Master Thesis

MSc Energy for Smart Cities

# Environmental-Economic analysis of WWTPs, with different sizes and innovative designs

## REPORT

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# Review

This work is aiming to define different pathways that could be followed in order to make WWTP a more sustainable system. To evaluate the possible innovative solutions to follow it has been decided to investigate the economical viability and environmental impact of each plant proposed. Taking into account also two fundamental aspects of a WWTP, the size and the different streams concentration. The traditional paradigm of WWTP will be proposed to change through the application of different treatments.

The thesis will first define all the possible technologies and innovation that can be applied to a WWTP, with a proposal of integration with a renewable power methane system (power to gas) inside the original WWTP. Firstly, two reference WWTPs will be analysed in terms of costs and technologies applied. In addition, a third WWTP will be added to understand how the size influences costs and environment.

Secondly, the carbon redirection and nutrients recovery possibility has been evaluated in the same terms, to understand if thanks to pre-concentration and ion-exchange unit, it would be possible to make more sustainable a WWTP. This is possible environmentally but not economically, since it has revealed way more expensive than the conventional activated sludge system.

Thirdly, it will be proposed a new and innovative scheme that is aiming to include in one plant two different treatment, with totally different purposes, but that could be advantageous for both and especially for the community/municipality. On one side, there will be the clarification service of water while, on the other side, it will be accomplished the ancillary service of balancing the grid though the production of renewable methane.

In addition, a great value has been given to all the obtainable products from a WWTP, in order to create an added value with them for instance, the use of sludge in the production process of bio-bricks. The final scope is to create a circular economy with all the products recoverable from a WWTP, since it is where all human wastes is focused.

The major obstacle for the further development of more sustainable WWTPs is represented by the social acceptance. Indeed, the level of consciousness of the potentiality of a WWTP are pretty low, and at the same time there is a low acceptance in using waste for the production of human dedicated products. That's where the main efforts will be needed in the future. Even if, all the technologies needed for making a more sustainable WWTP are ready, but the products obtainable from it would never be sold, than all the investment won't make any profit.

# Summary

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# 1. Introduction

The interest and the attention paid, in the latest years, to the impact that anthropogenic activities have on the environment, the ecosystem and the planet, has drastically increased. An awareness of the problem of climate change has led to the choice, by many nations, of taking a path that would guarantee, at least in part, an even greater use of energy production from renewable energy sources (RES). This was always followed by strategies of incentive as well as put more resources on the research of new and more efficient technologies.

Related to this new awareness many other sectors have been developed and all with the same aim of reducing the human impact on the environment together with decreasing the human footprint on the planet. The circular economy is one of them, being for several policies a framework and an umbrella, following the purpose of use at the best all resources available in the best economical way, keeping in mind that the scope is not only economic savings but the least damaging for the planet creating an added value for the society.

Indeed, the main scope of the thesis is to analyze different processes inside of wastewater treatment plants (WWTPs), which are high energy consumers and big producers of waste. WWTPs are characterized by many losses and inefficiencies, this concern mainly to the low rate of resource and energy recovery. These topics will be mainly discussed in the thesis since are the two areas from which it is possible to obtain and recycle the most. Other processes are discussed as well but without important value propositions, like water reclamation [1].

The scope of WWTPs is to reduce the presence of harmful substances coming from the human body modifying its composition and quality [2]. The following step is to inject the treated water into the water system or if it respects all the safety standards can be conditioned for different uses, e.g., industrial, agriculture, etc. Apart from the waterline, in the WWTP we are going to analyze the sludge and gas line. We will start from a reference case study which includes all the typical steps and similar configurations that are also present in the majority of WWTP.

One of the main concern highlighted from different studies is that WWTPs are designed without sufficient consideration on energy and nutrients recovery while it's mainly focused on effluent requirements [7]. Therefore, the energetic losses connected with that are relevant, some studies revealed that in the Netherlands for instance, the use of biogas for electrical and heating generation, from the anaerobic digestion, would correspond to 4% of the heating demand of the entire country and 1% of the Dutch electricity demand [1]. In Italy, for example, in many WWTPs, it is not considered the option to install a heat recovery system with a combined heat cycle (CHP), due to the high costs. Therefore, the biogas generated after the Anaerobic digestion from the sludge is directly released into the atmosphere.

The supply potential of a WWTP may vary depending on various voices: composition of the resource, recovery technologies and various bottlenecks related to economics, health, environment and policy issues.

That's why the role of wastewater management, from the early phases of construction of the plant, is necessary to address not only to prevent the wastewater downstream from health risks but also to further improve the WWTP on an economic, energetic and circular economy level. For instance, technologies like conventional activated sludge (CAS), is no longer considered sustainable due to its low rate of resource recovery, high energy demand (mainly caused by aeration process) and large environmental footprint, besides, it is also not economically attractive due to its low-cost effectiveness.

The key feature for future WWTPs will be to transform its structure from pollutant removal to resource recovery, in other words, redesign the plant into a water resource factory (WRF) towards a more circular resource flow. That's why the figure of Wastewater Management Utilities (WMU) is needed to have a better knowledge of different and new technologies to choose the technology with the highest implementation potential, both economically and environmentally, and also to move from a WWTP to a WRF[1].

Different parts in the WWTP process need to be improved to make it an energy producer, a nutrient recovery site and finally self-sustainable. Indeed, one of the key points in the new concept of WWTP is to recover all products possible from the influent water, from biogas to Nitrogen and Phosphorous and finally also all the products recoverable and obtainable from sewage sludge. In this way, a WWTP could be interesting also on an economical level, since it could be self-sustainable both in environmental and economical terms.

Many nutrients could be recovered in the form of fertilizer and that could be sold, considering also that the European Union depends on third markets for fertilizer supply at a high price. Indeed, the requirements of European legislation obliges WWTP to reduce TSS, COD, BOD, N and P concentrations of effluent discharges to within certain limits. It is important also to consider how the natural recovery of fertilizer would prevent many $CO_2$ emissions that are normally released into the atmosphere [5]. As mentioned before, the safety and the quality of the water effluent will remain the primary objective in a WWTP, but from now onwards it is needed also to improve the sustainability of the plant on different aspects, keeping in mind that to apply circular economy, the innovation of resource recovery needs to brought into the entire process of the WWTP.

In conclusion, it is crucial to achieve effective wastewater treatment, not only for public health reasons but also for avoiding pollution of water sources and the wider environment. In developing countries, it is typical that sewage is often discharged into water bodies. In developed countries, stricter effluent requirements, population growth and urbanization are putting pressure on existing wastewater infrastructure. That is why, the creation of a cost-effective, sustainable and safe sanitation solution with a small footprint will bring innovation but most of all significant social benefits.

# 2 State of the art and opportunities of innovation

## 2.1 Description of typical WWTP

A typical representation of WWTP is depicted in fig. 1, where the three main process lines that are possible to follow are: waterline, sludge line and gas line. The scope in the waterline is to produce a treated effluent that respects all the environmental limits imposed by the EU. At the same time, the sludge line aims to redirect all the possible pollutants into the sludge. While the gas line that is present in big and medium WWTP, it is not in small WWTP, here the main scope is to generate the maximum amount of biogas to then maximise energy production.

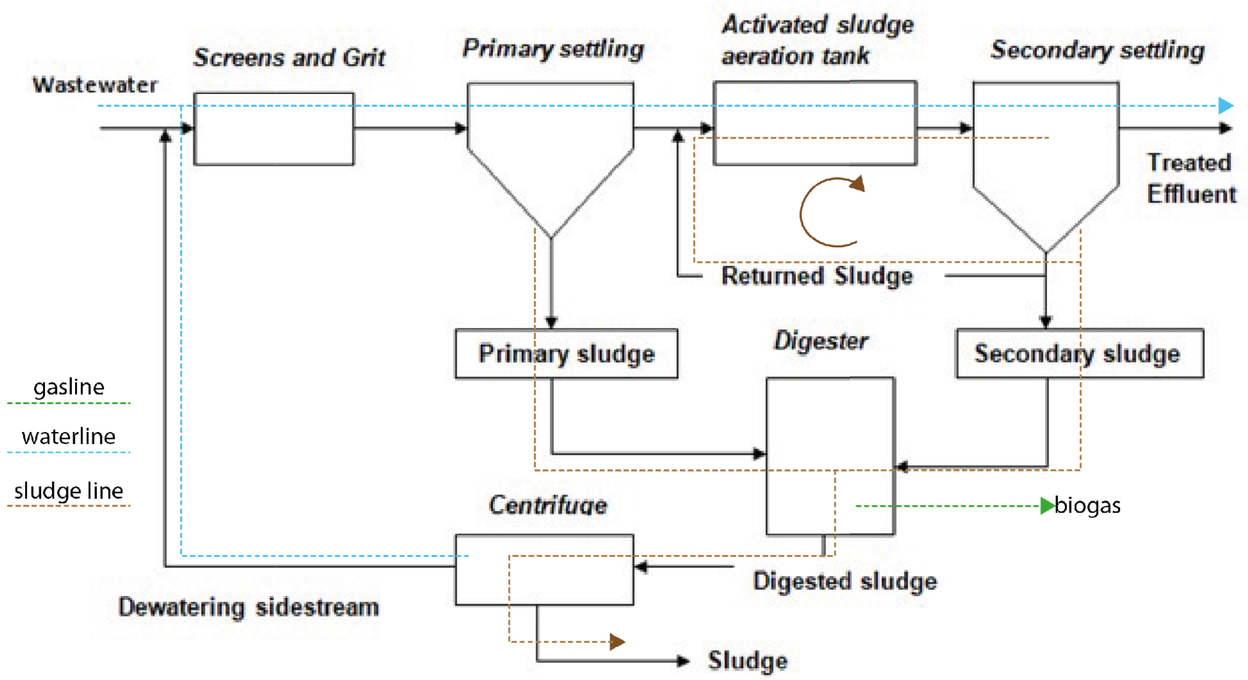


*fig. 1 Conventional WWTP with activated sludge typical layout*

### Waterline

Once the wastewater enters in the treatment plant, the first operation *(pre-treatment process)* is a gross and a fine screening *(physical method)* where the aim is to detect big and small substantial matters. The solid waste is then collected by a hydraulic conveyor, which deposits it in a compactor and finally discharges it the form of solid urban waste. After that, the water undergoes a de-gritting and degreasing process, where the water follows a sharp section increase and a linear velocity decrease that forces the sedimentation of suspended sand [12].

In the primary sedimentation, the plant has a pair of primary clarifiers (settlers), that reduce the solids load and obtaining the primary sludge ready for the gravity thickener. Consequently, the wastewater is brought to the bioreactor (biological treatment) where one of the most significant sources of energy consumption is installed, the aeration process (energy-intensive method). The air is supplied through diffusers to remove carbon particles [13].

After the biological treatment, the flow undergoes to the second sedimentation further reducing the solids load where are collected through a flotation thickener. As a final step, the water needs to be treated, before being injected into the environment, through chlorination (chemical method) that disinfects the effluent water [19].

### Sludge line

In this part of the plant, the main scope is to minimise the environmental impact and the volume of sludge to be handled quickly and with lower costs for transportation. The sludge collected in the primary and secondary settler, as said before, is then thickened in a gravity and flotation thickener, respectively, to increase the sludge concentration [2].

After that, the two sludge are mixed in the mixing tank, to stabilise further it is necessary mesophilic anaerobic digestion at 37°C in the absence of oxygen with the annexe removal of volatile solids. The main factors that ensure the smooth progress of digestion are the mixing of the sludge and the temperature. Therefore, it is essential to have a sludge heating circuit performed by heat exchangers that keep constant the temperature but also the recirculation of sludge from the digester to the exchangers to obtain a homogenisation. Particular attention needs to be paid to accurately mix fresh sludge with digested sludge to prevent accumulations of new sludge from forming inside the digester [13]

An aeration system can also be used to further stabilise the sludge, but with higher operating costs. Anaerobic digestion applied in the sewage sludge treatment is common in big and medium WWTP; it is not for small ones since it is not economically feasible.

Finally, sludge undergoes the dewatering process, that is carried out by centrifuges to reduce its volume. It is a mechanical process to reduce the moisture weight of 20-25%, through the separation of the liquid component, to make it compatible with the final disposal.

## Gas line

The gas produced during the anaerobic digestion is redirected to the combined heat cycle to produce electricity and heat that can be used inside the plant. The estimations of energy production are around 50% of the energy needs inside a WWTP. This is the general layout for a large/medium-sized WWTP but not for a small one, since a cogeneration unit is not usually installed for the high costs [8].

The design of a WWTP has three main scopes, clarification of water, stabilisation of the organic content (making it non-perishable) and destroy the pathogenic organisms presents, and finally decrease the high content of water in the sludge accumulation. Essentially, it is a process that removes the contaminants in the wastewater of urban origin. Indeed, most of the times, sludge contains toxic substances derived from human activities; that is why the wastewater needs to undergo a treatment to be re-injected into the environment. Therefore, also the sludge must undergo a series of treatments necessary to make them suitable for disposal, for example, in special landfills or for reuse in agriculture as such or after composting [2].

The technologies for the treatment of influent wastewater can be organised into three big areas:
1. Physical methods. It includes a set of technologies in which filtration is the dominant player and can be referred to as liquid-solid separation method.
2. Chemicals methods. Chemical substances are utilised to remove contaminants and pollutants from water or to neutralise their effect.
3. "Energy Intensive" methods. This category includes water sterilisation processes for domestic use, but also technologies for the specific treatment of sludge generated by the purification process.
The main waste product exiting from a WWTP is sludge. In an urban context, the volatile component is dominant, formed by deposited organic material, flocculated organic pollutants and excess biomass. A typical household sewage treatment plant produces three types of sludge [20]:

- Primary sludge: it is formed by suspended solids in the sewer water, separated by simple decantation or sedimentation without having undergone any type of transformation. The process from which they mainly originate is called clarification.

- Secondary or biological sludge: it is composed of excess biomass, including colonies of bacteria, absorbed or mechanically trapped volatile matter. The level of putrescence depends on the type of biological treatment carried out.

- Tertiary sludge: it is produced by filtration, flocculation or precipitation following a biological treatment. In the presence of a simple filter, without the addition of inorganic reagents, the nature of the sludge is similar to the one of biological sludge. Otherwise, chemical reagents are present in variable percentages depending on the applied process. In some cases, different types of sludge can be mixed within the same water treatment chain. For instance, recirculation of tertiary or secondary sludge can be expected in the primary sedimentation tank, to obtain an increase in the performance of the flocculation action exerted by the excess biomass and obtain a better level of thickening. Unfortunately, in the majority of WWTP, the tertiary treatment is not included in the layout, but only primary and secondary sludge is produced.

In this thesis, three different WWTPs will be compared with different sizes in terms of costs and environmental damages, and for this reason, is necessary to have a general view on which are the technologies utilised in the different processes. The size of a WWTP greatly depends on the influent inflow rate capacity that varies depending on the number of households served by the particular WWTP. The amount of households is determined in population equivalent (PE), that is the unit utilised to define the capacity of a WWTP together with the amount of $m^3$ of treated wastewater per day. To have a reference value to determine the PE unit it has been estimated that 1 PE corresponds to 54 grams of Biochemical oxygen demand (BOD), and each influent flow has a different value depending on the flow characteristics. In Table 1 are summarised all the technologies used for different sized WWTPs basing their size on their inflow rate capacity. The possible technologies usable are many, but the most utilised are depicted here.

| | Small (< 30.000 PE) | Medium/Large (>30.000 PE) |
|---|---|---|
| Screens and Grit | X | X |
| Primary settling | X | X |
| Activated sludge aeration tank | X | X |
| Secondary settling | X | X |
| Anaerobic digester | - | X |
| Centrifuge | - | X |
| Cogeneration unit (CHP) | - | X |

*Table 1. Features of different sized WWTPs*

## 2.2 Energy consumptions

The typical configuration of a WWTP consists of primary, secondary and advanced stages. A more detailed specification is given in fig. 2 below with the detailed energy consumptions for the singular processes.

