	Scenario 3
energy						
	electricity pretreatment	€/y	422'171	422'171	422'171	422'171
	electricity biological process	€/y	516'157	516'157	516'157	47'438
	electricity disinfection	€/y	132'651	288'441	2'277	652'613
	electricity sold	€/y	-	-	-	-71'157
chemical						
	PAA at 16% w/w	€/y	-	-	542'580	-
	PAC for P removal	€/y	30'903	30'903	30'903	-
	NaOH	€/y	871	871	871	871
	external carbon	€/y	33'055	33'055	33'055	192'201
	NaOCl	€/y	-	-	-	118'414
	citric acid	€/y	-	-	-	26'389
equipment replacement						
	UV lamps replacement	€/y	125'804	268'064	-	-
	membrane replacement	€/y	-	-	-	1'222'153
waste disposal						

screening disposal	€/y	19'929	19'929	19'929	19'929
Crop irrigation					
P fertiliser purchased	€/y	16'559	9'626	9'626	3'652
N fertiliser purchased	€/y	113'520	66'042	66'042	-
water from irrigation drainage	€/y	189'048	-	-	-
reclaimed water	€/y	-	189'048	189'048	189'048
Personnel					
staff	€/y	60'000	60'000	60'000	60'000
TOTAL QUANTITY	€/y	1'660'667	1'904'305	1'892'658	2'883'723

3.5.3.4 *Life cycle impact assessment*

This LCA uses a midpoint oriented approach for impact assessment, mainly based on the indicator models described in the Dutch LCIA method ReCiPe 2008 (Harclerode et al., 2020), reporting the impacts on the physical effect level of the respective category of environmental concern. The use of midpoint indicators gives a detailed picture of all relevant fields of environmental impact without further aggregation of the results along the causa-effect chain (Crone et al., 2016). The eight categories selected for the impact assessment in this LCA are listed in **Table 3-28**

Table 3-28. Investigated impact categories through ReCiPe 2008 Midpoint.

Impact category	Acronym	u.m.
fossil depletion	FDP	kg oil-Eq
freshwater eutrophication	FEP	kg P-Eq
freshwater ecotoxicity	FETPinf	kg 1,4-DCB-Eq
climate change	GWP100	kg CO_2-Eq
human toxicity	HTPinf	kg 1,4-DCB-Eq
terrestrial acidification	TAP100	kg SO2-Eq
terrestrial ecotoxicity	TETPinf	kg 1,4-DCB-Eq
Water depletion	WDP	m^3 water-Eq

The assessment has been conducted using UMBERTO LCA+.

3.5.4 UMBERTO Software

Umberto LCA+ is a software tool that helps to calculate the potential environmental impacts of products. It uses graphic modelling of the product life cycle and allows analysing, assessing and visualizing the environmental impacts in different impact categories.

To do a life cycle assessment analysis, the starting step plans to draw the life cycle model (or SYSTEM MODEL). Processes (sketched as a squared box) represents the core of the model. As a prerequisite for a successful calculation of all material and energy flows of the system, and subsequently for the LCIA results, all processes shall be specified. A process specification can be made by entering materials on the input and output side of the process and specifying a coefficient for each entry. These coefficients don't have to be absolute values. Rather do they represent the size of flows on the input and the output side in relation to each other.

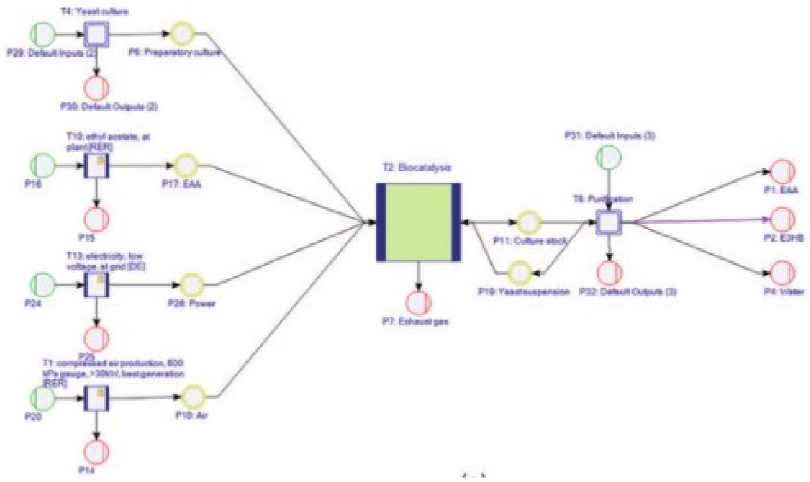


Figure 3-17. Example of product model created in Umberto LCA+

For a unit process this model stub has one input and an output place, to which elementary exchanges will be assigned, and two connection places: one for the intermediate exchanges on the input side, and one for the intermediate exchange(s) on the output side (typically the reference flow).

These inputs and outputs are the called intermediate exchanges since these flows run between the processes, within the technosphere. They could be flows that are outputs of a technical process, such as a product, a semi-finished product, processed goods or a component. Using Ecoinvent as the master data, intermediate exchanges can be used to expand the process chain, and choose a process that delivers a certain material into a process.

Elementary Exchanges, on the contrary, are the flows that cross the system boundary and play a central role in impact assessment as they do have characterization factors assigned, for which the contribution to an environmental impact is calculated. Typically, elementary exchanges are not defined by the practitioner as individual flows but are predefined in the master material databases.

It is also possible to define a new intermediate exchange in the project clicking on the button 'New Material'. The information for the newly created intermediate exchange material that can be edited in the Property Editor window is the material name (and description), the unit type (unit of measure) and material type (good, bad, or neutral). Materials with the material type GOOD are expenditures of raw materials, intermediate products or auxiliary materials. The products of any process also have the material type GOOD.

Direct emissions, as well as wastes causing indirect emissions (like waste being transported to the landfill), are shown with the material type BAD. Materials which should not contribute to the life cycle inventories are marked with the material type NEUTRAL. In multi-output processes, the material type will also be used to determine the products and call for the allocation settings between the products of a process (main product, coproduct).

When calculating the product life cycle model, all material expenses (raw materials, energy, components) in the life cycle inventory are considered with their quantities and their characterization factors for impact assessment. For newly defined intermediate exchanges, typically no such characterization factors exist, and the intermediate exchanges will most likely not appear in the life cycle impact assessment as contributing to environmental impacts.

Background data are available through the implementation of Ecoinvent v3 database within the Umberto LCA+ software. Ecoinvent activities typically are available as both 'Unit' and 'System terminated' ('Result') type. They can in most cases be chosen from one of the three systems:

- consequential system model. It uses different basic assumptions to assess the consequences of a change in an existing system.
- Allocation, at point of substitution (APOS) model. It follows the attributional approach in which burdens are attributed proportionally to specific processes.
- Allocation cut-off system model. It considers the producer as fully responsible for the disposal of its wastes, and so he does not receive any credit for the provision of any recyclable materials.

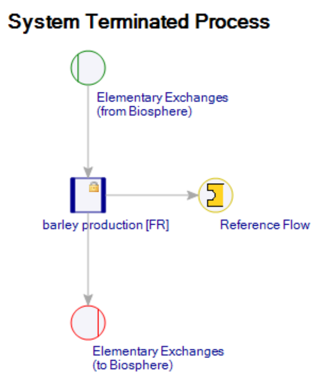


Figure 3-18. Schematic implementation of RESULT process in Umberto LCA +

For a result (system terminated) process, the approach used int his study, the model stub has one input and an output place, to which all elementary exchanges are assigned, and one output-sided connection place for the reference flow. Result activities include all upstream activities and therefore also include the system boundaries.

The system model can also be divided into different life cycle phases: e.g 'Raw Materials', 'Assembly', 'Distribution', 'Use', and 'End-of-Life/Disposal'. It will help in the interpretation and discussion of the results.

After a model has been built up and all processes have been properly specified, it can be calculated. As a prerequisite for launching the calculation, it is required to enter at least one flow manually. This start flow can be located anywhere in the model, but it typically is the flow of one unit of product for which the model is calculated. Because of the model calculation, ideally, all other flows will be determined.

At this point, the mass and energy flows within the system model are evaluated. They refer to Inventory results. To obtain LCIA results, an impact assessment should be performed. It is the part in LCA where predictions on environmental effects of the production system are made. It is required to choose the methodologies (ReCiPe, Traci, CML, etc) and impact categories, as well as the level of detail, depending on the goal and scope of the study. The link between life cycle inventory outcomes and impact categories are the characterization factors for each elementary flow.

In Calculating the Life Cycle Model, is important to say that the product for which the life cycle model is built is represented by the reference flow of the system. In most cases, there will be just one reference flow ("single product system"), but the models in Umberto LCA+ are also capable of handling several reference flows ("multi-product systems"). This is the case, for example, when besides the main product there are also one or more co-products. In this case, an allocation must be made to properly assign process expenditures to the individual products. Finally, the results are provided in graphical form and several views. They shall also be exported as spreadsheet files allowing for creating any other customized table with selected results and diagrams based upon these.

The life cycle model can be displayed as Sankey diagrams, both for material and energy flows, as well as for weighted "impact flows", i.e. the environmental impact loads cumulated along the stages of the life cycle. Sankey diagrams are flow diagrams, where the width of the arrows represents the flow quantity. The Sankey diagrams are an integral part of Umberto LCA+, and the normal life cycle model view can be switched to a Sankey diagram view easily.

3.5.5 Life Cycle Costing

A simplified economic analysis is conducted. The total cost is reported as annual costs, summarizing the annual operational costs with the capital costs per annum:

$$Annual\ costs\ =\ OPEX\ (€/y)\ +\ CAPEX\ (€/y)$$

$$CAPEX\ =\ \frac{\sum investment\ costs\ (€)}{economic\ lifetime\ (y)}$$

Direct capital costs are obtained from (Metcalf & Eddy, 2003). They include the cost of structures, mechanical equipment and installation, and electrical and automation allowances: for the conventional treatment facilities were developed based on scaling of costs from comparable projects implemented by the authors, while costs for less common processes like AnMBR were estimated using equipment vendor pricing and estimated quantities for materials, such as concrete, tank covers, and pre-engineered buildings.

All costs reported in this study are net costs in Euro, thus not including value added tax (VAT). The effects of price development (e.g. rising energy prices) and inflation (i.e. the loss of value for money) are not taken into account in this calculation.

The economic lifetime was set to 25 years to be conservative since our investment cost include both construction and building with a typical lifespan higher than 30 years and machinery that are replaced every 20 year or less. This choice is supported by the ''EVALUATION of the Council Directive 91/271/EEC of 21 May 1991'' concerning urban waste-water treatment (EU, December 2019) that suggest a lifetime of 25 years for WWTPs.

4. Results and discussion

4.1 Data collection matrix for the implementation of a risk management plan in Mediterranean rural and urban areas

Aim of this section is to provide suggestions for the collection and the organization of required data for the implementation of WRRMPs. This work has been carried out through the analysis of existing literature, current international guidelines and the European legislation. *In particular, the suggested procedure for data collection follows the recommendations defined in the Regulation (EU) 2020/741 on minimum requirements for water reuse.* The analysis has been developed considering agricultural irrigation and aquifer recharge as possible water reuse applications.

Water Reuse Risk Management Plan (WRRMP) is a valid instrument used to address risk management in water reuse applications, with the main objective of removing or reducing any possible risk for the human health, for the environment or for the animals. International guidance and standards have been developed to uniform the evaluations and the procedures for developing the WRRMPs. The most widely used guidelines are:

- ISO 20426:2018 Guidelines for health risk assessment and management for non-potable water reuse,
- ISO 16075:2015 Guidelines for treated wastewater use for irrigation projects
- World Health Organisation (WHO) Guidelines and Manuals for the development and the implementation of Water Reuse Safety Plans (WRSPs).

The overall flow diagram for the implementation of the WRRMP is summarized in Figure 4-1. This includes 11 sections and stages, listed below:

- SECTION 1: SYSTEM DESCRIPTION
- SECTION 2: IDENTIFICATION OF ALL PARTIES INVOLVED
- SECTION 3: IDENTIFICATION OF HAZARDS AND HAZARDOUS EVENTS
- SECTION 4: IDENTIFICATION OF GROUPS AT RISK and ROUTE OF EXPOSURE
- SECTION 5: RISK ASSESSMENT
- SECTION 6: ADDITIONAL REQUIREMENTS
- SECTION 7: PREVENTIVE MEASURES
- SECTION 8: QUALITY CONTROL and PROCEDURES
- SECTION 9: ENVIRONMENTAL MONITORING SYSTEM
- SECTION 10: EMERGENCY PLAN
- SECTION 11: COORDINATION PLAN

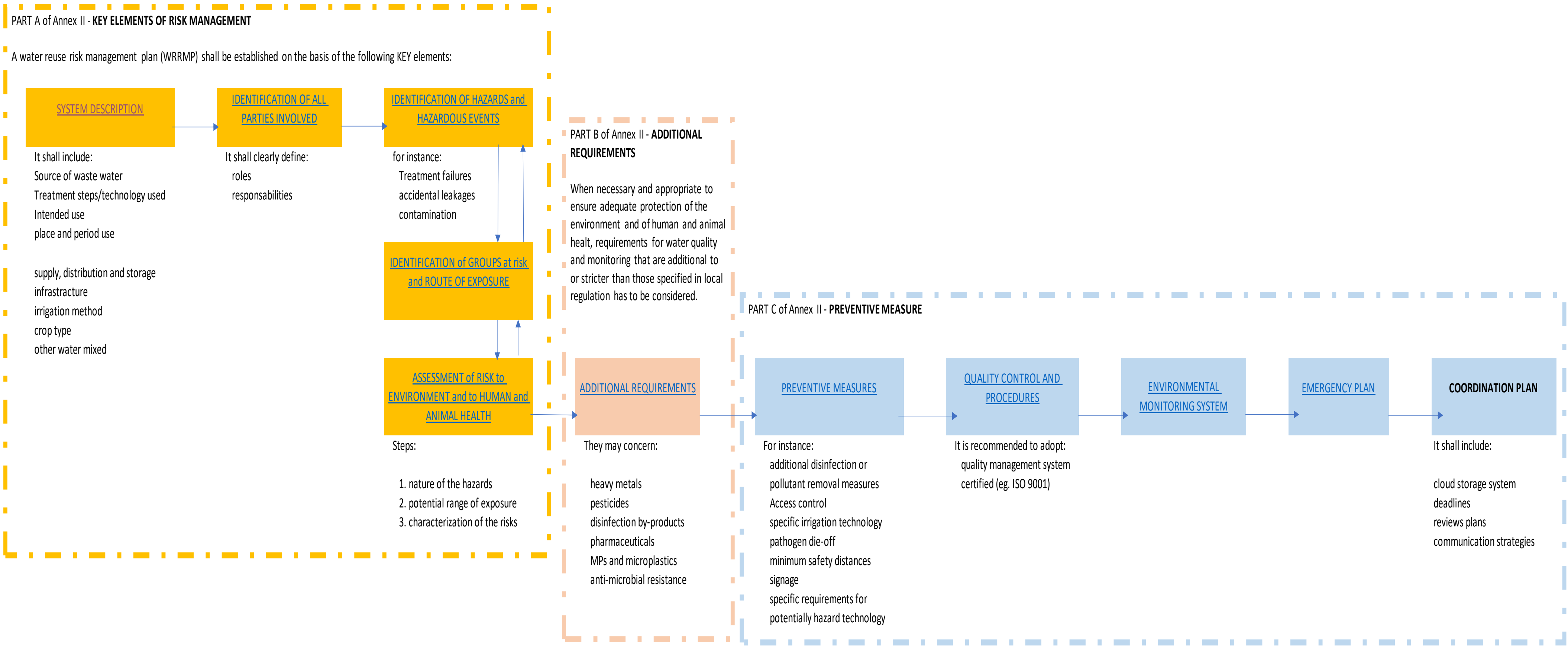


Figure 4-1. Overall flow diagram for the implementation of the WRRMP, as reported in Regulation (EU) 2020/741

Sections 1 to 5 lay down the KEY ELEMENTS FOR RISK MANAGEMENT (Part A of Annex II of Regulation (EU) 2020/741), Section 6 is about ADDITIONAL REQUIREMENTS (Part B of Annex II of Regulation (EU) 2020/741) and Sections 7 to 11 deal with the PREVENTIVE MEASURES (Part C of Annex II of Regulation (EU) 2020/741)

4.1.1 SECTION 1: SYSTEM DESCRIPTION

The first step for the development of a WRRMP is to get a synthetic but clear picture of the system in which the plan will be applied. In this section, the key elements to get a comprehensive description of the Integrated Wastewater Reuse System (IWRS) are provided. A flow diagram of the whole system should be constructed, in order to get a functional overview of the global picture and of all the parts involved. This preliminary work will facilitate the further steps for the identification of hazards and hazardous events, the associated risks and the most appropriate health protection measures to adopt in each specific case.

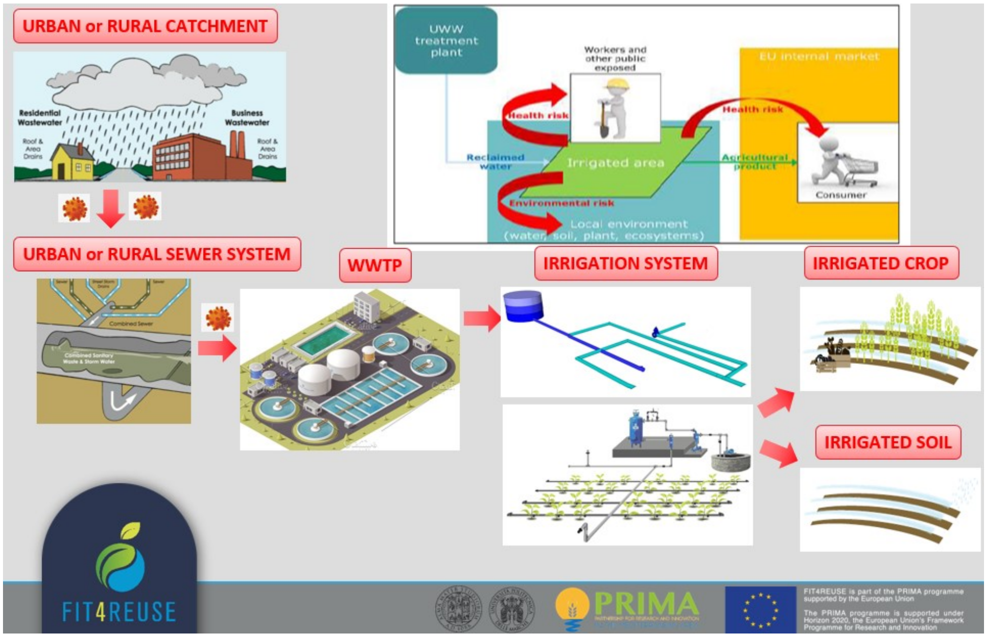


Figure 4-2 Integrated Wastewater Reuse System

The system boundaries are defined, together with its geographical and geopolitical context, since these aspects can affect regulatory quality requirements and the possible final reuse applications. The choice of the intended reuse application, especially in case of planning activities or project design, should consider policy restriction, surrounding land use and environmental impacts, other than economic and social evaluations. A summary of the information required for the general overview of the IWRS is provided in the following table.

Table 4-1.General information to be collected as the first step

CATEGORIES	DESCRIPTION	NOTES
Location	the area involved (City, region, country)	insert site-specific data
	land use (agricultural, industrial, residential…)	insert site-specific data; useful if planning phase

Overall system	flow diagram of the Integrated Urban Water Reuse System	
Boundaries	from catchment to final end-user	Sub-systems within the overall system boundary can be defined and then analyzed separately
Regulatory framework: quality standards/policy requirements	effluent discharge, regulations related to quality monitoring, surveillance	i.e.: relevant laws and by-laws, effluent discharge regulations, specific national regulations related to agricultural products, regulations related to quality monitoring, surveillance, and system auditing
	national/local guideline for water reuse	insert site-specific data
	national/local policy on water reclamation	insert site-specific data
	minimum requirements for water reuse set by law	insert site-specific data, if available
	acceptable health and environmental risk target set by policy	insert site-specific data, if available
Intended reuse application	irrigation of non-food crops	choose one or more objectives from the list or add a site-specific one. Keep in mind the surrounding land use
	irrigation of food crops consumed raw	
	irrigation of processed food crops	
	irrigation of recreational areas (amenity-related and environmental purposes)	
	aquifer recharge	
	industrial reuse	

The IWRS can be sub-divided in sub-categories, called nodes, that represent the stages or units that compose the system. For each node, the available qualitative and quantitative information about water flows should be reported (flow rates and operating parameters), highlighting the variability of each parameter, where possible. Missing information can be obtained through modelling or from literature data.

The first node is the catchment, that represents the territory from where wastewater is originated and collected. Since health-related risks in this node could originate from rain pollution, it is suggested to quantify or at least to estimate stormwater characteristics.

Table 4-2. Data to be collected for the node “catchment”.

IUWRS node	DATA CATEGORIES	Subcategories
CATCHMENT	stormwater characteristics	Flowrate
		pollution load
		rain intensity/height
		seasonal variability
	if stormwater characterization is not available, these data can be used in simulation modelling (e.g. SWMM):	
	Topography and drainage patterns	geographical and climatic conditions
		morphology/slopes
		surface/area (m^2)

		soil use (%urbanization)
		run-off time
	infiltration characteristics	Flowrate
	future planning activities	
	extreme and infrequent events	eg. Flood, earthquakes

The following node represents the sewer network. This sector includes all the pipelines (in combined or separated configuration), pumping stations, storage tanks and combined sewer overflows (CSOs) of the sewer system. The data needed to describe this node includes hydraulic information about flowrates and their periodic variations, as well as sewage characteristics.

In the case of missing real data, the catchment and sewer network can be modelled using open-access tools, such as EPA's Storm Water Management Model (SWMM).

Table 4-3. Data to be collected for the node "sewage network".

IUWRS node	DATA CATEGORIES	Subcategories
SEWAGE NETWORK	sewer configuration	combined or separated
	sewage wastewater characterization	flowrate (Qmean, Qmax)
		pollution load (i.e. physical-chemical parameters, microbial contamination)
		industrial loads
	if sewage wastewater characterization is not available, these data can be used in simulation modelling (e.g. SWMM):	
	sewage wastewater characterization	% of domestic resident
		% of domestic fluctuant
		% of industrial discharge
		% of hospital activities
		population served
		specific flowrate factor (l/PE/d)
	pipeline geometry	lenght/slope/diameter
	intermediate facilities presence	CSOs
		storage tanks
		equalization basin

The Wastewater Treatment Plant (WWTP) is a critical node for the control and the reduction of pollution loads and their associated risks. WWTP can be furtherly schematized into a sequence of treatment steps, considering each unit as a sub-node. Removal efficiencies of each process should be evaluated for the main contaminants, to determine the effectiveness of the treatment chain.

The quantity and the quality of the reclaimed water influence the choice of the possible applications, so a detailed characterization is required. It is also recommended to report all the digital data available, such as real-time data from sensors or probes since they contribute to risk control.

A similar approach should be repeated in case reclamation facility is located outside the WWTP, characterizing the removal efficiencies, the effluent quality and the control measures applied.

Table 4-4. Data to be collected for the node "Wastewater treatment plant".

IUWRS node	DATA CATEGORIES	Subcategories
WWTP	flow diagram of WWTP operation	
	Location	
	Influent/effluent characterization	Flowrate (Qmean, Qmax)
		flowrate variability (daily, seasonal, yearly)
		load variability (daily, seasonal, yearly)
		bacteria, protozoa, viruses concentration
		helminths concentration
		vector-borne pathogens concentration
		E.coli concentration
		COD
		BOD
		TN
		TP
		heavy metals
		NH_4-N
		PO_4-P
		TSS
		electrical conductivity
		pH
		TOC
		boron, chloride, sodium, cadmium, chlorine
		salinity, sodium
		Colour
		micropollutants, CECs
		algal counts
		disinfectant residuals and byproducts
	Treatment technologies	removal efficiencies (macronutrients, solids, heavy metals and CECs)
		log removal of microbial contamination (E. coli for pathogenic bacteria, F-specific coliphages, somatic coliphages or coliphages for pathogenic viruses, and Clostridium perfringens spores or spore-forming sulfate-reducing bacteria for protozoa)
	Operational monitoring/control	process change control
		automation systems
		backup system
		bypass provisions
		sampling frequency
		online control/measurement
		offline control/measurement
		alert system
		operator surveillance (eg. 24/7)
		maintenance programme

The reclaimed water must be supplied and distributed. Storage tanks and pipelines can represent potential sources for pathogen regrowth or solid sedimentation, while leakage or intrusion may occur along the pipeline. Therefore, information about physical characteristics and maintenance status of the infrastructures, materials employed, and the possibility of cross-connection with the external environment should be collected.

Table 4-5. Data to be collected for the supply, distribution and storage infrastructure.

IUWRS node	DATA CATEGORIES	Notes
Distribution system of reclaimed water	water dilution	yes/no, water quality and quantity
	pipeline length and slope	
	pipeline material	
	physical infrastructure integrity	good, poor status
	cross-connection presence (especially with drinking water distribution)	
Storage of reclaimed water	residence time	
	protection (covers, enclosures, access)	
	depth, material, size, storage capacity	
	algae and microbial activity	
	physical infrastructure integrity	good, poor status
	maintenance programme	

The next and final node involves end-uses. Considering the agricultural irrigation as intended water reuse, attention must be paid to the irrigation scheme applied and to the characteristics of the irrigated soil. Some irrigation techniques can avoid direct contact of reclaimed water with the edible part of the crops or may require appropriated specific preventive measures for workers. Irrigation method influences exposure routes for workers and for the local community next to the area of the irrigated field. For the same reasons, it is also necessary to collect information about the crops, their harvest procedures and the way they are consumed.

Table 4-6. Data to be collected if agricultural irrigation is the final end-use.

IUWRS node	DATA CATEGORIES	Subcategories
irrigation scheme	methods (by gravity, spray, drip, etc)	
	scheduled time (eg. Night-time only)	
	application rates	
	irrigation frequency	
	seasonal variation of use due to the type of crops and harvest	
irrigation site	type of soil (permeability, grain sizes)	
	soil characteristics (Ph, nutrients, metals, salinity) before and during water reuse	pH
		Nutrients
		Metals
		Salinity
	type of aquifer (confined aquifer, free water surface…)	
	groundwater characteristics (depth, quality, current uses)	
	Access restriction	

	distance to critical points (drinking water reservoir, residential area, recreational area, areas of high ecological value.. etc)	
crops	crop characteristics	food or not
		restriction (raw or processed, eatable roots, leaves)
		height from soil
	harvest options	how many days after the last irrigation (die-off pathogens period)

In case reclaimed water is used for groundwater recharge, aquifer characteristics in terms of permeability, thickness, salinity are essential for managing the associated risk.

Table 4-7. Data to be collected if aquifer recharge is the final end-use.

IUWRS node	DATA CATEGORIES	Subcategories
AQUIFER	aquifer characteristic	Permeability
		Confinement
		Thickness
		uniformity of hydraulic properties
		salinity of groundwater
		lateral hydraulic gradient
		Consolidation
		aquifer mineralogy
		redox state of native groundwater
	groundwater characteristics	redox state, chemical quality, final use
	recharge method	Surface spreading or direct injection
	distance to critical points (drinking water reservoir, residential area, recreational area, areas of high ecological value.. etc)	

4.1.2 SECTION 2: IDENTIFICATION OF ALL PARTIES INVOLVED

The second section aims to identify all parties involved in the water reuse system focusing on the roles and responsibilities. It is included in the "preparation" phase of the risk management plan (according to the WHO Guidelines). Following the EU Regulation 2020/741, the WRRMP requires the participation and the collaboration of the reclamation facility operator, all the responsible parties and the end-users. The 'Responsible party' is a person, representing a private entity or a public authority involved in the water reuse system, who is in charge for the control of the right execution of a task or activity and the respect of the expected deadlines. The role of the responsible party can be taken by the reclamation facility operator, the urban wastewater treatment plant operator (if it is different from the reclamation facility operator), the relevant authorities, the reclaimed water distribution operator or the reclaimed water storage operator.

The figure of the reclamation facility operator represents the private entity or public authority that operates or controls a reclamation facility. It is the main responsible for the quality of the reclaimed water at the point of compliance.

Once the parties involved are defined, a multidisciplinary team must be established, assuring the right balance of technical, health, environmental and social expertise, to optimize the identification of all the hazards and hazardous events, their characterization and the selection of the most appropriate preventive measures. The roles and responsibilities in the risk management are generally shared between the parties, but specific roles must be clearly defined and reported in a table, outlining the main responsible party for each activity or task.

Suggestions about team composition are provided (Table 4-8), even if the final selection should be adapted to the specific application, to include all the figures of interest.

Table 4-8. Suggestion for TEAM composition

members		Roles
reclamation facility operator, the urban wastewater treatment plant operator where different from the reclamation facility operator, the reclaimed water distribution operator, or the reclaimed water storage operator (defined "responsible parties" in 2020/714 EU Regulation)	Catchment manager	provide information on wastewater quality and industrial activities impact
	plant Senior manager	TEAM LEADER
	operation manager	provide information on treatment chain, efficiencies. Help in the identification of risk
	quality manager	provide information on the procedure, documents and data quality
	sales manager	provide information on chemical, equipment and product quality
	IT manager	help in data collection and organization (cloud)
	Lab head	provide suggestions in monitoring parameters and procedure
	press service head	help in the communication phase
	workers representative	
	manager of the reclaimed water distribution system	
end-users of reclaimed water	farmers representative	provide information on current practices. They are the implementers of on-farm control measures
	local community (eg. Mayor, City Committee)	helpful for improving public acceptance, from early stages
local authorities, government institutions	public health official or expert	help in identifying the hazardous event
	research agencies (universities…), external consultants	
	environmental agency	help in identifying the hazardous event

4.1.3 SECTION 3: IDENTIFICATION OF HAZARD AND HAZARDOUS EVENTS

Next steps are focused on the core phase of risk assessment. As suggested by the 2020/741 EU Regulation, a semi-quantitative approach is proposed. The following procedure should be applied to each node of IWRS. First, all the possible hazards and hazardous events that can occur in every node must be identified. The main hazards to be investigated are of physical, chemical, or microbiological nature. Physical hazards, such as the intrusion of external material, metal fragments, undissolved and suspended solids in the wastewater may cause clogging problems and, most importantly, they may be vectors for pathogen agents. Chemical hazards include a wide range of organic and inorganic species, both from municipal and from industrial flows. The related chemical risks include a wide range of possibility. Some examples are causing toxicity to human, aquatic animals or plants, waterlogging of plant, increasing soil salinity, or soil degradation. Since the primary objective of every risk management plan should focus on health protection, microbiological hazards due to the presence of pathogen microorganisms in the reclaimed water require a specific and detailed characterization.

A list of potential hazardous events and related hazards that can occur in the IWRS is provided in Table 4-9. Similar to the previous suggestions, they may not be completely representative of every system and context, but they provide a general overview of the proper procedure to follow. The hazardous events listed should be taken into account if they are consistent with the site-specific conditions, and additional hazardous events must be reported when significant in the specific application.

Table 4-9. Suggested hazardous events and associated hazard, for each node of IWRS.

IUWRS node	HAZARDOUS EVENT	HAZARD
CATCHMENT	Poorly vegetated riparian zones, failure of sediment traps and soil erosion	microbiological, physical (turbidity)
	Road washing/RUNOFF water	chemical (lead and zinc, petrol/oil product, salinity, pesticides) and physical (turbidity)
	Salinity peak after de-icing salt spreading	salinity>> phytotoxicity
	Etc	Etc
SEWAGE NETWORKS	Illicit connections	microbial, chemical
	Seasonal peak flowrate due to Production activities or tourism	microbial, chemical
	Etc	Etc
WWTP	Equipment malfunctions	
	Process inefficiencies	
	Poor reliability of processes	
	Power failures	
	Etc	Etc
DISTRIBUTION SYSTEM	Biofilm, sloughing and resuspension, regrowth	Microbiological
	Misleading identification of pipeline in the cross-connection sections	microbiological, chemical
	Etc	Etc
STORAGE	Pathogens regrowth	Microbiological
	Leakage	microbiological, chemical
	Intrusion due to inadequate buffer zones and vegetation	microbiological, chemical
	Etc	Etc
IRRIGATION SITE	Change in pH, salinisation, soil structure decline, heavy metals accumulation	Chemical

	Human or livestock access, absence of exclusion areas	microbiological, chemical
	antibiotic resistance in soil microbiota	microbiological, chemical
	Etc	Etc
CROPS	Bioaccumulation of heavy metals	Chemical (toxicity)
	Irrigation use of no-compliant water	Microbiological, chemical
	Etc	Etc
AQUIFER RECHARGE	Contaminant migration in fractured rock and karstic aquifer	Chemical
	Etc	Etc

4.1.4 SECTION 4: IDENTIFICATION OF GROUPS AT RISK and ROUTE OF EXPOSURE

The fourth section aim is the identification of the environment and population at risk and the related exposure routes, considering the site-specific conditions, such as hydrogeology, topology, climate and weather, farming and irrigation practices. For each hazardous event, the possible exposure pathways must be identified. The main routes of exposure are ingestion, dermal contact, inhalation, and direct consumption of contaminated produces. The exposed population must be identified, with a particular focus on vulnerable or sensible subjects. The exposed groups include:

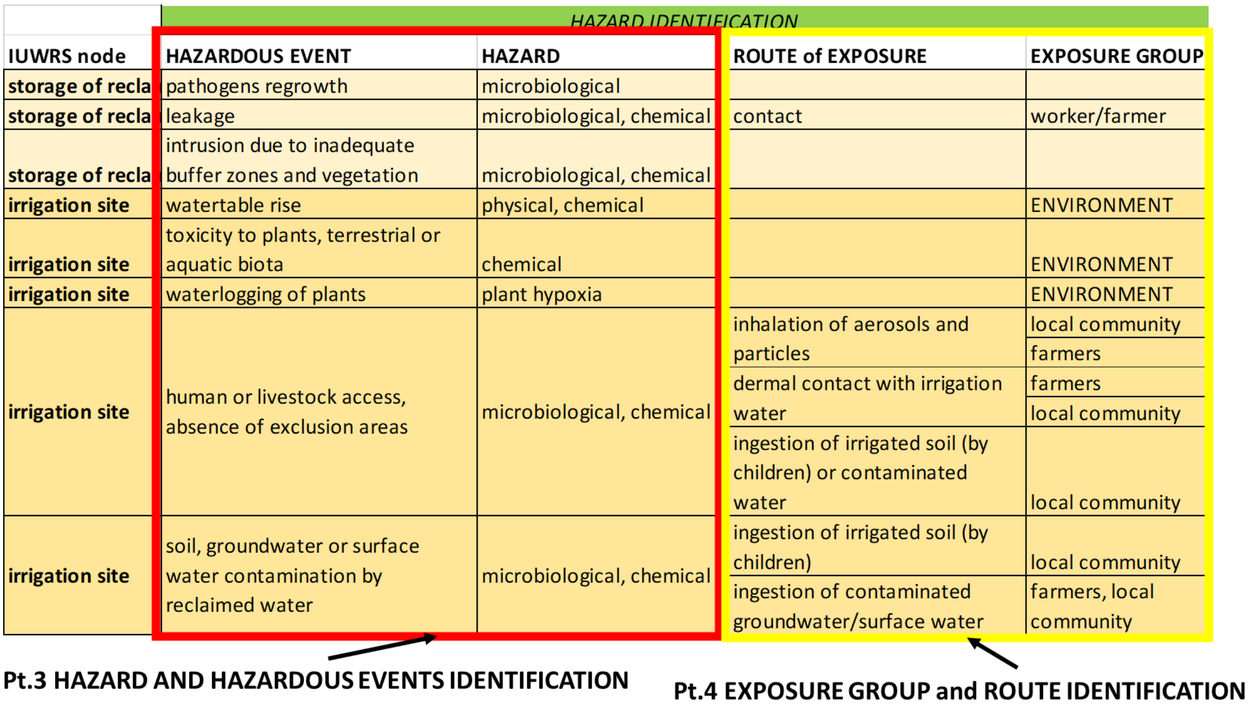
1. Workers that have direct skin contact with reclaimed water or could ingest aerosols in their usual working environment during irrigation or managing reclaimed water.
2. Consumers that may have direct oral contact or inhalation by eating contaminated crops or meat from livestock fed with crops irrigated with reclaimed water.
3. People that can have direct skin contact with reclaimed water or may ingest aerosols when exposed to readily accessible areas where reclaimed water is used (e.g., parks, playing fields, open public spaces, golf courses and residential gardens).
4. Children that may fall or touch the grass and then have hand-to-mouth contact or accidentally ingest a large amount of reclaimed water during playing or swimming.

Table 4-10 lists the associated exposure routes or exposed groups for some of the proposed hazardous events.

Table 4-10. Examples of the suggested route of exposure and exposure group associated with hazardous events

IWRS NODE	HAZARDOUS EVENT	ROUTE OF EXPOSURE	EXPOSURE GROUP
DISTRIBUTION SYSTEM	Exposure to reclaimed water during pump and pipe repair procedures	Dermal contact with reclaimed water, ingestion after contact with reclaimed water	Workers
STORAGE	Leakage	Contact	Workers
IRRIGATION SITE	Human or livestock access, absence of exclusion areas	Inhalation of aerosols and particles	Local community
			Farmers
		Dermal contact with irrigation water	Farmers
			Local community
		Ingestion of irrigated soil or contaminated water	Local community

	Antibiotic resistance in soil microbiota	Plant adsorption and crop consumption	Local community
		Dermal contact	Workers, local community
		Ingestion of irrigated soil or contaminated water	Workers, local community
CROPS	Bioaccumulation of heavy metals, contaminants of emerging concern (CECs)	Consumption of contaminated products	Local community



	HAZARD IDENTIFICATION			
IUWRS node	HAZARDOUS EVENT	HAZARD	ROUTE of EXPOSURE	EXPOSURE GROUP
storage of recla	pathogens regrowth	microbiological		
storage of recla	leakage	microbiological, chemical	contact	worker/farmer
storage of recla	intrusion due to inadequate buffer zones and vegetation	microbiological, chemical		
irrigation site	watertable rise	physical, chemical		ENVIRONMENT
irrigation site	toxicity to plants, terrestrial or aquatic biota	chemical		ENVIRONMENT
irrigation site	waterlogging of plants	plant hypoxia		ENVIRONMENT
irrigation site	human or livestock access, absence of exclusion areas	microbiological, chemical	inhalation of aerosols and particles	local community
				farmers
			dermal contact with irrigation water	farmers
				local community
			ingestion of irrigated soil (by children) or contaminated water	local community
irrigation site	soil, groundwater or surface water contamination by reclaimed water	microbiological, chemical	ingestion of irrigated soil (by children)	local community
			ingestion of contaminated groundwater/surface water	farmers, local community

Figure 4-3. An illustrative example of the suggested hazardous events. From "RISK ASSESSMENT" sheet

4.1.5 SECTION 5: RISK ASSESSMENT

At this point, the responsible parties have to assess the risk for human health and the environment by the confirmation of the nature of the hazards, the determination of the potential exposure level or dose, and the characterization of the risks. The risk must be also prioritized considering the outocomes from the characterization phase.

The semi-quantitative method requires the attribution, assigned by the expertise of the team, of weights to quantify the likelihood and the severity of each identified hazardous event, filling a risk matrix (like the one proposed in "Risk Assessment" sheet). Weights must be multiplied, obtaining a score for each risk, as shown in the following equation.

$$\text{Risk} = \text{Severity} \cdot \text{Likelihood}.$$

Weights could be selected from a pre-defined labelling methodology, according to literature and guidelines suggestions, like the one proposed by WHO in the SSP manual (Table 4-11

Table 4-12), but other score systems could be applied, according to the local context and the site-specific conditions. Other reasonable periods could be considered for the attribution of frequency classes, or other effects on health or the environment can be taken into account for severity classification.

Table 4-11. Suggested weights for likelihood (ref. WHO 2016)

	happened in the past	frequency	weight
Very Unlikely	no	improbable to occur 1/year	1
Unlikely	no	may occur exceptionally 1/year	2
Possible	possible	may occur regularly 1/year	3
Likely	yes	likely to occur 1/year	4
Almost Certain	yes	almost certain to occur 1/year	5

Table 4-12. Suggested weights for severity (ref. WHO 2016)

	consequence	Weight
Insignificant	negligible health effect	1
Minor	minor health effect	2
Moderate	self-limiting health effect or minor illness	3
Major	illness or injury, legal complains or regulatory non-compliance	4
Catastrophic	serious illness or injury, loss of life, regulator prosecution	5

	HAZARD IDENTIFICATION				*Risk assessment*				
IUWRS node	**HAZARDOUS EVENT**	**HAZARD**	**ROUTE of EXPOSURE**	**EXPOSURE GROUP**	**SEVERITY**	**FREQUENCY**	**LIKELIHOOD**	**RISK SCORE**	**Risk rating**
storage of reclai	pathogens regrowth	microbiological			high				
storage of reclai	leakage	microbiological, chemical	contact	worker/farmer	high				
storage of reclai	intrusion due to inadequate buffer zones and vegetation	microbiological, chemical			high				
irrigation site	watertable rise	physical, chemical		ENVIRONMENT					
irrigation site	toxicity to plants, terrestrial or aquatic biota	chemical		ENVIRONMENT	high				
irrigation site	waterlogging of plants	plant hypoxia		ENVIRONMENT	medium				
irrigation site	human or livestock access, absence of exclusion areas	microbiological, chemical	inhalation of aerosols and particles	local community					
				farmers					
			dermal contact with irrigation water	farmers	high				
				local community	medium				
			ingestion of irrigated soil (by children) or contaminated water	local community	high				
irrigation site	soil, groundwater or surface water contamination by reclaimed water	microbiological, chemical	ingestion of irrigated soil (by children)	local community	high				
			ingestion of contaminated groundwater/surface water	farmers, local community	high				

Pt.5 RISK ASSESSMENT

Figure 4-4. An illustrative example of the suggested risk matrix to be adapted to the site-specific case. From "RISK ASSESSMENT" sheet.

The WRRSP team may choose to develop its own definitions for likelihood and severity based on the system peculiarity and local context or follow the definitions set out by international guidelines.

4.1.6 SECTION 6: ADDITIONAL REQUIREMENTS

According to the European Regulation 2020/741 on "Minimum Requirements for Water Reuse", it should be appropriate to set additional requirements for reclaimed water in terms of quality objectives, depending on the local context and the outcomes from risk assessment. For instance, in case of reuse schemes in which chemical inputs from catchment are significant, the identification of specific pollutants should be implemented, to include all possible hazards that could occur in the present case. At the same time, if the initial ecological status of the irrigation site is already compromised, additional or stricter prescriptions in terms of effluent characteristic should be required to avoid further deterioration.

Additional water quality requirements should be identified whenever considered appropriate, to ensure health safety and environmental protection. The choice should be based on the outcomes of the risk assessment. Competent authorities may impose stricter or additional requirements on:

- heavy metals
- pesticides
- micropollutants and microplastics
- pharmaceutical
- anti-microbial resistance

In Table 4-13 some examples of the above-mentioned categories are presented. It also suggested, when available, the maximum concentrations in the soil to avoid pollutants transport to people via the food-chain (Reference: WHO guidelines).

Table 4-13. Example of parameters to which additional requirements may be necessary.

	Substances	Maximum soil concentration mg/kg		Substances	Maximum soil concentration mg/kg
			Organic micropollutants	Aldrin	0.48
HEAVY METALS	Antimony	36		Benzene	0.14
	Arsenic	8		Chlordane	3
	Barium	302		Chlorobenzene	211
	Berylliuma	0.2		2,4-D	0.25
	Boron	1.7		DDT	1.54
	Cadmium	4		Dichlorobenzene	15
	Fluorine	635		Dieldrin	0.17
	Lead	84		Dioxins	0.00012
	Mercury	7		Heptachlor	0.18
	Molybdenuma	0.6		Hexachlorobenzene	1.4
	Nickel	107		Lindane	12
	Selenium	6		Methoxychlor	4.27
	Silver	3		PAHs (as benzo[a]pyrene)	16
	Thalliuma	0.3		PCBs	0.89
	Vanadiuma	47		Pentachlorophenol	14
				Phthalate	13733
PHARMACEUTICAL	Beta blocker			Pyrene	41
	Antibiotic			Styrene	0.68
	Anti-cholesterol			2,4,5-T	3.82
	Antibiotic			Tetrachloroethane	1.25

	Anti-hypertensive			Tetrachloroethylene	0.54
	Diuretic			Toluene	12
	Contrast medium			Toxaphene	0.0013
	Anti-inflammatory			Trichloroethane	0.68
	Anti-diabetic				
	Psychiatric drugs		Chloroform		0.47

4.1.7 SECTION 7: PREVENTIVE MEASURES

To prevent or to eliminate a health or environmental risk, as well as to reduce it to an acceptable level, appropriate action or activity must be put in place. After the first draft of risk evaluation, a multi-barrier approach is considered in the evaluation of the control measures applied or to be implemented for risk minimization. The preventive or corrective measures may include:

- Treatment measures, that rely on treatment and process performances, removal efficiencies, on-line monitoring level and system robustness
- Technical measures such as the application of appropriate irrigation techniques, that even if not strictly related to treatment, allow the reduction of risks
- Behavioural measures, that include the use of personal protective equipment (PPE), hand washing and hygienic practices, the selection of appropriate harvesting methods, waiting periods before harvesting or commercialisation, produce washing or processing.

For each hazardous event identified, one or more preventive measures are suggested in Table 4-14. This list is not conclusive, other preventive measures may be more appropriate for a specific water reuse scheme or different options can be considered.

Table 4-14. Suggested preventive measures

IWRS NODE	HAZARDOUS EVENT	PREVENTIVE MEASURES
CATCHMENT	rain intensity/extreme events which cause inflow rate increase, dilution of contaminants, leaves and branches introduction	intermediate facilities (equalization basin, CSOs, etc)
	changes in industrial flows	WWTP reliability, Early warning system/online sensors
		technological treatment (primary)
SEWER NETWORK	seasonal peak flowrate due to production activities or tourism	flow meters, WWTP reliability, Early warning system/online sensors
	accidental trade-waste discharge	intermediate facilities (equalization basin, CSOs, etc)
		WWTP reliability, Early warning system/online sensors
WWTP	Equipment malfunctions	back-up system, alert system, Early warning system/online sensors
	overdosing of chemicals for P removal	quality control of chemicals (eg. Avoid the use of eco-toxic compounds), flow meter of chemical dosage, Early warning system/online sensors

	disinfection malfunctions	alert systems, backup, online sensors (eg. Pathogens), Early warning system
DISTRIBUTION SYSTEM	Exposure to reclaimed water during pump and pipe repair procedures	Use of personal protective equipment
		immunization fo typhoid
		Training on safe handling
STORAGE	pathogens regrowth	covering storages and post-disinfection
	exposure to reclaimed water during storage tank maintenance procedure	Use of personal protective equipment
		immunization for typhoid
		Training on safe handling
IRRIGATION SITE	Eutrophication of surface waters	nutrient balancing
		do not irrigate directly adjacent to surface waters. Provide buffer distances and buffer plantings
	change in pH, salinisation, soil structure decline, heavy metals accumulation	increase soil washing or improve ground drainage
		application of soil ameliorants
		crop selection
CROPS	bioaccumulation of heavy metals	selection of crops with low HM uptake, test on bioaccumulation, soil pH control
	contamination of fodder for livestock	fodder has to be dried or ensiled before packaging

Preventive measures influence weights attribution for the severity category, since they reduce the gravity of the consequences related to a hazardous event and thus, the so-called "residual risk" is recalculated, taking into account the reduction on the severity "score", caused by the preventive measure put in place or planned. The new residual risk calculation follows the same procedure previously used, multiplying the new lower value of severity with the likelihood:

$$\text{Risk} = \text{Severity} \cdot \text{Likelihood}$$

IUWRS node	HAZARDOUS EVENT	HAZARD	preventive measure	SEVERITY	FREQUENCY	LIKELIHOOD	RESIDUAL RISK SCORE	residual Risk rating
storage of recl	pathogens regrowth	microbiological	covering storages and post-disinfection	high				
storage of recl	leakage or evaporation	microbiological, chemica	ground cover with impermeable materials (clay, plastic)	high				
storage of recl	intrusion due to inadequate buffer zones and vegetation	microbiological, chemica	restricted access to treatment or use sites (signage and fencing)	high				
irrigation site	change in biodiversity from increased nutrients applied through reclaimed water	chemical, physical	nutrient balancing, decrease concentration in reclaimed water	high				
irrigation site	terrestrial eutrophication	chemical, physical	nutrient balancing	high				
			buffer distances and buffer plantings to strip nutrients from runoff					
irrigation site	eutrophication of surface waters	chemical, physical	nutrient balancing	high				
			do not irrigate directly adjacent to surface waters. Provide buffer distances and buffer plantings					
irrigation site	change in pH, salinisation, soil structure decline, heavy metals accumulation	chemical	increase soil washing or improve ground drainage	medium				
			application of soil ameliorants					
			crop selection					

PREVENTIVE MEASURE PROPOSED **RESIDUAL RISK CALCULATION**

Figure 4-5. An illustrative example of the proposed preventive measures. From "PREVENTIVE MEASURE" sheet.

4.1.8 SECTION 8: QUALITY CONTROL and PROCEDURES

Within this phase, adequate quality control measures, procedures and maintenance programs must be defined.

According to WHO guidelines, received also in the EU regulation 2020/741 on "Minimum Requirements for Water Reuse", there are three monitoring phases, each one with specific goals: validation, operational monitoring, and verification.

- The validation monitoring consists in proving that the system can meet its design requirements. It is performed at the initial phase, when a new system is developed or when new processes are added.
- The operational monitoring is used on a routine basis and provides information regarding the operational functioning of individual units considered as health protection measures. It relies on parameters that can be measured quickly and easily, helping managers making rapid and incisive corrections.
- The verification monitoring is applied besides to the operational protocols, to verify the compliance with regulatory requirements for the quality of the reclaimed water and the receiving environment.

This section concerns the operational monitoring. If dealing with an existing plant, a routine monitoring procedure is expected to be already implemented, to monitor treatment performances and ensure compliance with regulatory requirements. The strategy already put in place can be improved, to monitor and to control the correct functioning of the measures for risk minimization. Significant control points, monitoring parameters, indicators or surrogate must be defined, together with the related frequencies and sampling methods, to get rapid and affordable feedbacks. Guideline suggestions include the monitoring of total suspended solids, algae presence, turbidity, COD, pH, temperature and nutrients concentrations, but specific parameters should be added depending on the risk considered or site-specific conditions.

Table 4-15 should be filled with the existing procedure applied in every point of the IWRS and the same template may be used once the new monitoring plan is developed ().

Table 4-15. Template to collect useful information to lay down the operation monitoring procedure

IUWRS nodes	monitored parameters	monitoring method [a]	degree of automation	frequency	responsible for sampling
WWTP					
Supply, distribution and storage infrastructure					

End-user: irrigation site and final produce					
a: Automatic or manual b: Online system, manual switch on, etc					

4.1.9 SECTION 9: ENVIRONMENTAL MONITORING SYSTEM

The verification phase (or environmental monitoring system) should ensure that the system is achieving its specified targets, showing a stable trend over time. The verification monitoring is focused on the characterization of the reclaimed water delivered and the environmental matrices involved in the final use. As recommended by international guidelines, microbial contamination, soil salinity and groundwater characteristics, such as nitrates concentration, should be investigated. This monitoring process may be conducted by public health agencies.

A template to record the stated procedure is proposed in Table 4-16.

Table 4-16. Suggested template to organize the verification data

IUWRS node	parameter	limit	date	responsible	Method

4.1.10 SECTION 10: EMERGENCY PLAN

The procedures and adequate contingency provisions to address unforeseen events which may lead to health or environmental damages or harms must be defined and reported in a document shared with the operative personnel. Emergency Management Plan should encompass a summary of events and issues that affect recycled water quality and cause non-compliances with limit values. It also includes details of corrective actions/response procedures to follow.

IUWRS node	Incident giving rise to hazard	possible causes	Consequences	Risk (likelihood and consequence)	Response action	Reporting protocols	Preventive measures
	Wastewater/ reclaimed water overflow						
	Failure or breakdown of wastewater pumps, pipes or equipment	Power failure or interruption					
		Natural events such as floods and fires, cyclones or heavy storms					
		Discharge of hazardous substances to the wastewater stream					
		Malicious actions and vandalism					
	etc						
	etc						

Figure 4-6. Example of Emergency Management Plan

4.1.11 SECTION 11: COORDINATION PLAN

As the final step, it is recommended to define the coordination plan and procedure, together with the improvement plan. The coordination and communication aspects include the choice of a proper cloud storage system, the choice of a successful communication strategy and the definition of the expected deadlines for each activity or task. The WRRMP needs to be continuously updated, whenever a significant change or event occurs, and periodically reviewed.

4.2 Peschiera Borromeo WWTP

4.2.1 Mass and energy balances

In this section, the technical performance of the plant is evaluated.

The average daily flow rate of L1 and L2 was 62040 m^3/d and 64282 m^3/d, respectively, in 2019. The annual average values are used as input for the mass balance calculation and are reported in Table 4-17. The variations in time of the two the water lines are shown below.

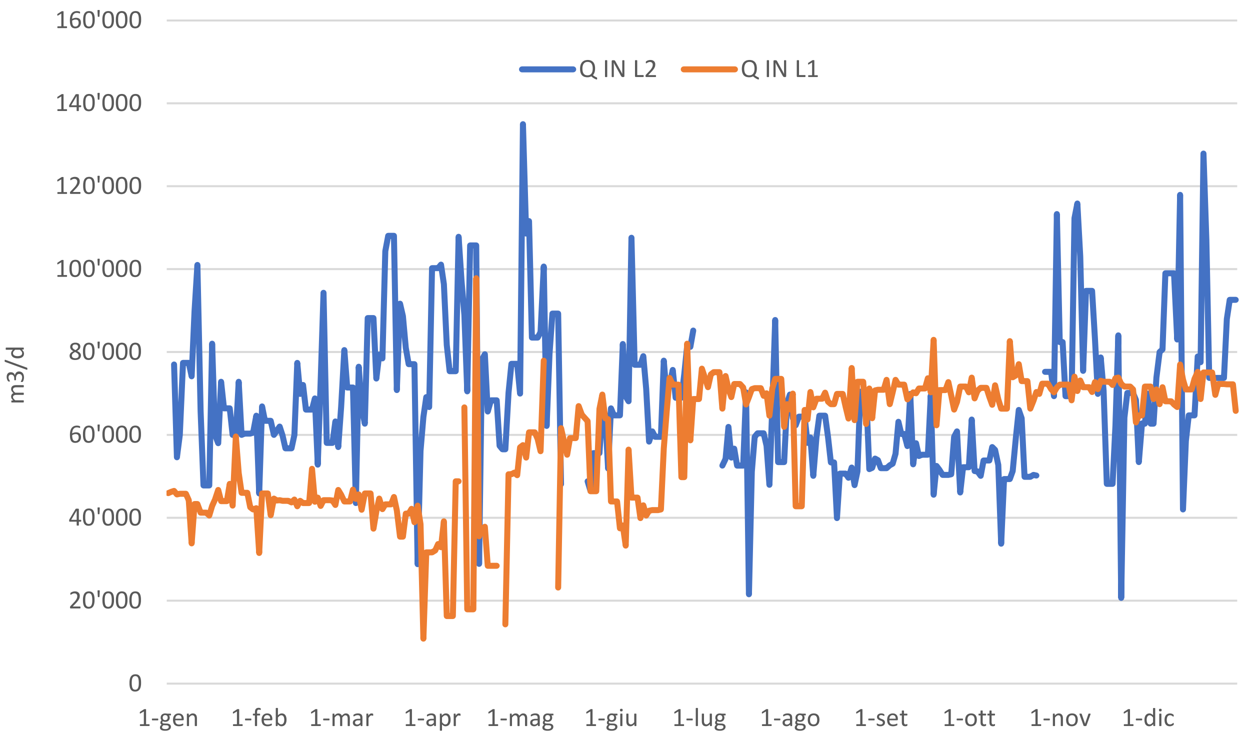


Figure 4-7. Variation of flowrate along 2019. Peschiera Borromeo WWTP

Table 4-17. Annual average value influent characteristic of Peschiera Borromeo year 2019.

	Flowrate	COD	BOD5	TN	NH_4-N	TP	TSS
	m^3/d	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
L1	62040	297	163	38	32	4	145
std dev.	12999	164.2	99.0	29.0	26.4	2.4	83.7
L2	64282	246	130	30	23	3	139
	19422	166.4	75.0	9.9	8.9	1.5	109.1

There is a maximum peak of concentration in April and all the macro pollutants have generally the same trend. Figure 4-8 shows the variations of the influent concentrations to L1 along the year, while Figure 4-9 is referred to L2.

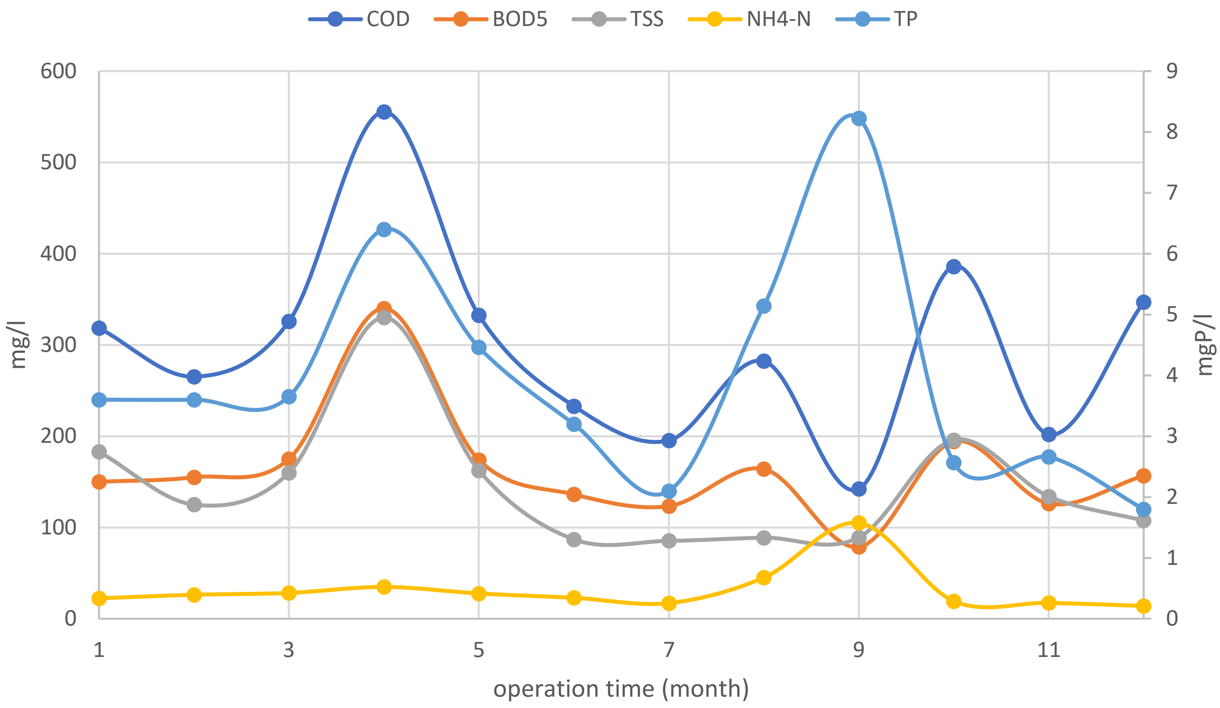


Figure 4-8. Variation of influent concentration of L1 along the operation year 2019.

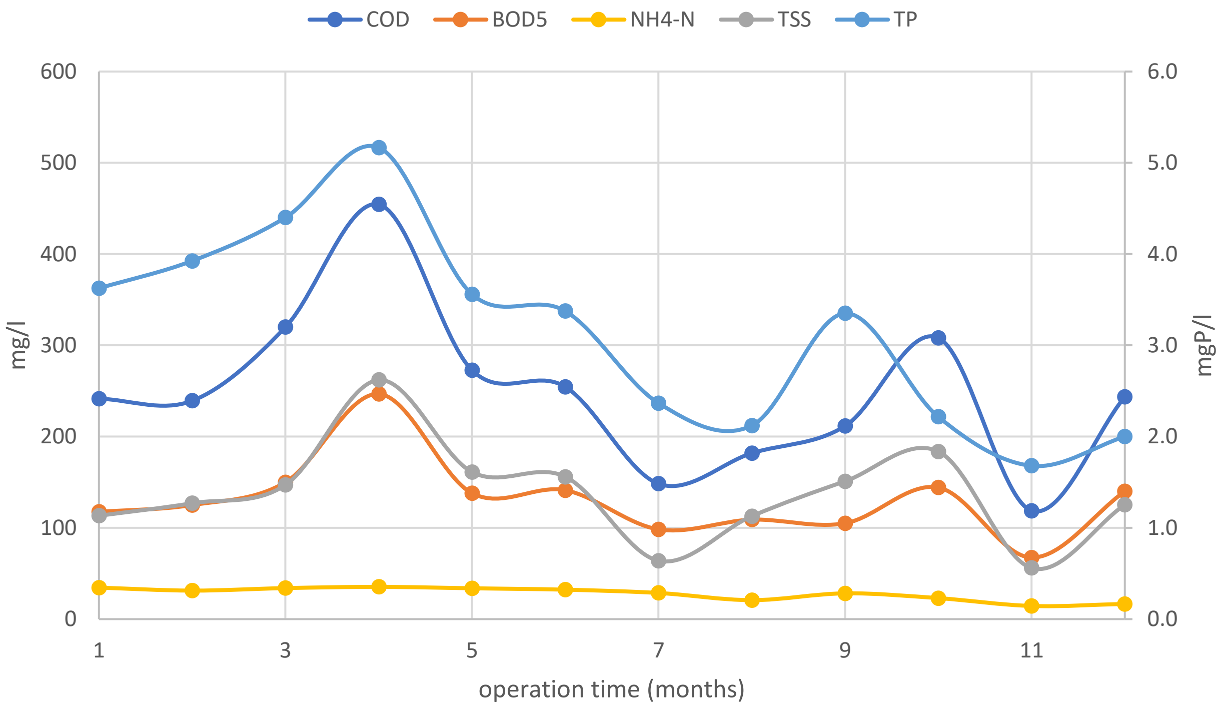


Figure 4-9. Variation of influent concentration of L2 along the operation year 2019.

Concerning the effluent concentration, the same considerations may be carried out. A maximum peak is registered in according to the maximum influent concentration, while for the rest of the year the plant is able to produce an effluent with almost constant quality. No evident case of non-compliance is detachable.

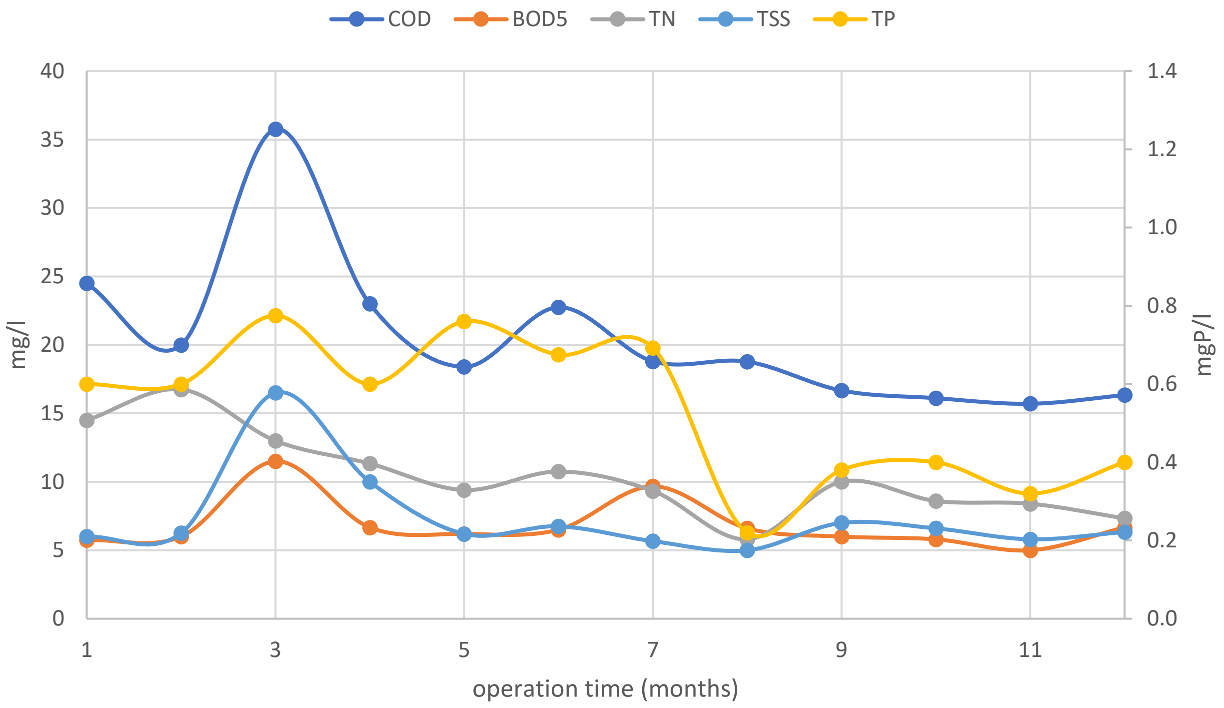


Figure 4-10. Variation of effluent concentration of L1 along the operation year 2019.

Figure 4-11. Variation of effluent concentration of L2 along the operation year 2019.