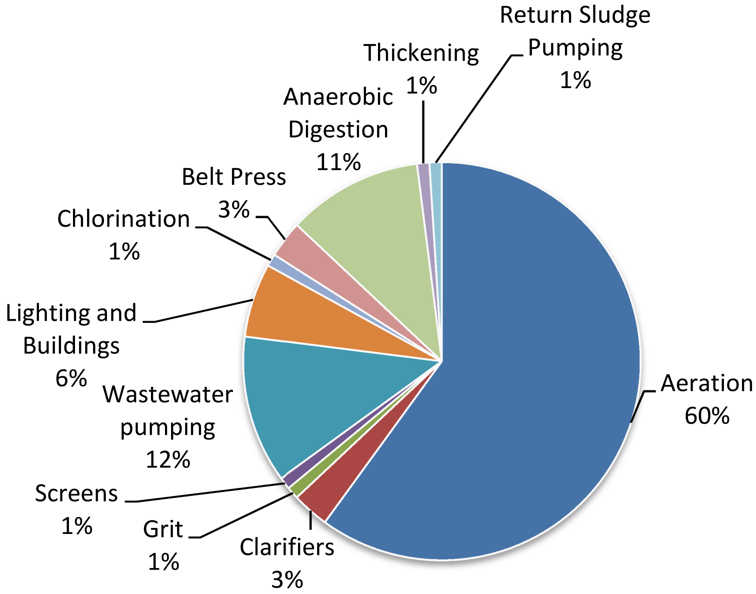


*fig. 2 Energy consumptions distribution in WTTPs (font: cost of Urban Wastewater Treatment and eco-taxes)*

The total energy consumptions amount for a total of 0,375-0,75 kWh/m$^3$ of treated wastewater as can be seen in fig. 2 aeration is the process with the highest consumptions of energy around 50-60%. At the same time, sludge treatment consumes 15-25% of energy and finally the secondary sedimentation that includes recirculation pumps. Consumptions will further increase in case of advanced WWTP due to the use of energy for the recovery of nutrients, reaching 0,45-0,75 kWh/m$^3$ of treated wastewater [6].

Another essential variable to consider is the size of WWTP, for which different technologies are applied, and has a significant impact on energy consumptions. Indeed, the unit electricity consumption of all these four processes decreases with the increasing size of the plant [21]. For instance, the inflow rate, of a reference WWTP, that is around 100-8.500 m$^3$/day with an energy consumption of 0,44-2,07 kWh/m$^3$ while for a plant with an inflow of 600-283.000 m$^3$/day the energy consumptions are 0,30-1,89 kWh/m$^3$. These results are attesting that with the increase of inflow, there is a decrease in energy consumptions [6].

Moreover, it is also needed to consider the location where the plant is installed and for WWTP with low capacity is challenging to be totally energy self-sufficient. One of the reason is due to the low cost-effectiveness of building anaerobic digestion in WWTP with a capacity lower than 30.000 PE (population equivalent, one unit equals 54 g of BOD). Therefore, the majority of the energy that is contained in the wastewater is lost and wasted [22]

The increase in energy costs and concerns about climate change are highlighting the need to realize energy self-sufficiency in WWTPs. Even though, it seems a challenging task to achieve in the literature has been demonstrated that it is feasible to establish energy self-sufficiency in WWTPs. The challenges remain clears, especially in the higher costs and investments for innovative technologies.

## 2.3 Energy potential

WWTPs are big consumers of energy, and as it has been projected by 2030 with business as usual, the consumptions, will increase up to 550 TWh of electricity (as depicted in fig. 3). Therefore, the other two scenarios are defined to reach energy self-sufficiency and to decrease the consumptions.

As a consequence of high consumptions there are also high emissions; indeed, the entire sector of waste and wastewater has a share of the 3% on the totality of the emissions.

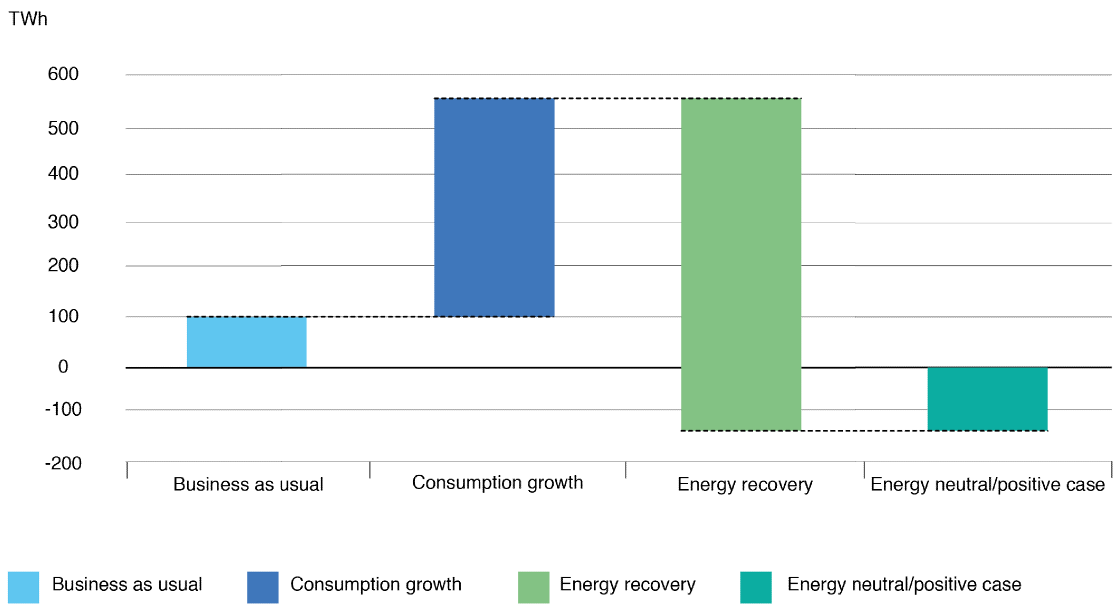


*fig. 3 Projection of the energy consumptions in WWTP, by 2030 (font: [23])*

The energy potential contained in wastewater is way higher than the energy needed by a CAS system to operate. So not all the potential chemical energy contained is utilised at the best, indeed at the moment, only 25% of the overall potential is exploited [3]. The leading cause for a low energy-recovery rate is due to the high energy needed to evaporate the super important content of water in the sludge that amounts almost to 80% also after the dewatering process.

A promising solution is to use the heat exceeding the on-site demand, produced during the cogeneration process, to feed other utilities and users. For instance, the surplus of heat could be used as a seasonal heating storage system for a local community otherwise, this heat would be lost [2].

For instance, in the Netherlands, the potential heat recovery from the WWTP effluent is 40% higher than the heat energy that is recovered. Therefore, biogas is the primary source of energy in a WWTP, and it is produced through anaerobic digestion [1]. That's why the use of biogas is considered as a sustainable way of recovering energy from WWTPs.

The products and technologies that can be used to recover energy both in the thermal and electrical form are:

*Methane-* is an excellent source of energy that is freely available in significant quantities, and it is generated employing of anaerobic digestion, in detail 80% of the biodegradable COD fraction is converted into methane. There are some costs associated in case, the methane obtained is not burned on site, due to transportations costs while for the production of methane, pressurisation is needed. Methane, if burned on-site could generate up to 40% of the required energy, the main concern is the rate of conversion to electricity of about 60% of losses. A new way to increase the production of methane would be to apply up concentration or carbon redirection, where based on past studies [5], the electricity generated is doubled, drastically reducing electricity costs. The meaning of doing so is it due to the low concentration of organic carbon in municipal wastewater, that's why the redirection of carbon particle is so crucial. An interesting innovation already utilised in many WWTPs is that a mix of kitchen wastes and sludge is released for anaerobic co-processing to increase organic loads, biogas yields, energy recovery and reduce investment.

*Sludge incineration-* only some countries are allowed to burn sludge, and the combustion process is generally done after digestion, so once the biogas is generated. Doing this has a drawback since the raw heating value is 30-40% higher than the digested one, so there are some energy losses. Many countries are not allowed to burn digested sludge since it is possibly composed of substances that if ignited, could be harmful.

The main concern is related to the high content of water inside of sludge that is partly dried trough a de-watering step done by a centrifuge. An innovative system would be to install a heat energy recovery system, that will take the waste heat coming from the CHP unit and re-direct it through a heat exchanger (HEx) to the dewatering system to add more heat to the process[2].

*Hydropower-* electricity generation in WWTPs is possible to achieve thanks to small turbines installed in the effluent stream or along with the treatment. The power output mainly depends on the rate of flow and the hydraulic head. The applicability is strictly dependent on the energy prices rise and on physical circumstances. The plants with natural differences in heights can use hydroelectric power. The biggest problem with small turbines is the low reliability and the high cost [17].

## 2.4 Resource recovery potential

### 2.4.1 Carbon redirection

The majority of WWTPs are based on the conventional activated sludge (CAS) [4], the process requires extensive aeration (high energy consumptions) to obtain the mineralisation of organic matter and the production of effluent with an organic content below the legal requirements. In addition, a large amount of sludge to be treated or the $CO_2$ emissions inherent in a CAS process also brings economic but mainly sustainability problems. Furthermore, when using CAS, the carbon present in wastewater (300-800 mg COD $L^{-1}$) is not fully recovered as it is partially oxidised into carbon dioxide. That is why the needs to transform WWTPs from being energy consumers and nutrient removal sites to energy producers and nutrient recovery sites.

A solution could be the implementation of carbon redirection that together with a level of chemical oxygen demand (COD) above 5 g/L, will lead to having a production of biogas high enough to cover the overall heat input costs. The carbon redirection technologies are capable of removing particulate from the system and finally producing a high amount of sludge.

One of the most successful processes for carbon redirection is the high rate activated sludge (HRAS). The final scope is to minimise the nitrogen removal by maximising the COD and the total suspended solids (TSS) removal. Considering that 50% of COD is removed in the AD, it is estimated that through carbon redirection, 35% of the influent COD will be converted into biogas.

Another process that needs attention is the pre-concentration process by bio-sorption and bio-oxidation of wastewater. The efficiency of bio-sorption depends on sludge characteristics, sludge retention time, hydraulic retention time and dissolved oxygen in the reactor. Anyway, the treatment achieves recovery of 60% of the carbon present in wastewater is redirected to the sludge phase, decreasing the production of $CO_2$. The energy potential that is recoverable after the anaerobic digestion has increased by around 25%.

Therefore, the key point to achieve energy recovery is to capture COD from wastewater as much as possible for anaerobic digestion, followed by a bio-sorption and a bio-oxidation step in order to redirect carbon from mineralisation to biogas generation [5].

## 2.4.2 Nitrogen removal and recovery

EU is in lack of crucial elements like phosphorous and nitrogen (ammonia) that are recoverable from wastewater and usable as fertilisers [14]. Indeed, the prominent use of ammonia is as fertiliser to feed crops. When ammonia is not used as a fertiliser the crop yields result in lower quantities, which affect the possibility to feed the whole population. It is also predictable that ammonia prices also affect food pricing, that is why the price for ammonia needs to be kept low, in other words, to keep the food price low around the world.

Cities are significant producers of phosphorous and nitrogen since it is mostly contained in human excreta. On a global average the total fertilizer demand could be covered, between 18-30% by wastewater N recovery. Nitrogen recovery is crucial since having too high rates of N presents in effluent streams could have negative consequences. Indeed, in the EU's wastewater treatment facilities are required to meet nitrogen discharge targets [9].

Currently, there are two ways to recover nitrogen from wastewater:

- indirectly, through ion-exchange using zeolites.

- directly, spreading sewage sludge into agricultural crops.

The direct method is followed by some severe problem related to contamination of the soil; high contaminant loads are usually found in the effluent flow. Another reason to not consider the land application of sludge as the best solution is also connected with the high cost to transport sludge that still with high water content even after the dewatering process.

The indirect method, shown in fig.4, is done through an ion exchange treatment utilising regenerable granular zeolites to concentrate ammonium. The zeolites have demonstrated a high affinity with ammonium $NH_4^+$, creating 40 times higher ammonium concentration than the influent. Zeolites should be protected by a glass filter and an ultra-filtration (UF) unit as a pre-treatment [14]. The use of zeolites allows obtaining a quality effluent regarding the concentration of ammonium that has been found to be ultra-low. This pre-concentrated N-stream should be concentrated using different technologies (e.g., liquid-liquid membrane contactors, hot stripping, etc.) that allow obtaining a liquid fertiliser as can be seen in fig. 4 [9].

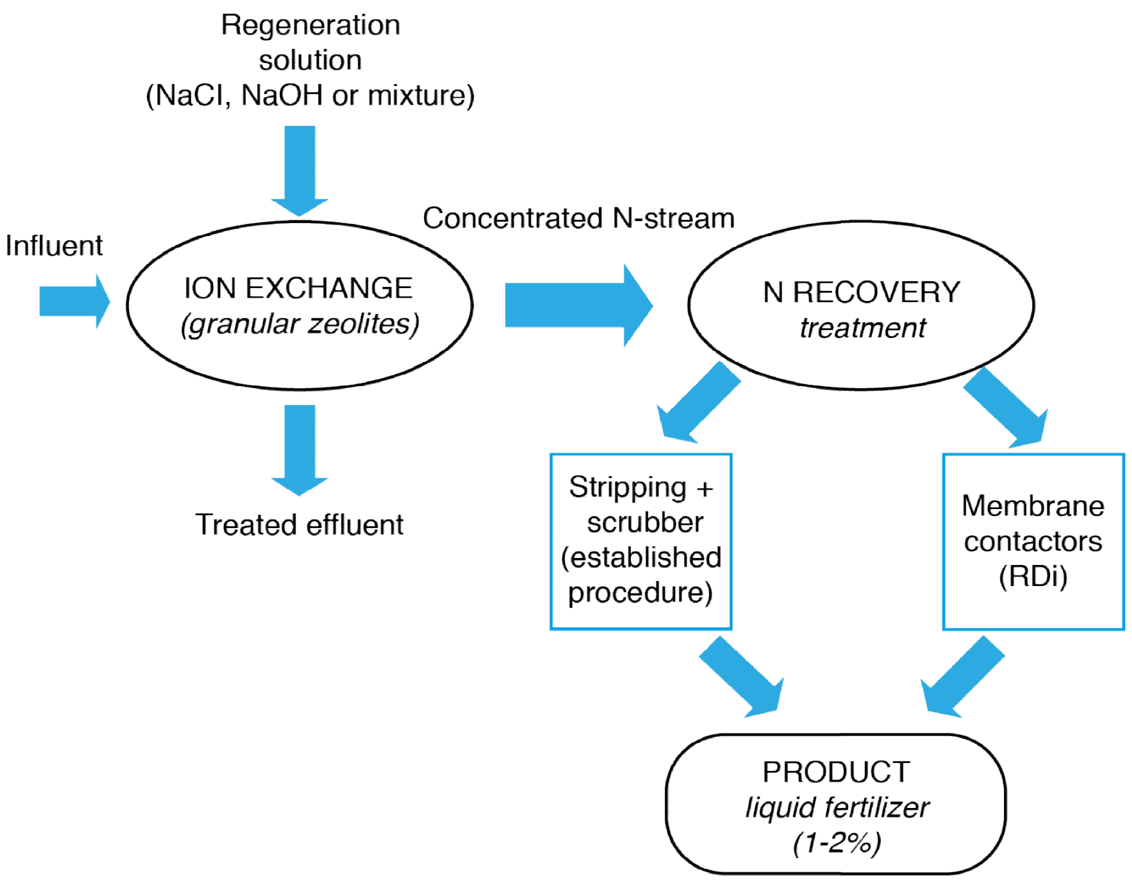


*fig. 4 Nitrogen flow stream (font:[14])*

This helps to avoid environmental impact with relevant benefit on that side, almost 71% less impact than a standard WWTP. Besides, the process avoids the emission of dinitrogen monoxide ($N_2O$) that is a typical emission of the conventional system of nitrification/de-nitrification. Using an ion-exchange technology is possible to recover almost 99% of the nitrogen present in wastewater and for 90% in the form of fertilisers or contained in the sludge.

## 2.4.3 Phosphorus recovery/disposal

The reserves of phosphorus will last 300 years at most at the actual rate of mining since P is mined as a mineral [10]. Thus, phosphorus is a limited resource, and its commercial value will inevitably increase as the reserves will decrease. Therefore, the market value of some wastewater components will continue to rise, and their value is a crucial driver factor for resource recovery from wastewater.

Considering that wastewater is an essential source of concentrated nutrients and taking into account that fertiliser prices are also increasing, any alternative that considers their recovery at an acceptable cost must be regarded as to save money and resources, obtain added-value products and improve the final water quality.

WWTPs are often equipped also with P removal after this process almost 90% of the P is transferred into the sewage sludge that is further disposed into lands. The recovery of P can be cost-neutral if P is recovered as struvite from the aqueous phase. Struvite is a phosphate mineral, and it is sparingly soluble in neutral, alkaline conditions, but readily soluble in acid. Struvite also has a high economic value since its fertilising efficiency is three times higher than phosphate. This type of process is not feasible for streams with low P concentration, so a nutrient enrichment is needed upwards in the process. Moreover, the magnesium is added to eliminate phosphorous from the effluent stream [10]. In case sewage sludge is incinerated, it is possible to recover up to 70-90% of the P contained in the wastewater inflow.

## 2.5 Other products obtainable from a WWTP

None of the following products has been fully developed in the up-scaling application, but only for small-case experiments.

**Volatile fatty acids (VFA):** are generated from the acid fermentation during the middle stage (acidogenesis and acetogenesis) of anaerobic digestion, from VFA it is possible to obtain high added value products, but this is not economically preferable to biogas generation [19].

The value products obtainable from VFA are:

**-Polyhydroxyalkanoates (PHAs):** it is fully biodegradable biopolyesters that are able to substitute polymers derived from fossil-fuel, also defined as bioplastics. The main drawback is that this converting process's cost would increase of about 20-80%.

-**Carbon-chain elongation**: this process is aiming to improve the downstream processing by extension of the carbon chain.

-**Single-cell protein (SCP):** this process will be further developed in the thesis through an integration system that will consider the industrial production of hydrogen and renewable methane. In this procedure electrical energy, produced in excess by renewable energy, is used to produce $H_2$ by electrolysis, to function as an electron donor for $H_2$ oxidising bacteria.

**-Cellulose:** it is also possible to recover cellulose from wastewater since it has a domestic origin. Toilet papers are found in high percentages in wastewater, that consequently contains a lot of cellulose, which is a considerable fraction of the influent COD. There is a drawback that recovering cellulose means decreasing by 10% of the production of biogas. The cellulose can be used for soil conditioner, aggregate for construction materials like asphalt. It is also possible to use it for the production of new toilet papers, but it is uncertain if consumers would buy it [2].

Recently, has been criticised for the integration of methane recovery from COD by integrating AD, due to its high energy losses, only reaching an energy efficiency of about 15% overall. While the COD as a separate product thanks to its higher monetary value, the major barrier will be consumer's association that won't encourage to buy wastewater-derived products with faecal matter, that's why marketing campaigns that promote these derived products positively are essential [20].

That is why the figure of WMUs it is growing in the WWTP panorama since many bottlenecks would be avoided by the correct resource recovery routes (RRR). This new utility would take the responsibility to transform an energy-intensive structure, such as a WWTP, into a resource recovery system where all the resources are redirected or recovered for a second scope or just insert into a circular stream. Not all the drawbacks would be avoided with the right recovery routes; it is needed to overcome the bottlenecks related to the distribution and the transport of recovered resources. Moreover, to reduce the process costs and to verify that the quality requirements are met the figure of WMU is needed, so the role of WMU also includes the design process. Finally, the WMUs model can develop strategies to convince policymakers and users about the necessity of harmlessness of an RRR.

## 2.6 Water reclamation

Wastewater reclamation has been under study over the years, but no single process could completely resolve the problem of water purification. Therefore, integrated approaches are required to possibly bring the new paradigm towards a profitable utilisation of clarified wastewater, for example, as toilet water [1].

Over the years wastewater reclamation has been considered better than water desalination or long-distance water transport, especially in cities where the supply of water is limited and the population is growing. It can be reused for crops, ground water recharges or for many other water uses. Exceptionally, reclaiming for potable water use has been proved in a few cases as in Windhoek (Namibia), where almost 25% of the potable water of the city is provided by WWTPs, but in general it is stopped by social resistance. In Israel 1/4 of the country's water demand is met by wastewater treated. In some cases it can also be used as a toilet flushing, gardening cutting the consume of water by 50% in the University of Xi'an in China [1]. In Italy, the effluent water is injected in a water grid dedicated to agriculture. In the WWTP of Vilanova (Catalonia, Spain) the effluent water is directly injected in the sea, and this represents a significant waste of resource that otherwise could be used in many different ways depending on the rate of purification of the system installed. In addition, other technologies could be used to obtain different qualities of water for different purposes, for which some impurities must be removed for different use of the water. For instance, if the water is used for crops irrigation purposes, it is not needed to remove phosphates or nitrates. In order to obtain potable water, other processes are needed, such as granular media filtration, ultraviolet radiation, granular activated carbon adsorption, reverse osmosis, air stripping, ozonation and chlorination [27]. All these examples are useful to understand why it is important to decrease the water demand in cities and dry regions by water reuse [2].

The technologies that will be mentioned and briefly described are:

*Membrane ultrafiltration*- It is a separation process that by means of high pressures of concentration gradients lead to a separation through a semipermeable membrane. It doesn't need too much space since it's a physical barrier and it removes most bacteria, even some viruses, proteins and produces high quality effluents. One example it can be found in Singapore, in which the process consists of several treatment steps and it obtains a good amount of reclaimed water, enough to refill natural drinking-water reservoirs [24].

Different types of membranes are under investigation, and a promising one is the membrane bioreactors (MBRs), that combines activated sludge process with microporous ultrafiltration membranes for solid-liquid separation, that is a great advantage to control sludge and hydraulic retention times separately. The disadvantages are related mainly with the more complex system, higher costs due to aeration, membrane cleaning compared with a CAS process. It has been demonstrated that membrane filtration technologies always require a lot of electricity consumptions, that means cost ineffectiveness [26].

*Activated carbon (AC) filtration-* the materials used as AC are made of coals, peat, petroleum coke and nutshells. These substances are started by physical and chemical agents under high temperatures, removing effectively COD and a wide range of organic pollutants. The combination of AC filtration with oxidation by ozone removes 90% of different pesticides in the production of potable water. The functioning of the combined system is based on AC that acts as a catalyst in the ozonation reaction, while ozone increases the pore size and active surface area of AC [19].

*Advanced oxidation process (AOP)-* it has a high rate of destruction of many non-biodegradable organic contaminants such as pharmaceuticals, pesticides, bacteria, protozoa and viruses, in particular thanks to Ozone. It is usually applied in the final disinfection step or as a pre-treatment that breaks down organic contaminants. This system can also be configured depending on the contaminant concentration and composition. The drawbacks are related mainly to the high costs of reagents such as hydrogen peroxide and ozone, but the main disadvantage is the high energy demand and the short stability of ozone, in the ozonation process. While UV irradiation, is a cost-effective process, and it is a promising alternative to chemicals procedures [2].

The UV irradiation system is also utilised in Paris as a purification system of potable water for the entire city [27]. One of the most common and widely used systems to eliminate viruses, bacteria and protozoa is chlorination, even though it has been demonstrated that harmful molecules could be generated that are resistant to chlorination. Therefore, it is usually advisable that the chlorination step should be followed by some advanced treatments.

The aim is to understand how to reclaim water and further how to re-inject the water in the grid of the city since the already existing infrastructure is not built based on the concept of water reuse. Therefore, a new distribution network or a change in the current network is needed. In a district of Tokyo, a new pipeline network has been installed, using reclaimed wastewater to flush toilets. While in Catalunya, the government is promoting to use the reclaimed wastewater to recharge the aquifer, preventing water scarcity [1].

The main bottleneck in the reuse of wastewater as potable water is the lack of legislations; it is already really challenging for a water management utility to invest on these systems that would actually help in the future where it will become more common to have water shortages, also due to climate change. That is why it will be important to involve the population in these types of choices to build a strong feeling of trust between citizens and decision-makers.

The last drawbacks regarding the use that can be made with wastewater, due to the lack of common legislation at the European level it's really difficult to implement investments and it still not an attraction for business venture capital to invest in the reclamation of water.

## 2.7 Sludge management

Sludge is the putrescent product exiting from WTTP, is a difficult product to manage due to its complex and diversified composition, that varies for each municipality and inside of a WWTP the design may vary significantly due to different inflow streams. The typical sludge line in a WWTP is depicted in fig. 5. Besides, in Europe, billions of tons of sludge that has not been displaced yet and this represents a significant lack of efficiency since this product has a value that could be valorised [19]

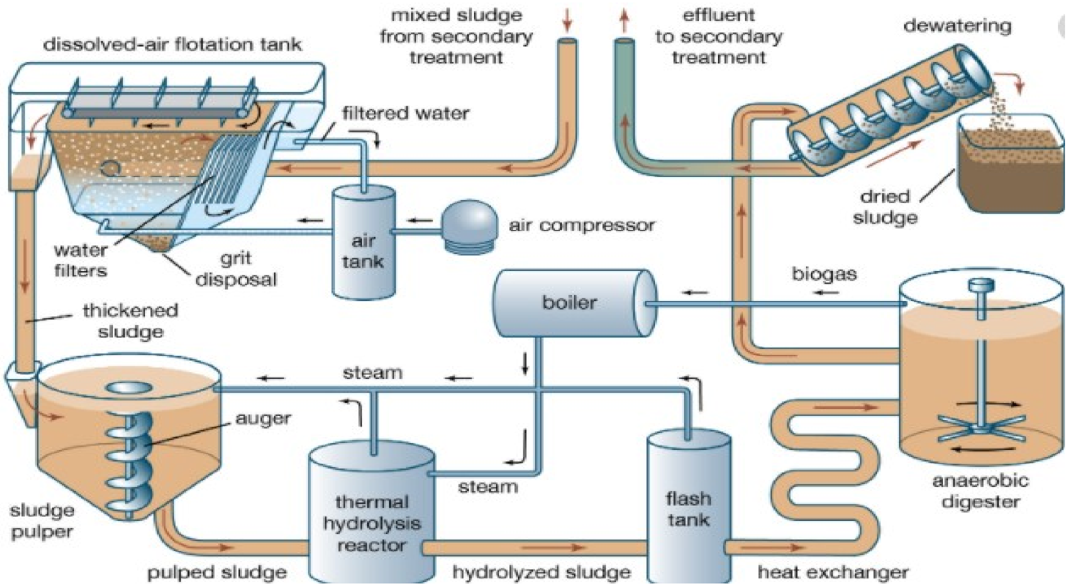


*fig. 5 Sludge line general treatment (font: Britannica)*

The traditional way to dispose sludge for many countries, while for others is totally forbidden, is the land filling and has always been a cost-effective way to dispose sludge [19]. As mentioned before in many countries the land disposal of sludge is strictly forbidden, since has been found in many countries trace of harmful substances for the human body. In Germany for instance, only the ash resulting from sludge incineration can landfilled. This was the easier and cheaper way to dispose sludge and from the literature it was accounting between 15-20% of the operational costs.

Most used methods for the final disposal of sludge are represented in the fig. 6,and listed below:

- Disposal in landfills.

- Agricultural use after composting.

- Incineration.

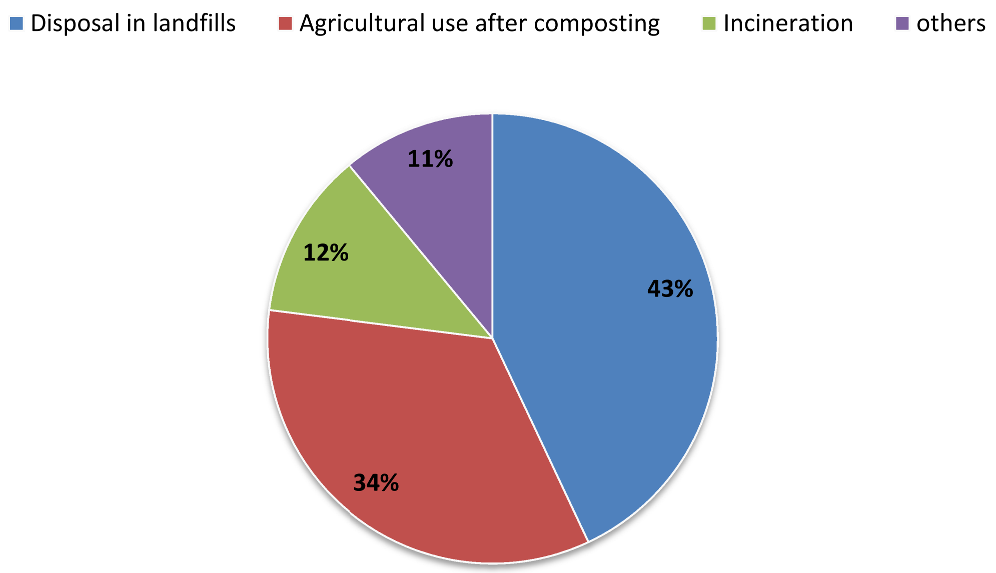


*fig. 6 Principal sludge's disposal methods (font. Britannica)*

Before 1998, the sludge was discharged into marine waters or used as fertilizer in the agricultural sector. From that date, through subsequent updates, the EU has imposed on member states, through a community directive (UWWTD), a ban on dumping at sea, to preserve the environment from the damage caused by this practice. Since then, agricultural use has become the main method of disposal beyond landfilling.

## 2.8 Agricultural use

Sludge contains nitrogen and phosphorus, which makes them particularly suitable for use as fertilizer, as these elements are essential for plant growth. However, sludge can contain at the same time several other elements which can be harmful if introduced into the human body, such as heavy metals. The reuse of sludge in agriculture has been regulated by the EU with the EC landfill directive (1999/31/EC), the main purpose of which is to protect the soil and humans from the presence of harmful substances. Not only this, the use of sludge as fertilizers also involves difficulties of a technical and social nature. Technical problems arise due to the fact that the sludge is produced in all periods of the year, while their application to the ground takes place once or twice a year, making storage operations necessary. In addition, the content of certain compounds must comply with explicit regulatory criteria, for example that of heavy metals, which are normally contained in sludge that can be toxic to humans. The use of sludge for agricultural purposes is not always frowned upon by the consumer, hence a social problem, which is still present despite the expansion of the legislation in this regard, and which still creates debate among legislators, farmers and consumers [2]

## 2.9 Incineration

Incineration is very attractive as a sludge disposal method, as it produces several advantages:

-Great decrease in volume. Research has shown that the final volume of sludge after incineration is about 10% of that after mechanical dewatering.

-Thermal destruction of toxic organic components.

- Minimization of the generated odor.

- Possibility of heat recovery.

Despite everything, incineration is not a complete disposal method, as about 30% of the solids remain in the form of ashes as a waste product. The latter is almost always prepared for landfill and is considered highly toxic due to the high concentration of metal present. One of the main concerns that can hold back the development of this process is the potential emission of harmful gases. Appropriate technologies for the abatement of nitrogen oxides, sulfur oxides and particulate matter must therefore be applied to incineration plants, which can significantly affect plant costs [28].

## 2.10 Innovation in dewatering process

The dewatering processes adopted until now in the treatment of purification sludge can go as far as to obtain a moisture content of 60%. Thermal drying is the only process that allows to go further to reach a sufficiently low degree of humidity to ensure combustion without auxiliary fuels. The logistically best operation would be to dry the sludge on the production site, to greatly reduce its volume and facilitate its transport. However, this type of process is not normally present in WWTPs, and it is therefore more realistic to hypothesize its integration in the plant in question [2].

One way to produce the heat needed for the drying process would be the recirculation of flue gases, from the system to inside the tank of sludge drying, avoiding the costs of a heat exchanger and the fuel needed. The recovered heat won't be enough in order to dry efficiently and in reasonable times all the sludge that needs to be finally disposed. For this reason, additional heat can be provided by thermal solar panels or even better hybrid solar panels, from which both thermal and electrical energy can be provided by the same panel.

As a second option, the electro-dewatering process is currently developed by various European universities with the aim of increase the rate of dried sludge. The process would consist in separating water and sludge through the use of electricity, in the meanwhile the whole stream undergoes the process of centrifuge.

As final option, in the literature is argued if it would be socially acceptable to use sludge as material resource, indeed some European producers of bricks already implemented a dedicated system to include sludge inside the melting process in the bricks' production.

Moreover, there are also many other possibilities to set dry and wet sludge into the circular economy, some studies have been carried on for the use of sludge in the production of bricks that could be used for different purposes [29]. From the literature, it would be possible to mix wet sludge and clay in the burning process for the final production of brick. Different percentages of sludge in the final brick were evaluated and tested, this process has been followed also for the asphalt production. The additional point for the asphalt solution is the higher social acceptance, since using a bio-brick produced derivations of wastewater it can be socially not accepted. Finally, a good solution but only feasible in specific situations is the disposal of sludge in lands that need a quality requalification to become fertile.

## 2.11 New concept applied in a WWTP

An innovative proposal in which a WWTP and the recovery of energy and nutrients could fit perfectly is the renewable methane generation through the electrolysis and methanation process. This could be a win-win configuration for both the generation of renewable methane and for of the construction of innovative WWTP. The main reason for which this plant has been designed is the flexibility that could bring to the electrical grid, but most of all it will prevent the price of electricity from falling going below zero [18].