In Table 4 18 the effluent quality is compared to minimum requirements for water reuse set out by the new EU Regulation 2020/741 and the current Italian policy on wastewater reuse DM 185/2003. As concern heavy metals, aluminium and iron are considered, since they are used for the chemical phosphorus removal. The current effluent generally complies with the class C reclaimed water quality. It means that water reuse shall be permitted only using irrigation method that avoids direct contact with the edible part of the crop, like the drip irrigation.

Table 4-18. Effluent concentrations and wastewater reuse limits

Parameters	unit	Effluent L1	Effluent L2	DM183/2005	Class A	Class B	Class C
E.coli	CFU/100ml	284	847		<10	<100	<1000
COD	mg/l	19.3	17.9	<100	-	-	-
BOD_5	mg/l	6.7	6	<20	<10	<25	<25
TN	mg/l	10.3	8.4	<15	*	*	*
NH_4	mg/l	3.9	1.1	<2	*	*	*
TP	mg/l	0.5	0.7	<2	*	*	*
TSS	mg/l	7.2	6.5	<10	<10	<35	<35
Al	mg/l	0.19	0.12	<1	*	*	*
Fe	mg/l	0.19	0.31	<2	*	*	*

*defined according to a site-specific risk assessment to be carried out

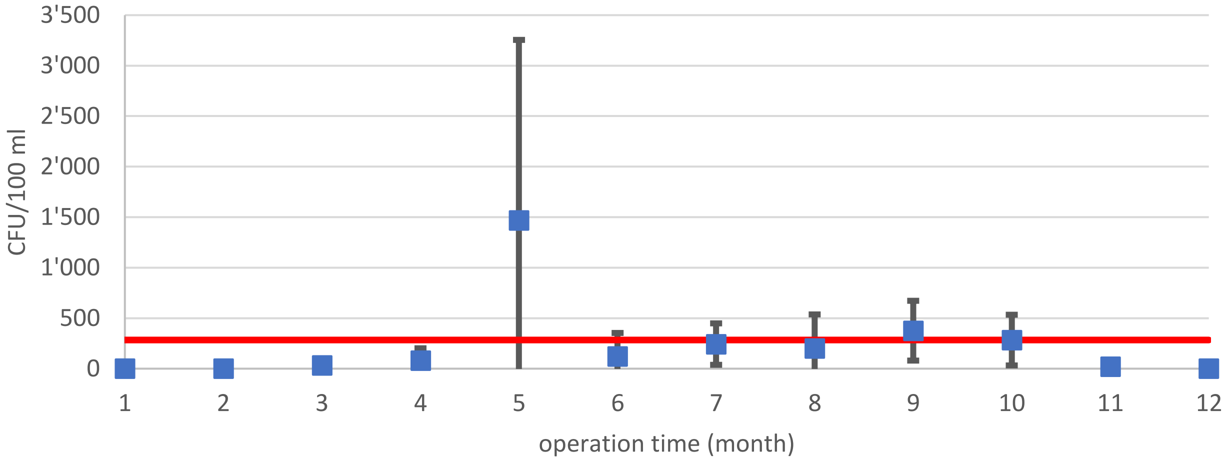


Figure 4-12. Variation in times of E.coli concentration in the L1 effluent. Pescheria Borromeo year 2019

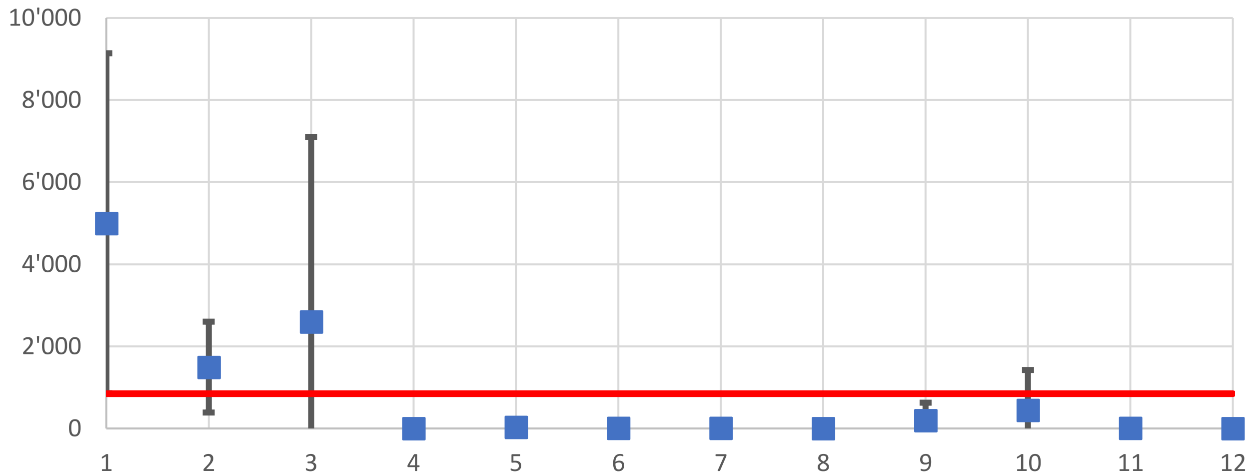


Figure 4-13. Variation in times of E.coli concentration in the L2 effluent. Peschiera Borromeo year 2019

Based on the current Italian legislation, the effluent, as reported in Table 4-18, needs an improvement of the disinfection step to be suitable for reuse since the only parameter non compliant is the pathogen load. The same measure must be adopted to increase the class of water quality defined by EU Regulation and hence, reuse the reclaimed water for a wider range of agricultural applications.

Such a quality is based on the current removal of the plant that are now described. The overall view of the mass balance is reported in Appendix. In this work the main results are reported.

The high HRT (3.5 h vs typical 2 h) of the primary settling in L1 ensures high removal of total suspended solids (62%) but at the same time fermentation issue can occur within the settler. At the same time, the 40% of the organic matter is assumed to be removed and sent to pre-thickener as primary sludge. After primary sedimentation, the flow is partially diverted to Biofor® modules and to CAS treatment. The last one operates extended aeration with a solid retention time of 15 days. In such a way in line with Metcalf & Eddy (2003), the 90% of the organic matter is oxidize, while less than 60 % of the influent ammonia nitrogen is converted to the inorganic forms. Hence, the Biofor® process results to be essential to comply with the strict limit on N and P for discharge in sensitive area. In this perspective, 120 l/h of Aluminium Chloride are dosed on the return activated sludge flow for a total daily consumption of 3226 kg/d of reagent.For the same purpose, Iron chloride was used in 2018.

The secondary effluent enters to the Biofor®, together with the rejected water from the sludge line (1274m3/d). The addition of external carbon source (230 l/h) must be carried out to ensure denitrification of NO3 since by the CAS almost all the carbon content of the wastewater is removed. Hence a COD/N ratio higher than 10 must be provided adding an exogenous carbon. In Peschiera Borromeo a glycole-based product is used. The producer ensures a minimum concentration of 360000 mg COD/l, dosing 230 l/h in L1, corresponding to 1325 kg of methanol.

The Biofor® removal efficiencies are computed as difference between the influent characteristic to the unit (based on our previous made hiring) and the measured concentration of the effluent plant. The disinfection via peracetic acid, indeed, acts only against the microorganisms (bacteria, protozoa and fungi). The average log reduction obtained by calculation is equal to 2.22, corresponding to an average concentration of E.coli in the Biofor® effluent equal to 47132 CFU/100 ml. The disinfection unit works with a contact time of 50 miniutes and dosing 24 l/h of PAA in solution. It means that 1.7 mg of PAA as pure substance is used per liter of wastewater. To comply with the current Italian policy DM 185/2003 on water reuse (E.coli <10) a minimum log reduction of 3.67 is required. It should be achieved increasing the dosage up to 5 mg/l, according to literature studies (Antonelli et al., 2013).

Water line 2 adopts different technical solutions from the line 1, in a more compact system. It is a common practice when an existing plant must increase the treatment capacity and there is not enough space for new infrastructure, like in Peschiera Borromeo WWTP. The primary settling, for instance, operates with lamella settler and by calculation it removes the 60 % of the influent TSS and around 50% of organic matter as COD. So, both lines run on the same order of magnitude of removal efficiencies. The influent solid load to the SEDIPACTM is made up by the influent wastewater and the backflush flow from the Biofor ® with an average concentration of 350 mg TSS/l and a mass load of 5075 kgTSS/d, composed by mainly MLSS, with a corresponding load of organic matter. On the backflush flow is dosed 90 l/h of Al2O3 in solution at 5% to remove chemical phosphorous producing an extra amount of primary sludge, properly called chemical sludge. It accounts only for 2% of the total sludge sent to the pre-thickener from the primary sedimentation: 169 kgTS/d on the total amount of 8777 kgTS/d. The effluent from primary treatment passes through the Biofor® modules, where 90% of the COD is oxidized. The combination of DN and C-N modules ensures the complete nitrification of ammonia nitrogen and consequent denitrification of NO3 in nitrogen gas. The kinetic of this process is favoured by the addition of 90 l/h of the glycol-based solution, equal to a daily COD loading of 778 kg/d. The same effect may be obtained through the addition of 518 kg of methanol per day. The equivalence between the current carbon source employed in the plant and the methanol will be used both in carbon footprint calculation and LCA since the methanol production is a more well-established process, so easier to be found available in a database.

The last step is the disinfection through UV technology that acts only on the pathogenic load. By measured data, a log reduction of 1.53 was achieved in 2019. It consumed 2517 kWh/d, that means the unit operated at almost half of its capacity. It is computed that 419 lamps are working instead of the 912 that are installed. To achieve the class A quality or comply with DM 183/2005, the log reduction must be enhanced over 3.46. Hence, it is needed a UV dose of 80-100 mWs/cm2 instead of the estimated actual dosage 50-60 mWs/cm2 currently imposed (DEMOWARE et al., 2015).

Concerning the sludge line, 500 m3/d of waste activated sludge (1.2% dry solids) come from L2 and are thickened up to 4% DS in a screw thickener with the addition of polyelectrolyte. At the same time, the primary sludge from both water lines is first screened and then thickened up to 3.8% DS. Hence, 15 m3 of WAS are sent to a two-stage digester while 437 m3/d of primary sludge is sent to one single stage digestion step. It is computed that 24.23 % of TSS are destroyed, as a weighted average value. While it is measured a biogas production of 4894 Sm3/d with an average CH4 content of 51%. The digested sludge is then post-thickened by gravity up to 5.9% DS. 285 m3/d of sludge finally are dewatered by a centrifuge with the addition of polyelectrolyte and daily 56912kg/s at 30% DS are sent to AGROSISTEMI's patented system for defecation lime production. 1274 m3/d of reject water are produced from the sludge line and sent upstream of the Biofor® in L1, resulting in an additional load of 568 kg COD and 445 kg TSS per day.

With the energy balance, indeed, the electrical consumption of each unit process is computed (Table 4 19). In the sludge line, moreover, the heat demand is estimated based on the biogas production and machinery equipment. In the specific, a total flow of 12694 thermal kWh per day are provided to the digesters to keep the operating temperature of 33-35°C. This energy is supplied by the 6 boilers feeding with 3 Sm3/d of natural gas and 462 Sm3/d of biogas. Therefore, more than 99% of the thermal energy provided comes from renewable energy source. The 87% of the biogas produced is valorized in CHP unit and so its chemical energy is converted to 8180 kWh/d of electricity self-consumed within the plant and 10218 kWh/d as heat (80% of the heat demand of digester). A schematic view of the energy flow is provided in Figure 4 13.

Table 4-19. Electricity consumption of each unit process. Peschiera Borromeo year 2019

Line 1	kWh/d	Line 2	kWh/d
Coarse screening	175	Coarse screening	158
Pumping	4428	Pumping	3612
Fine screening	84	Fine screening	137
Grit and oil removal	724		
I sedimentation	137	SEDIPAC™	1078
Intermediate pumping	1626	Intermediate pumping	3024
CAS	5682		
II settling	946		
Biofor ®	2549	Biofor ®	9792
PAA disinfection	14	UV disinfection	2517
Sludge line			
Coarse screening	249		
Pre-thickening	228		
Dynamic thickening	707		
Digestion	3458		
Post-THICKENING	40		
Centrifuge	1691		

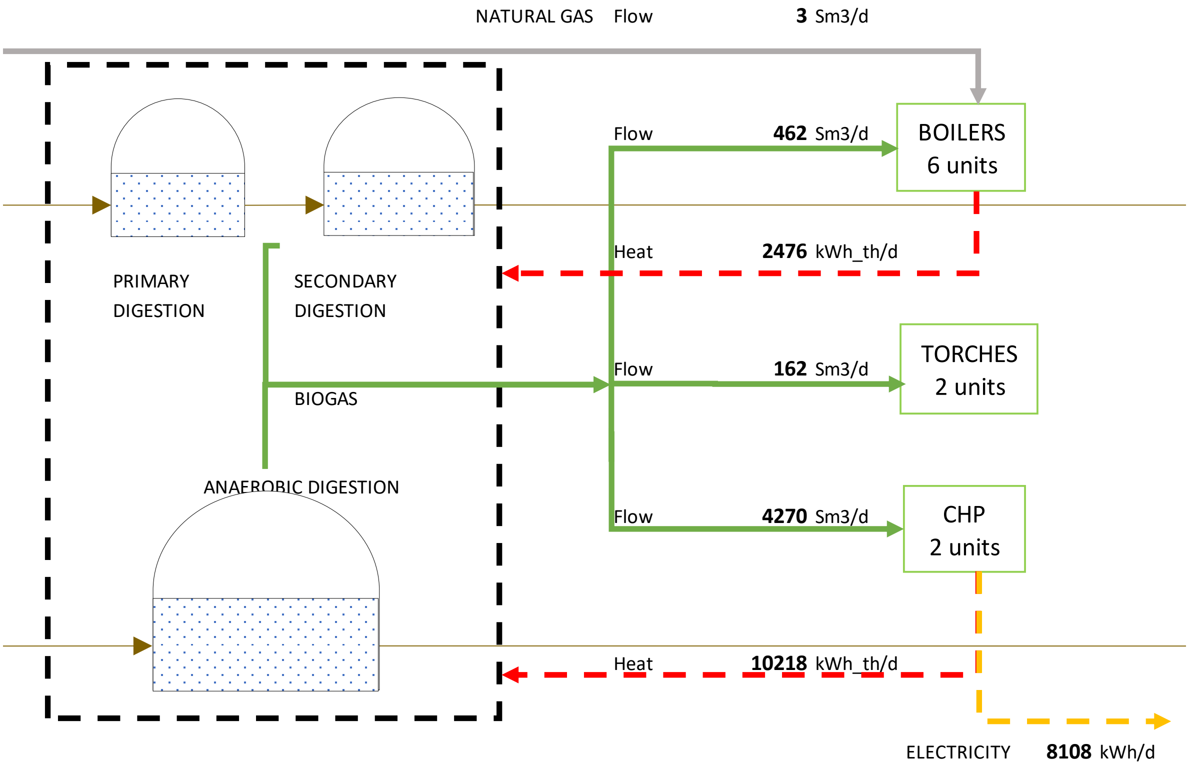


Figure 4-14. Schematic view of the energy flow in the digestion unit. Peschiera Borromeo WWTP

4.2.2 Carbon footprint results

With reference to the calculation of the carbon footprint of Peschiera Borromeo WWTP, the following data are related to the quantification and reporting of GHG emissions obtained by the predictive parametric calculation, according to the ISO 14064:2019.

4.2.2.1 *Direct emissions*

Below is presented a detail of direct emissions of methane, nitrous oxide and carbon dioxide produced on-site. They are related to combustion of biogas through torches, gas engines or gas boilers, to the biological process along the water line, sludge line (sludge storage) and air treatment units. They also include fugitive emissions of biogas that is assumed to be partially lost during biogas production in the closed anaerobic digesters and not fully combusted during conversion to useful energy carriers in the CHP units.

Direct emissions from internal combustion

Direct emissions of CH4 from biogas use	tonCH4/	0.033	tonCO2eq/y	0.88
Direct emissions of N2O from biogas use	tonN2O/y	0.003	tonCO2eq/y	0.93
Direct emissions of CO2 from biogas use			tonCO2eq/y	1820
Total direct emissions from internal combustion			*tonCO2eq/y*	1822

Direct emissions related to processes – water line

Direct emissions of CH4 in air	tonCH4/	5.5	tonCO2eq/y	155
Direct emissions N2O in air	tonN2O/y	5.1	tonCO2eq/y	1351
Direct emissions CO2 in air			tonCO2eq/y	1528
Total direct emissions related to processes – water line			*tonCO2eq/y*	3035

Direct emissions related to processes – sludge line

Direct emissions di N2O from sludge storage	ton N2O/y	0.006	tonCO2eq/y	1.7
Direct emissions of CH4 from sludge storage	ton CH4/y	0.092	tonCO2eq/y	3.0
Direct emissions of CO2 from sludge storage			tonCO2eq/y	0.2
Total direct emissions sludge storage			*tonCO2eq/y*	5.0

Direct emissions related to processes - deodorisation

Direct emissions di N2O from deodorisation	ton N2O/y	1.52	tonCO2eq/y	403
Direct emissions of CH4 from deodorisation	ton CH4/y	20.50	tonCO2eq/y	5741
Direct emissions of CO2 from deodorisation			tonCO2eq/y	259
Total direct emissions from deodorisation			*tonCO2eq/y*	1236

Direct fugitive emissions

Direct fugitive emissions of CH4	ton CH4/y	38.63	tonCO2eq/y	1082
Direct fugitive emissions of CO2			tonCO2eq/y	98

Total direct fugitive emissions	*tonCO2eq/y*	1180

4.2.2.1 *Indirect emissions*

The following are the indirect emissions of CO2-eq related to all indirect emissions that result from wastewater treatment activity but are generated outside the operational boundaries. They include emissions from dissolved gas in the effluent wastewater, imported energy, chemical production, transport activities and waste disposal.

Indirect emissions from energy consumption

The following are the indirect emissions of CO2-eq related to energy consumption, purchased from the grid, within the plant.

Total imported electricity	MWh/y	14179
Indirect emissions from energy consumption	tonCO2eq/y	6296

Waste transport

Sludge disposal	ton N2O/y	0.001	tonCO2eq/y	0.27
	ton CH4/y	0.001	tonCO2eq/y	0.04
			tonCO2eq/y	29.11
Grit disposal			tonCO2eq/y	0.23
Screening disposal			tonCO2eq/y	0.19
Total emissions from waste transport			tonCO2eq/y	30

Transport for chemicals supply

Chemicals transport	tonCO2eq/y	105

The following are the indirect emissions of CO2-eq related to the production of each single chemicals used in the treatment chain.

Chemicals

PAC	tonCO2eq/y	621
Polymers	tonCO2eq/y	176
Sodium hydroxide (NaOH)	tonCO2eq/y	7
Methanol	tonCO2eq/y	501
FeCl3	tonCO2eq/y	48
Peracetic acid	tonCO2eq/y	801
Total emissions chemicals	tonCO2eq/y	2153

The following are the direct emissions of methane, nitrous oxide and carbon dioxide related dissolved gases present in the effluent wastewater and discharge to water body.

Indirect emissions to surface water body

Indirect emission of CH4 to water body	ton CH4/y	15.51	tonCO2eq/y	882
Indirect emission of N2O to water body	tonN2O/y	31.51	tonCO2eq/y	4110
Indirect emission of CO2 to water body			tonCO2eq/y	1945
Total indirect emissions to water body			tonCO2eq/y	6937

The following are the direct emissions of CO2eq related to the sludge management processes. In the case of Peschiera Borromeo WWTP they refer to the production of defecation lime.

Sludge handling (direct Emissions from lime stabilization) - ONSITE

Emissions of N2O from lime stabilization	tonN2O/y	1.07	tonCO2eq/y	283
Emissions of CO2 from lime stabilization			tonCO2eq/y	470
Total emissions from lime stabilization			tonCO2eq/y	753

The following are direct emissions of CO2eq related to the defecation lime application on soil.

Sludge handling (indirect emissions from limed sludge application) OFF-SITE

Emissions of N2O from lime application	tonN2O/y	9.217	tonCO2eq/y	2443
Emissions of CH4 from lime application	tonCH4/y	0.163	tonCO2eq/y	5
Emissions of CO2 from lime application			tonCO2eq/y	4264
Total emissions from lime application			tonCO2eq/y	753

The following are the indirect emissions of CO2eq that are saved avoiding the production of material substituted by the use of waste. In such a case, defecation lime application offset the production and use of mineral fertilizer. It is also included the amount of carbon sequestration.

Avoided emissions of mineral fertiliser production

Avoided emissions for N fertilizer			tonCO2eq/y	-505
Avoided emissions for P fertilizer			tonCO2eq/y	-91
Avoided emissions for K fertilizer			tonCO2eq/y	-17
Total avoided emissions for fertilizer production			tonCO2eq/y	-613

Avoided emissions of mineral fertiliser application

Direct emissions of N2O from fertilizer use	tonN2O/y	-1.29	tonCO2eq/y	-343
Direct emissions of N2O from fertilizer use	tonN2O/y	-0.11	tonCO2eq/y	-29
Total avoided emissions from fertiliz. application			tonCO2eq/y	-372

Carbon sequestration

Total carbon present in the sludge	ton C	-60
Carbon sequestration	tonCO2eq/y	-220

The following are the indirect emissions of CO2eq related to the production of defecation lime, such as emissions due to energy and chemicals consumption.

Sludge handling (indirect emissions from limed sludge production) OFF-SITE

Total emissions of CO2 off-site	tonCO2eq/y	3532

4.2.2.2 *Parametric GHG inventory (ISO 14064-1: 2019)*

The following is the summary of GHG inventory collected for the Peschiera Borromeo WWTP. In FIG a graphical view of the contribution of each category defined by the ISO 14064.

GHG INVENTORY - (UNI EN ISO 14064-1 2019)	CO_2 SOURCE	TOTAL $TonCO_2eq/y$
Direct emissions		
Direct emissions from stationary combustion	b	1822
Direct process emissions	n.b.	4271
Direct fugitive emissions	b	1185
Indirect emissions from imported energy		
Indirect emissions from imported energy consumption	n.b.	6298
Waste transport	n.b.	30
chemicals transport	n.b.	105
Chemicals production	n.b.	2153
Indirect emissions to receveing water body	b	6937
defecation lime production	b	753
TOTAL of on-site WWTP (operational boundaries)		
TOTAL CF biogenic and not biogenic		23554
specific CF treated flowrate		0.0005
specific CF per PE (on COD basis)		0.08
Direct OFF SITE		
Defecation lime application	b	6711
Other indirect emission		
Avoided emissions from fertilizer production	n.b.	-613
Avoided emissions from fertilizer application	n.b.	-372
Removal due to carbon sequestration	b	-220
Defecation lime production OFF-SITE	b	3532
Total on-site and off-site		
Total CF biogenic and not biogenic		32592
specific CF treated flowrate		0.0007
specific CF per PE (on COD basis)		0.11

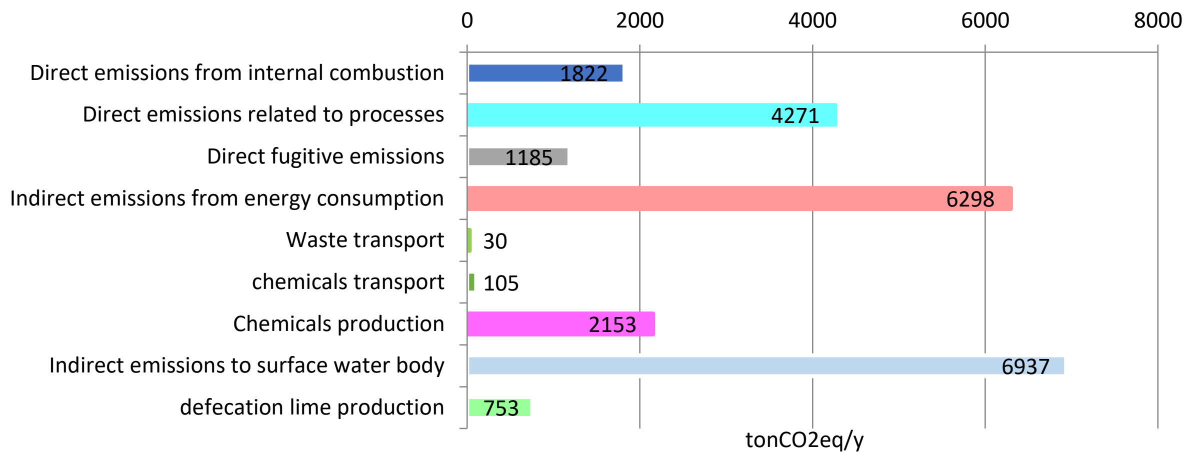


Figure 4-15. GHG inventory of Peschiera Borromeo WWTP year 2019

Results of the analysis performed are shown in Figure 4-15. They are related to the GHG emitted directly and indirectly by the plant in 2019. For Peschiera Borromeo WWTP, indirect emissions to the receiving water bodies had the highest share (29%) in the total CO_2e emission, followed by the energy consumption (27%) and the direct process emissions (18%).

The comparative analysis with the literature data showed that the estimated total CF both including or not the off-site contribution falls within the reported ranges. It should be only used as reference for an order of magnitude, since the wide variety of different operational strategies can change the final EFs considerably.

Table 4-20. Comparison computed CF with literature range. (Maktabifard et al., 2019)

CF expressed in	Peschiera Borromeo	Literature data	Reference
$kgCO_2eq/PE$	80-110	7-108	Gustavsson&Tumlin (2013)
		61-161	Mamais et al (2015)
$KgCO_2eq/m^3$	0.5-0.7	0.1-2.4	Li et al (2017)
		0.1-0.96	Wang et al (2016)
		0.18-1.18	Mannina et al (2019)
		2.21	Koutsou et al (2018)
		0.33	Vourdoubas (2018)
$tonCO_2eq/ton\ N_{removed}$		6.5-12.6	Delre et al (2019)

4.2.3 Energy audit results

A Decision Support analysis is conducted for Peschiera Borromeo WWTP, since disaggregated energy consumption data are available from the energy audit performed by CAP Holding in 2018. List of equipment with relative information about electrical motors (power and use factor) and working hours is available. At the same time, influent and effluent concentrations of main wastewater characteristic are recorded and elaborated from the O&M 2018 report. Finally, the pollutants removals in each stage are derived from the mass balance. According to the ENERWATER methodology presented in section 3.3, Peschiera Borromeo WWTP is identified as a TYPE 3.

Since two different water lines are present in the WWTP configurations, data are reported separately when possible. The first step consists of collecting the main INFO on the WWTP.

Table 4-21. Main information collected as a preliminary step.

MAIN CHARACTERISTICS	L1	L2	WWTP	u.m
SIZE (design)	316'000	250'000	566'000	[PE]
SIZE (real)	220'237	141'535	361'772	[PE]
FLOW RATE	30'857'808	23'712'612	54'570'420	[m^3/y]
FLOW RATE	84'542	64'966	149'508	[m^3/d]
COD_in	326	294	312	[mg/L]
TN_in	22	26	24	[mg/L]
TP_in	3	3	3	[mg/L]
TSS_in	193	168	182	[mg/L]
E.Coli_in	54'186	8'944'339	3'917'245	[UFC/100mL]
Sludge Disposed	-	-	13'177	[t/y]
Sludge Disposed	-	-	36'101	[kg/d]
Dry Content	-	-	36.00%	%
Biogas Produced	-	-	4279	[m^3/d]
Energy to the Grid	-	-	-	[kWh/y]
Electrical energy produced	-	-	2'995'638	[kWh/y]
Thermal energy produced	-	-	3'588'382	[kWh_th/y]
Energy Bill (1 year)	-	-	14'541'993	[kWh/y]
COD_out	24	27	25	[mg/L]
TN_out	11.9	13.3	13	[mg/L]
TP_out	0.50	1.30	1	[mg/L]
TSS_out	9	10	9	[mg/L]
E.Coli_Out	326.5	1575.5	869	[UFC/100mL]

According to the ENERWATER stage definitions, the operation units present in Peschiera Borromeo WWTP are allocated to the different stages as shown in Figure 4-16.

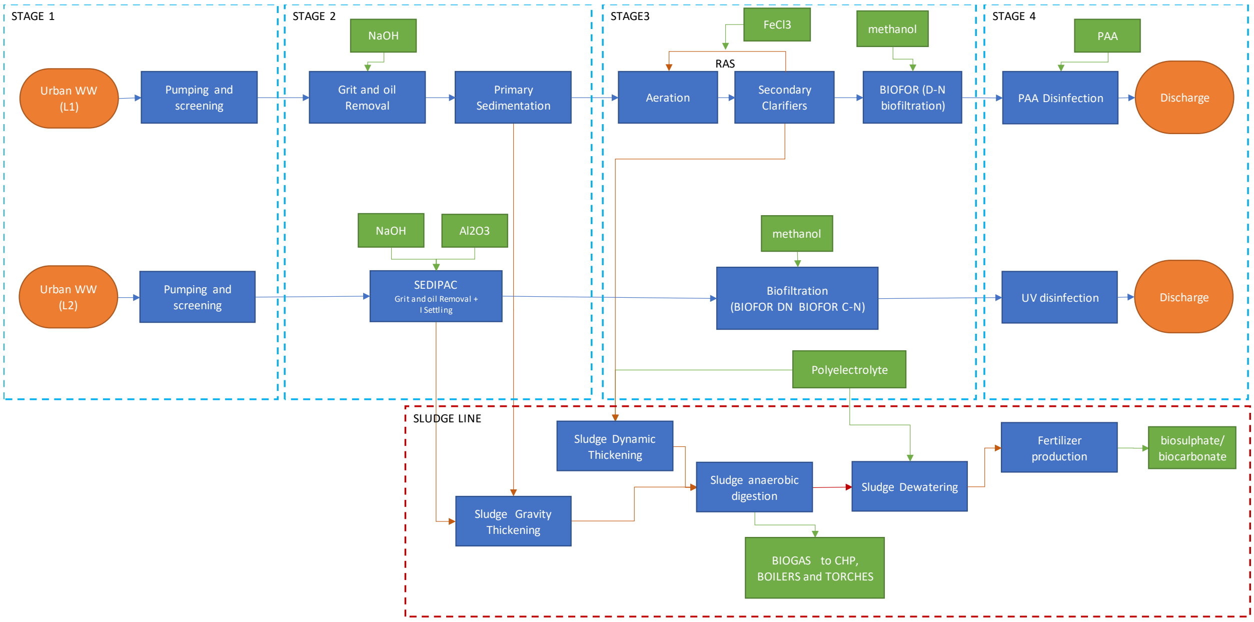


Figure 4-16. Schematic view of stage allocation in Peschiera Borromeo WWTP

The energy was evaluated in terms of gross and net energy consumption according to the procedure described in section 3.3.1.1. The electricity consumption was estimated knowing the following parameters:

- Type of equipment (to allocate it to the right stage)
- Quantity of pieces
- Power installed in kW
- Power adsorbed in Kw
- Working time as hours per day
- Diversity factor

In particular, we assumed to allocate the Sedipac™ units (waterline 2) to two different stages. The unit carries out three processes: degritting, grease removal and primary settling. The first two fall within stage 1, the last one was included in stage 2. In the detailed list of electrical instrumentation, motors at the service of each different function are specified.

Table 4-22. Electricity consumption Peschiera Borromeo (year 2018) WWTP

		STAGE 1	STAGE 2	STAGE 3	STAGE 4	STAGE 5
L1	kWh/d	7'037	137	9'177	14	-
L2	kWh/d	7'918	91	9'792	4'707	-
WWTP	kWh/d	14955	228	18970	4721	6374

The chemical energy consumption was calculated as the product of chemicals daily dosed (data from CAP reports) and the specific chemical energy (kWh/kg) provided by the ENERWATER guidelines (data obtained from Ecoinvent database)

Table 4-23 Chemical energy consumption Peschiera Borromeo (year 2018) WWTP

		STAGE 1	STAGE 2	STAGE 3	STAGE 4	STAGE 5
L1	kWh/d	7'037	137	9'177	14	-
L2	kWh/d	7'918	91	9'792	4'707	-
WWTP	kWh/d	14'955	228	18'970	4'721	6'374

Hence, the gross energy consumption was calculated as the sum of electricity and chemical energy consumption. By definition, the gross energy consumption refers to the total amount of energy that is consumed by the plant regardless of its source.

Table 4-24. Gross energy consumption Peschiera Borromeo (year 2018) WWTP

		STAGE 1	STAGE 2	STAGE 3	STAGE 4	STAGE 5
L1	kWh/d	7'072	137	27'061	1'671	-
L2	kWh/d	7'953	10'707	9'792	4'707	-
WWTP	kWh/d	15'026	10'844	36'853	6'378	6'819

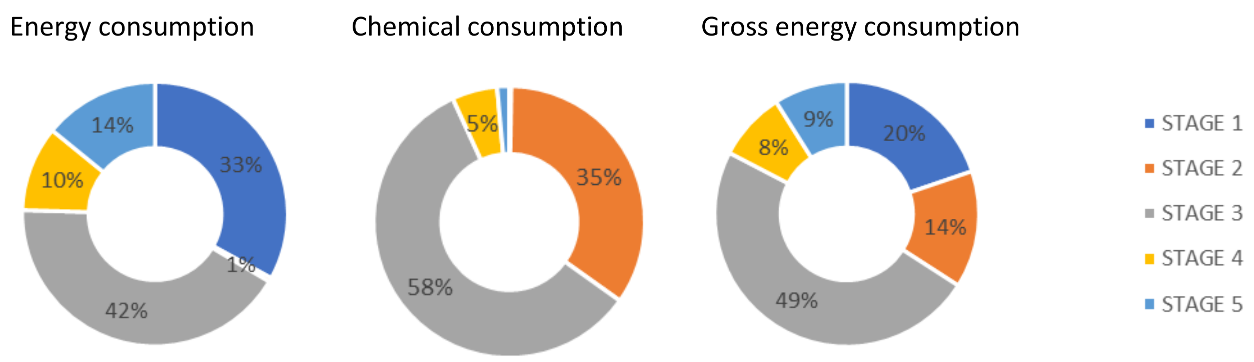


Figure 4-17. Comparative analysis of single stage contribution. Peschiera Borromeo (year 2018) WWTP

Since the at service of the Peschiera Borromeo there is also a CHP unit where the self-produced biogas is valorized to produced heat and electricity, we needed also to calculate the resulting net energy consumption of the plant. It is defined as the amount of energy that is consumed by the plant excluded the amount of renewable energy created on-site It reflects the plant self-sufficiency in the use of energy.

The net energy is calculated decreasing the gross energy consumption for each stage of the percentage of the self-produced energy referred to the overall consumption of the plant.

In Peschiera Borromeo WWTP, 2995638 kWh were produced by the CHP unit while 25382634 kWh were consumed in 2018 resulting in 0.12% of self-consumed energy. The net energy consumption for each stage is reported in Table 4-25.

Table 4-25. Net energy consumption Peschiera Borromeo (year 2018) WWTP

		STAGE 1	STAGE 2	STAGE 3	STAGE 4	STAGE 5
L1	kWh/d	6'238	121	23'867	1'473	-
L2	kWh/d	7'015	9'443	8'637	4'152	-
WWTP	kWh/d	13'252	9'564	32'504	5'625	6'014

From the mass balances, the following parameters were considered to calculate the KPI performances based on the same removal efficiencies and log reduction obtained for 2019 and reported in the mass balance section.

Table 4-26. Parameters to evaluate KPI Peschiera Borromeo (year 2018) WWTP

	parameter	u.m.	L1	L2	WWTP
STAGE 1	m^3	m^3/d	84'542	64'966	149'508
STAGE 2	TSS rem	kg/d	10'108	6'673	16'781
STAGE 3	TPE	kg/d	47'246	26'314	68'836
STAGE 4	log red	(logred m^3)	187'683	243'891	546'279
STAGE 5	TSE	kg/d	-	-	30'563

Table 4-27 reports the KPIs obtained for Peschiera Borromeo WWTP. They must be compared with the database distribution function using equations 7 to obtain the percentile. It is a normalized manner to express the performance of the plant for a given KPI. Therefore, they are denominated energy performance indicators (EPI).

Table 4-27. KPI of Peschiera Borromeo (year 2018) WWTP

			GROSS			NET		
1. estimation		unit	L1	L2	WWTP	L1	L2	WWTP
STAGE 1	KPI1	kWh/m^3	0.084	0.122	0.101	0.074	0.108	0.089
STAGE 2	KPI2	kWh/TSS rem	0.014	1.605	0.646	0.012	1.415	0.570
STAGE 3	KPI3	kWh/TPE	0.573	0.372	0.535	0.505	0.328	0.472
STAGE 4	KPI4	kWh/(logred m^3)	0.009	0.019	0.012	0.008	0.017	0.010
STAGE 5	KPI5	kWh/TSE	-	-	0.223	-	-	0.197

Table 4-28. EPI of Peschiera Borromeo (year 2018) WWTP

			GROSS			NET		
2. normalization		unit	L1	L2	WWTP	L1	L2	WWTP
STAGE 1	EPI1	kWh/m^3	0.820	0.943	0.890	0.763	0.912	0.844
STAGE 2	EPI2	kWh/TSS rem	0.277	1.000	1.000	0.246	1.000	1.000
STAGE 3	EPI3	kWh/TPE	0.855	0.654	0.828	0.803	0.590	0.772
STAGE 4	EPI4	kWh/(logred m^3)	0.209	0.425	0.264	0.190	0.377	0.236
STAGE 5	EPI5	kWh/TSE	-	-	0.460	-	-	0.407

Hence, the WTEI (water treatment energy index) is calculated after a weighting step. The EPIs are multiplied for the weight of Table 3-6 and added together. In such a way the significance of each stage is taken into account. Peschiera Borromeo WWTP obtains a WTEI equal to 0.687 that matches class F. The WTEI achieved considering the net energy is slightly lower but still, the plant should be classified within the class F.

Table 4-29. Label of Peschiera Borromeo (year 2008).

	GROSS			NET		
	L1	L2	WWTP	L1	L2	WWTP
STAGE 1	G	G	G	F	G	G
STAGE 2	B	G	G	B	G	G
STAGE 3	G	F	G	G	F	F
STAGE 4	D	F	E	D	F	D
STAGE 5	-	-	C	-	-	C
WHOLE PLANT	F			F		

As a conclusion, the investigated plant offers considerable scope for improvement. Possible measures are the substitution of the inefficient motors with IE4 motors or the optimization of the control system of the processes. The differences between gross and net energy consumption are not evident. Only the secondary process has an improvement.

Further, comparing the two water lines, it is evident that UV disinfection acts worse even if the gross energy consumption takes into account the primary energy required for the production of peracetic acid used in the other line. Extra comparison between the two water lines may lead to misunderstanding. Indeed, phosphorous is removed in the second stage in the L2, while for L1 chemicals are doses in the third stage. The process itself has a low electricity demand, but the primary energy related to the production of the reagent is included in the gross energy calculation.

As concern the choice of KPI, the kWh/kg $TSS_{removed}$ considered for the second stage does not fit properly the primary treatment of water line L2 that removes not only solids but also phosphorous through chemical addition. This second goal requires high quantity of primary energy (for PAC production) that is indeed allocated only to the removed TSS.

It is recommended to make an energy audit at regular interval time to keep monitor the efficiencies of single stage and verify the effectiveness of optimizatioin strategy adopted.

ENERGY AUDIT RESULTS

		UNIVPM	**18/05/2020 for**
WWTP	PESCHIERA BORROMEO		
size PE	566000	**interval (year)**	
Electricity consumption [kWh/d]	45247	**scenario**	
Overall energy consumption [kWh/d]	75919	**samples**	

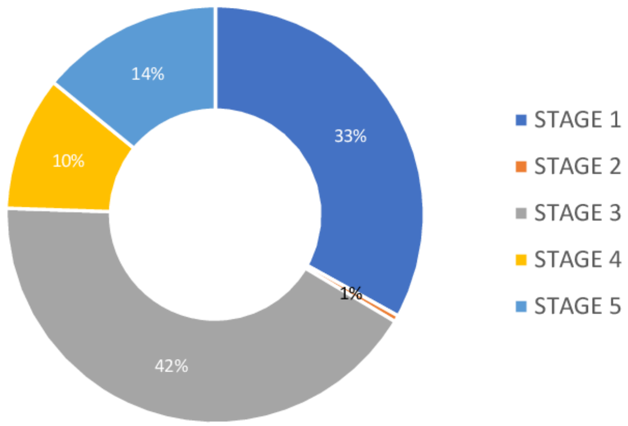
Calculation & Ranking WTEI

	GROSS	*NET*
A		
B		
C		
D		
E		
F	F	F
G		

	GROSS	*NET*
STAGE 1	G	G
STAGE 2	G	G
STAGE 3	G	F
STAGE 4	E	D
STAGE 5	C	C

Energy consumption

From kWh/d: 45247



KPIs and EPIs

ENERGY CONSUMPTION kWh/d		Unit	KPIs	EPI
STAGE 1	15'026	kWh/m3	0.101	0.890
STAGE 2	10'844	kWh/TSS rem	0.646	1.000
STAGE 3	36'853	kWh/TPE	0.535	0.828
STAGE 4	6'378	kWh/(logred m3)	0.012	0.264
STAGE 5	6'819	kWh/TSE	0.223	0.460

4.3 Pilot-scale AnMBR: Mass and energy balances

The main characteristics of the influent for each operational period is given Table 4-30. The pH of the influent remained stable (7.5). The total alkalinity of the influent ranged from 270.9 mgCaCO3/l to 352.0 mgCaCO3/l, with the highest concentration observed in the first period. The addition of a primary treatment decreased the organic fraction and the suspended solids of the UASB influent and the consequent OLR of the anaerobic system.

Table 4-30. Influent characterization in each configuration

Parameter	u.m.	Conf 1	Conf. 2[a]	Conf. 3[a]
pH	-	7.5±0.2	7.5±0.1	7.5±0.1
Alkalinity	mg/L	352.0±46.4	270.9±70.2	296.9±40.3
COD	mg/L	374.1±165.8	189.5±92.1	143±18.1
TSS	mg/L	227.7±91.7	92.2±58.4	65.0±14.1
BOD5	mg/L	167.5±31.5	193.0	76.8±1.6
TN	mg/L	34.0±5.1	24.1±8.1	21.8±3.3
TP	mg/L	4.8±1.1	3.8±0.9	3.67±1.1
NH_4-N	mg/L	22.1±4.8	10.6±7.9	14.03±2.8
PO_4-P	mg/L	2.3±1.5	3.1±1.13	n.a.
SO_4^{-2}				
E.coli	UFC/100mL	1’000’000	1’000’000	1’800’000

a: values refer to the UASB influent that is pre-filtrate through SALSNES Filter.

To evaluate the system performances, mass and energy balances were computed for each configuration. The detail schemes of mass balances are reported in Annex I. In this section, the main effects are critically described.

First, the COD mass balance is investigated to monitor the biogas production.

Table 4-31 lists the COD concentration of all different stream, given as the percentage of the UASB influent concentration, while Figure 4-18 shows the overall removal efficiency obtained in each period and the single removal performances of the different operation units.

Table 4-31. COD concentration of all stream given as the percentage of the UASB influent concentration

		Conf 1	Conf 2	Conf 3
COD in the influent to UASB	%	100	100	100
COD in the produced biogas	%	0.27	0.21	0.26
COD wasted with Excess sludge	%	4	6	1
COD in the permeate	%	20	20	22
COD in the permeate as dissolved CH_4	%	0.6	0.8	0.6

COD in the AnMBR headspace	%	0.27	0.12	0.39
COD accumulated within the UASB reactor	%	75	73	76
Overall removal		80.4	82.9	81.6

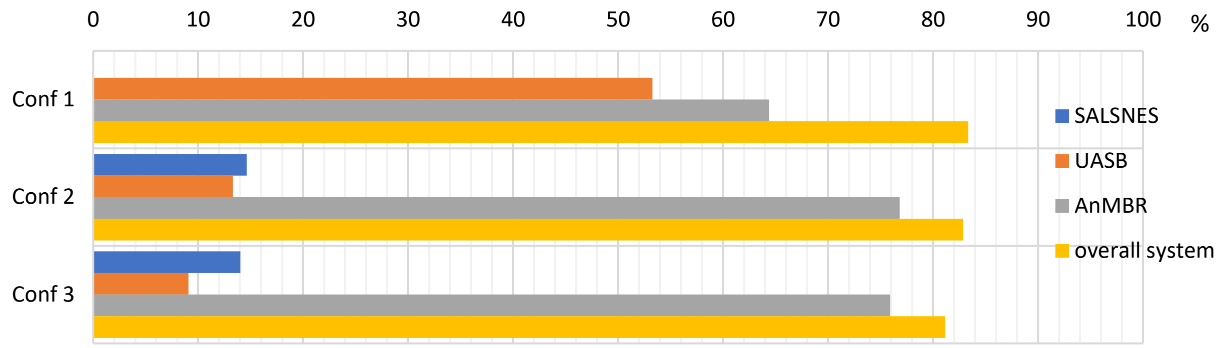


Figure 4-18. COD removal efficiency for each period and each operation unit

The first evidence, common to all the configurations, is that even if the overall system is able to remove around the 80 % of influent COD loading mass, a great amount of COD is accumulated within the system or better is not used for methane production. If we consider the stoichiometric gas production at standard conditions (0.35 l CH_4/g COD) we should produce 9.54, 5.16 and 3.75 l CH_4/d in the first, second and third period, respectively. Currently, the performance of the pilot-scale system is much lower as shown by data in Table 4-32The main hypothesis of such inefficiency can be attributed to a generic low methanogenic activity. It should be caused by no optimal temperature or low-loaded influent. On the other hand, even competition between sulphate reducing bacteria (approximately 2 g COD/g SO_4-S removed) and methanogenic microbes for available carbon can occur when the influent COD/SO_4-S ratio is too low. Besides, fluid dynamic conditions may limit the wastewater sludge contact time or favour floating sludge preventing gas leave the UASB reactor.

Information about the produced "biogas" flowrate and methane content is first obtained as raw data from the milligas counter and the gas speciation through acoustic spectrography. They include a fraction of nitrogen gas that is used instead of biogas, as will occur in full -scale plant, to remove the cake layer on the membrane module and it is recirculated to the UASB reactor. It is assumed that the complement to 100 % of the sum of CH_4 and CO_2 is all nitrogen gas. In this way, we also calculate the amount of N_2 within the recycling stream and therefore we obtain the nitrogen content in the AnMBR headspace by difference with the feeding gas to the membrane module. Hence, the "biogas flow" and related speciation in Table 4-32 refers to the mixture of CH_4 and CO_2. The methane and carbon dioxide content in the AnMBR headspace is instead calculated by the difference between the dissolved gas concentration influent to the membrane reactor and the dissolved gas concentration in the permeate.

Table 4-32. Comparison between data of biogas production during the different configurations

Configuration		Conf 1	Conf 2	Conf 3	Literature
Operating parameters					
type of influent	-	wastewater	filtered ww	filtered ww	
Temperature	°C	31	30	37	30-35
OLR	kgCOD/m^3/d	1.70	0.8	0.6	1-20
N_2 sparging flow	m^3/h	1.00	1.00	1.50	
Biogas production UASB					
Flow to milligas meter	L/d	0.161	0.054	0.063	
%CH_4	%	17.0	22.0	20.6	
%CO_2	%	0.5	3.4	2.8	
biogas flow[a]	L/d	0.028	0.014	0.015	
CH_4%[a]	%	97	87	88	
CO_2%[a]	%	3	13	12	
CH_4 flow	l/d	0.0274	0.0118	0.0130	
CO_2 flow	l/d	0.001	0.002	0.002	
Stripped biogas AnMBR					
stripped flow	m^3/h	0.08	0.08	0.12	
CH_4 flow	l/d	0.0280	0.0067	0.0138	
CO_2 flow	l/d	0.649	0.010	0.020	
Overall system: UASB+AnMBR					
Total methane flow	l/d	0.0554	0.0185	0.0268	
methane Yield	LCH_4/gCODr[b]	0.0027	0.0017	0.0034	0.07-0.3
Overall system: UASB+AnMBR assuming to strip all the dissolved methane					
Total methane flow	l/d	0.113	0.065	0.053	
methane Yield	LCH_4/gCODr[b]	0.0055	0.0060	0.0068	0.07-0.3

a: Without considering the N_2 contribution, b: COD removed

The stability of anaerobic process was monitored through the α factor (Figure 4-19). After a first stationary phase, it started slightly to increase at the end of the first period but even if it exceeded the optimum value of 0.3 it always remained with an acceptable range.

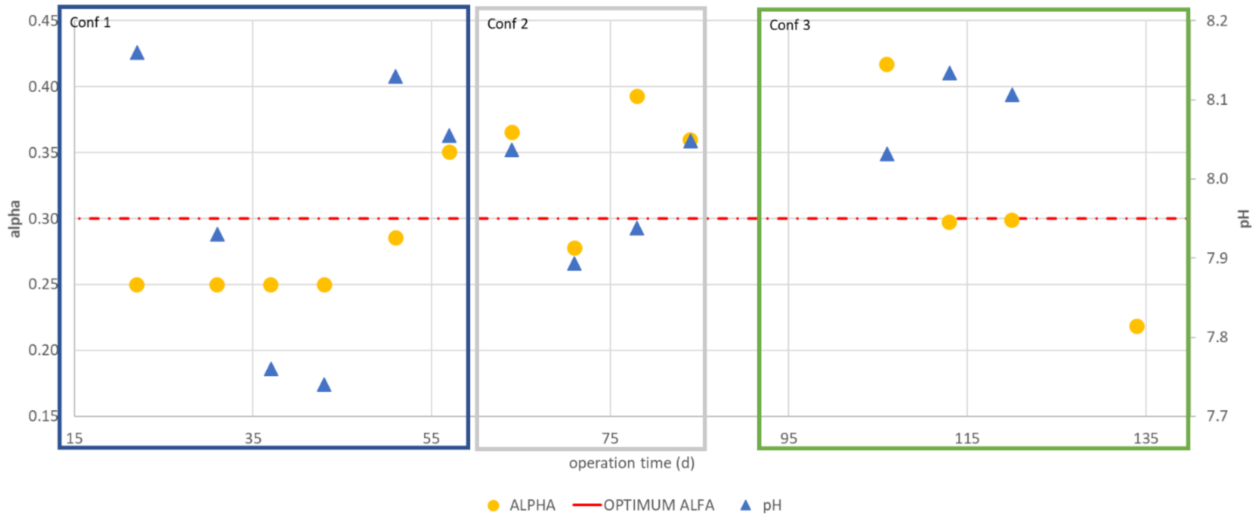


Figure 4-19. Variations of UASB effluent pH and α factor at different periods of operation time

The production of biogas throughout the second configuration was expected to decrease due to the low OLR produced by the filtration step. It was confirmed by the sampling campaign as shown in Figure 4-20 where the biogas flow refers to gas exiting from the UASB reactor. At the same time, increasing the temperature we would expect biogas flow rises since it would increase the enzymatic activity of methanogenic bacteria. At the same, according to Henry's law on the solubility of a gas in a liquid, the double effect of higher temperature and increased gas sparging rate should decrease the solubility of methane in water.

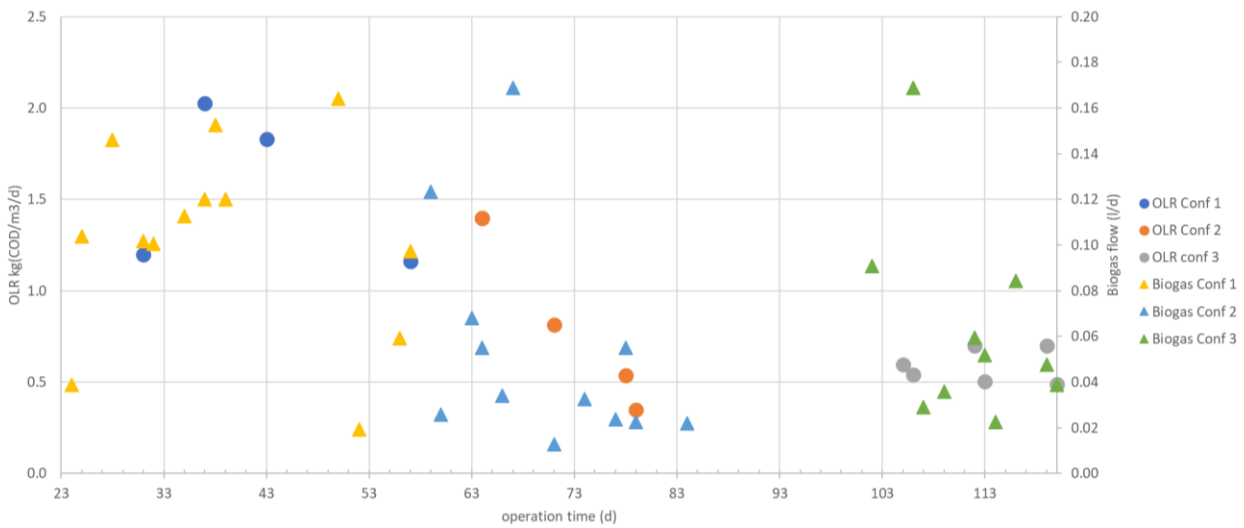


Figure 4-20. Variations of OLR and biogas flow at different period of operation time

This mentioned effect is shown in Figure 4-22. Operating at same OLR (Conf 2 and Conf 3), the percentage of dissolved methane in respect to the total produced CH_4 decreased while increased the amount stripped in the AnMBR headspace (gas sparging flowrate of Conf 3 is 50% higher than the one in Conf 2). Estimates of dissolved methane losses are typically based on concentrations calculated using Henry's Law but advection limitations can lead to supersaturation of methane between 1.34 and 6.9 times equilibrium concentrations and 11-100% of generated methane being lost in the effluent. In well-mixed systems such as AnMBRs which use biogas sparging to control membrane fouling, current concentrations approach equilibrium values (Remy et al., 2013).

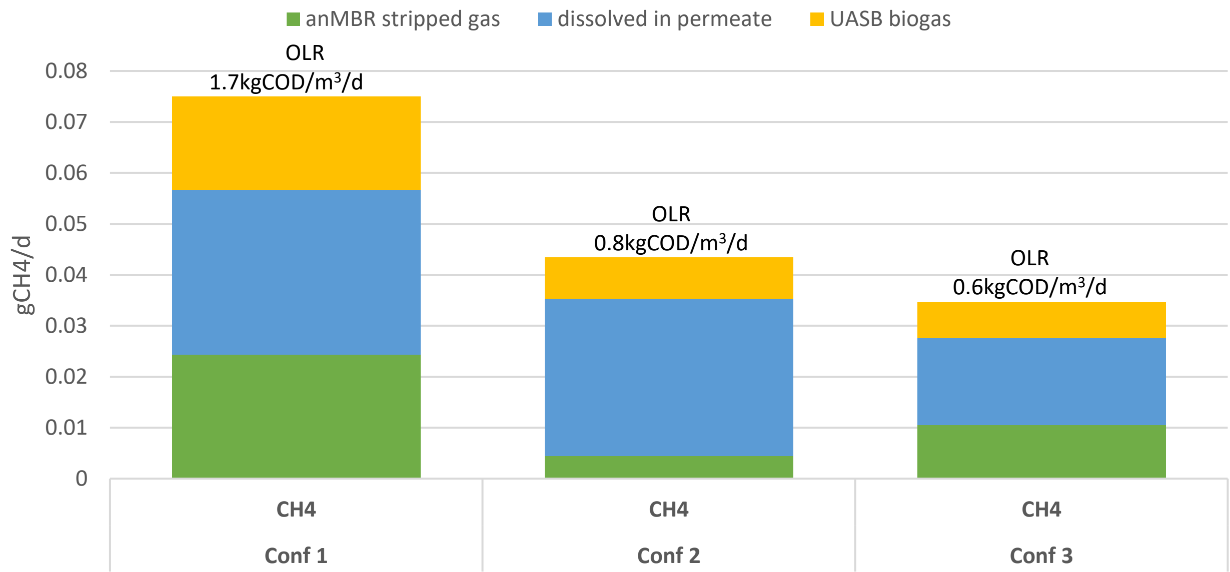


Figure 4-21. Methane mass loading in the three configurations

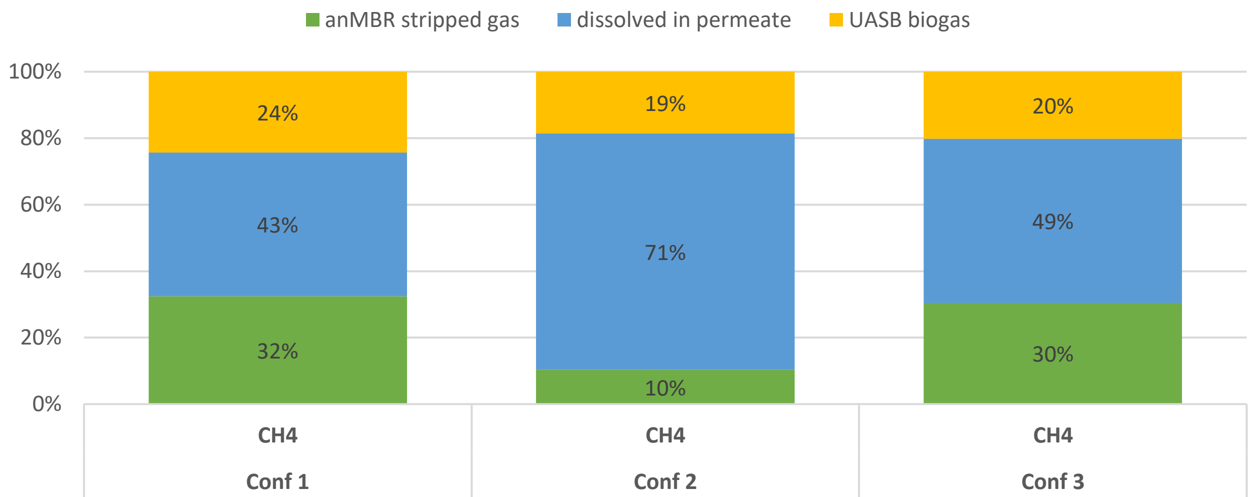


Figure 4-22. Methane distribution between the different stream for each period.

Considering the overall flow of methane produced by the system as the sum of CH_4 stripped and CH_4 in the biogas, with low values of OLR, 0.5 kg/m^3/d, the methane production decreased of 67 %, while the increase of operating temperature to 37-38°C enhanced it of 42%. (Figure 4-23). The methane yield (L CH_4/kgCOD_r) had the same behaviour. It is calculated as the ratio of methane produced and COD removed.

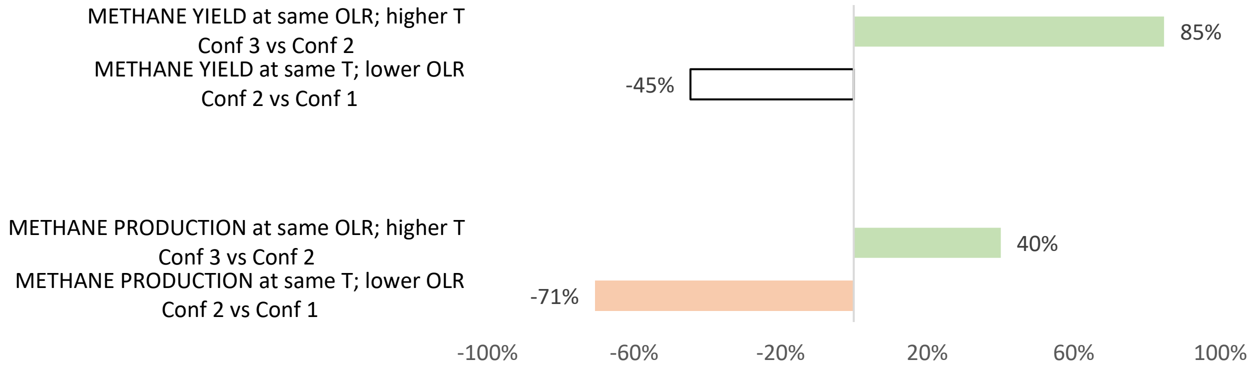


Figure 4-23. Comparison of methane production between the three operating conditions

The methane content of the biogas was almost constant throughout the entire operation time (82.7±12.1 %) if we exclude the starting phase.

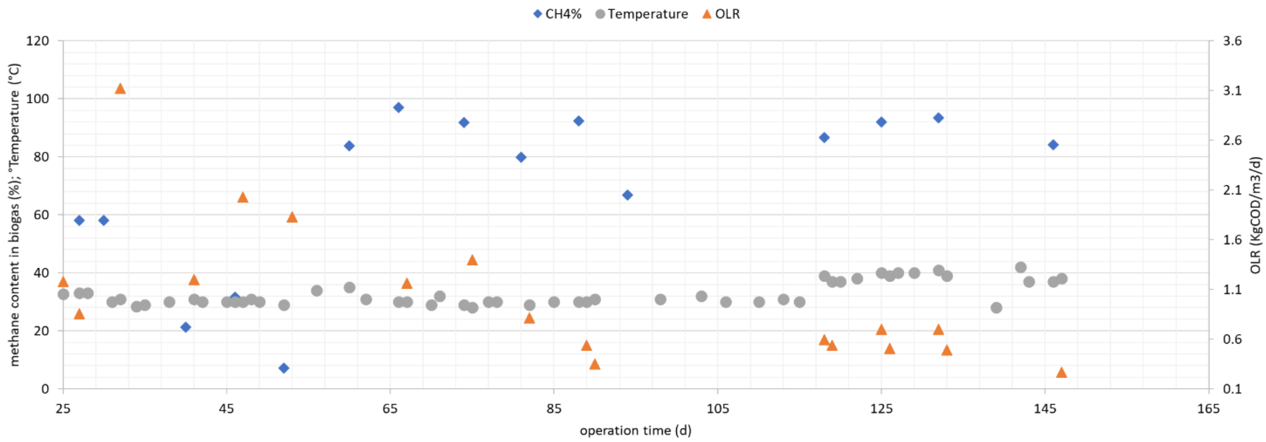


Figure 4-24. Variation of methane content in biogas, temperature and OLR during the operation time

Anyway, the benefit of using a UASB+AnMBR technology is not only the capability to reduce energy demand and produce biogas. We were also interested in the capability to achieve effluent quality suitable for water reuse for irrigation. Hence the final effluents coupling UASB and AnMBR during Periods 1, 2 and 3, are reported in Table 4-33, to make a comparison with the new limit set out in 2020/741 "*Regulation of the European Parliament and the Council*" on minimum requirements for water reuse.

Table 4-33. Effluent quality of UASB+AnMBR in different configurations

Period	COD	BOD5	TSS	TN	TP	E. coli
	mg/l	mg/l	mg/l	mg/l	mg/l	CFU/100 ml
Conf 1	61.00±41.88	38.85±38.85	0	27.60±3.65	2.94±1.02	<10
Conf 2	35.5±8.19	29	0	17.83±7.89	3.67±2.09	0±0
Conf 3	27.67±17.16	16.25±6.72	0	15.13±1.27	2.72±0.65	<10
2020/741 class A	Not defined	<10	<10	Not defined	Not defined	<10
2020/741 class B	Not defined	<25	<35	Not defined	Not defined	<100

2020/741 class C	Not defined	<25	<35	Not defined	Not defined	<1000

During the entire experimental period, the permeate complied with the EU regulation in terms of total suspended solids. Moreover, during the second period, it also complied the limit for class A reclaimed water in terms of E.coli but the BOD5 concentration was slightly higher of the minimum set out. In the first and the second period, instead, the E.coli concentration was within the limit valid for class B reclaimed water, but again the BOD5 exceeded the permitted threshold. We can conclude that the experimental permeate should be reuse as class C reclaimed water in a drip irrigation system for food crops consumed raw where the edible part is produced above ground and is not in direct contact with reclaimed water, or processed food crops and non-food crops including crops used to feed milk- or meat-producing animals.

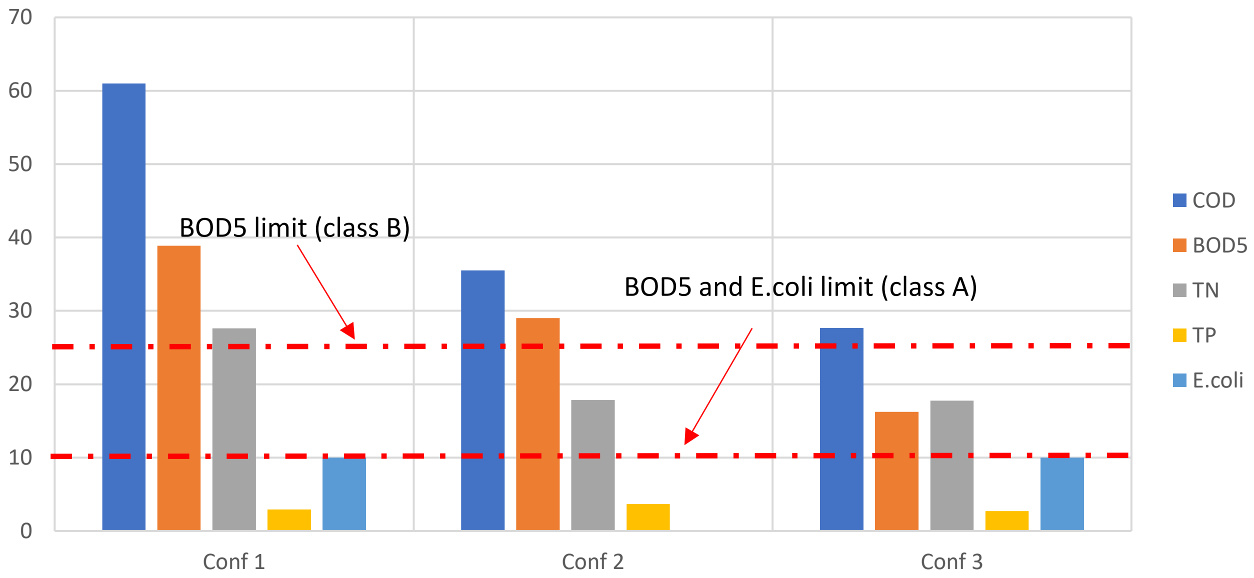


Figure 4-25. Effluent characterization of permeate in the three periods

Moreover, the UASB+AnMBR effluent can be applied in fertigation due to the high nutrient content. An increase in the concentration of soluble forms of the nutrients occurred in the effluent because of the degradation of the organic matter, which entails the solubilisation of the organic nitrogen and phosphorous to ammonium and phosphate (Moñino et al. 2017).