Therefore, wastewater and sludge could be used as a source of bio energy in the form of biogas, the net effect on climate change is positive, as it is considered a kind of residues. It does not generate any emission from land-use, therefore avoiding any land-use competition.

### 2.11.1 Renewable power integration and energy storage

The main challenge for the future grid it will be the higher integration of renewable energy into the grid, it is known that RES has a marginal cost (MC) that is equal to zero gaining the first position when comes to decide the energy mix. The fact that RES has no fuel to inject, decrease their operational costs and therefore MC to the lowest value between various technologies and this is expected to be damaging for the future of the energy industry. For instance, during the pandemic periods, the price of electricity has gone below zero for many days because the supply and the demand were not matching due to the low industrial production. As a final effect, the investments on renewable energies will be affected.

High shares of fluctuating renewable power from wind and solar will shape the future energy supply. Around 20% of total power generation will be required as balancing power to ensure technical supply security and stability of grid operation. Hydro and fossil power are specially designed for high peak demand periods. Bioenergy is a storable source and can thus provide balancing power that is also one of its strategic function. It will be tough for only bioenergy to balance the grid since the electricity demand is way higher, but it will be a help for different communities.

Furthermore, a large amount of surplus power will be available as wind and solar power generation will often exceed the power demand. Although electrical networks will be extended all around Europe, and grid operation will be optimised by load management, energy storage capacities will be needed as a balancing reserve (backup power) [18]. At the moment, the only technologies available on the market that can store a high amount of energy are pumped hydro and compressed air storage, also for seasonal purposes, the best solution are solar ponds and geothermal energy. The main focus nowadays it's on lithium-ion batteries, that are mainly used for uninterruptible power supply, some types of batteries

(Sodium-sulphur) are suitable for large-scale applications but still too expensive.

The key point that the electrical network will need to face in the future is the two weeks bridge of wind calms and low sun that can only be met by long-term storage facilities. Until now, the only option available was hydrogen, but due to high costs, security challenges and missing infrastructure it has some limitation. If the focus is brought to the missing infrastructure, it is true that the most extensive existing storage with proven technology is the gas network. That has a capacity of hundreds of TWh, and it is consequently available to cover the two weeks gap.

## 2.11.2 Standard concept of Power to Gas ($CH_4$) and WWTP integration

The idea is based on using the surplus production from renewable power once the daily share reaches more or less 75% and store it in the natural gas grid and therefore increasing the electricity demand.  Renewable methane can be reconverted into power and stabilise grid operation by providing ancillary services. A clear overview of the process is given in fig. 7 here below.

The concept of renewable methane is based on the mutual linking of the power grid with the natural gas grid. Renewable power is converted via electrolysis (with purified water) into hydrogen and oxygen. The hydrogen is then combined with $CO_2$ and converted into methane through a methanation process. The $CO_2$ can be recovered from CHP (Combined heat cycle) with CCS (Carbon Capture System). The renewable natural gas substitute (SNG) can be stored, distributed and reconverted on-demand in balance power [18].

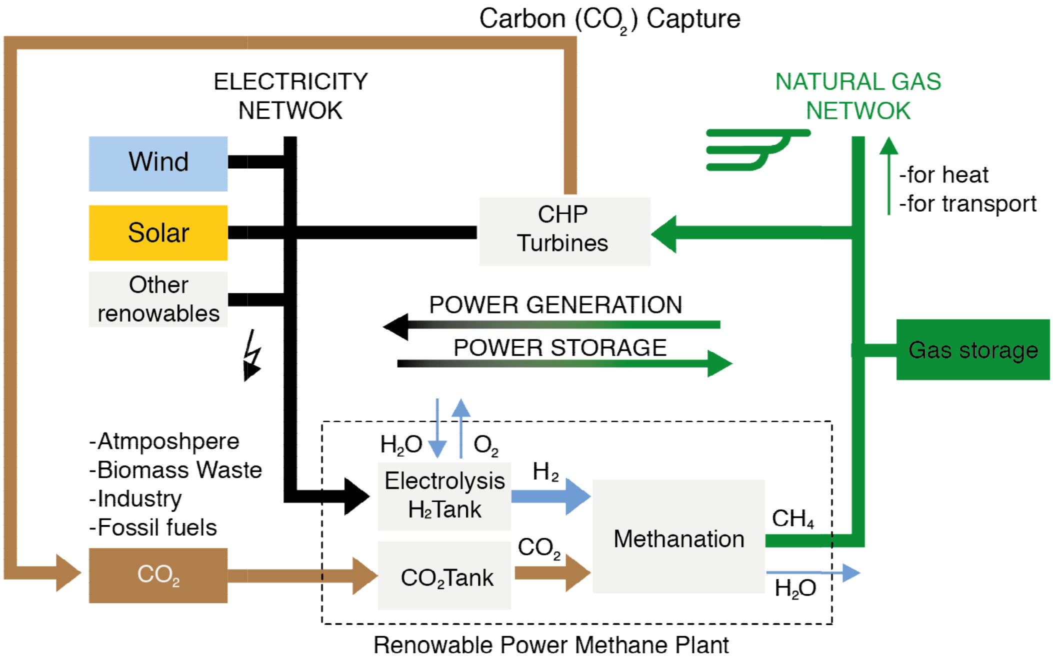


*fig. 7 Typical Power to gas plant*

Moreover, the two main significant advantages of natural gas are the already existing network infrastructure and the higher energy density compared with hydrogen. Energy transfer capacities of gas are much larger than electrical power lines, which is another advantage of using the existing natural gas network for renewable energy.

This new concept allows the use of renewable power in heat supply and transport and substitutes high-energy-density fuels. Indeed, renewable methane can be further compressed or liquified and used for long-distance traffic and in some specific transport segments.

This system could be further adapted to the design of WWTPs changing some steps. The surplus of electricity production form renewable sources will still be used for the production of hydrogen by means of electrolysis. The obtained hydrogen will be further mixed with $CO_2$, separated from the methane after anaerobic digestion, into a Sabatier reactor. In the Sabatier reactor the mix will undergo a methanation process, and the methane produced will be further injected into the gas distribution grid. The same will happen with the methane formed after the biogas upgrading, and as well it is injected and sold to the gas distribution grid.

# 3 Objectives

The general objective, is to make an estimation on how new WWTP's layout could affect overall costs and environmental damages in comparison with conventional CAS systems. Considering, also two fundamental aspects of WWTP, that are the size and the different streams concentration.

In order to fulfill the general objectives, the thesis has been structured as follows:

-Firstly, it will be given an overview of the characteristics of two reference WWTPs and a WWTP that is needed for comparison. The three different sizes WWTPs that have been chosen, Murcia-Este (big size of 1.088.889 PE) [12], Vilanova i la Geltru (medium size 130.050 PE)[13] and a simulated small WWTP (10.000 PE) [25];

-Secondly, it will be deepened the possibility to implement nutrients recovery in WWTPs such as carbon and nitrogen recovery, this is needed to highlight the change of paradigm on WWTP facilities from waste management facility to resource recovery;

-Thirdly, it will be evaluated the different plants in terms of size and cost-effectiveness, the environmental benefits and how the price of fertilizers needs to change to reach cost neutrality;

-Lastly, it will be analyzed an innovative merged solution with renewable methane production, in the same terms of the previous WWTPs.

## 3.1 Case studies

Three WWTP of different sizes (Murcia-Este, Vilanova i la Geltru and a simulated small WWTP) are used as case studies and baseline scenarios in this analysis. The first two plants are operated by AQUALOGY Medio Ambiente, S.A (Agbar group) and aguas de Murcia respectively. The data for the small WWTP were collected through a literature survey on small WWTP in South Europe, comparing different WWTPs.
The choice of the plants was driven by the similarity in the treating wastewater process, and by their geographical position, indeed the first two WWTPs are located close by a water source with similar costs (electricity, construction, labor costs) and technologies.

While the choice of the third plant was done to compare different sizes, where for instance anaerobic digestion is not implemented with a consequent lack in biogas production. Furthermore, the biogas production in both plants reach up to almost 50% of the WWTP electricity requirements and in both plants, nutrients recovery processes are implemented but removals or discharging processes [12], [13].

The interesting differences between the three plants were the treatment capacity and consequently the main difference in the number of PE (population equivalent), that permitted to study how the Cost-benefit analysis would have changed for various integration of innovative systems in the configuration of the WWTPs analyzed. Besides, it has been also calculated which would be the price of nutrient fertilizers and how much energy could have been produced to try to reach self-sustainability and independence.

### 3.1.1 Characterization of the three plants

*Vilanova i la Geltru*

*fig. 8 Aerial view of Vilanova WWTP*

Vilanova i la Geltru WWTP, depicted in fig. 8 treat a mix of municipal and industrial wastewater of Vilanova i la Geltru and Sant Pere de Ribes municipalities with an overall capacity of 25.500 $\mathrm{m^3/day}$, that correspond to 130.050 PE. The plant is equipped with the conventional activated sludge (CAS) to remove carbon and as a general overview is composed by a wastewater line, sludge line and a gas line.

The wastewater line consists of pre-treatment (screen, grit and fats), primary sedimentation (primary settler), biological aerated reactor (biological reactor) and secondary sedimentation (secondary settler). The treated effluent is partially utilized as service water, after chlorination, another part is used as industrial water and the remaining part is discharged into the sea.

The sludge line is formed by sludge thickening (primary sludge by gravity; and secondary sludge by flotation), AD at mesophilic conditions (37°C) and centrifuges needed for the dewatering process. The sludge is further moved to thermal drying installations. Finally, the gas line consists of a gasometer, engine cogeneration and a heat exchanger. Thanks to the cogeneration unit the WWTP is able to produce 50% of the WWTP's energy need. Completing the features, there is a chemical deodorizing system at the principal odor emission points [13].

For what concern nutrients removal, organic matter and suspended solids are successfully removed along the process, with respectively an average of removal of about 91% biochemical oxygen demand ($BOD_5$), 85% of chemical oxygen demand (COD) and 84% of total suspended solids (TSS). All these data are summarized for both plants in Table 2.

*Murcia-Este*

The Murcia-Este WWTP is situated in the city of Murcia (Spain) and treats wastewater collected from the municipality of Murcia. The plant occupies an area of 12,5 ha and it is designed to treat a flow of 100.000 $m^3$ /day.

The general layout of the plant is equal to the Vilanova WWTP and it is possible to see it from the fig.8 above, that’s why these two WWTPs have been chosen as a reference scenario. Apart from the variant configuration of the conventional activated sludge treatment that is called A20, that includes anaerobic, anoxic and aerobic stages, allowing nitrogen (N), phosphorus (P) and organic matter removal. This system is composed of a compartmentalized anaerobic area equipped with mixing agitators that ensure close contact between the influent and the re-circulated biomass in the absence of oxygen. While the anoxic area ensures close contact between the influent and the internal re-circulation and finally the aerobic chambers.

Other two differences have been taken into account that is the capacity and nutrients concentration in the inflow wastewater stream. In this case, the remaining part of the effluent, after being treated and partially redirected to water services and industrial water facilities, is discharged into the Segura River [12].

| | Vilanova i la Geltru | Murcia-Este |
|---|---|---|
| Nominal Capacity ($m^3/day$) | 25.500 | 100.000 |
| PE (1 population equivalent=54 g of BOD) | 130.050 | 1.088.880 |
| Influent $BOD_5$(mg/L) | 360 | 588 |
| BOD removal efficiency (%) | 90 | 94,2 |
| Effluent $BOD_5$(mg/L) | 36 | 34,1 |
| Influent TSS (mg/L) | 453 | 404 |
| Suspended solids removal (TSS) efficiency (%) | 86 | 97,5 |
| Effluent TSS (mg/L) | 63,42 | 10,1 |
| Influent COD (mg/L) | 802 | 654 |
| COD removal efficiency (%) | 95 | 94,2 |
| Effluent COD (mg/L) | 40,1 | 37,9 |
| Influent N (mg/L) | 47 | 76,8 |
| Nitrogen removal efficiency (%) | 49 | 77,7 |
| Effluent N (mg/L) | 23,97 | 17,12 |
| Influent P (mg/L) | 10 | 9,1 |
| Phosphorus removal efficiency (%) | 63 | 78,3 |
| Effluent P (mg/L) | 3,7 | 1,9 |

*Table 2. Influent/effluent flow characteristics of the two reference WWTPs*

*Small WWTP*

In this section, small WWTP will be analyzed under different aspects but the focus will be mainly on the overall costs and on the environmental benefits.

In addition, the valuation of small WWTP can be interesting for small and rural communities and for effective wastewater treatment. Even though, the rate of people living in small communities is lower compared with big cities, most of them are located in the tourist and sensitive areas where is needed a clean and environmentally safe area. This is essential both for the generation income and for the environment, that is why the next section will be focused on the valorization of small communities.

The small WWTP is defined with data collected from the literature regarding small WWTP in South Europe. The capacity of this plant has been selected to be 10.000 PE that corresponds to 2000 ($m^3$ /day) of treated wastewater [4].

The reason why it has been selected this capacity is due to lack of presence of anaerobic digestion, if AD is missing then also a cogeneration unit is useless, therefore a decrease in price compared with previous WWTPs could be expected. But is important to consider that statistically small WWTPs, have higher costs due to higher labor costs and a lack of own energy production.

The water line is composed of a mechanical pretreatment (screening and grit removal), for the carbon removal has been utilized the CAS system and finally secondary sedimentation and chlorination (by means of NaOCl). The sludge line instead, is composed by thickening and dewatering of sludge that can be obtained by means of air drying and a mechanical process, then the sludge is ready for the final disposal.

## 3.2 Implementation of carbon redirection and nitrogen recovery

The reference scenarios of Vilanova and Murcia were needed to study the introduction of a carbon redirection and nitrogen recovery, aiming the self-sustainability. This solution in the WWTP process is based on the combination of a carbon redirection unit (pre-concentration + AD) and a nutrient recovery unit. This will help to achieve both a higher production of biogas and the recovery of nutrients to be more feasible while in the two reference cases (Vilanova and Murcia-Este) there was only nutrients removal. Therefore, it would be possible to increase the production of energy that can be used in the same plant.

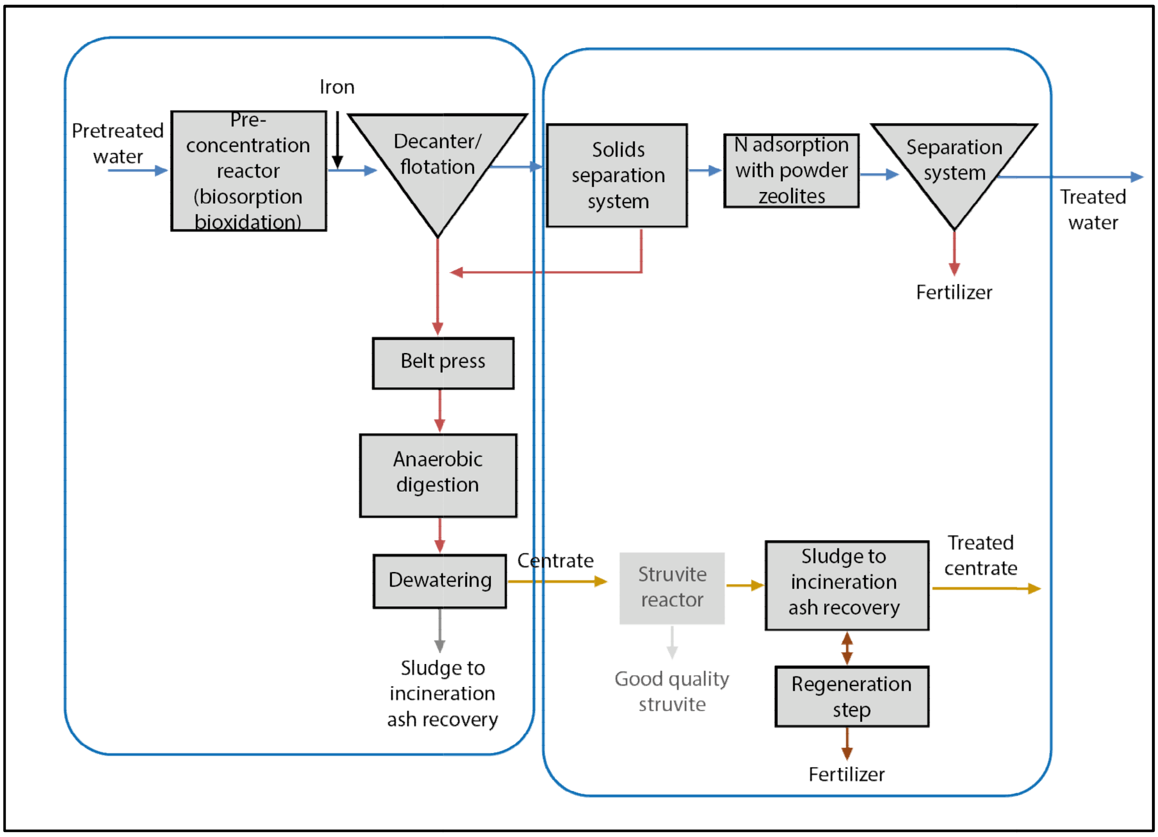


*fig. 9 Carbon + nutrient recovery scheme*

### *Carbon redirection unit*

The carbon recovery unit, depicted in fig.9 has been defined to be composed of two consecutive steps: a pre-concentration and an AD unit. In the pre-concentration reactor, the bio-sorption it is aimed to be maximum to minimize the nitrogen removal. Then the flow enters in a decanter where the sludge is separated from treated water that is then redirected in the nutrients recovery process. The sludge undergoes a belt press for the thickening process to be finally treated in an anaerobic reactor to convert the thickened sludge into biogas. Then the thickened and digested sludge is stored in the same tank but divided into two parts.

The sludge then is injected in the dewatering process, where it loses a lot of its weight, then is ready for the final incineration or agricultural disposal.

*Nutrient redirection unit*

The nutrient recovery unit is based on a pre-treatment unit where is positioned firstly a glass filter and ultrafiltration (UF) followed by an ion-exchange unit by means of granular zeolites columns. The pre-treatment unit has been selected to protect the zeolites and remove the part of COD particulate and suspended solids left.

Therefore, as depicted in fig. 9 above, the products obtained are not the final fertilizers but only ammonia is recovered.  At the end of the process, to regenerate zeolites is needed the use of chemicals such as hydrochloric acid (HCl) and sodium hydroxide (NaOH).

An improvement is expected compared with the reference system in the reduction of energy consumptions and carbon footprint while it is expected a drastic increase in the nutrients recovery. These improvements are summarized here below in Table 3, which data were collected from previous literature.

| Target | CAS system | C+N redirection system |
|---|---|---|
| Energy self-sufficiency (electricity) | 20-40% | 60% |
| Nutrient recovery | 0% | 70% |
| Carbon footprint reduction | 0% | 30% |

*Table 3. Estimated target with a nutrient redirection unit (font:[5])*

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# 4. Methodology for the economical and environmental assessment

The economical and environmental assessment analysis has been conducted by defining the two reference WWTPs, from that base the cost and environmental damages will be calculated for a small WWTP. Further on, the same will be done with an innovative WWTP layout, composed of carbon and nitrogen recovery and making a comparison between all these systems. Finally, it will be analyzed how the integration of a WWTP together with renewable power methane system will affect the previous WWTP both in economical and environmental terms.

-Reference scenario: two WWTP of different size (large and medium), for which real data were collected. Both plants are geographically located in Spain and both are close to a water source (sea and river), therefore carbon and nitrogen are not removed from wastewater but discharged into the water source.

-Small WWTP: it has been studied since one of the scopes of this thesis is to evaluate the different sizes of WWTP in terms of costs and environmental damages. The system has been evaluated with the implementation of aeration. Aeration system is often used in activated sludge, it consumes a lot of energy, but requires zero attention by the plant's employee, therefore, reducing labor cost.

- Innovative WWTP. The assessment has been conducted following the results of a project that developed a pilot scale for nutrients recovery in Vilanova, from which it was possible to collect the data needed to compare the large and medium-sized WWTP with the implementation of resource recovery. The assumptions are important: indeed, the electricity mix is dependent on the country and in some cases also on the region. The emission factor, of a WWTP with carbon redirection and nitrogen removal, considered, is equal to 0,34 kg$CO_2$ /kWh, while the cost is equal to 0,1€/KWh.

-Renewable Power Methane (RPM). It will be evaluated how the cost will be reduced thanks to the introduction of a new stream of revenues and the environmental impact.

## 4.1 The base unit

The purpose to define a base unit is to have a reference to which different comparison can be made with a common basis to be sure these comparisons have an economical meaning. Therefore, since the capacity of a WWTP is defined by the amount of $m^3$ of treated wastewater, this will be the functional unit chosen by this thesis.

## 4.2 Assumptions and boundaries

For the definition of the analysis, it is important to define the assumptions made in order to be possible to estimate environmentally and economically the WWTPs under evaluation.

-WWTP in size. The size of WWTP is essential in this thesis since for the implementation of carbon and nitrogen recovery has a sense only for WWTP with anaerobic digestion this is also considered for the implementation of RPM in a WWTP. Anaerobic digestion is present only in WWTP with a capacity >30.000 PE, therefore it won't make sense to implement these technologies in small WWTP.

-Same technologies. It has been assumed that both reference plants (Vilanova and Murcia) had the same type of CAS, while in reality the WWTP of Murcia uses an A20, that is a little variation from the conventional activated sludge.

-Sludge disposition. A great expanse for WWTP is the sludge disposition. Indeed, if a WWTP wants to get rid of the sludge produced needs to give it to farmers but are not the farmers paying for the product. Indirectly, the citizens are the ones that pay the sludge disposition to farmers. So, for each ton of sludge that is disposed of in an agricultural crop, the farmer is usually paid 150€.

-The manufacturing process related cost for the different units of all the plants considered has not been taken into account.

-The electricity consumptions for illumination, air conditioning, sensors etc. are not considered.

-Chemical consumptions. In the small WWTP, only polymers for sludge dewatering has been considered, while for the reference scenario also the iron-salts for the nitrogen removal in the anaerobic digester is added. Finally, for the nitrogen recovery and carbon redirection design, the chemicals are also consumed in the solid separation unit.

-The energy recoverable from carbon and nitrogen redirection increase of around 25% if compared with conventional WWTPs (lower energy requirements, thanks to 20-40% energy intensity of aeration).

-The concentration of nitrogen in the effluent for a nitrogen recovery system, is 90-95% lower than for a conventional WWTP.

-95% of the total COD, can be removed in the innovative configuration.

-99% of the total nitrogen can be recovered in the form of fertilizers (90%) or into sludge (9%);

-The price of fertilizers has been evaluated based on present market value (0,04 €/$m^3$)

-The share of the tax revenues paid by the citizens for the wastewater treatment has an average share of 10% on the overall price (price estimation of Aguas de Barcelona) paid by $m^3$ wastewater treated (0,056 €/$m^3$).

- Transport costs. Related with the transport of sludge (between sludge production and final disposal) and chemicals (between chemical suppliers and the WWTP) were taken as a given data from previous studies.

- Fugitive emissions. 2% of losses of $CH_4$ has been estimated on average.

- Legal framework. There is a lack of common European legislation for the use of fertilizers derived from the waste, and therefore a missing market where it is possible to sell the recovered products. What is expected in the future is that discharge requirements will constantly decrease that's why new technologies are needed.

## 4.3 Economical assessment

*Reference case medium and large WWTP*

First, it will be shown how CAPEX and OPEX had been calculated for a big sized WWTP, the one in Murcia-Este (100.000 $m^3$/day), and for a medium-sized WWTP in Vilanova (25.500 $m^3$/day). The operational data were taken from reports and documents describing these plants for the calculation of the reference scenario. Both plants discharge their wastewater and consequently nutrients content into the sea or a river. To make it comparable with the nutrient recovery, it is needed to consider that there will be higher consumptions of electricity of around 19,4% due to higher aeration in the biological reactor for nitrification/denitrification process.

To assess all the costs that will occur during the whole lifespan of the project, different prices were considered. For the calculation of operation and maintenance expenses were considered electricity consumptions, personnel cost, waste disposal and chemicals.

*Capital expenditure CAPEX, reference case*

To quantify the CAPEX, it is needed to have the past two years capital expenditures of the utility, in this case, this is not possible. Therefore, it has been taken into account the average of the annual equivalent cost (AEC) obtained by multiplying the capacity of the plant with the estimated yearly price of a large/medium-sized WWTP. The CAPEX is then conveyed through the following equation:

$$AEC = \frac{CAPEX}{\frac{1-(1+i^{-n})}{i}}$$

where i is equal to the discount rate=0,05 and n is the lifespan of the plant, that has been selected to be 20 years.

*Vilanova*

Indeed, a conventional WWTP has an overall cost (capital and operational expenditure) of about 17-30 € per PE per year (23,5€ has been considered), for WWTP with a capacity of > 100.000 PE [5]. The price that has been chosen is then 17€ per PE per year for the Vilanova plant. It is known that 1PE correspond to 54 g of BOD, and the content in Vilanova is around 360 g/L of wastewater, while the overall amount of $m^3$ treated in a year is 9.307.500. Therefore, if expressing in terms of the functional unit we obtain 0,2 €/$m^3$ of wastewater treated in a conventional WWTP, this cost is then split into CAPEX and OPEX. The CAPEX obtained is equal to 0,059 €/ $m^3$ of treated wastewater, that is composed by the different unit costs of: pre-treatment ($1,18*10^{-3}$€/$m^3$), bioreactor + secondary settler (0,02832€/$m^3$), anaerobic digestion ($7,08*10^{-3}$€/$m^3$), cogeneration ($5,9*10^{-3}$€/ $m^3$) primary settler($2,95*10^{-3}$€/ $m^3$), sludge thickener($8,85*10^{-3}$€/ $m^3$) and dewatering ($4,72*10^{-3}$€/ $m^3$).

*Murcia- Este*

The same procedure has also been followed for the WWTP of Murcia-Este, also, in this case the price chosen per year taken is the average of 23.5 € per PE per year [5]. The content of BOD that was possible to collect from the reference papers [11] has changed to 588 g/L; this is caused by the fact that different flows have different concentration values. Therefore, it is expected to be lower due to the higher oxygen content. This will also help the higher production of biogas during anaerobic digestion and thus a higher energy production in the cogeneration unit. Therefore, the new price will be 0,167 €/$m^3$ (decrease of almost 20%) that also correspond to the estimation made by with a CAPEX equal to 0,05 €/ $m^3$of treated wastewater [4], that is composed by the different unit costs of pre-treatment ($1*10^{-3}$ €/$m^3$), bioreactor + secondary settler (0,024 €/$m^3$), Anaerobic digestion ($6*10^{-3}$€/$m^3$), cogeneration ($5*10^{-3}$€/$m^3$), primary settler($2,5*10^{-3}$€/$m^3$), sludge thickener ($7,5*10^{-3}$€/$m^3$) and dewatering ($4*10^{-3}$€/$m^3$).

For the share costs of the CAPEX, the analysis has started taking an average share for the different procedures from the literature, in fact, it is known that the bio-reactor is the most expensive step both in terms of capital costs and operational costs. The bioreactor accounts on average between 40-45% of the CAPEX of a WWTP but without aeration for the nitrification/de-nitrification that this time is taken into account, so in total it has been estimated to be equal to 48% of the total CAPEX. For what concern the sludge line, it is known to be an important voice cost in the capital costs, indeed it generally accounts to 35% of the overall capital expenditures, and it is subdivided into sludge thickener (15%), anaerobic digestion (12%) and dewatering (8%). What remains has to be shared by the cogeneration unit and the pre-treatment, the cogeneration unit has been estimated to cover 10% of the CAPEX and the remaining part to the pre-treatment. The resulting costs are depicted in Table 4.

| | CAPEX percentages | Cost Vilanova(€/year) | Cost Murcia-Este (€/year) |
|---|---|---|---|
| **Pre-treatment** | 0,02 | 10.982,85 | 36.500 |
| **Bioreactor + secondary settler** | 0,48 | 263.588,40 | 876.000 |
| **Anaerobic Digestion** | 0,12 | 65.897,10 | 219.000 |
| **Cogeneration** | 0,10 | 54.914,25 | 182.500 |
| **Primary settler** | 0,05 | 27.457,13 | 91.250 |
| **Sludge Thickener** | 0,15 | 82.371,38 | 273.750 |
| **Dewatering** | 0,08 | 43.931,40 | 146.000 |
| **Total CAPEX** | | 549.142,50 | 1.825.000 |

*Table 4. CAPEX reference cases*

*OPEX (Operation and maintenance costs)*

For the evaluation of the cost for the OPEX per $m^3$ of wastewater treated, it was simply determined by subtracting to the overall unit cost the part covered by the CAPEX. Therefore, the OPEX for the Vilanova WWTP has been evaluated to be 0,141 €/m$^3$ (0,2-0,059 €/m$^3$) of wastewater treated, while for the plant in Murcia it has been evaluated to be around 0,117 €/m$^3$. This is showing that the operational costs are covering almost 70% of the annual expenditures.

To maintain the same system assets annually, it has been considered to divide the OPEX starting from the labor cost, that always represents the highest share, it has been estimated to be around 50%. Even if, the plant generates enough energy to cover around 50% of the self-energy consumptions, it has been taken into account rise of 19,4% in the electricity costs due to the simulated introduction of nitrification/de-nitrification system that requires a lot of aeration. The final shared value is around 24% for electricity, and it has been allocated, according to works of literature, to maintenance costs (14%), waste and sludge management (10%), and the chemicals around 4% of the annual cost. The previous data have been collected in the Table 5 below for both plants.

| | OPEX percentages | Vilanova Cost (€/year) | Murcia Cost (€/year) |
|---|---|---|---|
| **Electricity** | 0,24 | 314.965,80 | 1.027.548 |
| **Chemicals** | 0,04 | 52.494,30 | 171.258 |
| **Staff** | 0,48 | 629.931,60 | 2.055.096 |
| **Maintenance** | 0,14 | 183.730,05 | 599.403 |
| **Waste and sludge** | 0,10 | 131.235,75 | 428.145 |
| **Total OPEX** | | 1.312.357,5 | 4.281.450 |

*Table 5. OPEX reference cases*

## 4.3.1 Small WWTP

The higher cost for small WWTP is mainly related to operational costs since in WWTP with a capacity lower than 30.000 PE is not possible to install anaerobic digestion and therefore the electricity expenses would be higher.

That's why at first sight the price of a small WTTP should decrease since the cogeneration unit and the anaerobic digestion are not installed, but it is important to consider that the operational cost would increase considering, apart from the electricity cost, an increase in the staff price as the plant size decrease. A solution that has been taken into account to face the high labor price, is to utilize an aeration system, that will increase the electricity consumptions, but needs almost zero attention by the staff, therefore reducing the labor price especially for rural areas.

Some other considerations that are needed for the calculation of WWTP's expenditures are the location, for instance, the cost of a particular location may be very high or the soil may have particular conditions affecting the plant. Another aspect is the proximity with residential areas that can add capital cost for the control of odor by some covers or buildings, also the operational cost can be affected with an increasing need for chemicals, but all these variable has not been taken into account.

A conventional WWTP with a small size capacity of around 10.000 PE has an average price of around 30-40 euro per PE per year. The price considered for a 10.000 PE is equal to 35 euro per PE per year, with a capacity more than ten times lower than the reference case in Vilanova (9.307.500 $m^3$/year of Vilanova VS 730.000 $m^3$/year of small). The content of BOD that has been calculated as an average from is 61,2 % lower if compared to the flow concentration of a medium WWTP and it is equal to 139,68 g/L [21]. The overall amount of treated wastewater is equal to 730.000 $m^3$/year, therefore following the same procedure for the calculation of the overall cost of the plant per cubic meter treated is 0,24 €. This respect the increase of the price of around 20% compared with the medium WWTP, that as we will see will be covered by the operation costs. What is expected is that the cost for CAPEX will be decreased due to the lack of presence of anaerobic digestion and cogeneration, while the OPEX will be increased by higher consumption of electricity mainly cause by the aeration system implemented [15].

*CAPEX*

The capital expenditure has been obtained by subtracting the unit price of the anaerobic digestion and cogeneration to the reference price of Vilanova, therefore obtaining a value equal to 0,046 €/ $m^3$.