In the second scenario, partial nitrification occurred within the accumulation tank feeding the UASB reactor and it justifies the higher removal efficiency in terms of total nitrogen. It was avoided in the third scenario accumulating the filtrate stream only for two days. Nitrifiers bacteria had no sufficient time to grow and oxidize ammonia if Salsnes filter operated every other day, on equal terms of ambient temperature.

Phosphate release is not documented since data for the third period are missing due to malfunctioning of the analytical instrumentation.

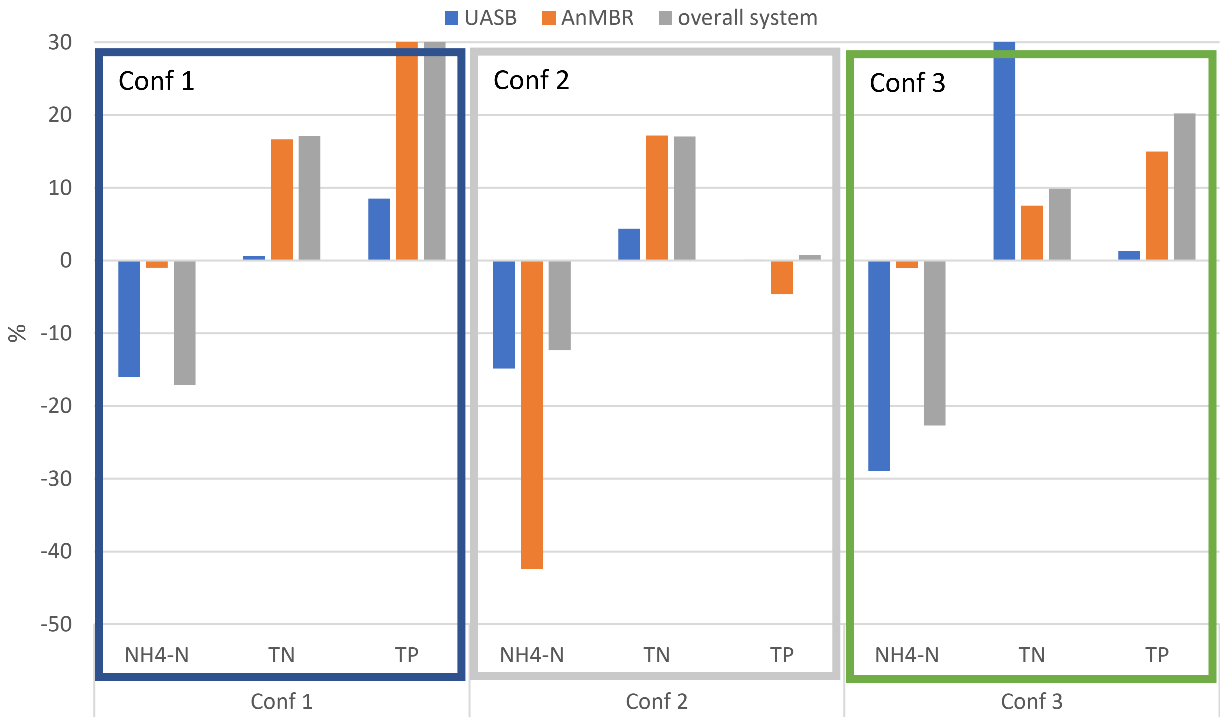


Figure 4-26. Removal (positive values) and release (negative values) of nutrients in each period

Table 4-34. Removal efficiencies in the three configurations.

		SALSNES	UASB	AnMBR	Overall system
Conf 1	COD		53.3	58.1	80.4
	TSS		67.4	100.0	72.1
	NH_4-N		-16.0	-18.9	-37.9
	TN		0.6	1.9	2.5
	TP		8.5	19.6	26.4
Conf 2	COD	14.6	13.3	76.8	82.9
	TSS	22.9	40.0	100.0	100.0
	NH_4-N		-14.8	-42.4	-12.3
	TN		4.4	17.2	17.0
	TP		0.1	-4.6	0.8
Conf 3	COD	14.0	9.1	75.9	81.2
	TSS	12.6	4.8	100.0	100.0
	NH_4-N		-28.9	-1.0	-22.7
	TN		0.2	7.5	9.9
	TP		1.3	15.0	20.2

The addition of primary treatment in the second and third configuration slightly lowered the fouling rate. Figure 4-27 shows the beneficial effect of the chemical membrane cleaning performed before starting the last scenario. The initial permeability of the membrane was restored, but quite rapid fouling seems to be ongoing. It is worth mentioning that in last days some operational issues like electrical black-out and misfunctioning of backflush pump occurred and should affect the measurement of biogas production and fouling rate.

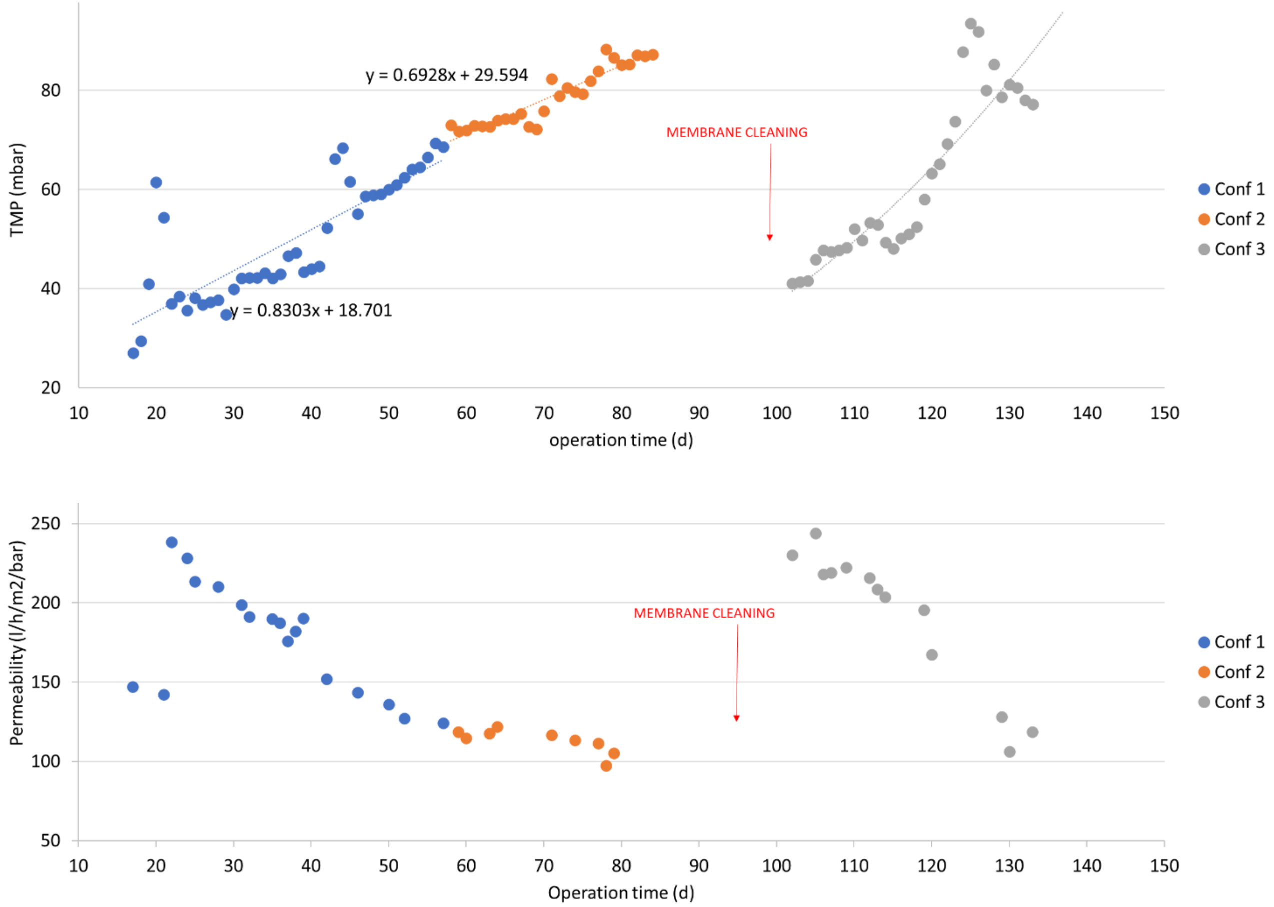


Figure 4-27. Variation of TMP (above) and 20°C-permeability of the membrane (below) in different period of operation time

So far, considerations of mass flow have been made but no less significant is the energy balance. The electrical devices needed to operate the system are listed in Table 4-35 and mainly consist in pumps for fluid (gas and liquid) circulation and valves to regulate the process phases in time. The electrical consumption is strongly affected by the dimension of the plant and the scale of the system plays an important role.

Table 4-35. List of equipment operating in the UASB-AnMBR pilot-scale system

stage	Equipment	Power installed	use factor	working time	Electricity Consumption
		W	%	h/d	kWh/d
SALSNES	filtermesh	550	80%	0.13	0.06
	mixer for accumulation tank	250	80%	24.00	4.80
UASB	UASB feeding peristaltic pump	5	80%	15.16	0.06

	recycling peristaltic pump	40	80%	24	0.77
AnMBR	permeate piston pump	180	80%	21.6	3.11
	backwash piston pump	180	80%	2.4	0.35
	solenoid valves (permeate/backwash)	9	80%	24	0.17
	Solenoid valves (N_2 sparging)	9	80%	1.92	0.01

More interesting is the thermal energy required by the system and its variation during the three scenarios. Table 4-36 and Table 4-37 summarize the parameters used in the calculation of the required capacity of heat-exchanger to keep the system operating at the design temperature.

Table 4-36. Heat requirements for pilot-scale UASB reactor

Parameters	u.m.	Conf 1	Conf 2	Conf 3
UASB volume	L		16.60	
inlet flowrate	L/d	72.86	77.81	74.94
Reactor diameter	m		0.15	
Reactor depth	m		1.00	
wall area	m^2		0.47	
Bottom area	m^2		0.02	
Top area	m^2		0.02	
Thermal conductivity	W/m°C		0.19	
Plexiglass thickness	m		0.015	
Heat transfer coefficient	W/m^2°C		12.67	
Ambient Temperature	°C		28.00	
Influent Wastewater Temperature	°C		24.00	
Operating temperature	°C	31.00	31.00	38.00
Specific heat of sludge/wastewater	J/kg°C		4200.00	
Heat requirement for wastewater	J/d	2141982	2141982	4283965
	kWh/d	0.5950	0.5950	1.1900
Heat loss by conduction by lateral side	J/d	1547171	1547171	5157238
Heat loss by conduction by the bottom	J/d	58019	58019	193396
Heat loss by conduction by top	J/d	58019	58019	193396
Total losses	J/d	1663209	1663209	5544031
	kWh/d	0.4620	0.46	1.54
Required heat-exchanger capacity	J/d	3805191.73	3805191.73	9827996.02
	kWh/d	1.06	1.06	2.73
Drop in temperature	°C/d	54.58	54.58	140.96

The first two scenarios required the same amount of energy to heat the wastewater since both operating and ambient temperature was assumed to be equal. However, the high heat demand is mainly due to poor insulating properties of the plexiglass which reactor is made of. The heat transfer coefficient of the system was 12.67 W/m^2°C against the 5.0-5.5 W/m^2°C of the most common inefficient full-scale digester (Beavis & Lundie, 2003)

Table 4-37. Heat requirements for pilot-scale membrane reactor

Parameters	u.m.	Conf 1	Conf 2	Conf 3
membrane volume	L		60.29	
inlet flowrate	l/d	72.86	77.81	74.94
Reactor width	m		0.29	
Reactor length	m		0.39	
Reactor depth	m		0.54	
Wall area	m^2		0.73	
Bottom area	m^2		0.11	
Top area	m^2		0.11	
Thermal conductivity	W/m°C		0.19	
Plexiglass thickness	m		0.005	
Heat transfer coefficient	W/m^2°C		38.00	
Ambient Temperature	°C		28	
Influent Wastewater Temperature	°C	31.00	31	38
Operating temperature	°C	31.00	31	35
Specific heat of sludge	J/kg°C		4200.00	
Heat requirement for wastewater	J/d	0.00	0.00	-939849.38
	kWh/d	0.0000	0.0000	-0.2611
Heat loss by conduction by lateral side	J/d	7180358	7180358	16583208.69
Heat loss by conduction by the bottom	J/d	1099708	1099708	2539801.44
Heat loss by conduction by the top	J/d	1099708	1099708	2539801.44
Total losses	J/d	9379778	9379778	21662811.57
	kWh/d	2.6055	2.61	6.02
Required heat-exchanger capacity	J/d	9379774.08	9379774.08	20722962.18
	kWh/d	2.61	2.61	5.76
Drop in temperature	°C/d	37.04	37.04	81.84

In both configurations, the energy required to heat the UASB reactor is around 70 % of the total energy demand. To increase the operating temperature of 7°C, we had to provide 132% more heat than the first scenario.

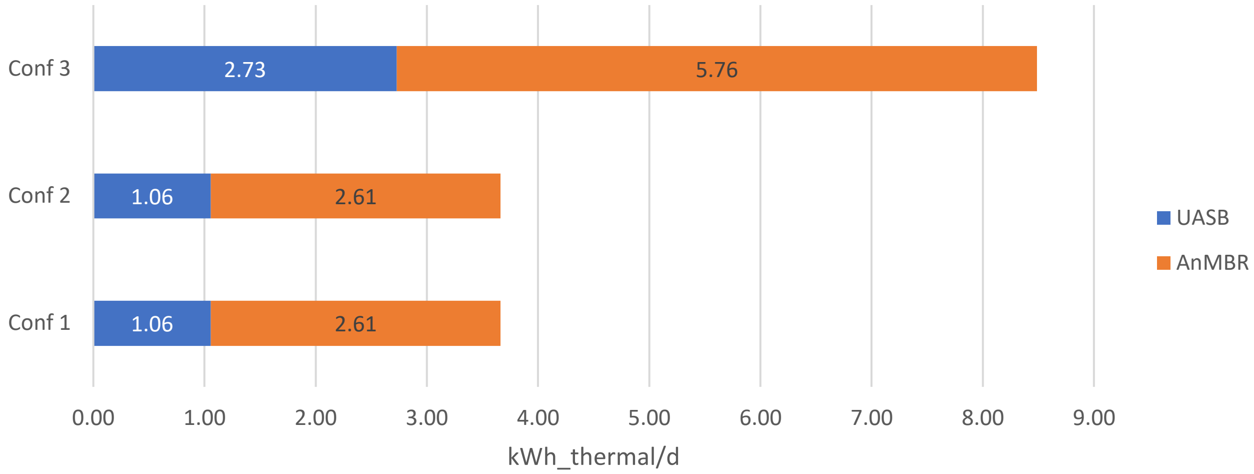


Figure 4-28. Heat demand of the system in the three configurations

Hence, the daily heat demand was of 3.67 kWh in the first and second period and raised to 8.49 kWh in the third (Table 4-38). Besides, the electric water heater, installed in the pilot-hall, operated for around 3 and 6.5 hours per day when UASB operated at 31°C and 38°C, respectively.

Table 4-38. Heat demand and energy consumption in the different configgurations

Parameter	u.m.	Conf 1	Conf 2	Conf 3
working time	h/d	2.8	2.8	6.46
electricity consumed	KWh/d	4.18	4.18	9.684
thermal energy produced	KWh_th/d	3.662	3.662	8.486

To be auto sufficient in terms of heat request, the UASB+AnMBR system should produce 409 LCH_4/d if consumed in boilers (assumed 90% efficiency) or 920 litres of methane per day if valorized in a CHP with heat recovery. It is valid for the first two periods, it should rise to 948 and 2133 LCH_4/d in the third scenario.

4.4 Life Cycle Assessment results

In this section we answer to the research questions defined before here recalled.

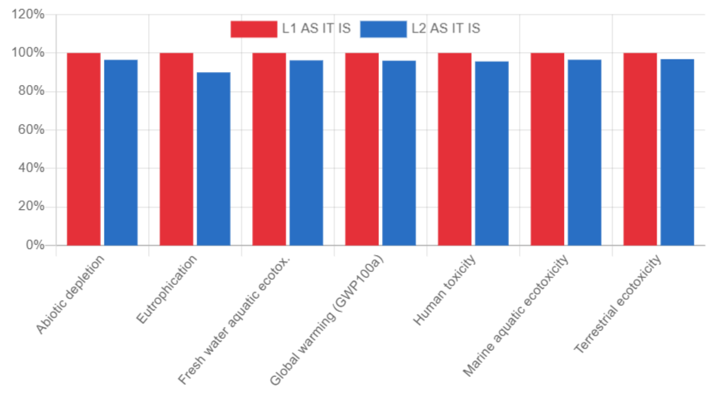
- Which are the environmental impacts of the current configuration of Peschiera Borromeo WWTP?
- In the two water lines, the designer made different technological choices: conventional activated sludge process VS biofiltration or compact VS extensive footprinting system, for instance. How does it affect the overall environmental impact? Are there significant disparities between the two lines contributions?
- How do environmental impacts change when irrigation systems use wastewater?

The first two questions are addressed within section 4.4.1, while the last one in section 4.4.2. Section 4.4.1 reports the results obtained in the early stages of the research when a simplified approach was carried out.

4.4.1 OPENLCA application results

In this section are visualized the outcomes of the software calculation. It is possible now to compare the environmental impact of the two water lines. They consist in different technological solutions addressing the same objective. It is crucial to highlight that the influent and effluent concentrations are similar within the two waterlines, so the volumetric functional unit guarantees a proper comparison.

First the outcomes obtained through the CML 2001 assessment method are reported, in analytical form (**Table 4-39**) and in bar chart (Figure 4-29) where for each impact category, the maximum result is set to 100%, and the result of the other line is displayed in relation to this result.



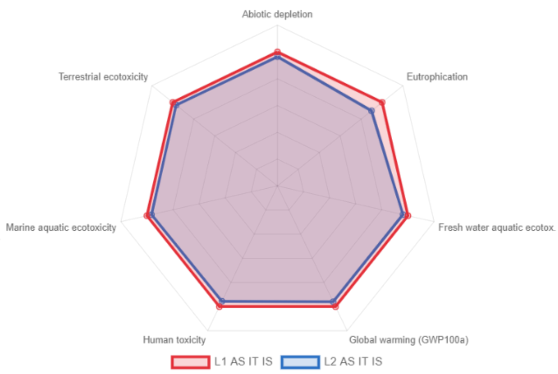


Figure 4-29. Bar chart of L1 VS L2 LCIA relative results based on CML 2001Figure 4-30 – Radar chart of L1 VS L2 LCIA relative results.

Table 4-39. LCIA results based on CML2001 for the AS IT IS configuration.

Indicator	L1 AS IT IS	L2 AS IT IS	Unit
Abiotic depletion	1.13138e-8	1.09100e-8	kg Sb eq
Eutrophication	8.50784e-3	7.65013e-3	kg PO_4--- eq
Freshwater aquatic ecotox.	7.38278e-5	7.09840e-5	kg 1,4-DB eq
Global warming (GWP100a)	1.32991e-1	1.27616e-1	kg CO_2 eq

Human toxicity	2.98512e-3	2.85225e-3	kg 1,4-DB eq
Marine aquatic ecotoxicity	5.22890e+0	5.04554e+0	kg 1,4-DB eq
Terrestrial ecotoxicity	3.46466e-5	3.35426e-5	kg 1,4-DB eq

The contribution of the L1 water line is the most significant in all the impact categories analyzed. L2 treatments employ only NaOH for the grease neutralization and the Al2O3 for the chemical phosphorus removal. On the other hand, the L1 water line, using PAA for disinfection and external carbon source for denitrification, implements more chemical transport than L2 ones. It results in a higher impact. Figure 4-31 clarifies the concept.

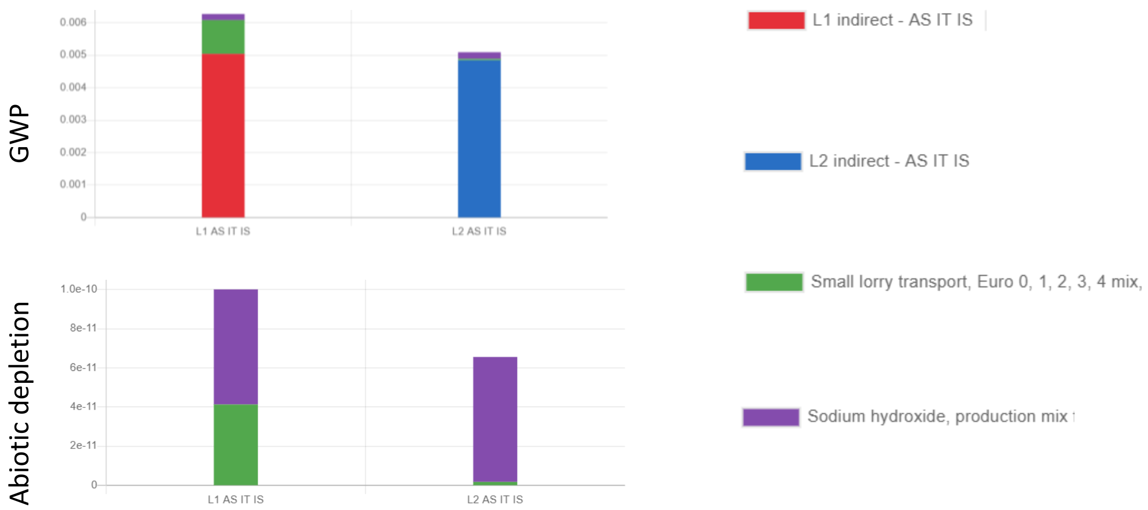


Figure 4-31. Examples of how every single process contributes to the L1 VS L2 LCIA, excluding electricity production.

The foreground system directly affects only the global warming potential through the direct GHG emissions of the biological stages, and the eutrophication thanks to the emissions in water of nitrogen and phosphorous compounds. For those impact categories, the outcomes of both lines are of the same order of magnitude. The back-ground process of electricity production strongly affects almost all the investigated categories, as shown in Figure 4-32.

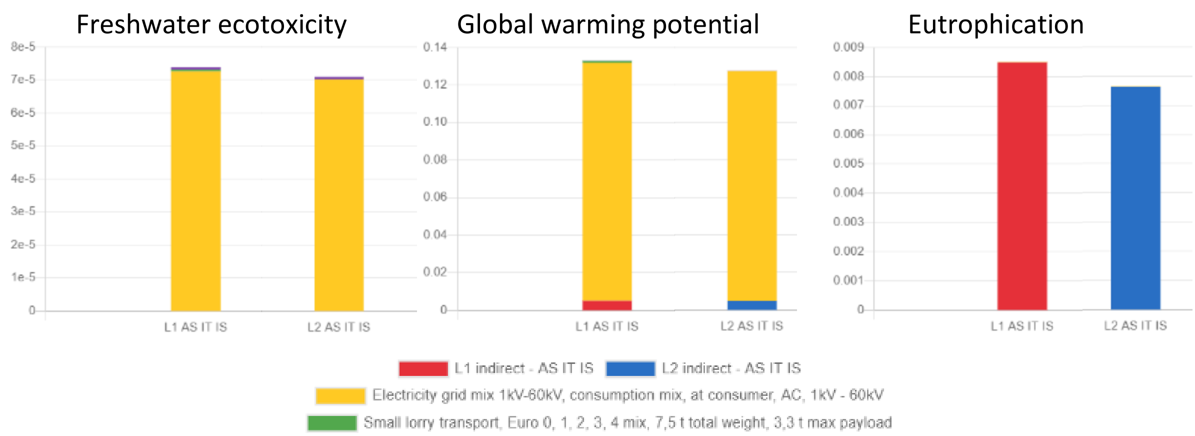


Figure 4-32. Processes contribution in the L1 VS L2 LCIA results based on CML2001 method

Figure 4-33 and Figure 4-34 show, instead, the analytical LCIA results based on the EDIP 2003 assessment method. Like the previous results, the L1 water line provides higher impacts. It is not valid for the aquatic eutrophication since the L2 effluent has a higher P-content (0.7 mg/l) than the total P discharged with L1 (0.5 mg/l).

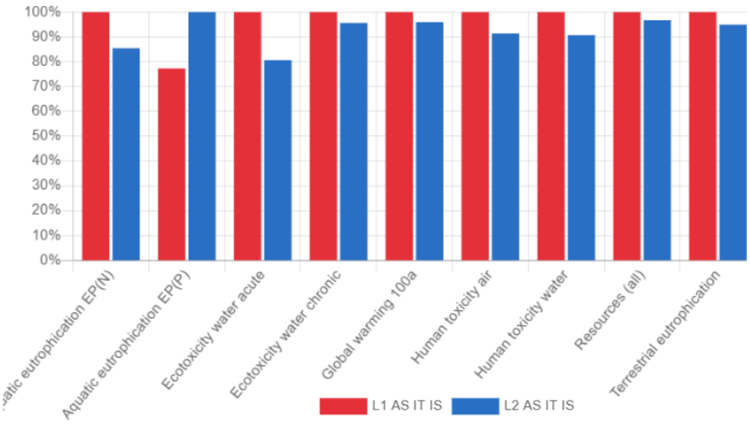


Figure 4-33. Bar chart of L1 VS L2 LCIA relative results based on EDIP 2003

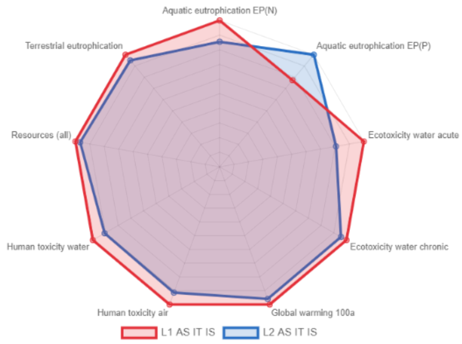


Figure 4-34 – Radar chart of L1 VS L2 LCIA relative results.

Since the EDIP assessment method also includes the characterization factors for heavy metals, the foreground system affects the aquatic eutrophication, global warming, and even the toxicity-related categories, as in detail listed in Table 4-40. Additionally, electricity and NaOH productions give a similar contribution to both water lines. On the other hand, the transportation process impacts more on the L2 system since more chemicals are needed for the treatment. This outcome is consistent with the previous results based on CML 2001 LCIA method.

Table 4-40. L1 VS L2 LCIA results detailed on the process contribution according to EDIP 2003.

		L1 SYSTEM				**L2 SYSTEM**			
		L1 indirect	Electr. prod.	Small lorry	NaOH prod	L2 indirect	Electr. prod.	Small lorry	NaOH prod
R	PR2004		7.89E-05	6.90E-10	1.31E-08		7.63E-05	6.33E-15	1.42E-08
AE N	kg N	6.85E-03	1.45E-05	7.91E-07	3.75E-08	5.85E-03	1.40E-05	7.26E-12	4.07E-08
AE P	kg P	6.09E-04	5.40E-09	3.99E-10	5.29E-10	7.87E-04	5.22E-09	3.66E-15	5.75E-10
TE	m^2		7.47E-05	1.47E-06	1.70E-09		7.22E-05	1.35E-11	1.84E-09
EWA	m^3	1.93E+01	1.62E-01	1.15E-03	2.39E-04	1.56E+01	1.56E-01	1.05E-08	2.60E-04
EWC	m^3	1.03E+02	1.58E+00	1.12E-02	2.38E-03	9.89E+01	1.53E+00	1.03E-07	2.58E-03
GWP	kg CO_2eq	4.87E-03	1.26E-01	1.04E-03	1.82E-04	4.69E-03	1.22E-01	9.55E-09	1.98E-04
HTA	person	6.88E-01	2.1E+02	1.3E+01	5.44E-02	6.64E-01	2.1E+02	1.21E-04	5.90E-02
HTW	m^3	1.83E+0	1.05E-01	4.38E-04	3.11E-03	1.66E+0	1.01E-01	4.02E-09	3.38E-03

Now, the result of comparative LCA on water reuse, defined in section 3.5.1, are interpreted.

Table 4-33 and Figure 4-36 show the LCIA results based on the CML 2001 assessment method.

The effects of the INDIRECT/DIRECT scenario differ from the AS IT IS configuration only for the eutrophication indicator. The inputs values of both life cycle inventories are the same. On the other hand, the output emissions affect the freshwater and the terrestrial environment when the indirect or mixed reuse method is applied, respectively. However, only the nutrients concentration, within the CML 2001 characterization, causes environmental impacts. The direct reuse scenario, instead, reaches the highest indicator values since more chemicals in L1 or more electricity in L2 is required to achieve a discharge limit below 10 CFU/100 ml of E.coli. Any other physicochemical parameter of treated wastewater changes within the three investigated scenarios.

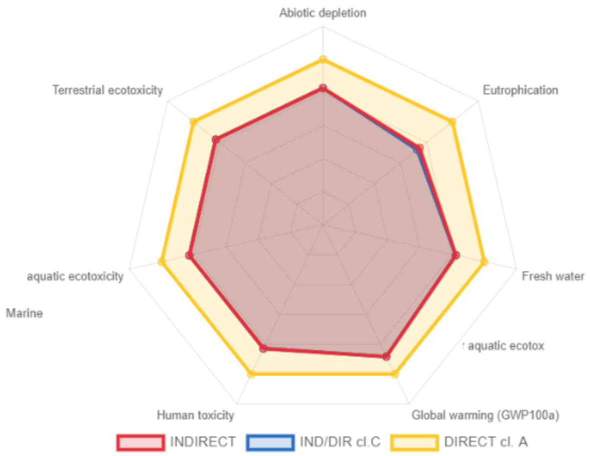


Figure 4-35. Radar chart of REUSE scenarios results. CML 2001

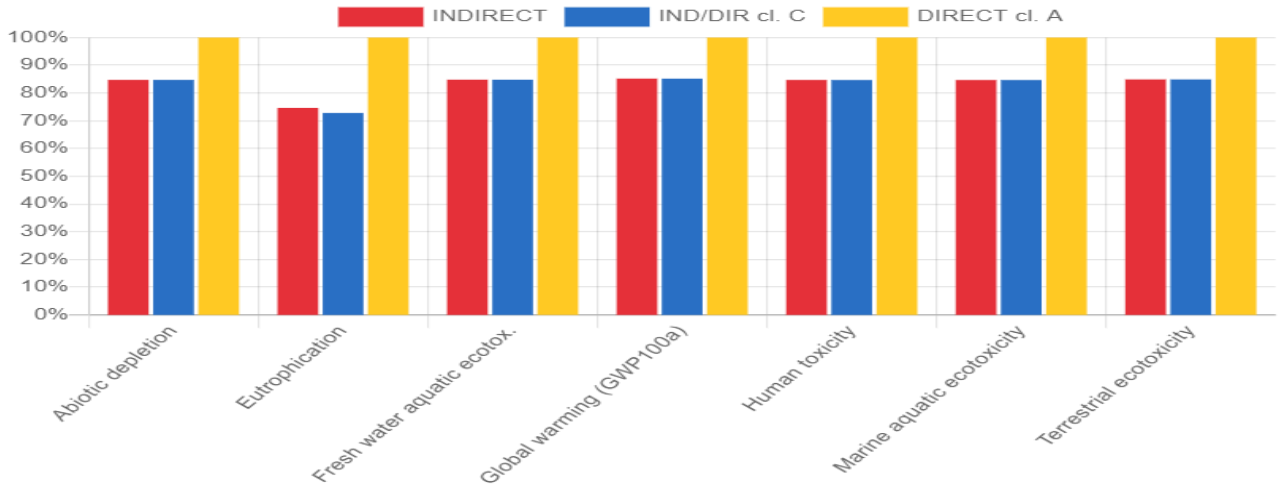


Figure 4-36. Bar chart of REUSE scenarios results. CML 2001

Figure 4-38 shows the LCIA results based on EDIP 2003. The indirect scenario significantly impacts on the aquatic eutrophication, the ecotoxicity via water, and human toxicity via water.

The discharge in the Lambro river justifies this pattern. On the other hand, the soil-related indicators suffer mainly from the effluent destination for crop irrigation. The direct reuse method provides the highest impact for the terrestrial eutrophication, ecotoxicity, and human toxicity via soil. Results show, as expected, that the contribution of enhanced tertiary treatment increases the GWP and resource indicator, as well the human toxicity via air. It is mainly related to the back-ground processes influence.

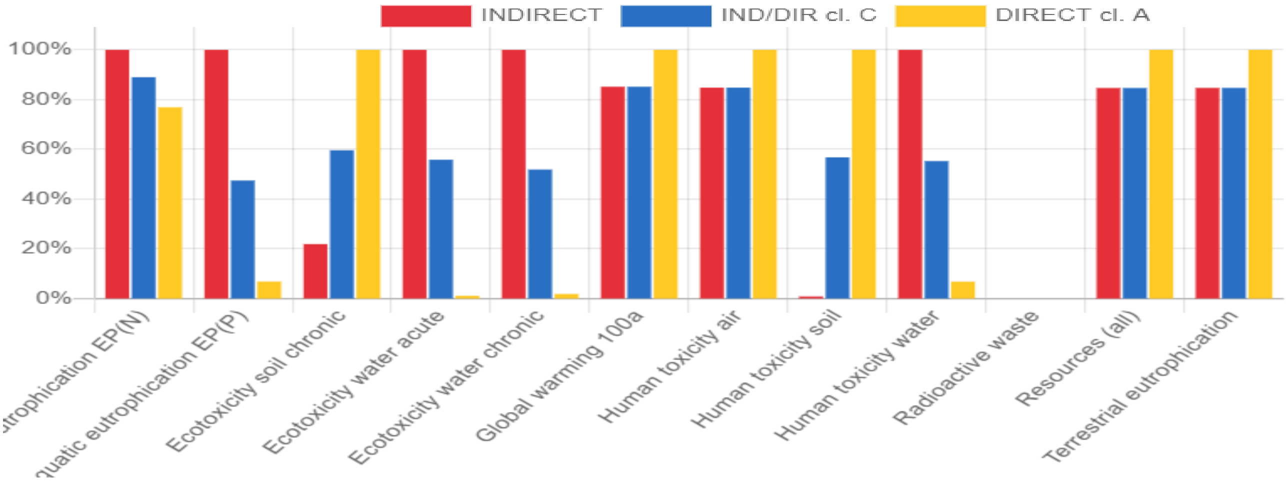


Figure 4-37. Bar chart of REUSE scenarios results. EDIP 2003

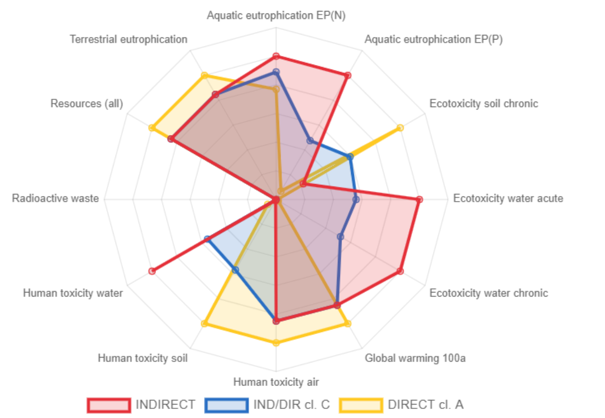


Figure 4-38. Radar chart of REUSE scenarios results. EDIP 2003

Even for the REUSE scenario comparison, the EDIP 2003 assessment method better characterizes the toxicological impact.

So far, the main objective of this work was to start to be confidential with Life Cycle Assessment approach and the instruments, like the OpenLCA software, that support us in the calculations.
Within this first phase, we included lots of simplifications. We used a free database, and its limitations were explained previously. However, the implementation of the Ecoinvent database will solve this aspect. The impact of using $FeCl_3$ instead of dosing Al2O3, for instance, will be assessed.
Additionally, in the next stage, a more complex system boundary must be evaluated both for the water lines comparison and the evaluation of different reuse scenarios. For example, we should expand the system to include the benefits of:

- employing sludge-based fertilizer, instead of a mineral one.
- Reusing wastewater instead of another source of water.

We also want to include the impact deriving from the construction phase of the UWWTP, and therefore, we need to establish the lifespan and collect new information.

Looking at the assessment phase, we saw how relevant the applied methodology could influence the final effects. For the next phase, we have to accurately choose the assessment method according to the recent development and the main goal and scope of this study.

Such improvements are the subject of the next sessions.

4.4.1 Peschiera current state results

This final phase of results interpretation refers to the Life Cycle Assessment of Peschiera Borromeo. It is investigated the current environmental performance of the plant, as it is. This should outline the more impacting stages, with a focus on possible differences between waterline L1 and the L2.

As expected, the construction phase provides a minimum contribution to all the investigated categories. Any evident difference must be highlight also between the two waterlines. On the contrary, the direct emissions from the plant strongly affect the freshwater eutrophication potential expressed as kgP-eq and slightly impact on climate change category. In the first case, direct emissions correspond to the discharge of phosphorus still present in the effluent of the plant. While the kgCO_2-eq referable to direct emission is the GHGs produced during the biological process (within the secondary treatment and sludge handling) as well as from biogas utilization in CHP and boilers.

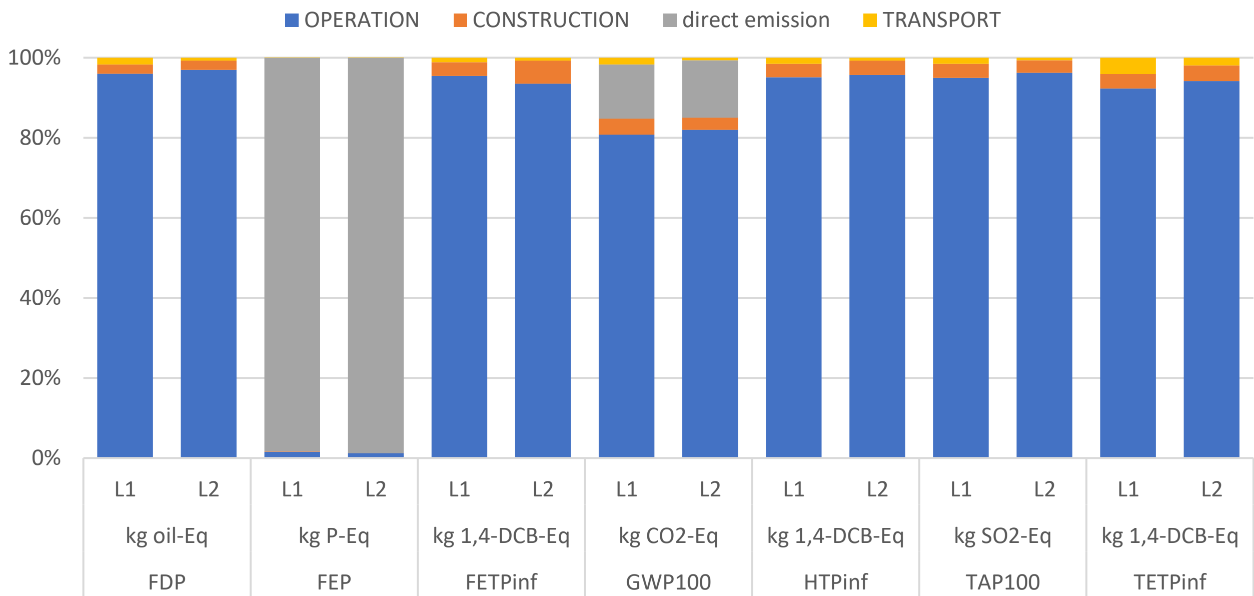


Figure 4-39. Contribution of construction and operation in each impact category. Bar chart.

Figure 4-41 and Figure 4-40 are two different way to represent the same data. They confirm that there is no evidence of a best-performing line.

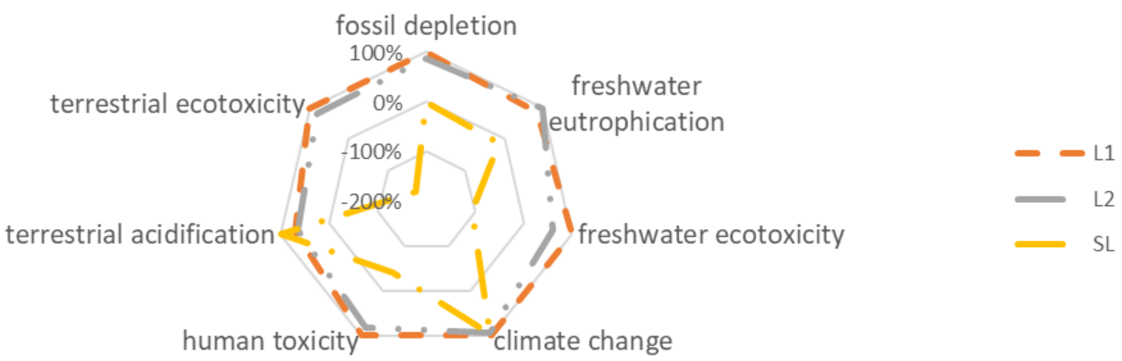


Figure 4-40. Contribution of construction and operation in each impact category. Radar chart

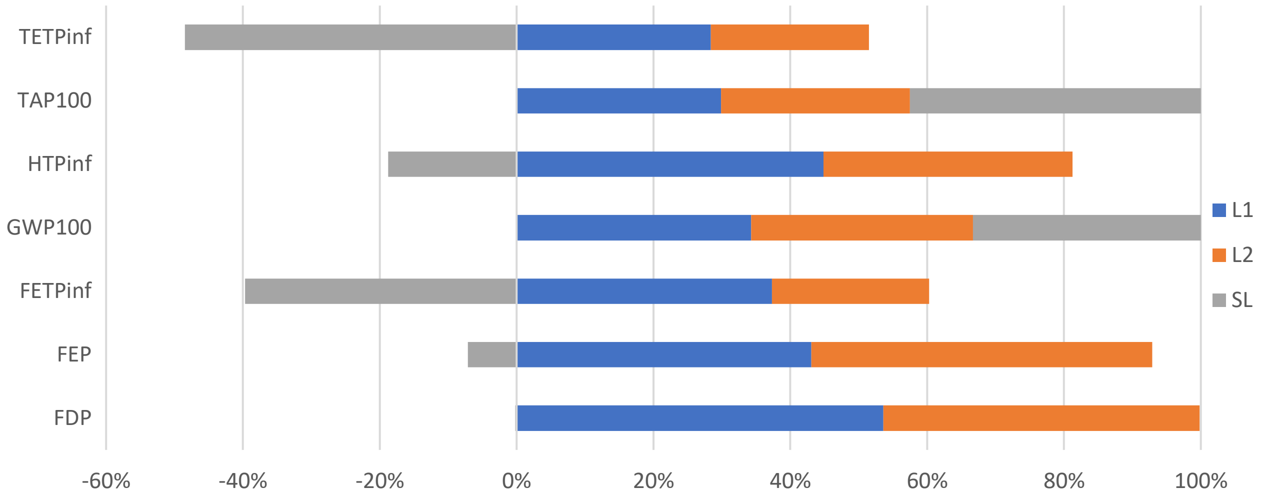


Figure 4-41. Contribution of each water line and sludge in each impact category.

The sludge line, instead, takes advantages of the electricity and fertiliser credits. The latter produces the greater offset in all the impact categories as shown in Figure 4-42. On the other hand, the life cycle phases with the highest impact are the secondary processes and sludge treatment.

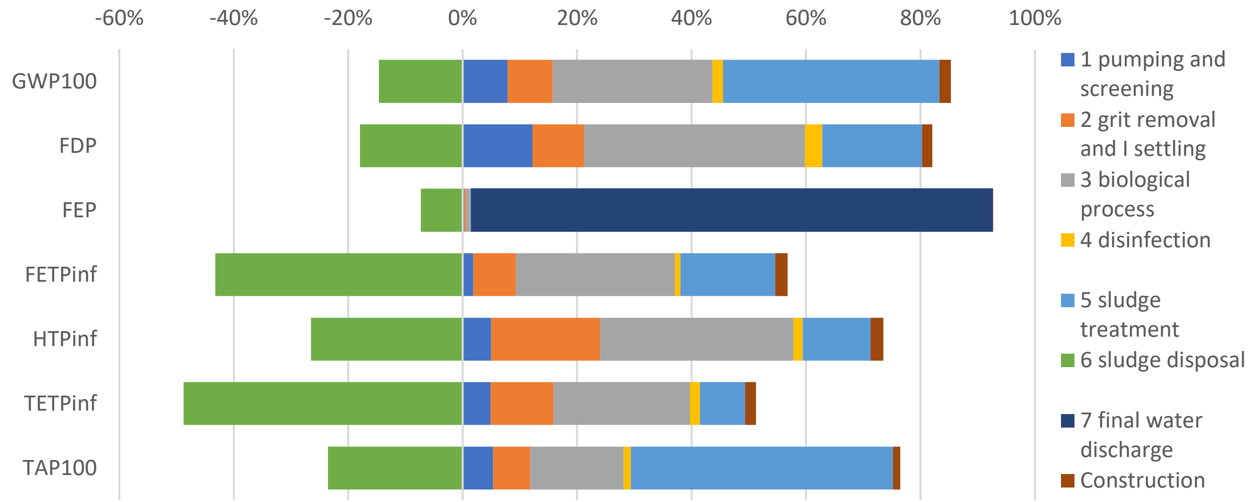


Figure 4-42. Contribution of each life cycle phase to the environmental impact.

A detailed contribution analysis helps to identify the relative contribution of each subprocess (e.g. biological process, disinfection) and each type of input (e.g. electricity, chemicals, infrastructure) to the respective environmental indicator (Remy et al., 2013). Like (Beavis & Lundie, 2003), the UV disinfection of L2 impacts more than the chemical alternative due to the higher energy consumption. While the contribution of replacing the UV lamps is negligible. It is worth mentioning that the "ultraviolet lamp production, for water disinfection" dataset of Ecoinvent v3.6 is quite limited since only includes materials inputs only. It excludes forming of materials, energy inputs for production and assembly, water consumption, wastes and emissions to environment that could occur during fabrication of the lamp.

Previous published works already identified that electricity consumption, chemicals and primary solids are the main contributors to climate change and fossil depletion (e.g. Hospido et al., 2004; Rodriguez-Garcia et al., 2011) and nutrients discharged to the receiving water bodies (defined as direct emission in this study) are the most important contributors to eutrophication (e.g. Hospido et al., 2008).

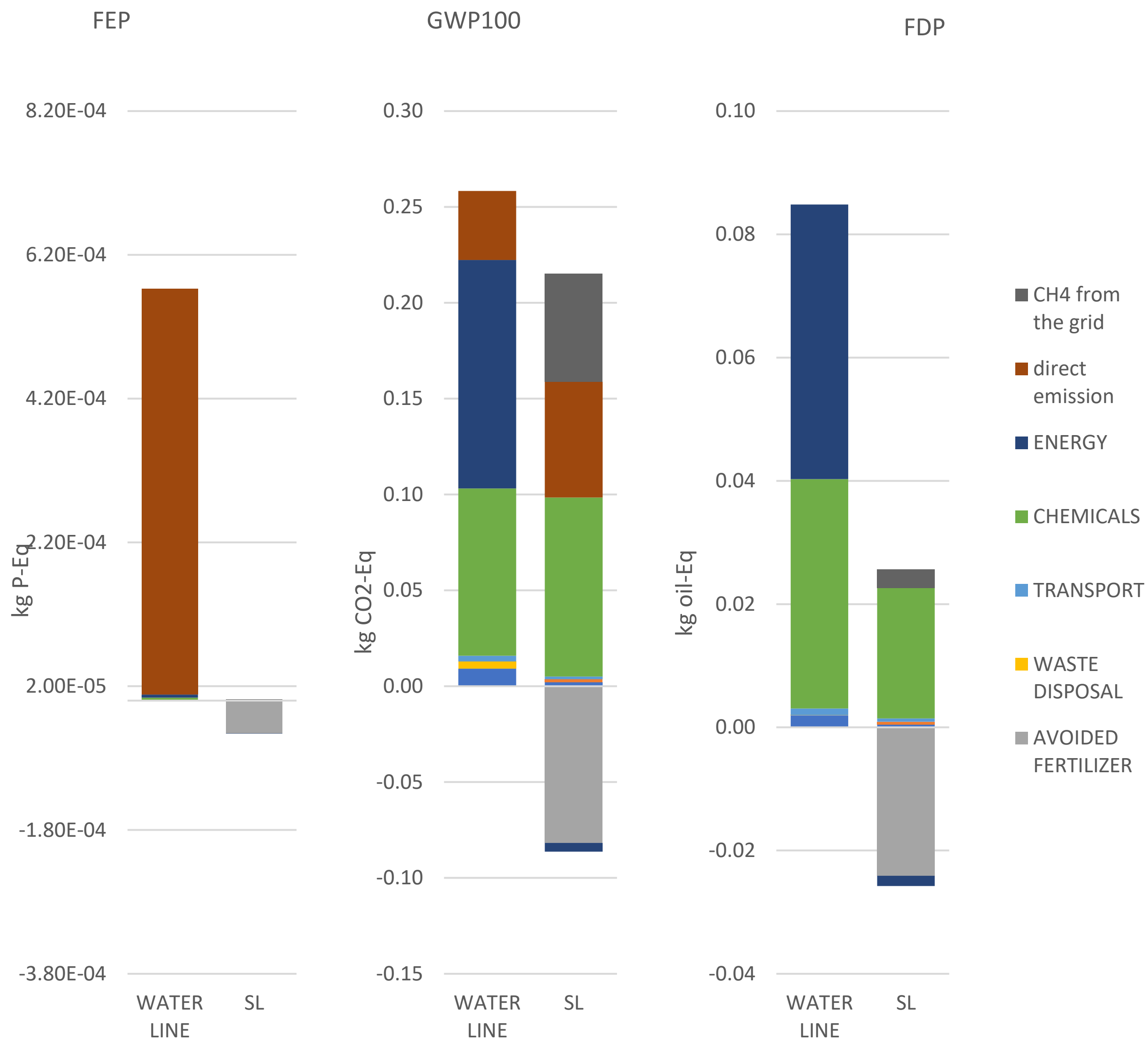


Figure 4-43. Comparison of environmental performance between water and sludge line.

Emissions generated by energy production influenced the climate change potential (Figure 4-44. Characterized impact of climate change.Figure 4-44), in particular, due to the CO_2 emitted from fossil fuels. Excluding the sludge line, being the phase with higher electricity demand (10.6 kWh/m^3), the biological process reported worse on this impact category followed by the pumping. The chemical production is a further main contributor to the GWP. The addition of PAC to chemically remove P within the SEDIPAC © shift the impact from phase 3 to phase 2 in L2.

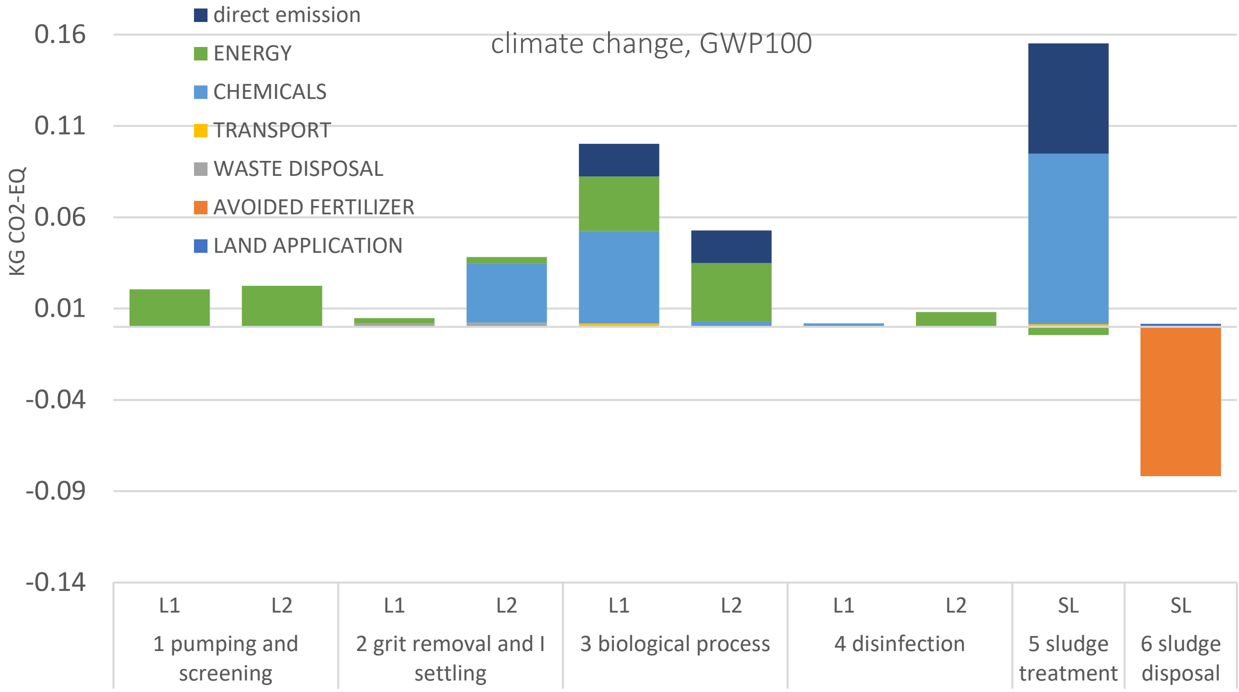


Figure 4-44. Characterized impact of climate change.

On the whole, L1 and L2 waterlines has comparable impacts while the overall waterline impacts more than the sludge line. This takes advantage of beneficial effect of producing electricity on-site and to apply an organic fertilizer like the defecation lime that decrease the energy and resource demand for mineral fertilizer production.

4.4.2 Comparison of reclamation solutions results

The environmental impact characterization results of scenarios described in section 3.5.3 are here discussed.

Concerning the Baseline, a summary of life cycle characterization results is shown on Figure 4-45. The relative contributions of different phases of the plant's life cycle to the respective environmental impacts categories are shown in Figure 4-45b.

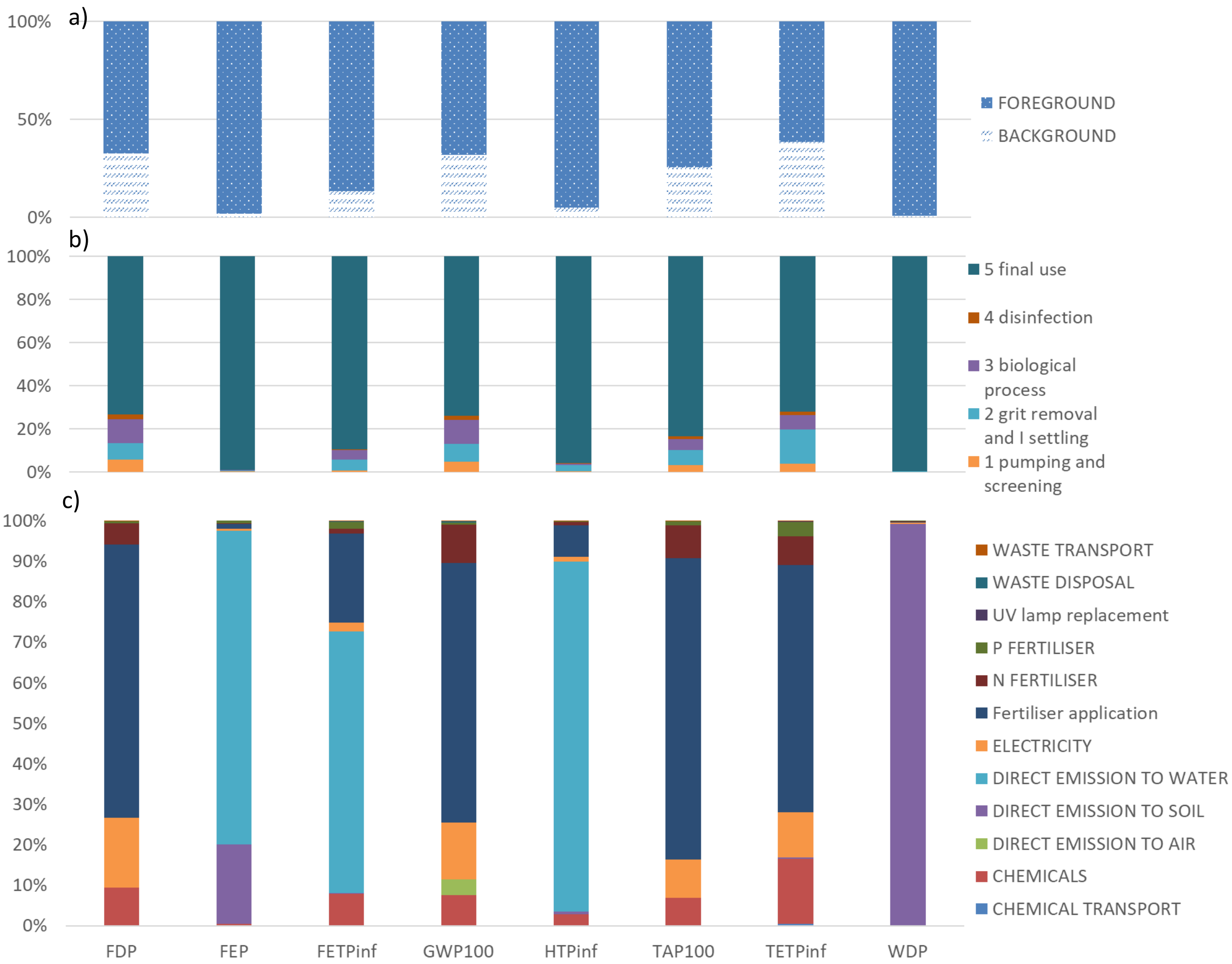


Figure 4-45

The fertilizer application has a significant impact contribution to global warming, fossil depletion and terrestrial eutrophication potential. While the the direct emissions to water contribute significantly to freshwater eutrophication, freshwater toxicity and human toxicity. As concern, the foreground impact is dominating among all impact categories.

As demonstrate in Figure 4-46, the baseline scenario represents the most significant impact in most impact categories, except for HTP and TETP

In general, water depletion is only affected by the no reuse of wastewater in the Baseline scenario. It will be no more investigated. The lowest energy consumption of Scenario 3 leads to less terrestrial acidification and fossil depletion since they are strongly related to fossil fuel combustion for transport and energy production. The dissolved CH_4 of permeate (Scenario 3) lowers the gap in terms of climate change potential between the more energy-intensive treatment chain (Baseline, Scenario 1 and 2) and AnMBR.

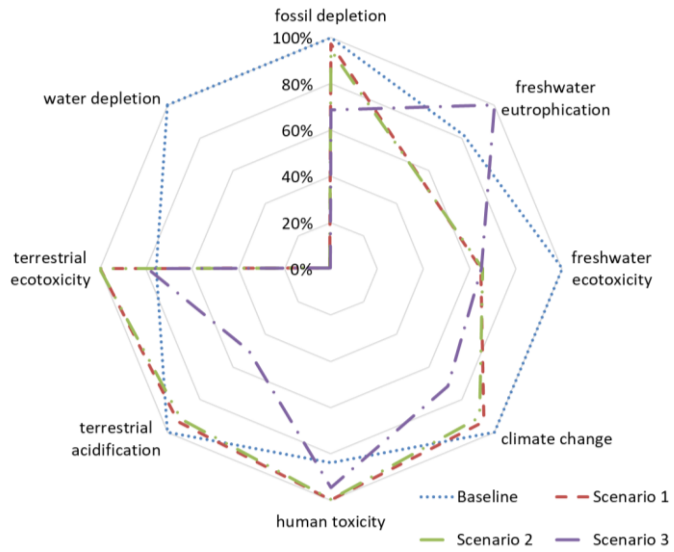


Figure 4-46.Comparison of relative impact on the investigated category in a radar chart form.

Analyzing the toxicity-related categories and as we may expect, the toxicity in the water environment is more influenced by the Baseline where the traces of heavy metals present in the wastewater flows to the river. While the reuse scenarios contribute to increasing the the terrestrial and human toxicity. Then, the lower impact of Scenario 3 as HTP and TETP is caused by the avoided production and spreading of fertilizer.

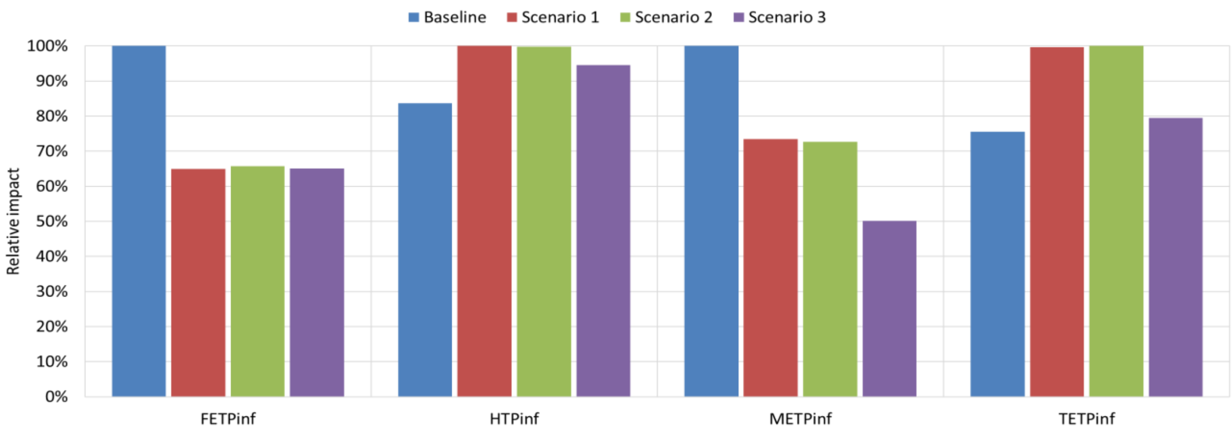


Figure 4-47. Relative impact of different scenarios in the toxicity impact categories

As concern the Scenario 1 (UV disinfection at higher UV dosage), although there is higher electricity consumption GWP show a 7% net negative wich is due to avoided emissioins as a result of the displaced fertilizer. At the same time FEP is significantly reduced due to the avoided direct emission to water. Similarly, a clear trade-off between FETP on one side and HTP and TETP on the other is caused by the higher direct emissions to soil. It is also evident in Scenario 2 since the disinfection step does not influence the heavy metals removal. Scenario 2 produced an additional impact in GWP and FDP as a result of chemicals but it is displaced by the avoided impact from reduced fertilizer and energy savings.

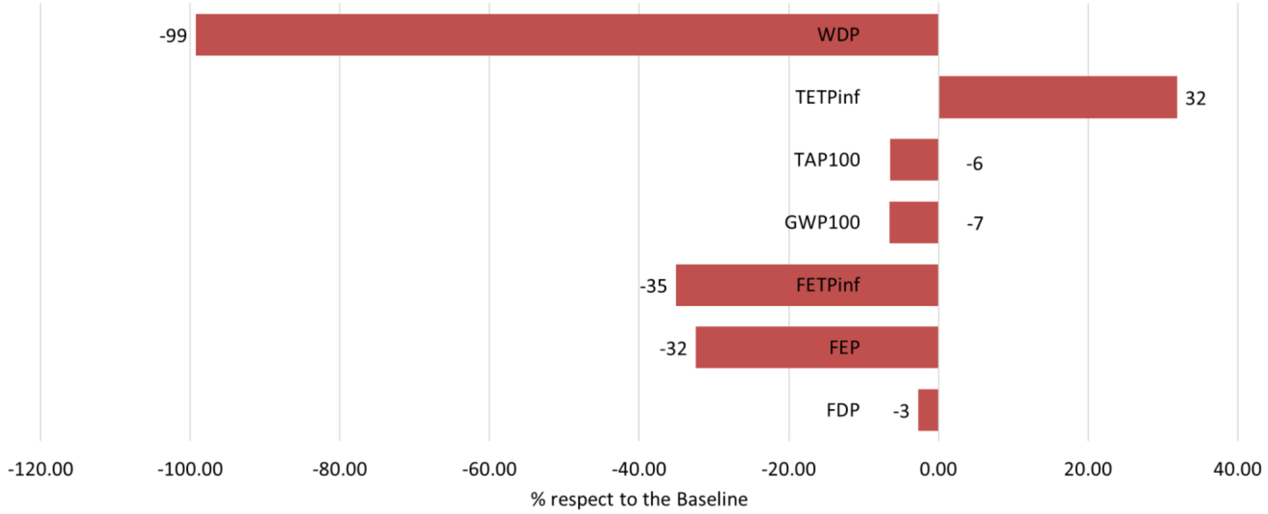


Figure 4-48. The relative impact of Scenario 1 compared to the Baseline.