For the share costs of the CAPEX, the analysis has been carried out re-allocating the percentages for the remaining technologies utilized. The resume of the different costs for the CAPEX analysis are shown in the Table 6. The bio reactor remains the highest costs that accounts for 52,4% of the total share, followed by the sludge thickener with 19,4 %. The remaining costs were distributed between dewatering (12,4%), primary settler (9,4%) and pre-treatment with 6,4%.

| | CAPEX percentages | Cost (€/year) |
|---|---|---|
| **Pre-treatment** | 0,064 | 2.149 |
| **Bioreactor +secondary settler** | 0,524 | 17.596 |
| **Sludge Thickener** | 0,194 | 6.515 |
| **Dewatering** | 0,124 | 4.164 |
| **Primary Settler** | 0,094 | 3.157 |
| **Total CAPEX small WWTP cost** | | 33.580 |

*Table 6. CAPEX small WWTP*

*OPEX*

For the evaluation of the cost for the OPEX per of wastewater treated, it was simply determined by subtracting to the overall unit cost the part covered by the CAPEX. Therefore, the OPEX for the small WWTP has been evaluated to be 0,194 €/$m^3$. In this case, the OPEX is 80,8% of the overall annual expenditures for a small WWTP. The share of the different costs that compose the overall OPEX is depicted in Table 7 below.

The electricity share is equal to 48% since the electricity consumptions are two times the Vilanova WWTP per of wastewater treated. This is because in the Vilanova plant has half of the electricity consumptions thanks to the cogeneration unit that is not present in small WWTPs. An increase in the staff cost is also applied since the maintenance cost, and staff cost for small WWTP are summed together as one voice (38%). What is left is divided by waste and sludge disposal (10%) and the chemicals (4%).

| | OPEX percentages | Cost (€/year) |
|---|---|---|
| **Waste and sludge** | 0,10 | 14.162 |
| **Chemicals** | 0,04 | 5.665 |
| **Labor** | 0,38 | 53.816 |
| **Electricity** | 0,48 | 67.978 |
| **Total OPEX small WWTP cost** | | 141.620 |

*Table 7. OPEX of small WWTP*

### 4.3.2 Carbon redirection and Nitrogen recovery

The data, of the influent and effluent, were collected from the literature in order to be able to calculate the CAPEX and OPEX of the WTTP with the innovative design.

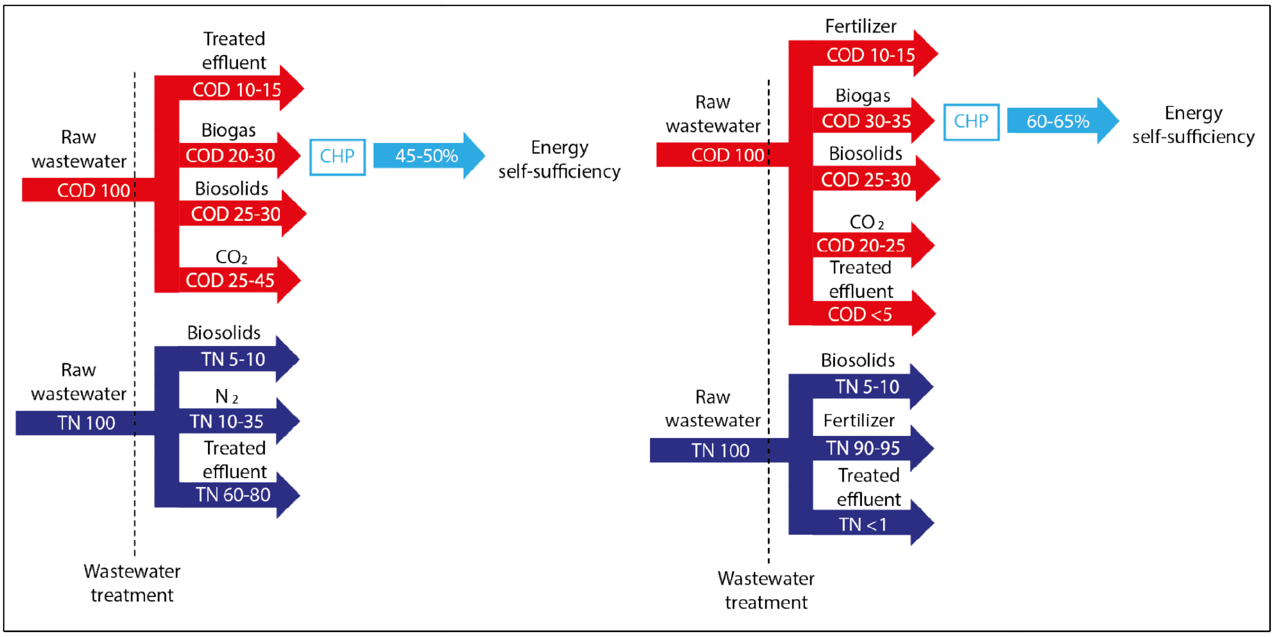


*fig. 10 On the left, influent/effluent streams in a conventional WWTP, on the right, with carbon redirection and nitrogen recovery (font:[5])*

Starting from the energy recovery, according to fig. 10, there is an increase of biogas production of 10-15 units, in the new proposal, and at the same rate, there is an increase of energy production through the CHP system. The emission of nitrogen ($N_2$) is totally avoided while $CO_2$ emissions are reduced by 5-20 units. Also, in the treated effluent, the traces of nitrogen and carbon are way lower, especially nitrogen (from 60-80 to less than 1 unit), than in the inflow stream.

From previous studies, it has been estimated that cost, per $m^3$ of treated wastewater, of a WWTP equipped with carbon redirection and nitrogen recovery to be almost twice (85% more) of a conventional WWTP layout. It will be further studied the CAPEX and OPEX of the new configuration implemented in the two reference WWTP of Vilanova and Murcia.

*Capital expenditure (CAPEX)*

The analysis starts first with the plant of Vilanova in which the economical assessment for the CAPEX is equal to 0,37 €/$m^3$ of wastewater treated. The CAPEX calculation is carried out through the same methodology but this time it has been considered a higher annual expenditure due to almost a doubled cost estimation. Then, the obtained CAPEX is equal to 0,109 €/$m^3$ (30% of the total cost as for the reference scenario). The same procedure has been followed with the WWTP of Murcia where the expenditure per $m^3$ treated is equal to 0,308 €/$m^3$, with a CAPEX equal to 0,0926 €/$m^3$.

As it is shown in Table 8, the highest investments are associated with nutrient recovery unit, and that's also the reason why the cost has almost doubled. In detail, the solids separation unit based on ultra-filtration (27%) and granular zeolites (18%) share 45,5% of the total CAPEX. The additional carbon redirection unit is composed by pre-concentration (3%), settlers (6%) and carbon oxidation unit (7%) that helps to achieve the best concentration of nitrogen. The sludge line amount to 37% of the CAPEX, obtained by the sum of sludge thickener (11%), cogeneration (10%), anaerobic digestion (11%) and dewatering (5%).

| | CAPEX percentages | Vilanova Cost (€/year) | Murcia Cost (€/year) |
|---|---|---|---|
| Pre-treatment | 0,02 | 20.290,35 | 67.598 |
| C-oxidation unit | 0,07 | 71.016,23 | 236.593 |
| Anaerobic Digestion | 0,11 | 111.596,93 | 371.789 |
| Cogeneration | 0,1 | 101.451,75 | 337.990 |
| Pre-concentration | 0,03 | 30.435,53 | 101.397 |
| Sludge Thickener | 0,11 | 111.596,93 | 371.789 |
| Dewatering | 0,05 | 50.725,88 | 168.995 |
| Settlers | 0,06 | 60.871,05 | 202.794 |
| Zeolites | 0,18 | 182.613,15 | 608.382 |
| N-recovery tech | 0 | 0 | |

| | | | |
|---|---|---|---|
| **Solids separation** | 0,27 | 273.919,73 | 912.573 |
| **Total CAPEX** | | 1.014.517,50 | 3.379.900 |

*Table 8 CAPEX with carbon and nitrogen recovery WWTP*

*Operation and maintenance cost (OPEX)*

In this case of OPEX, it is 85% more compared to the reference scenario, in fact, for the WWTPs of Vilanova and Murcia the new OPEX prices per $m^3$ treated are respectively equal to 0,261€/$m^3$ and 0,2154€/$m^3$ (70% of the overall cost). Also, in this case, as it is shown in Table 9, the costs associated with chemical consumptions are the highest (Zeolites+ chemicals = 52%), while the cost for the staff (25%) has decreased compared with the conventional case. The high chemical costs are mainly caused by the high consumptions and costs of sodium hydroxide (NaOH) used to regenerate zeolites, the high quantity of zeolites used as solid material for the ion-exchange process and high costs of phosphoric acid used in N-recovery technology. Another interesting point is the half cost of electricity (12%) compared with the reference case (24%).

The high costs both for CAPEX and OPEX are possible to be partially covered by the future expected high demand and price for nutrients, considering also the social benefit, that will decrease the necessity to industrially produce fertilizers with the consequent decrease of $CO_2$ quantity emission. Another help comes from the highest production of biogas and the consequent highest production of electricity for insight use.

| | OPEX percentages | Vilanova (€/year) | Murcia (€/year) |
|---|---|---|---|
| **Electricity** | 0,12 | 289.277,10 | 943.452 |
| **Chemicals** | 0,27 | 650.873,48 | 2.122.767 |
| **Waste and sludge** | 0,05 | 120.532,13 | 393.105 |

| | | | |
|---|---|---|---|
| **Staff** | 0,25 | 602.660,63 | 1.965.525 |
| **Maintentance** | 0,11 | 265.170,68 | 864.831 |
| **Zeolites** | 0,2 | 482.128,50 | 1.572.420 |
| **Total OPEX Vilanova cost** | | 2.410.642,50 | 7.862.100 |

*Table 9 OPEX with carbon and nitrogen recovery WWTP*

## 4.4 Integration of renewable methane in WWTPs

Many variations of the Renewable power methane (RPM) concept with waste management facilities are possible.

The scheme has been thought for the integration of WWTPs with RPM systems is depicted in fig. 11.

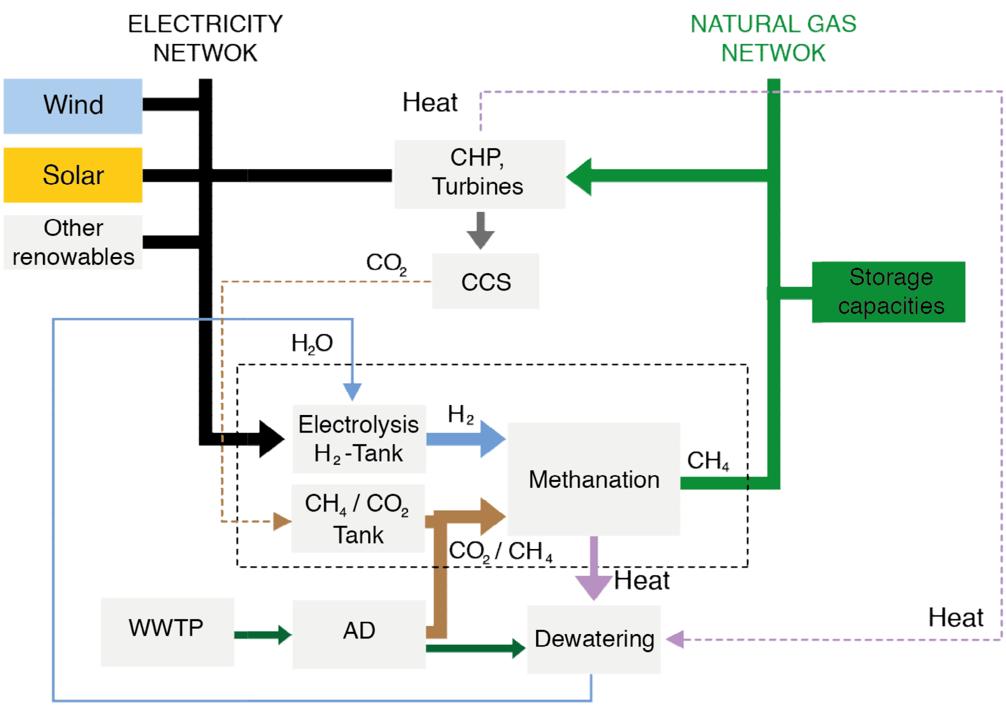


*fig. 11 RPM+WWTP configuration (font inspiration: [16])*

Sludge from wastewater is processed and digested to $CO_2$ and $CH_4$, and thus renewable methane plants can be integrated very easily. It can also be considered that the biogas production during anaerobic digestion is also another sourc of methane after the biogas upgrading.

A critical synergy could be the optimal use of surplus oxygen from electrolysis to be used into the wastewater treatment, in order to increase the presence of oxygen during the sludge activation process. This could be done to improve the sludge quality and the concentration of nutrients to be easily handled for the redirection and recovery. The interesting thing is that it won't be needed to invest in the carbon redirection unit, but only on the nutrients recovery for the WWTP. Since the oxygen demand of the WWTP will be satisfied by the surplus of oxygen from the electrolysis, and therefore the aeration system it would be useless [16].

*The function of the system*

The initial function of WWTP feautured with a methane production system, but keeping also the initial purpose of clarification of water..

Let's summarise the differences with the original WWTP, that are not drastic but needs to be mentioned to understand the possible implementation:

1) During anaerobic digestion, it is formed a biogas that is composed by 65% methane and 35% $CO_2$. Then the biogas is upgreated with the separation of $CO_2$, obtaining biomethane, by separation through membrane technology. The biomethane produced is injected into the gas network and not to the cogeneration unit. Where it is sold as a fuel product to be further burned to balance the grid;

2) To take advantage of the energy content of sludge, it will be further combined with hydrogen to produce methane;

3) The heat generated during the methanation process will be used during the dewatering process of the sludge. This injection of heat could significantly improve the effectiveness of the drying process;

4) The methanation process is carried out by means of hydrogen and $CO_2$. The $CO_2$ is the content in the biogas, that through upgrading separete the methane from $CO_2$. Then the hydrogen that has been produced from the renewable energy surplus it utilized into the Sabatier reactor for methanation, obtaining so a synthetic natural gas (SNG) that can be used as a stored energy.

The new plant won't change the occupied area significatively. This is simply due to the small space occupied by the electrolysis system and by the Sabatier reactor for the methanation process. The different interconnections inside the plant and with outside gas and the electrical grid would be probably the highest investment cost.

## 4.4.1 RPM conversion efficiency

The two main reactions that are happening in an RPM system are electrolysis, methanation.

The reactions that take place in an RPM are summarized with the relative efficiencies in the fig. 12.

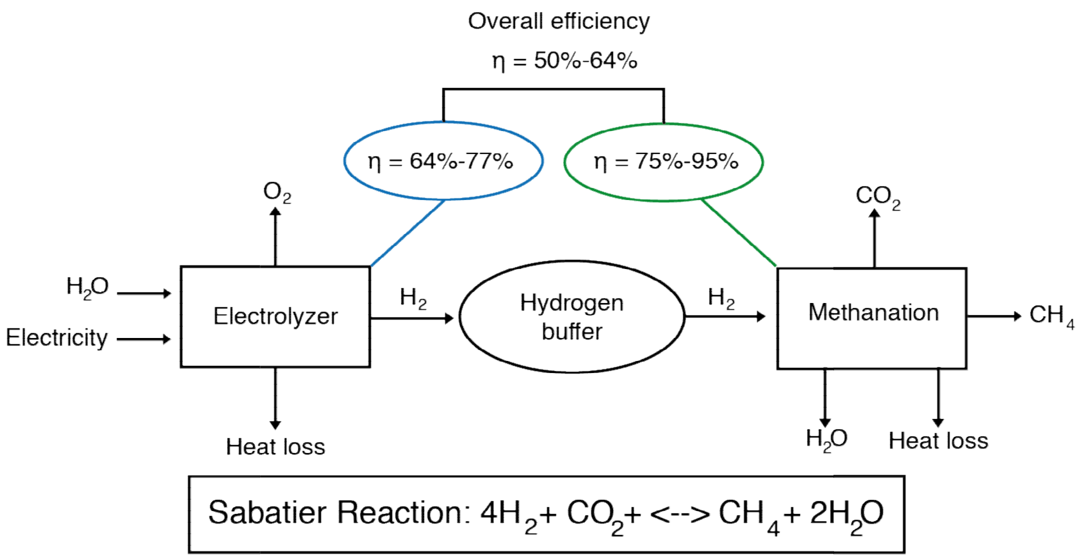


*fig. 12 Reactions efficiencies in a RPM (font: [18])*

The first reaction, <u>electrolysis,</u> is a pretty simple concept based on the use of an electrolyzer to produce hydrogen $H_2$. Essentially, the quota on renewable and energy consumption leads to massive overcapacity of PV and wind. The superfluous electricity may lead to negative electricity prices, therefore, this source of electricity production could be used in the electrolysis process together with water. This water could be provided by the same WWTP. In terms of efficiency, if we assume to have 100 units of electrical power, 25% of them will be lost in the electrolysis process.[16]

The second reaction, methanation, via Sabatier reaction that combines $H_2$ with $CO_2$. The $CO_2$ is stored in a dedicated tank. The process of methanation has an efficiency range that goes between 75 to 95%, but in a power to gas process is generally considered to lose 15% of efficiency in the methanation process. So, superfluous RES are indirectly stored via synthetic natural gas, which is then used sold to the grid, where it will be used for balancing the grid and produce electricity. The first part of the process could be ended up here, with an overall efficiency of 60% [18].

*Economical assessment*

The cost analysis, has been developed following the same costs of a conventional plant or of a plant with nutrients recovery. What will change is the stream of revenues that this time will include also the methane production.

Methanation process has also another interesting feature, Sabatier reaction is a thermodynamic process that emits heat that could be further used to solve a big issue such as the dewatering process one. As it has been mentioned previously, the content of water in sludge after treatments is around 70%, therefore the addition of heat could help to decrease this percentage way much than solar drying (in winter season). Moreover, it would be interesting to implement a solar hybrid PV system that could provide an additional amount of heat and water for the hydrolysis process for the final production of hydrogen [28].

For this analysis, we take only the methane production, by means of electrolysis as a first step and methanation as the second and final one. The methane will be injected into the grid and further stream of revenues will be added from there.

Assumptions

The new design will consider for the revenues stream of methane:

1) the price market value of methane that is direct to the producers of methane is on average equal to 0,08432 €/$Nm^3$ of methane produced. The value is actualized to 2020 for the italian market;
2) the average methane production in a WWTP together with methanation, it changes depending on the concentration streams, and it is equal to 0,09 $Nm^3$/ $m^3$ of treated wastewater in a WWTP with carbon redirection [5,16].

# 5. Results

The main goal of this thesis is to evaluate which technologies will suit the best with a WWTP to make it more attractive both, in terms of costs and the environment. Comparison of different sizes of WWTPs has been considered, in order to be possible to understand which are the possibilities to install innovative technologies for different sized WWTPs. The possible revenues will be analyzed on the base of the market value of the products that are possible to obtain from a WWTP.

It will be studied further how much the values of fertilizers should increase for a WWTP to be totally independent economically. Moreover, environmental benefits will be evaluated making a comparison based on the damages that each WWTPs make to the planet, in terms of emission reduction and added value given to the nutrients and to the biogas generated from AD.

Finally, an interesting solution will be introduced that would potentially drastically decrease the environmental impact of a WWTP, the purpose will be based on the simple application of a renewable power methane system in a WWTP.

## 5.1 Analysis of the costs and revenues

The data collected, as it will be further discussed, showed that is difficult to standardize the OPEX and CAPEX of a wastewater treatment plant for different reasons:

- there are a vast number of design alternatives in terms of type, size and technology:
- the location of the plant, different legislations and costs, even for regions of the same country.
- price breakdown is lacking, which means that the differences among the plants are hard to detect.

To overcome these issues, some assumptions are needed. The entire process can be broken down in a number of processes. To make a simpler start, the two plants where will be further applied innovative systems of treatments and the RPM were selected to have the same technology configuration but with the interesting aspect of the different size. To further analyze the change in cost with the changing in size a third WWTP has been introduced in the analysis. This is a small plant with approximately a capacity of 10.000 PE, the data were taken from an estimate cost reported in literature for small WWTP in south Europe. In the small plant both AD and CHP are not installed. The different legislations for each region were not considered to make a study as much standardized as possible, it has been chosen to follow the legislation of Spain.

The calculation for the revenues presents some challenges when it comes obtaining reliable values, due to the complex composition of a water tax. The different legislations and hidden costs made the research more challenging. The stream of revenues that have been chosen were substantially two: water tax and fertilizers.

Conventional WWTPs rely principally on the revenue stream coming from the water tax, mainly for two reasons: 1) the generation of biogas is not enough neither to cover the totality of the energetic demand of the plant, therefore is not possible to sell it to the grid; 2) the majority of the installed plant is not equipped with resource recovery, therefore there is no production of nutrients that can be sold to the fertilizer industry.

In addition, small WWTPs that are essential for rural communities, are most of the time expensive structures where the revenues are pretty low. This is caused by the low amount of water treated, and by the impossibility to install anaerobic digestion.

The calculation has been done by taking as reference the estimated cost for the water tax that is equal to 0,56 €/$m^3$ of wastewater treated. This cost has to be further discussed since this is the overall tax for water, that is composed of different voices. The majority is covered by the water supply that is around 60%, the remaining 40% is shared in equal parts between residual treatment, fixed costs, VAT and sewage plant.

Therefore, the part of the water tax dedicated to WWTPs is equal to the 10% of the entire tax, obtaining a final amount of 0,056€/$m^3$. These streams revenues will be applied to every WWTP analyzed in the thesis.

While the nutrient stream revenue is applicable only to the WWTPs with resource recovery and for the innovative configuration with the RPM installation. The price of the recovered product has been extrapolated from a cost estimation based on a life cycling cost (LCC) analysis of a WWTP with nutrients recovery [5]. This is due to the fact that a real market where to sell fertilizers produced in WWTPs doesn't exist. What has been done is to look for the value price for salts of Ammonium, but since that it was not possible, the analysis started looking at one of the possible obtainable products, such as ammonia. For instance, in Italy, it has been found that the price of ammonia is equal to 400 €/ton while in the US it is around

430 €/ton, values actualized in 2020. These are general values but the real ones are depending on the concentration of the stream of wastewater treated. The density of ammonia is equal to 1,769*$10^{-3}$ kg/$cm^3$ therefore, it has been possible to determine the market price that is equal to 4*$10^{-4}$ €/$m^3$. The price obtained is actually 100 times lower than the price estimated by the LCC, previously mentioned, this is caused by the higher estimation given to the production of ammonia in a WWTP, in order to be possible to cover a percentage of the WWTP cost. Even though, this price is not realistic, due to the lack of a market for fertilizers obtained from waste products, it has been chosen, for sake of simplicity, with a value equal to 4*$10^{-2}$€/$m^3$.

*WWTPs comparison based on the reference scenario (without nutrients recovery)*

For a conventional plant, the only source of revenues is given by the wastewater treatment, therefore what is interesting to see is how the difference between revenues and costs changes with the size. In Table 10 are listed the overall costs and revenues for each WWTP.

| | **Small WWTP** | **Medium (Vilanova)WWTP** | **Large (Murcia) WWTP** |
|---|---|---|---|
| **Annual Costs (€/year)** | 175.200 | 1.861.500 | 6.106.450 |
| **Annual revenues(€/year)** | 40.880 | 521.220 | 2.044.000 |
| **Difference(€/year)** | 134.320 | 1.340.280 | 4.062.450 |

*Table 10 Costs VS Revenues CAS WWTP*

Also, the overall capital investment in the 20 years has been estimated to be equal to 3.504.000 € (small WWTP), 37.230.000 € (medium WWTP) and 122.129.000 (big WWTP).

The most relevant data coming from this analysis are the different estimates between cost and revenues. Indeed, it is showing that the revenues in the small WWTP cover around 23,3 % of the overall cost, while for the large is 33,4% of the cost. This is showing how the costs are lower in comparison with small WWTP since the source of the revenues is the same. This is valid also for the medium WWTP, for which the revenues cover 28% of the overall cost. Therefore, a large WWTP can be estimated to be more cost-effective than a small

WWTP, but the way to reach self-sustainability still challenging. The highest part of the cost is occupied by operational and maintenance costs, especially for small WWTPs, where the labor costs per cubic meter of wastewater treated are higher than for medium and large WWTPs.

*WWTPs comparison based on carbon redirection + nutrients recovery scenario*

| | Conventional Medium WWTP | Redirection N recovery Medium WTTP | Conventional Large WWTP | Redirection N recovery Large WTTP |
|---|---|---|---|---|
| **Annual Costs (€/year)** | 1.861.500 | 3.425.160 | 6.106.450 | 11.242.000 |
| **Annual revenues(€/year)** | 521.220 | 893.500 | 2.044.000 | 3.504.000 |
| **Difference(€/year)** | 1.340.280 | 2.531.660 | 4.062.450 | 7.738.000 |
| **Difference in percentages** | | Increase of 53% | | Increase of 52,5% |

*Table 11 Costs VS Revenues CAS WWTPs, Carbon redirection + nitrogen recovery WWTPs*

The first thing, that is needed to analyze is how the difference between costs and revenues is behaving for nutrients recovery in WTTPs, summarised in Table 11. For the medium configuration the revenues cover 26% of the overall cost and this represents a decrease of 2% if compared with conventional WWTPs. The same behavior is shown for the large WWTP, for which the percentage is equal to 31,1%. Therefore, this is showing that the amounts of revenues compared with the costs, increase with the size, confirming that the economy of scale is affecting this kind of facilities. Therefore, larger plants will have higher advantages in terms of costs respect to small ones. The decreased rate of revenue is mainly caused by the substantial increase in price connected with the nutrients recovery unit.

The increase of revenues with nutrients recovery is around 41,6 % for large and medium WWTP that corresponds to the fertilizer contribution for the value of the revenue, as depicted in fig. 13. The new investment during the lifespan of the plant has been estimated to be equal to 68.503.200 € (medium WWTP) and 224.840.000 € (large WWTP).

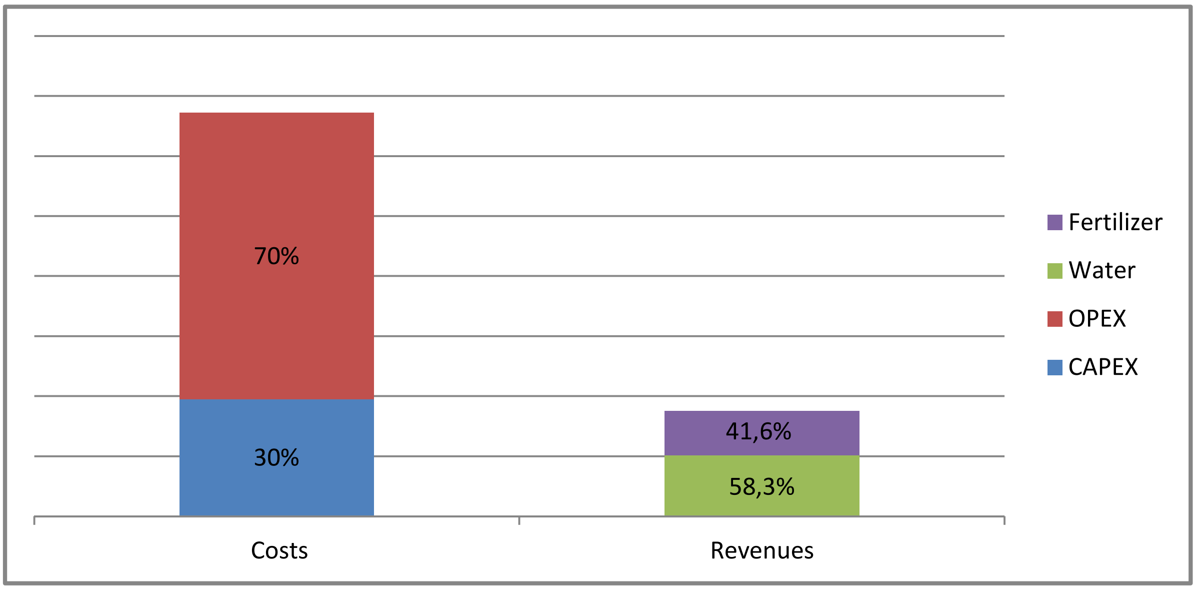


*fig. 13, Carbon redirection + nitrogen recovery for medium and large WWTPs, Share of CAPEX and OPEX, streams of revenues for Ammonia and water tax.*

*Carbon redirection + nitrogen recovery + RPM*

For the calculation of the revenues, it has been taken into account the same streams as before. This study only represents the costs and revenues related to the WWTP construction and market sale related to it. From some estimations, the investment costs (fixed cost) of an RPM plant is equal to 2000 €/$kW^{-1}_{el}$ for a plant of 5-10 $MW_{el}$ [16] and account for the: electrolyzer, methanation, compression, power electronics, piping, civil construction and control system. Another part of the fixed cost is the grid connection costs, it has been derived from bio-methane plants and amount to 250 €/$kW^{-1}_{th\_methane\_output}$. In this case, these numbers have not been taken into account to be comparable with the reference and innovative WWTPs layout. First is needed to calculate the amount of methane produced by each WWTP, that accounts for the one in Vilanova to 837.675 $Nm^3/m^3$ and for Murcia-Este to 3.285.000 $Nm^3/m^3$, and this depends on the amount of $m^3$ treated by each plant and by the concentration of oxygen in the wastewater stream. Therefore, the revenues from the selling of methane will be equal to 71.061,6 €/year for the plant in Vilanova and 278.671,12 €/year for Murcia-Este.

So, the new overall revenues will be equal to 964.561,6 €/year for Vilanova and

3.782.671,12€/year for Murcia-Este. The increase in revenues would be equal to 7,9% for both plants and the new revenues will help to cover respectively 28,2% (Vilanova) and 33,6% of the total annual cost for CAPEX and OPEX illustrated in Table 11.

## 5.2 Change in price of ammonia for the WWTP cost neutrality

For the different layouts of plants, it has been done a sensitivity analysis on the price of the products obtained. This study has been done for both revenues stream, even if increasing the water tax appears to be really difficult since it won't be socially accepted. The study consists of estimate the price of the revenues stream that would make a WWTP fully self-sufficient and economically independent.

*Ammonia price*

The market value price of ammonium, that has been considered during the thesis is around 400 €/ton. The variation in the price of ammonia is pretty consistent even for one year to the other, and the price reached now is one of the lowest peaks in many decades. For instance, the price in the US in 2013 was around 765 €/ton (900$/ton) and had reached in 2020 approximately 425 €/ton (500$/ton). The price utilized for the calculation has been transformed in the functional unit considering also that the ammonium obtained from wastewater has a higher value if compared with the industrial production of ammonia. This is because, it is a natural production of ammonium, therefore reducing the impact of an energy-intensive sector such as the one of ammonia production [11].

This new, sustainable production of ammonia (through zeolites), that avoids the emissions related with the industrial production, will possibly create a market in the next few years, due to the low quantities that will be available in Europe of fertilizers. In aid of this, the European Commission is forcing to recover all nutrients and resources from WWTP to decrease the dependence of third markets for manufacturing fertilisers. The greatest problem, for the further implementation of nutrients recovery, is given by the lack of a market for these products that are recovered from WWTP. This is caused by a mix of different factors such as the lack of social acceptance, the lack of legislations that regulate the market for these products and finally, a not good management of wastewater facilities.

The price that would allow the WWTP of Vilanova, with carbon redirection and nutrients recovery, to have cost neutral is equal to 0,312 €/m$^3$ while for Murcia it is equal to 0,252 €/m$^3$. The increase in price, in percentages, would correspond respectively, to 780% and 630%. Even if the increase of Murcia is lower, seems totally unrealistic to happen without a real market for the recovered products.

If instead, we consider the solution with RPM+WWTP the new price of fertilizers would be for Vilanova should be equal to 0,301 €/m$^3$ with an increase of 752%, while the price for the fertilizer produced in the WWTP of Murcia will be 0,244 €/m$^3$ that represents 610% increase respect to the original price of 0,04 €/m$^3$. The increase of price is still relevant, but if compared with previous cases it has greatly decreased.

*Water price*

For the water price changes, the same method has been utilized, but in this case, is needed to make a clarification. Indeed, at the contrary of fertilizers, it is not expected that this revenues stream will increase in the future. So, this will be only an estimate to make conventional and new configuration WWTPS cost neutral.

The cost estimation for conventional WWTPs. has been done in the same way as before, but in this case, the only revenues stream is the water tax accounted for the WWTP. The price of water that would allow the small WWTP to be cost neutral is equal to 0,24 €/m$^3$, for Vilanova 0,2 €/m$^3$, while for Murcia should be equal to 0,1673 €/m$^3$. The increase in price, in percentages, would correspond respectively, to 428%,375% and 298%.

If we do the same thing, but in this case keeping the price of fertilizer constant, it will be possible to see also how much the price of water tax should increase to obtain cost neutrality. In this case the price for the medium WWTP will be 0,328 €/m$^3$, with an increase of 580%. While, for Murcia, it will be equal to 0,268 €/m$^3$ with an increase of 478% from the original price given.