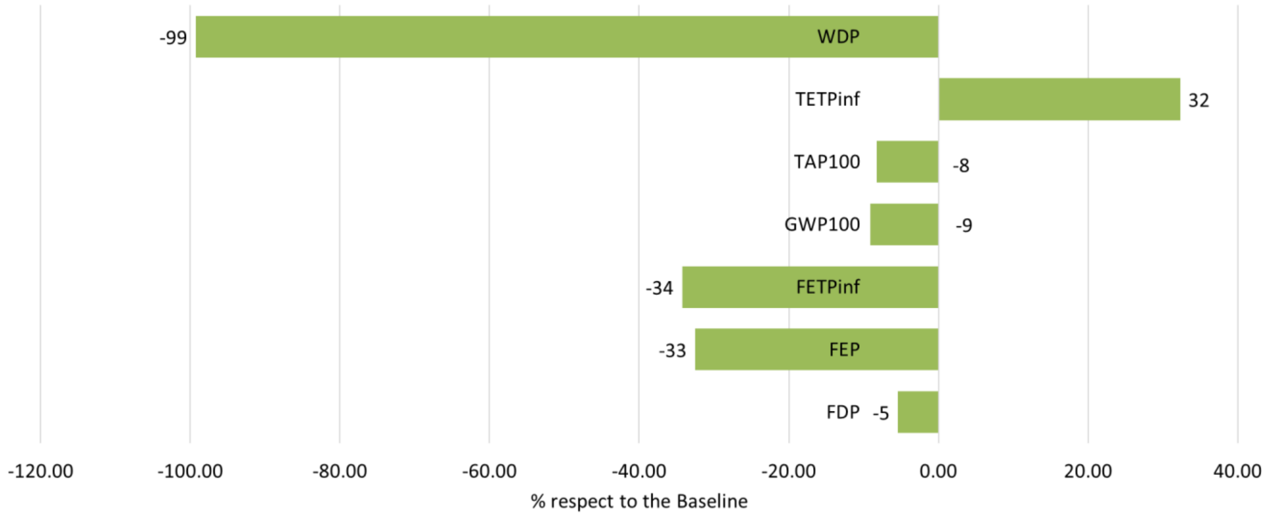


Figure 4-49. The relative impact of Scenario 2 compared to the Baseline.

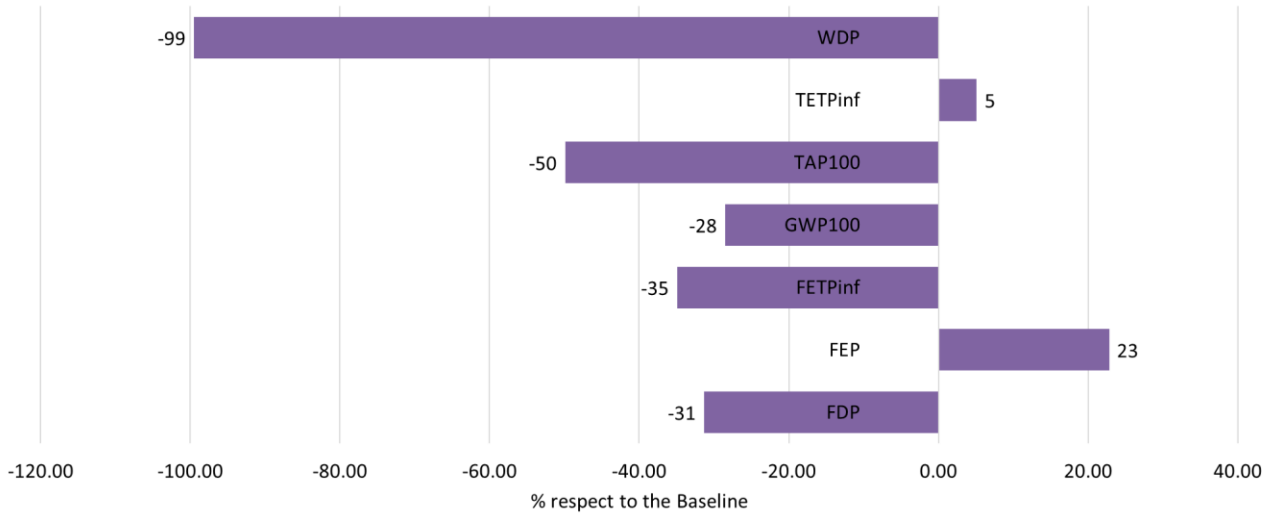


Figure 4-50. The relative impact of Scenario 3 compared to the Baseline.

Next, we investigate the FEP and GWP100 through a break-down analysis. In this way, it is easier to identify the relative contribution of each subprocess (e.g. biological process, disinfection) and each type of input (e.g. electricity, chemicals, transport) to the respective environmental indicator.

Freshwater eutrophication is influenced by the phosphorous content of released water. When reclaimed water is partially reused and therefore the nutrient load is shared with both soil and water compartments, is evident an FEP reduction (Scenario 1 and Scenario). It is not valid for the third Scenario since an excess of nutrient-rich water is produced and hence, discharged to the river.

The direct emission (in violet in Figure 4-51) is the main contributor to the freshwater eutrophication but with the permeate 0.9 kgP-EQ are wasted in the water against 0.5 kgP-EQ of Scenario 1 and Scenario 2.

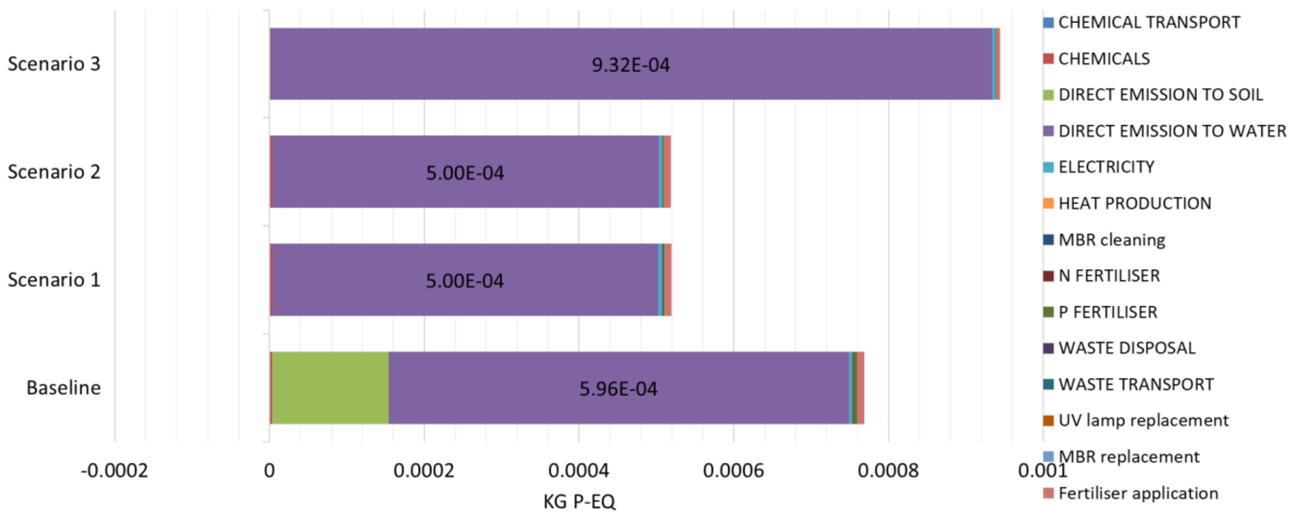


Figure 4-51. Freshwater eutrophication potential (FEP) of compared scenario

Since we include within the boundary even the crop production, unlike from WWTP LCAs, the main contributor to the GHGs emissions is the fertilising spreading. The related Ecoinvent dataset represents an example of a typical fertilizing process through a fertiliser broadcaster of 500l carrying capacity. It includes the diesel fuel consumption and the amount of agricultural machinery and of the shed attributed to broadcast fertilization. It was also taken into consideration the amount of emissions to the air from combustion and the emission to the soil from tyre abrasion during the work process. The following activities were considered part of the work process: preliminary work at the farm, such as attaching the adequate machine to the tractor; driving to the field (with an assumed distance of 1 km); fieldwork (for a parcel of land of 1 ha surface); driving to the farm and concluding work, like uncoupling the machine.

In Scenario 3, any addition of mineral nitrogen fertilizer is required and at the same time, the “organic substitute” is brought to the crop site through the water itself. It explains why in the fertigation case the offset of fertilizer production is more relevant than sludge land application. In that case, a fossil-based process must be taken into account anyway.

In terms of GWP100, all three proposed reclamation technologies have a beneficial effect on GHGs emission. The increase of energy and chemical demand in Scenario 1 and Scenario 2, respectively, is balanced with the reduced request of fertilizer. The AnMBR system, however, gives the best performances.

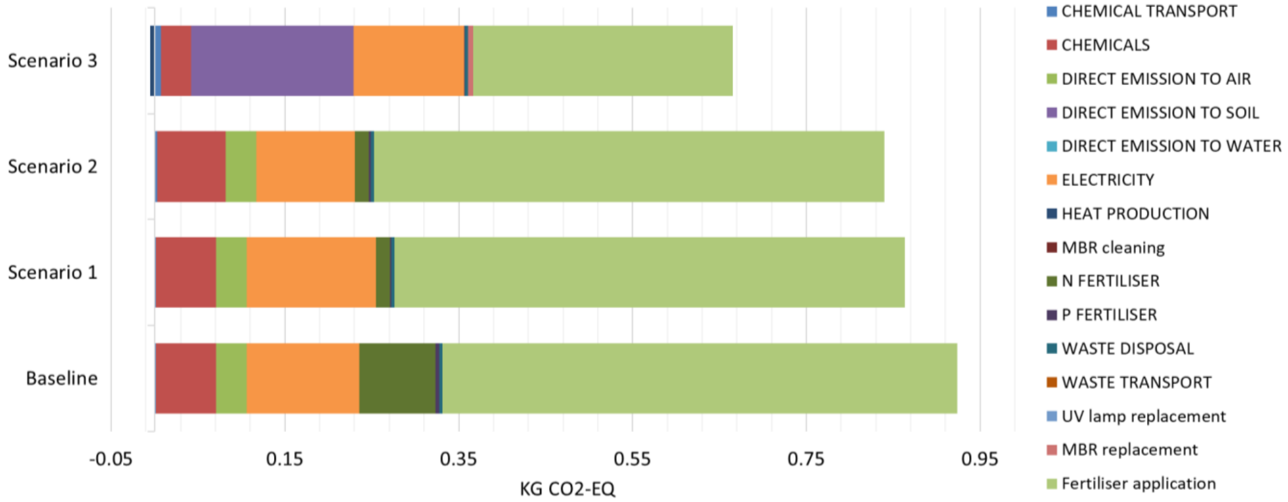


Figure 4-52. Comparison of different scenarios in the climate change category.

Excluding the impact of fertilizing, the process phase with the worst environmental performance is the biological process in case the BIOFOR © solution is adopted. While in Scenario 3, the energy demand of the filtration process (4th phase) summed to the dissolved CH_4 in the effluent cover more than 50% of the overall kgCO_2-EQ.

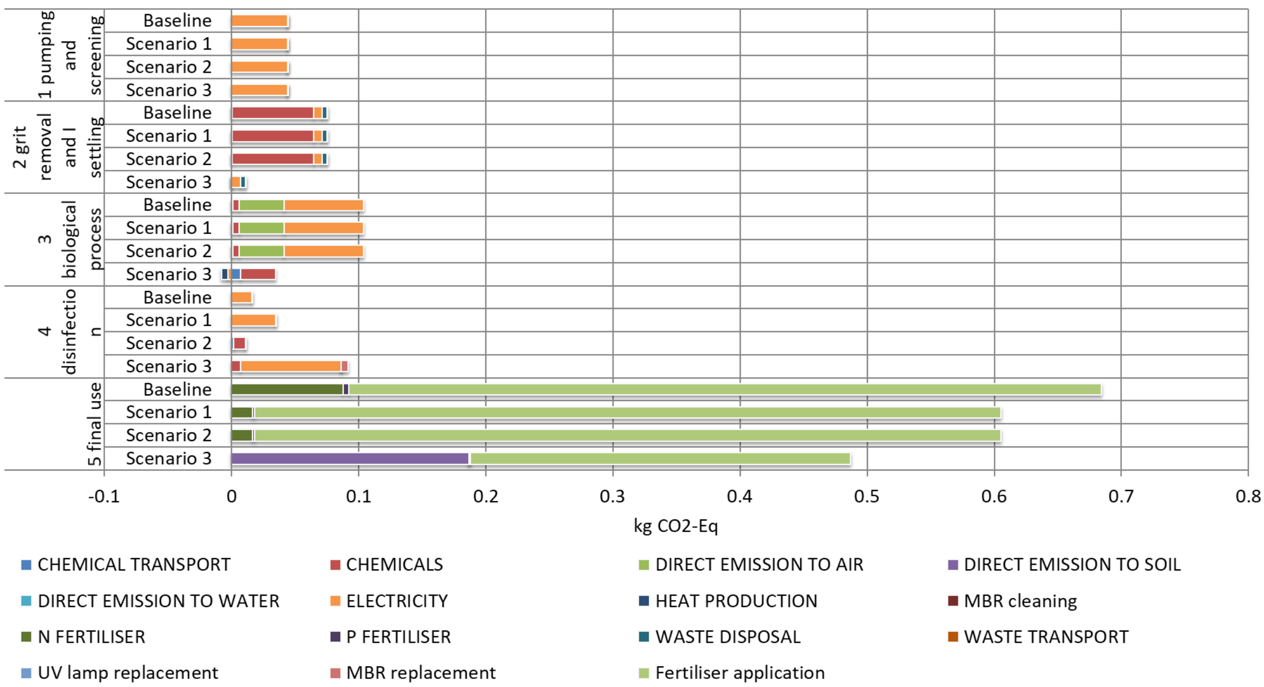


Figure 4-53. Specific contribution of process and phases to the GWP100.

Scenario 3 also causes 31% and 50% less impact than the Baseline in the fossil depletion and terrestrial acidification, respectively (Figure 4-50).

The results of the Life Cycle Costing analysis are shown in Figure 4-54 and Figure 4-55.

The third scenario that has the best environmental performances considering almost all the indicators, gives the worst outcomes in terms of economical sustainability. From a WWTP point of view, the environmental benefit of Scenario 3, however, should encompass the highest investment and operational cost of the membrane reactor. The replacement every ten years of the membrane modules contributes for 24% of the total cost in Scenario 3. To operate at flux of 10 $l/m^2/h$, we assumed to install 267842 m^2 of membrane surface to be replaced at 50€/m^2 unitary cost (Judd, 2010).

The differences between peracetic acid and UV disinfection are negligible. The increased cost for PAA supply in the second Scenario is balanced by the no need of replacing periodically expensive equipment like occurs with ultraviolet lamps. Instead, the AnMBR system required highest CAPEX cost both for the biological process (where is included the conditioning and valorization of methane) and disinfection due to the price of membrane modules itself and their maintenance.

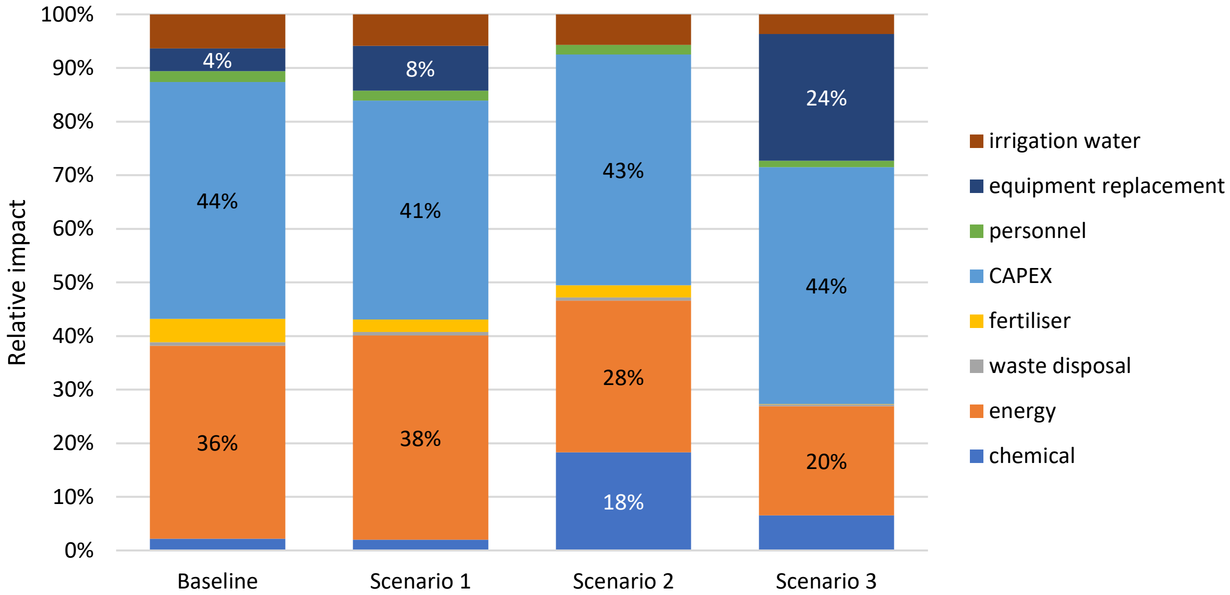


Figure 4-54. Relative impact of single cost items to the annual cost in three scenarios.

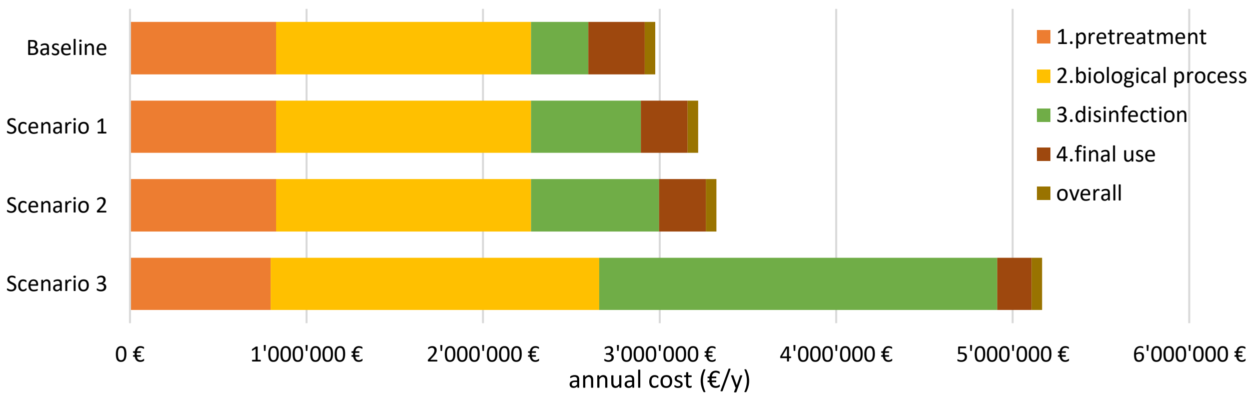


Figure 4-55. Annual cost distribution along the process phase in three scenarios.

An average of 151091 PE are served by water treatment line L2 in 2019. In the following specific annual costs are reported for each investigated scenarios. In Table 4-41, costs refer to the overall system boundaries defined for this LCC analyses, the same of LCA boundaries. Hence, they are the needed costs to treat 64282 m^3 of wastewater and irrigate and fertilize 1500 ha of crops.

Table 4-41. Annual total and specific costs for the overall system analyzed.

	u.m	*Baseline*	*Scenario 1*	*Scenario 2*	*Scenario 3*
CAPEX	€/y	1'314'415	1'314'415	1'429'507	2'282'327
OPEX	€/y	1'660'667	1'904'305	1'892'658	2'883'723
TOT	€/y	2'975'082	3'218'720	3'322'165	5'166'050
Specific cost	€/y/PE	20	21	22	34
	€/y/m^3	0.13	0.14	0.14	0.22

In the following specific costs related only to the water treatment are reported without considering the possible revenue of reclaimed water selling.

Table 4-42. Annual total and specific costs for wastewater treatment.

	u.m	Baseline	Scenario 1	Scenario 2	Scenario 3
CAPEX	€/y	1'314'415	1'314'415	1'429'507	2'282'327
OPEX	€/y	1'341'540	1'579'589	1'567'942	2'631'023
TOTAL COST	€/y	2'655'955	2'894'004	2'997'449	4'913'350
Specific cost	€/y/PE	18	19	20	33
	€/y/m^3	0.11	0.12	0.13	0.21

If we assume to sell the reclaimed water to the farmers at the same water price currently paid to the irrigation association, a 7%, 6% and 4% of savings should be obtained in the Scenario 1, Scenario 2 and Scenario 3, respectively (Table 4-43).

Table 4-43. Annual otal and specific costs for WWTP in case of reclaimed wastewater selling.

	u.m	Baseline	Scenario 1	Scenario 2	Scenario 3
REVENUE	€/y		189'048	189'048	189'048
NET COST	€/y	2'655'955	2'704'957	2'808'401	4'724'303
Specific cost	€/y/PE	18	18	19	31
	€/y/m^3	0.11	0.12	0.12	0.20

Finally, the cost for the farmers are reported in Table 4-44. From the farmer's point of view, since the cost of water remains constant throughout the different scenarios, the third Scenario gives the highest saving (Table 4-44). Indeed, the fertilizing cost is almost equal to zero Figure 4-54. Therefore, if the water fee shall be modulated on the nutrient content, the payback period of AnMBR installation will go down as well the specific cost per inhabitans.

Table 4-44. Annual and specific cost for the farmers in three scenarios.

	u.m	Baseline	Scenario 1	Scenario 2	Scenario 3
TOTAL	€/y	319'127	264'716	264'716	192'700
specific	€/y/ha	213	176	176	128

In the following a brief recap of the interpretation results.

As it can be seen in Figure 4-52, the absence of mineral fertilizers needs and the energy recovery as biogas constitutes the major CO_2 emission prevented thanks to the anaerobic treatment of the wastewater. These outcomes demonstrate that a combination of AnMBR with fertigation can notably reduce the environmental impact in comparison with conventional treatments such as CAS system (Baseline, Scenario 1 and Scenario 2). Furthermore, these outcomes highlight the need to change the traditional way we see WWTP since they can be considered as a resource recovery facilities in which not only water, nutrients and energy are recovered but also economic cost and carbon footprint are minimized. At the same time, this could report an economic benefit for farmers since they would reduce mineral fertilizers acquisition, resulting in a final economic and environmental win-win situation.

For the fertigation scenario, high environmental impacts were associated with eco- and human toxicity categories because of using reclaimed water in agricultural. If the background processes are not well documented, the increased toxicity appears to overwhelm the environmental benefits.

The impacts on eco- and human toxicity were primarily related to heavy metals application to soil. Tangsubkul et al. (2005) noted that increased impacts on terrestrial environments might be inevitable when selecting a technology that optimizes recycling of wastewater nutrients, due to the potentially higher metals loading associated with the higher nutrient recovery and reuse (Fang, et al. 2016).

In conclusion, all three configurations proposed to obtain class A water quality provide more environmental benefit than no reusing treated water. No great difference there is between operating with chemical disinfection or ultraviolet lamp. The impact of using peracetic acid is affected by the transportation conditions (distance and loading capacity of lorry), while the environmental contribution of UV disinfection is influenced by the mix of energy used. With the spreading of renewable energy, the impact of energy consumption can be upset. It is valid even in case the rate of self-produced energy in WWTP shall increase up to energy neutrality.

However, the better solution shall be the combination of AnMBR and CAS to overcome the eutrophication issue. This combination will make the modulation of the quality of the treated wastewater possible: AnMBR effluent will provide the crops with nutrients and water and CAS effluent will be used for nutrient dilution or for irrigation when only water is required. Temporal variability of the nutrients and water demands from crops will determine the flowrate partition between the two treatment lines. t can be noted that some characteristics of the AnMBR technology work in favour of this seasonality and flowrate partition, namely the fact that in the summer period when temperatures are higher, the same reactor volume will be able to treat a higher wastewater flow.

5. Conclusions

In this study, reclamation water systems are exploited through technical and assessment investigation.
The current effluent quality of both water treatment line of Peschiera Borromeo WWTP complying with class C reclaimed water may be reused in agricultural application only using irrigation method that avoids direct contact with the edible part of the crop, like the drip irrigation. Such quality still does not comply with the stricter Italian regulation currently in force. An enhancement of the disinfection step is needed. It should be sufficient to work on peracetic acid dosing (5 ppm was demonstrated to ensure a 4-log reduction) and on UV dosage (the simultaneous use of all the banks installed in the plant guarantees 80mW/cm^2).

The two water treatment lines are comparable in terms of environmental performances and there is no clear evidence to prefer one disinfection method respect the other. The chemicals demand of peracetic acid disinfection equals the electricity demand of ultraviolet lamps concerning primary energy requirements and the consequent impact on climate change, fossil depletion, terrestrial acidification. The freshwater eutrophication, expressed as kgPO4-eq, is mainly related to the nitrogen and phosphorus content of discharged water and so such tertiary steps do not contribute. On the other hand, the treatment chain of Peschiera Borromeo WWTP does not valorize the nutrient content of the wastewater. Through the denitro-nitro process, the influent ammonia is converted to inert N_2 consuming electricity and chemicals. The oxidation step (nitrification) is an energy-intensive process and external carbon source must be supplied to increase denitrification efficiency. Similarly, phosphorous is removed chemically with resource depletion and no recovery.

In this perspective, anaerobic processes are gaining more and more interest when fertigation is intended to be performed. The produced biogas can offset the energy demand for wastewater treatment while nutrients are converted to chemically available forms (e.g. ammonia and phosphate). But they required a tertiary treatment to reduce the pathogenic load, like the ultrafiltration. From a life cycle perspective, AnMBR technologies can drastically reduce the environmental impact due to the energy off-set and avoidance of fertilizer production and spreading. Particular attention must be paid to the eutrophication potential that the nutrient-rich effluent of AnMBR provides. Hence, in the design phase, the size and flexibility of the system should be accurately defined according to the water and nutrient requirements of the crops intended to be irrigated.

From the experimental investigation on the pilot-scale UASB-AnMBR, the capability of the system to release ammonia and phosphate is verified in all the configurations proposed. While the biogas production is strictly related to the operating conditions like temperature and organic loading rate OLR. At the same temperature condition, the methane production decreased by 67% operating at half of the original OLR. While at the same loading rate, an increase of 5-6 °C produces 42% more of methane.

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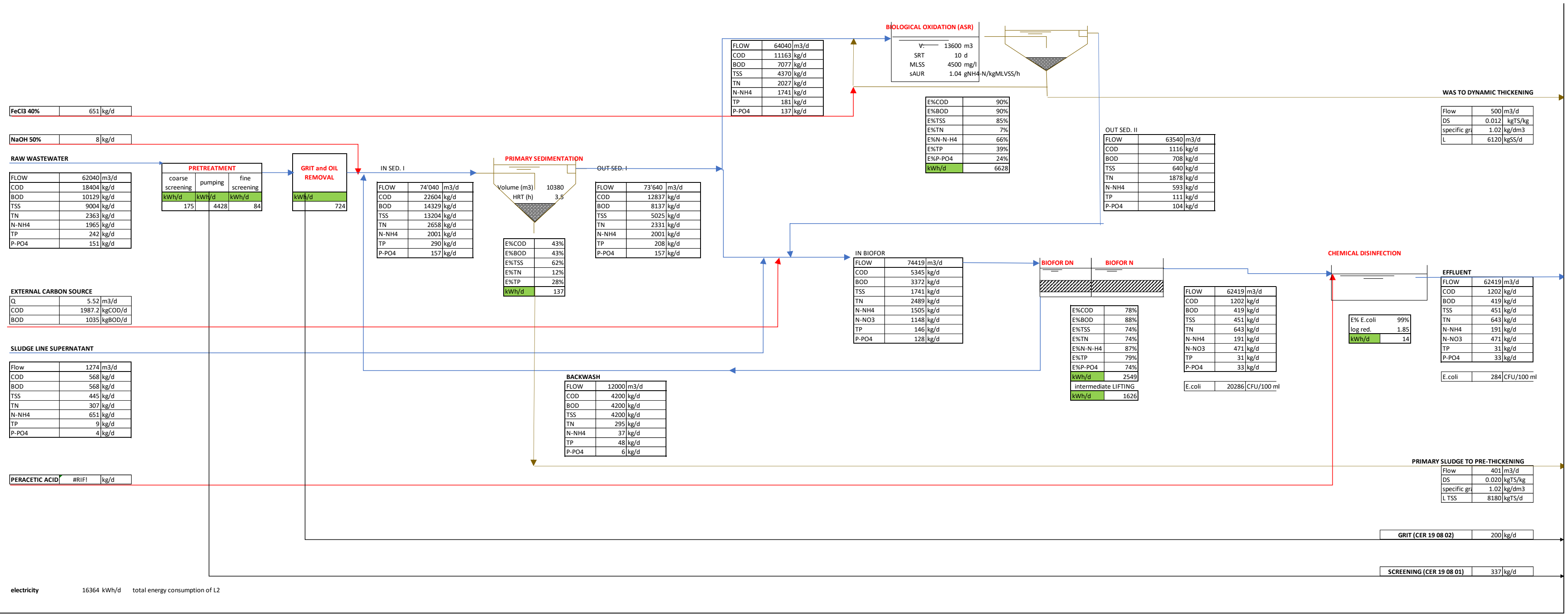
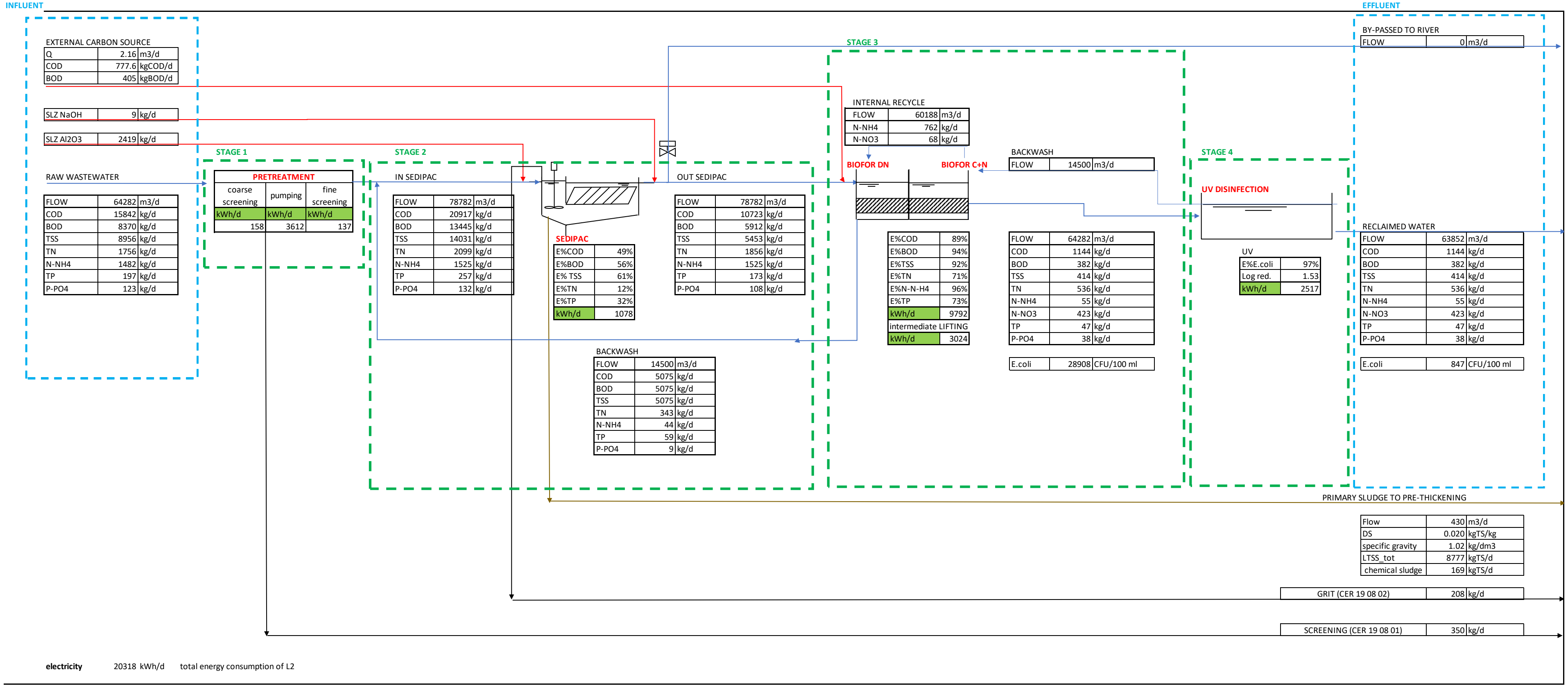
ANNEX I

Mass balance of water line L1. Peschiera Borromeo WWTP



Mass balance of water line L2. Peschiera Borromeo WWTP



EXTERNAL CARBON SOURCE

Q	2.16	m3/d
COD	777.6	kgCOD/d
BOD	405	kgBOD/d

SLZ NaOH	9	kg/d

SLZ Al2O3	2419	kg/d

RAW WASTEWATER

FLOW	64282	m3/d
COD	15842	kg/d
BOD	8370	kg/d
TSS	8956	kg/d
TN	1756	kg/d
N-NH4	1482	kg/d
TP	197	kg/d
P-PO4	123	kg/d