*Share of the overall costs between fertilizer and water tax*

Considering the option, that both revenues streams could contribute in equal manners to the overall cost neutrality the things would change and seems more realistic, even though, the price of water tax it is really unlikely to increase this much. The fertilizer would cover 41,6% of the overall cost and the water tax around 58,3%. The new price of fertilizer for the WWTP of Vilanova would be equal to 0,153 €/$m^3$ that corresponds to an increase of 382,5%, a similar increase it is notable for the water tax price, that increase to around 381% (0,2314 €/$m^3$). The same behaviour is followed by the big WWTP of Murcia-Este.

# 6. Discussion

New types of WWTPs are needed, and it is well accepted to move WWTPs from being energy consumers to energy producers and resources recovery. The European Union is progressively implementing measures to reduce the environmental impact of WWTP, through restrictions on the nutrients discharge limits and encouraging for the energetic self-independence. Is also true, that the main bottleneck to overcome is the social acceptance of using products derived from human waste, and this may will take much more time than find the right technologies and design for a sustainable WWTP.

In this thesis, different solutions have been studied and will need to be further investigated for the real application. In the next pages, the main advantages and drawback of the two main innovative layouts defined in the thesis will be summarised.

The evaluation of the carbon footprint of a WWTP has been developed first analyzing literature results for reference WWTPs by then comparing their emissions with the two innovative proposition (carbon redirection + nutrients recovery) considering all the assumptions necessary.

In terms of Climate change, the conventional scenario of Vilanova has an emission of carbon dioxide estimated to be around 0,148 $kgCO_2/m^3$ (reference value for the environmental benefit calculation). This is caused mainly by the high electricity consumptions in the plant, that is for the majority attributed to the aeration in the biological reactor (41%).

The carbon footprint has been assumed that with the introduction of carbon redirection and nitrogen removal units will reduce the impact on climate change of about 85% compared with the conventional configuration [5]. Also consider the impact of higher chemical consumptions, due to the great use of zeolites, the overall emissions are decreased. Indeed, it has been estimated, from the literature, that the average amount of emission of carbon dioxide is equal to 0,022 $kgCO_2/m^3$ for a system with carbon redirection and nutrients recovery [5].

The main reason for the avoided emissions is correlated with the decrease in the energy consumptions thanks to the pre-concentration unit and the anaerobic digestion. That allows to produce 10 -15 units more of biogas [5], that can be further transformed in useful methane to be injected in the cogeneration unit, therefore, producing more energy. While the emissions of fertilizer production are minimized by the possibility of recovering ammonium salts that are harmless. An important fact to highlight is that carbon footprint accounts for 54% on the overall climate change effect. Therefore, is where it will be concentrated the focus of the thesis.

*Carbon footprint analysis*

Through literature survey was possible to obtain how much contribute each step of a WWTP to the overall GHG emission, in conventional WWTPs and in nutrients recovery WWTPs. These data are reported briefly in fig. 14 and depicted in fig. 15. The scope is to apply this procedure to the WWTPs that are under evaluation especially for the further implementation into a renewable power methane system. To understand the different impact of different sized WWTP on the environment, but with the main focus on climate change.

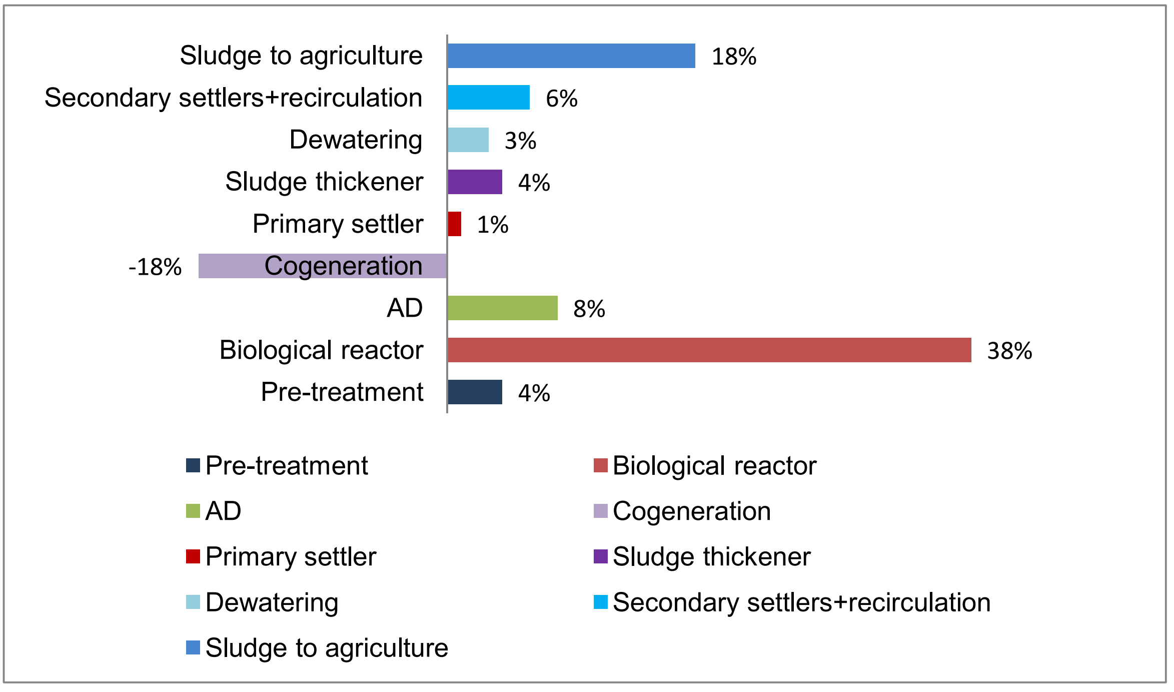


*fig. 14 Share of damages on climate change, of the different steps in a conventional WWTP*

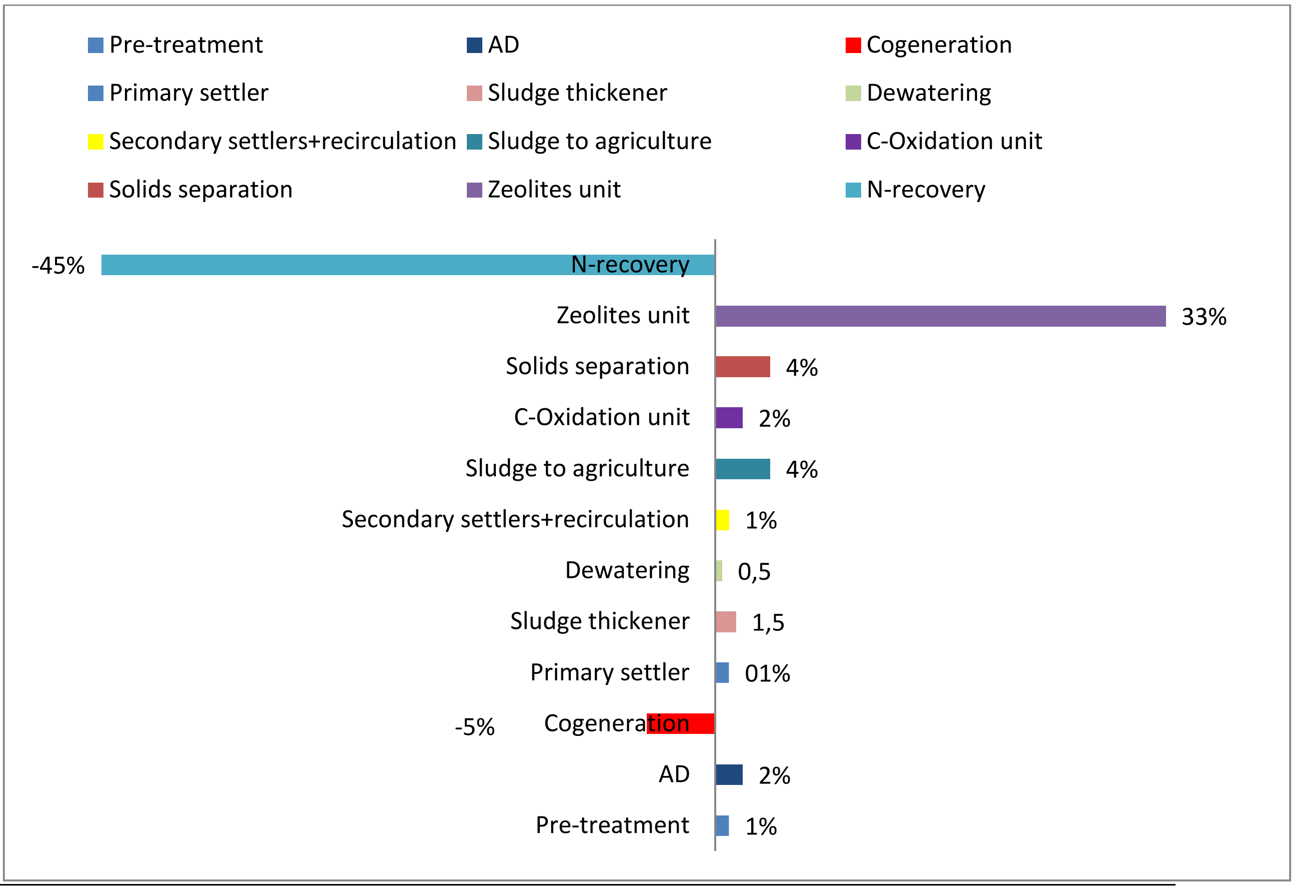


*fig. 15 Share of damages on climate change, of the different steps in a nutrient recovery WWTP*

An improvement between the two layouts is clear, indeed the overall carbon footprint damage has two main components that reduce the overall amount of emissions, that are N-recovery and cogeneration. If sum together reduces the overall carbon footprint of 50% in the new design. The highest advantage is the nitrogen recovery, that prevents from the industrial production, that is highly energy intensive. Another component that contributes to lower the emissions is the cogeneration unit, that in the new configuration has a lower impact than in the conventional scenario, where it was the only technology helping reducing greenhouse gases emission. In the carbon and nitrogen recovery, the use of granular zeolites shows the highest quantity of emissions, but this is essential for the ammonia recovery, that would be, otherwise, produced via industrial processes.

*Environmental benefits of new designed WWTPs*

The amount of emissions per cubic meter of treated wastewater in a conventional plant is equal to 0,148 $kgCO_2/m^3$, considering that the innovative layout of WWTP with carbon and nitrogen redirection as average decrease the emissions of $CO_2$ by 85% will be considered an overall amount of emissions equal to 0,022 $kgCO_2/m^3$, although the consumption of chemical for zeolites washing and for the transport of more chemicals are higher compared with conventional WWTP. Having said that, an enormous decrease in emission is expected thanks to the electricity production in the cogeneration unit and the avoided emissions of the fertilizers industrial production. Indeed, to produce 1 ton of Ammonia through a Habor-Bosch industrial process the corresponding emissions are 2,867 ton of $CO_2$ and these are all avoided emission counted in the estimation. Furthermore, it has been assumed that for the generation of 1KWh, 0,34 Kg $CO_2$ are emitted. The obtained values for all the different plants are summarized in Table 18.

| $CO_2$ emissions | | | | | |
|---|---|---|---|---|---|
| **Categories** | *SMALL* | *MEDIUM* | *LARGE* | *MEDIUM C+N REC* | *LARGE C+N REC* |
| **kg $CO_2$ emission per $m^3$ treated** | *0,148* | *0,148* | *0,148* | *0,022* | *0,022* |
| **$m^3$ treated/year** | *730.000* | *9.307.500* | *36.500.000* | *9.307.500* | *36.500.000* |
| **Avoided $CO_2$ emission** | *0* | *0* | *0* | *1.172.745* | *4.599.000* |

*Table 12. $CO_2$ emissions for all WWTPs understudy*

Therefore, the avoided emissions using the recovery units in case of the medium size plant are equal to 1.172.754 Kg $CO_2$that correspond to 82,6% less than the original configuration. While for the large size WTTP the overall reduction amounts are 4.599.000 Kg $CO_2$ avoided that equals 85% fewer emissions than a normal CAS configuration.

The real effectiveness of this system is depicted by comparing the numbers of the medium and large WWTP equipped with nutrients recovery and the emissions of a small WWTP. The interesting aspect is that the emissions of the medium WWTP equipped with the recovery system only double the emissions of the small WWTP. The difference in PE capacity is more than 10 times (small WTTP: 10.000PE, medium WTTP: 130.000 PE), while the emissions are almost equalized.

# 7. Conclusions

*Carbon redirection + nitrogen recovery*

The introduction of carbon redirection and nutrients recovery demonstrated to be an exciting option to reach self-sustainability of WWTPs, even though, from an economic point of view, it still far from being self-sufficient. Both processes may be implemented with other standard procedures, which makes the solution more adaptable to more functionalities.

The critical point to recover the maximum energy available in a WWTP is to capture COD from wastewater for anaerobic digestion as much as possible. While regarding nitrogen recovery, an ion-exchange unit is essential to encourage the healing of nutrients. By then, it will be possible to reduce its losses to the atmosphere and environment.

Advantages:

-10-15% more biogas production with a consequent conversion of organic matter into $CO_2$ reduced by 25%. The overall COD entering in a WWTP can be removed up to 95%,

-more energy can be produced becoming closer to self-sufficiency reaching 60% of the overall energy demand,

-the emissions of $N_2O$ are avoided,

-possibility to recover 99% of nitrogen from wastewater and 90% of it, and it can further be sold to the fertilisers industry. The further valorisation through the possible selling of the nutrients recovered from wastewater to the fertiliser industry, with an average increase of revenues of 41,6%. The left 9% can be found in the final sludge, that it can be finally disposed into the crops,

-40 times higher concentration of nitrogen thanks to the ion-exchange process implemented with granular zeolites,

-reduce the dependence on non-renewable resources creating a path to follow for the aimed sustainability of WWTPs and drastic lower carbon footprint,

-lower cost per unit of wastewater treated for large-medium WWTPs if compared with small WWTPs.

Drawbacks:

-CAPEX and OPEX are almost twice than a conventional WWTP, mainly caused by the nutrient recovery unit,

-the pre-concentration and anaerobic digestion (carbon redirection), are possible to apply only to medium and large WWTPs,

-lack of a common legislation at European level for the use of fertilisers derived from waste, therefore, a lack of a market where to sell the recovered nutrients,

-lack of common legislation at European level for the use of sludge for other purposes, such as bio-bricks,

-low level of social acceptance from products obtained from waste,

-impossibility of implementing in small WWTPs innovative configurations,

-the price estimated for the obtained nutrients recovered has been evaluated too low for being attractive for WWTPs.

*RPM+WWTP*

The implementation of a renewable power system into a WWTP can be considered an innovative solution, to change the traditional view of WWTP. This new scheme proposes to convert a conventional WWTP or even one equipped with carbon redirection and nutrients recovery, into a plant that also offers ancillary services for the electrical grid but at the same time also accomplish the regular tasks of a WWTP.

This new configuration would be relatively easy to implement into an already existing WWTP since only two new units need to be added electrolysis and methanation. The methane produced will be injected into the grid as a third stream of revenues.

This would be an interesting solution for already existing plant, since not too many changes are needed avoiding the costs for a pre-concentration unit.

Advantages:

- possibility to improve the conventional CAS system, the surplus of oxygen produced through hydrolysis could satisfy the oxygen demand inside the bioreactor,

- limited space occupation for this new proposed system integration,

- increase of revenues of 8% if compared with the nitrogen recovery + carbon redirection WWTP design, thanks to the new selling stream of methane.

Drawbacks:

- do not exist real estimations on costs for the implementation of RPM in a WWTP,

Economic and environmental benefits are shown to increase with the increase of the size of a WWTP, and this answer to the doubt if small-sized plants are convenient compared with large-sized ones. Furthermore, large-sized WWTPs fit perfectly with the RPM system that can offer a high production of surplus oxygen, during the electrolysis process. Finally, the implementation of carbon redirection and nitrogen removal would decrease the environmental impact substantially. The major bottlenecks for the performance of nutrients recovery are the high operational costs related with zeolites and the lack of a market where to sell the obtained ammonia.

In conclusion, the most significant effort that will be needed to accomplish for the success of the proposed solutions will be to create a social acceptance on the use of products derived from waste, such as sludge, or ammonia that would also help to legislate the selling of these kind of products.

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I would like to thank all the people that has been part of this long journey from day one until today, the end of my university career. I would start from all the great people I have met along this journey in Belgium and here in Barcelona. I have passed two unforgettable years, between high and low, that gave me the possibility to learn way more than I would never image. So many different traditions and cultures I have discovered during these two years, that literally opened my mind to other point of views.

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