PRETREATMENT

coarse screening	pumping	fine screening
kWh/d	kWh/d	kWh/d
158	3612	137

IN SEDIPAC

FLOW	78782	m3/d
COD	20917	kg/d
BOD	13445	kg/d
TSS	14031	kg/d
TN	2099	kg/d
N-NH4	1525	kg/d
TP	257	kg/d
P-PO4	132	kg/d

SEDIPAC

E%COD	49%
E%BOD	56%
E% TSS	61%
E%TN	12%
E%TP	32%
kWh/d	1078

OUT SEDIPAC

FLOW	78782	m3/d
COD	10723	kg/d
BOD	5912	kg/d
TSS	5453	kg/d
TN	1856	kg/d
N-NH4	1525	kg/d
TP	173	kg/d
P-PO4	108	kg/d

BACKWASH

FLOW	14500	m3/d
COD	5075	kg/d
BOD	5075	kg/d
TSS	5075	kg/d
TN	343	kg/d
N-NH4	44	kg/d
TP	59	kg/d
P-PO4	9	kg/d

INTERNAL RECYCLE

FLOW	60188	m3/d
N-NH4	762	kg/d
N-NO3	68	kg/d

BACKWASH

FLOW	14500	m3/d

E%COD	89%
E%BOD	94%
E%TSS	92%
E%TN	71%
E%N-N-H4	96%
E%TP	73%
kWh/d	9792
intermediate LIFTING	
kWh/d	3024

FLOW	64282	m3/d
COD	1144	kg/d
BOD	382	kg/d
TSS	414	kg/d
TN	536	kg/d
N-NH4	55	kg/d
N-NO3	423	kg/d
TP	47	kg/d
P-PO4	38	kg/d

E.coli	28908	CFU/100 ml

UV

E%E.coli	97%
Log red.	1.53
kWh/d	2517

BY-PASSED TO RIVER

FLOW	0	m3/d

RECLAIMED WATER

FLOW	63852	m3/d
COD	1144	kg/d
BOD	382	kg/d
TSS	414	kg/d
TN	536	kg/d
N-NH4	55	kg/d
N-NO3	423	kg/d
TP	47	kg/d
P-PO4	38	kg/d

E.coli	847	CFU/100 ml

PRIMARY SLUDGE TO PRE-THICKENING

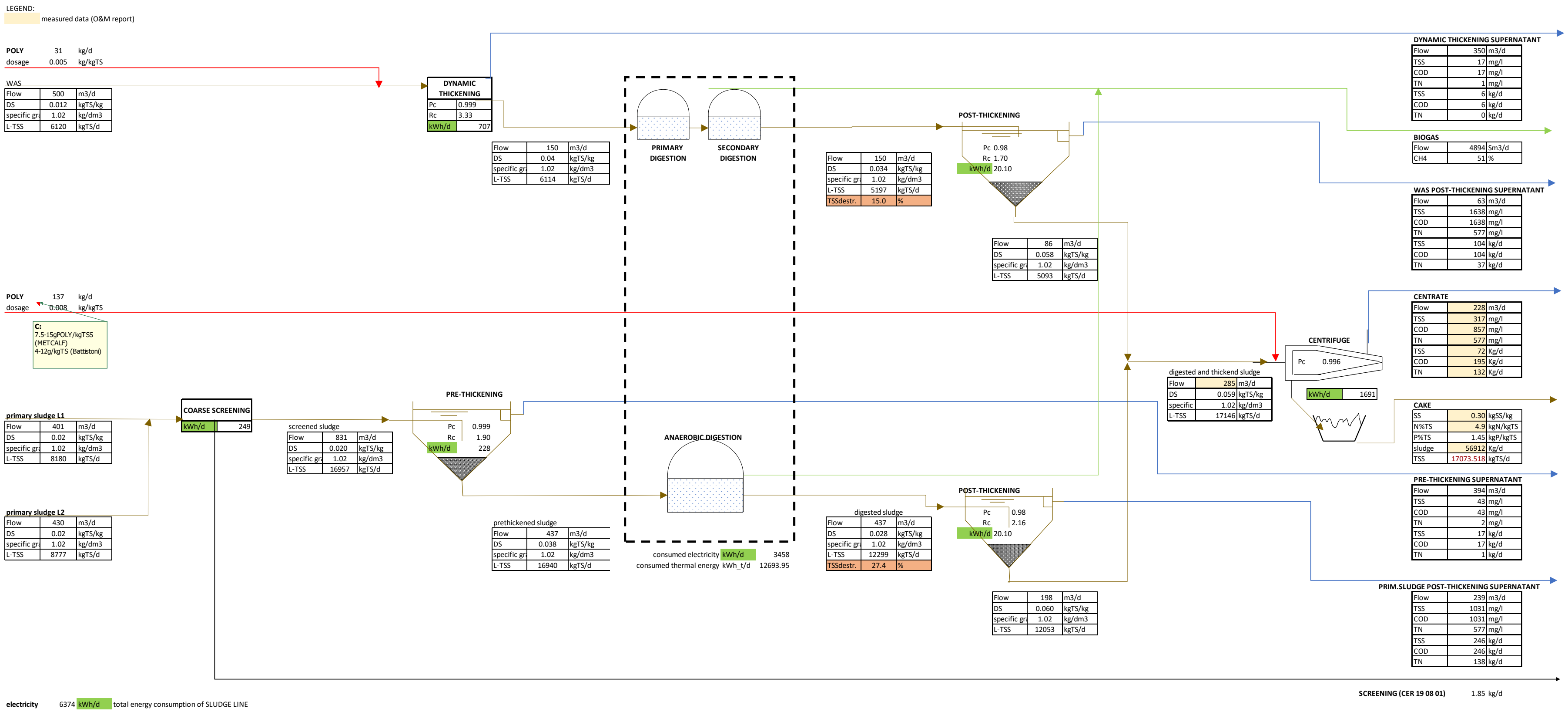
Flow	430	m3/d
DS	0.020	kgTS/kg
specific gravity	1.02	kg/dm3
LTSS_tot	8777	kgTS/d
chemical sludge	169	kgTS/d

GRIT (CER 19 08 02)	208	kg/d

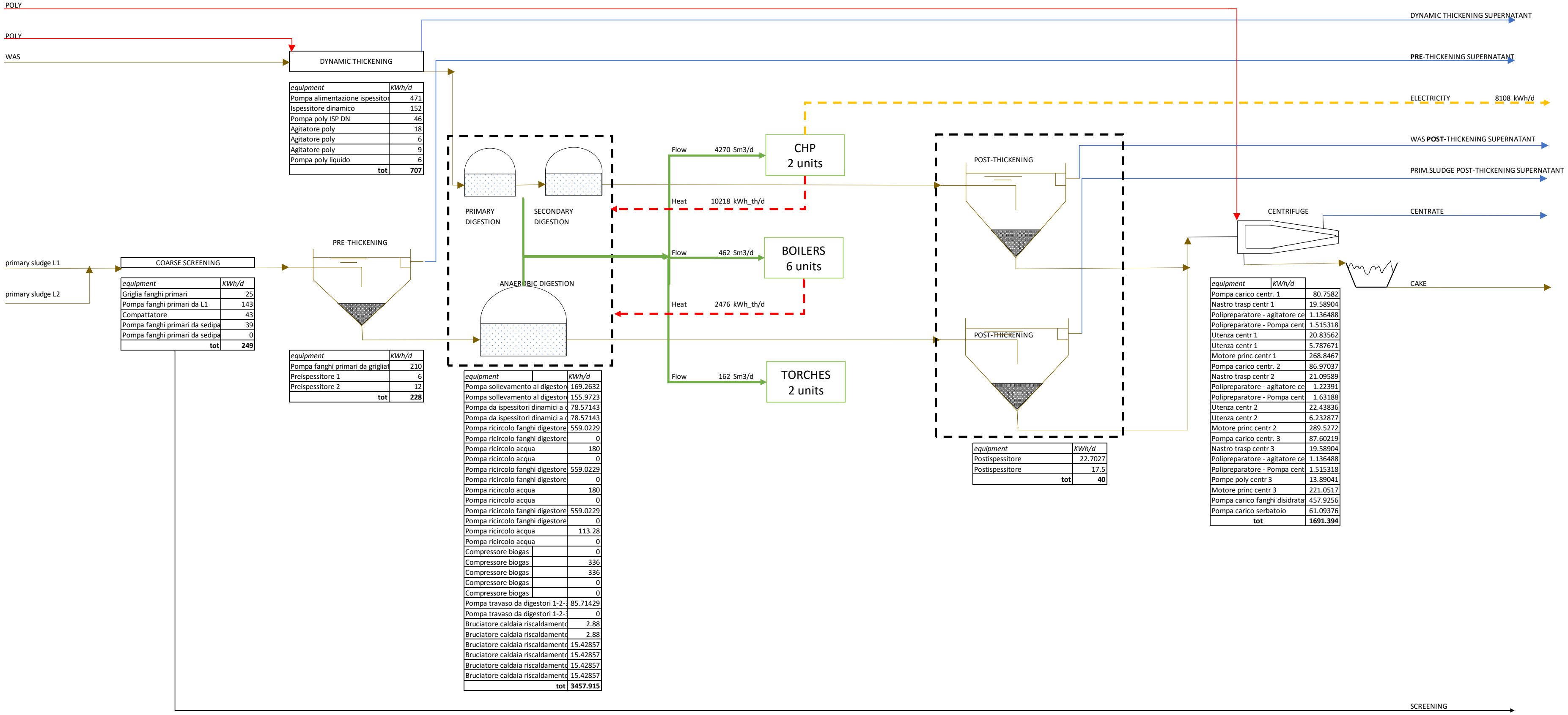
SCREENING (CER 19 08 01)	350	kg/d

electricity 20318 kWh/d total energy consumption of L2

Mass balance of sludge line. Peschiera Borromeo WWTP



Energy balance of sludge line. Peschiera Borromeo WWTP



DYNAMIC THICKENING

equipment	KWh/d
Pompa alimentazione ispessitor	471
Ispessitore dinamico	152
Pompa poly ISP DN	46
Agitatore poly	18
Agitatore poly	6
Agitatore poly	9
Pompa poly liquido	6
tot	707

COARSE SCREENING

equipment	KWh/d
Griglia fanghi primari	25
Pompa fanghi primari da L1	143
Compattatore	43
Pompa fanghi primari da sedipa	39
Pompa fanghi primari da sedipa	0
tot	249

PRE-THICKENING

equipment	KWh/d
Pompa fanghi primari da grigliat	210
Preispessitore 1	6
Preispessitore 2	12
tot	228

ANAEROBIC DIGESTION

equipment	KWh/d
Pompa sollevamento al digestore	169.2632
Pompa sollevamento al digestore	155.9723
Pompa da ispessitori dinamici a d	78.57143
Pompa da ispessitori dinamici a d	78.57143
Pompa ricircolo fanghi digestore	559.0229
Pompa ricircolo fanghi digestore	0
Pompa ricircolo acqua	180
Pompa ricircolo acqua	0
Pompa ricircolo fanghi digestore	559.0229
Pompa ricircolo fanghi digestore	0
Pompa ricircolo acqua	180
Pompa ricircolo acqua	0
Pompa ricircolo fanghi digestore	559.0229
Pompa ricircolo fanghi digestore	0
Pompa ricircolo acqua	113.28
Pompa ricircolo acqua	0
Compressore biogas	0
Compressore biogas	336
Compressore biogas	336
Compressore biogas	0
Compressore biogas	0
Pompa travaso da digestori 1-2-3	85.71429
Pompa travaso da digestori 1-2-3	0
Bruciatore caldaia riscaldamento	2.88
Bruciatore caldaia riscaldamento	2.88
Bruciatore caldaia riscaldamento	15.42857
Bruciatore caldaia riscaldamento	15.42857
Bruciatore caldaia riscaldamento	15.42857
Bruciatore caldaia riscaldamento	15.42857
tot	**3457.915**

POST-THICKENING

equipment	KWh/d
Postispessitore	22.7027
Postispessitore	17.5
tot	40

CENTRIFUGE

equipment	KWh/d
Pompa carico centr. 1	80.7582
Nastro trasp centr 1	19.58904
Polipreparatore - agitatore ce	1.136488
Polipreparatore - Pompa centr	1.515318
Utenza centr 1	20.83562
Utenza centr 1	5.787671
Motore princ centr 1	268.8467
Pompa carico centr. 2	86.97037
Nastro trasp centr 2	21.09589
Polipreparatore - agitatore ce	1.22391
Polipreparatore - Pompa centr	1.63188
Utenza centr 2	22.43836
Utenza centr 2	6.232877
Motore princ centr 2	289.5272
Pompa carico centr. 3	87.60219
Nastro trasp centr 3	19.58904
Polipreparatore - agitatore ce	1.136488
Polipreparatore - Pompa centr	1.515318
Pompe poly centr 3	13.89041
Motore princ centr 3	221.0517
Pompa carico fanghi disidratat	457.9256
Pompa carico serbatoio	61.09376
tot	**1691.394**

Mass balance of the first configuration UASB-AnMBR

BIOGAS

Ritter Flow	L/d	0.16
%CH4	%	17.00
%CO2	%	0.50
%N2	%	82.50
CH4 flow	l/d	0.03
CO2 flow	l/d	0.001
N2 flow	l/d	0.13
CH4 load	g/d	0.02
COD (CH4) load	g/d	0.073
CO2 load	g/d	0.000
N2 load	g/d	0.24
biogas real flow	L/d	0.03
real CH4%	%	97.14
real CO2%	%	2.86

STRIPPED GAS

Flow	m3/h	0.08002
CH4 load	g/d	0.02
CO2 load	g/d	1.19
N2 load	g/d	3512
COD (CH4) load	g/d	0.07
CH4 flow	l/d	0.03
CO2 flow	l/d	0.65
N2 flow	l/d	1920
%CH4	%	0.001
%CO2	%	0.034
%N2	%	99.97

PRE-TREATED URBAN WASTEWATER

Q	l/h	3.04
COD	mg/L	374
TSS	mg/L	228
BOD5	mg/L	168
TN	mg/L	34
TP	mg/L	5
NH4-N	mg/L	22
PO4-P	mg/L	2.3
E.coli	UFC/100mL	1000000
COD	g/d	27
TSS	g/d	17
BOD5	g/d	12
TN	g/d	2.5
TP	g/d	0.35
NH4-N	g/d	1.61
PO4-P	g/d	0.17

UASB

interval time (d)	41	
T°C	31	
HRT (h)	5.55	
OLR (kgCOD/m3/d)	1.70	*0.8-2*
v up (m/h)	0.98	
Volume (L)	16.60	
Surface (m2)	0.02	
SRT (d)	34.00	

UASB EFFLUENT

Q	l/h	3.03
COD	mg/L	175
TSS	mg/L	74
BOD5	mg/L	122
N	mg/L	34
P	mg/L	4
NH4-N	mg/L	25.73
PO4-P	mg/L	3.45
CH4 dissolved	mg/L	0.780
CO2 dissolved	mg/L	57
E.coli	UFC/100mL	300000
COD	g/d	13
TSS	g/d	5
BOD5	g/d	9
TN	g/d	2.46
TP	g/d	0.3
NH4-N	g/d	1.87
PO4-P	g/d	0.25
LCH4 dissolved	g/d	0.1
LCH4 dissolved_COD	g/d	0.2
LCO2 dissolved	g/d	4.1

AnMBR

Period (d)	41
tank HRT (h)	23.11
J (LMH) a 20°C	8
Volume (L)	70
dTMP/dt (mbar/d)	3
Area (m2)	0.5
pore size (µm)	0.03

PERMEATE

Q	l/h	3.65
COD	mg/L	61
TSS	mg/L	0
BOD5	mg/L	39
TN	mg/L	28
TP	mg/L	3
NH4-N	mg/L	25
PO4-P	mg/L	4
CH4 dissolved	mg/L	0.435
CO2 dissolved	mg/L	34
E.coli	UFC/100mL	100
COD	g/d	5.34
TSS	g/d	0.00
BOD5	g/d	3.40
TN	g/d	2.42
TP	g/d	0.26
NH4-N	g/d	2.22
PO4-P	g/d	0.34
LCH4 dissolved	g/d	0.04
LCH4 dissolved_COD	g/d	0.15
LCO2 dissolved	g/d	2.95

N2 GAS SPARGING

nominal flow	m3/h	1.00
Specific flow	m3/m2/h	2
frequence	%	8%
real flow	m3/h	0.0800
%N2	%	100
N2 flow	L/d	1920
N2 load	g/d	3512

WASTE SLUDGE

waste sludge mass	g	6200
waste sludge load	g/d	151
waste sludge flow	l/h	0.01
specific gravity	g/l	1000
TS%	%	1.6
TVS/TS%	%	34
COD/VSS	-	1.42
N%TS	%	4.3
P%TS	%	3.3
TSS	g/d	2.4
VSS	g/d	0.8
COD	g/d	1.2
N	g/d	0.10
P	g/d	0.08

N2 RECYCLE

Q N2	m3/h	5.55E-06
N2 flow	L/d	0.13

Mass balance of the second configuration SALSNES -UASB-AnMBR (31°C)

PRE-TREATED URBAN WASTEWATER

Q	l/h	3.24
COD	mg/L	222
TSS	mg/L	120
BOD5	mg/L	156
TN	mg/L	23
TP	mg/L	4
NH4-N	mg/L	15
PO4-P	mg/L	2.8
E.coli	UFC/100mL	1200000
COD	g/d	17
TSS	g/d	9
BOD5	g/d	12
TN	g/d	1.8
TP	g/d	0.31
NH4-N	g/d	1.20
PO4-P	g/d	0.22

DYNAMIC FILTER

interval time	27

PRIMARY SLUDGE

COD	g/d	2.5
TSS	g/d	2.1
BOD5	g/d	-2.9
TN	g/d	-0.1
TP	g/d	0.0
NH4-N	g/d	0.4
PO4-P	g/d	0.0

UASB INFLUENT

Q	l/h	3.24
COD	mg/L	190
TSS	mg/L	92
BOD5	mg/L	193
TN	mg/L	24
TP	mg/L	4
NH4-N	mg/L	11
PO4-P	mg/L	3.1
E.coli	UFC/100mL	1000000
COD	g/d	15
TSS	g/d	7
BOD5	g/d	15
TN	g/d	2
TP	g/d	0.29
NH4-N	g/d	0.82
PO4-P	g/d	0.24

BIOGAS

BIOGAS	l/h	0.002
Ritter Flow	L/d	0.05
%CH4	%	21.96
%CO2	%	3.37
%N2	%	74.66
CH4 flow	l/d	0.0118
CO2 flow	l/d	0.002
N2 flow	l/d	0.04
CH4 load	g/d	0.01
COD (CH4) load	g/d	0.031
CO2 load	g/d	0.003
N2 load	g/d	0.07
biogas real flow	L/d	0.01
real CH4%	%	86.69
real CO2%	%	13.31

UASB

interval time (d)	27	
T°C	30	
HRT (h)	5.13	
OLR (kgCOD/m3/d)	0.78	0.8-2
v up (m/h)	0.97	
Volume (L)	16.60	
Surface (m2)	0.02	
SRT (d)	31.32	

WASTE SLUDGE

waste sludge mass	g	2800
waste sludge load	g/d	104
waste sludge flow	l/h	0.01
specific gravity	g/l	1000
TS%	%	1.0
TVS/TS%	%	59
COD/TVS	-	1.42
N%TS	%	4.1
P%TS	%	3.3
TSS	g/d	1.0
TVS	g/d	0.6
COD	g/d	0.9
TN	g/d	0.04
TP	g/d	0.03

UASB EFFLUENT

Q	l/h	3.23
COD	mg/L	165
TSS	mg/L	56
BOD5	mg/L	125
TN	mg/L	23
TP	mg/L	4
NH4-N	mg/L	12.16
PO4-P	mg/L	3.57
CH4 dissolved	mg/L	0.456
CO2 dissolved	mg/L	35
E.coli	UFC/100mL	15500
COD	g/d	13
TSS	g/d	4
BOD5	g/d	10
TN	g/d	1.80
TP	g/d	0.3
NH4-N	g/d	0.94
PO4-P	g/d	0.28
LCH4 dissolved	g/d	0.04
LCH4 dissolved_COD	g/d	0.14
LCO2 dissolved	g/d	2.7

N2 RECYCLE

Q N2	m3/h	1.67E-06
N2 flow	L/d	0.04

STRIPPED GAS

Flow	l/d	1919.98
Flow	m3/h	0.08000
CH4 load	g/d	0.00446
CO2 load	g/d	0.018
N2 load	g/d	3512
COD (CH4) load	g/d	0.02
CH4 flow	l/d	0.01
CO2 flow	l/d	0.01
N2 flow	l/d	1920
%CH4	%	0.000
%CO2	%	0.001
%N2	%	99.999

AnMBR

Period (d)	27
tank HRT (h)	21.65
J (LMH) a 20°C	9
Volume (L)	70
dTMP/dt (mbar/d)	2
Area (m2)	0.5
pore size (µm)	0.03

N2 GAS SPARGING

nominal flow	m3/h	1.00
Specific flow	m3/m2/h	2
frequence	%	8%
real flow	m3/h	0.0800
%N2	%	100
N2 flow	L/d	1920
N2 load	g/d	3512

PERMEATE

Q	l/h	3.47
COD	mg/L	36
TSS	mg/L	0
BOD5	mg/L	29
TN	mg/L	18
TP	mg/L	4
NH4-N	mg/L	16
PO4-P	mg/L	4
CH4 dissolved	mg/L	0.3704
CO2 dissolved	mg/L	37
E.coli	UFC/100mL	0
COD	g/d	2.96
TSS	g/d	0.00
BOD5	g/d	2.42
TN	g/d	1.49
TP	g/d	0.31
NH4-N	g/d	1.34
PO4-P	g/d	0.34
LCH4 dissolved	g/d	0.03
LCH4 dissolved_COD	g/d	0.12
LCO2 dissolved	g/d	3.06

Mass balance of the third configuration SALSNES-UASB-AnMBR (37°C)

BIOGAS

BIOGAS	l/h	0.003
Ritter Flow	L/d	0.07
%CH4	%	16.11
%CO2	%	2.20
%N2	%	81.69
CH4 flow	l/d	0.0105
CO2 flow	l/d	0.001
N2 flow	l/d	0.05
CH4 load	g/d	0.01
COD (CH4) load	g/d	0.028
CO2 load	g/d	0.003
N2 load	g/d	0.10
biogas real flow	L/d	0.01
real CH4%	%	88.00
real CO2%	%	12.00
SGP su volume reattore	LCH4/m3/d	0.63
SGP su COD ingresso	LCH4/gCOD	9.80E-04
SGP su COD rimosso	LCH4/gCOD	0.0141

STRIPPED GAS

Flow	l/d	2879.99
Flow	m3/h	0.12000
CH4 load	g/d	0.011
CO2 load	g/d	0.042
N2 load	g/d	5268
COD (CH4) load	g/d	0.04
CH4 flow	l/d	0.02
CO2 flow	l/d	0.02
N2 flow	l/d	2880
%CH4	%	0.001
%CO2	%	0.001
%N2	%	99.999

PRE-TREATED URBAN WASTEWATER

Q	l/h	3.12
COD	mg/L	166.33
TSS	mg/L	74.33
BOD5	mg/L	#DIV/0!
TN	mg/L	22.31
TP	mg/L	3.86
NH4-N	mg/L	14.89
PO4-P	mg/L	#DIV/0!
E.coli	UFC/100mL	#DIV/0!
COD	g/d	12.47
TSS	g/d	5.57
BOD5	g/d	#DIV/0!
TN	g/d	1.67
TP	g/d	0.29
NH4-N	g/d	1.12
PO4-P	g/d	#DIV/0!

DYNAMIC FILTER

interval time (d)	36

PRIMARY SLUDGE

COD	g/d	1.75
TSS	g/d	0.70
BOD5	g/d	#DIV/0!
TN	g/d	0.04
TP	g/d	0.01
NH4-N	g/d	0.06
PO4-P	g/d	#DIV/0!

UASB INFLUENT

Q	l/h	3.12
COD	mg/L	143.00
TSS	mg/L	65.00
BOD5	mg/L	76.80
TN	mg/L	21.80
TP	mg/L	3.67
NH4-N	mg/L	14.03
PO4-P	mg/L	#DIV/0!
E.coli	UFC/100mL	1800000
COD	g/d	10.72
TSS	g/d	4.87
BOD5	g/d	5.76
TN	g/d	1.63
TP	g/d	0.28
NH4-N	g/d	1.05
PO4-P	g/d	#DIV/0!

UASB

interval time (d)	36	
T°C	38	
HRT (h)	5.32	
OLR (kgCOD/m3/d)	0.54	0.8-2
v up (m/h)	0.97	
Volume (L)	16.60	
Surface (m2)	0.02	
SRT (d)	13.44	

WASTE SLUDGE

waste sludge mass	g	1500
waste sludge load	g/d	42
waste sludge flow	l/h	0.01
specific gravity	g/l	1000
TS%	%	0.4
TVS/TS%	%	51
COD/TVS	-	1.42
N%TS	%	4.1
P%TS	%	3.3
TSS	g/d	0.2
TVS	g/d	0.1
COD	g/d	0.1
TN	g/d	0.01
TP	g/d	0.01

UASB EFFLUENT

Q	l/h	3.12
COD	mg/L	130.33
TSS	mg/L	62.00
BOD5	mg/L	65.05
TN	mg/L	21.80
TP	mg/L	3.63
NH4-N	mg/L	18.12
PO4-P	mg/L	#DIV/0!
CH4 dissolved	mg/L	0.37
CO2 dissolved	mg/L	30.81
E.coli	UFC/100mL	1000000
COD	g/d	9.74
TSS	g/d	4.64
BOD5	g/d	4.86
TN	g/d	1.63
TP	g/d	0.27
NH4-N	g/d	1.36
PO4-P	g/d	#DIV/0!
LCH4 dissolved	g/d	0.03
LCH4 dissolved_COD	g/d	0.11
LCO2 dissolved	g/d	2.30

N2 RECYCLE

Q N2	m3/h	2.22E-06
N2 flow	L/d	0.05

AnMBR

Period (d)	36
tank HRT (h)	22.47
J (LMH) a 20°C	10
Volume (L)	70
dTMP/dt (mbar/d)	3
Area (m2)	0.5
pore size (μm)	0.03

N2 GAS SPARGING

nominal flow	m3/h	1.50
Specific flow	m3/m2/h	3
frequence	%	8%
real flow	m3/h	0.1200
%N2	%	100
N2 flow	L/d	2880
N2 load	g/d	5268

PERMEATE

Q	l/h	3.54
COD	mg/L	28
TSS	mg/L	0
BOD5	mg/L	16
TN	mg/L	18
TP	mg/L	3
NH4-N	mg/L	16
PO4-P	mg/L	#DIV/0!
CH4 dissolved	mg/L	0.201
CO2 dissolved	mg/L	28
E.coli	UFC/100mL	60
COD	g/d	2.35
TSS	g/d	0.00
BOD5	g/d	1.38
TN	g/d	1.51
TP	g/d	0.23
NH4-N	g/d	1.37
PO4-P	g/d	#DIV/0!
LCH4 dissolved	g/d	0.02
LCH4 dissolved_COD	g/d	0.07
LCO2 dissolved	g/d	2.34

Inventory of operation phase. Peschiera Borromeo WWTP

Peschiera Borromeo WWTP
STATE of the ART

			Quantity by	L2					L1					SLUDGE LINE		
				phase 1	phase 2	phase 3	phase 4	phase 7	phase 1	phase 2	phase 3	phase 4	phase 7	phase 5	phase 5	phase 6
			Unit	Pumping and screening removal	SEDIPAC grit, oil and grease removal + prim. Sedimentation	BiofiLtration BIOFOR DN + BIOFOR C+N	UV Disinfection	Discharge	Pumping and screening removal	Grit, oil and grease removal+primary sedim	Actived sludge + BIOFOR DN-N	PAA Disinfection	Discharge	SUM SLUDGE LINE no defecation	Sludge composting (AGROSISTEMI)	defection lime application
Input																
INFLUENT		Wastewater	m3/d	64282	-	-	-	-	62040	-	-	-	-	0.00	-	-
ENERGY		Consumed electricity	kWh/d	6931	1078	9792	2517	-	6313	861	9177	14	-	6373.20	167.62	-
ENERGY		Consumed CH4	m3/d	-	-	-	-	-	-	-	-	-	-	4894.00	-	-
CHEMICALS		Sodium hydroxide	kg/d	-	9	-	-	-	-	8	-	-	-	-	-	-
CHEMICALS		external carbon source	kg/d	-	-	1324.8	-	-	-	-	518.4	-	-	-	-	-
CHEMICALS		Al2O3 for P removal	kg/d	-	2419	-	-	-	-	-	3226	-	-	-	-	-
CHEMICALS		FeCl3 for P removal	kg/d	-	-	-	-	-	-	-	260.4	-	-	-	-	-
CHEMICALS		Peracetic acid	kg/d	-	-	-	-	-	-	-	-	104.1408	-	-	-	-
CHEMICALS		POLY for sludge line	kg/d	-	-	-	-	-	-	-	-	-	-	150.00	-	-
CHEMICALS		CaO for defecation lime	kg/d	-	-	-	-	-	-	-	-	-	-	0.00	5473.73	-
CHEMICALS		H2SO4 for defecation lime	kg/d	-	-	-	-	-	-	-	-	-	-	0.00	10057.99	-
TRANSPORT (operative phase)		Sodium hydroxide	km/d	-	0.50	-	-	-	-	0.45	-	-	-	-	-	-
TRANSPORT (operative phase)		external carbon source	km/d	-	-	23.49	-	-	-	-	9.19	-	-	-	-	-
TRANSPORT (operative phase)		Al2O3 for P removal	km/d	-	4.94	-	-	-	-	-	-	-	-	-	-	-
TRANSPORT (operative phase)		FeCl3 for P removal	km/d	-	-	-	-	-	-	-	0.05	-	-	-	-	-
TRANSPORT (operative phase)		Peracetic acid	km/d	-	-	-	-	-	-	-	-	14.89	-	-	-	-
TRANSPORT (operative phase)		POLY for sludge line	km/d	-	-	-	-	-	-	-	-	-	-	-	-	-
TRANSPORT (operative phase)		chemicals for defecation lime	km/d	-	-	-	-	-	-	-	-	-	-	-	11.84	-
Output																
EFFLUENT		Effluent to river (water)	m3/d	-	-	-	-	64282	-	-	-	-	62040	-	-	-
WASTE		Screenings 19 08 01 (to incineration)	kg/d	350	-	-	-	-	338	-	-	-	-	-	-	-
WASTE		grit 19 08 02 (landfill waste disposal)	kg/d		208	-	-	-	-	201	-	-	-	-	-	-
CO-PRODUCTS		Fertilizer (biosulphate and biocarbonate)	kg/d	-	-	-	-	-	-	-	-	-	-	-	54052	-
TRANSPORT		Screenings, (landfill waste disposal)	km/d	0		-	-	-	0	-	-	-	-	-	-	-
TRANSPORT		grit 19 08 02 (landfill waste disposal)	km/d	-	0	-	-	-	-	0	-	-	-	-	-	-
TRANSPORT		Fertilizer (biosulphate and biocarbonate)	km/d	-	-	-	-	-	-	-	-	-	-	-	33	-
EMISSION	to air	non-biogenic CO2	kg/d	-	-	-	-	-	-	-	-	-	-	4987	-	-
EMISSION	to air	biogenic CO2	kg/d	-	-	3579	-	-	-	-	5888	-	-	36	1261	-
EMISSION	to air	Methane	kg/d	-	-	8	-	-	-	-	8	-	-	106	-	-
EMISSION	to air	NH3	kg/d	-	-	-	-	-	-	-	-	-	-	-	814	5
EMISSION	to air	N2O	kg/d	-	-	7	-	-	-	-	7	-	-	-	-	95
EMISSION	to water	PO4	kg/d	-	-	-	-	116	-	-	-	-	100	-	-	-
EMISSION	to water	NO3 surface	kg/d	-	-	-	-	1875	-	-	-	-	2085	-	-	1594
EMISSION	to water	NO3 groundwater	kg/d	-	-	-	-	-	-	-	-	-	-	-	-	2073
EMISSION	to soil	C (carbon sequestration)	kg/d	-	-	-	-	-	-	-	-	-	-	-	-	590
ENERGY		Biogas produced	m3/d	-	-	-	-	-	-	-	-	-	-	4894	-	-
ENERGY		Produced electricity	kWh/d	-	-	-	-	-	-	-	-	-	-	8108	-	-
avoided product		nitrogen fertiliser	kgN/d	-	-	-	-	-	-	-	-	-	-	-	-	-624
avoided product		phosphorous fertiliser	kgP2O5/d	-	-	-	-	-	-	-	-	-	-	-	-	-3334