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Definition, design and start-up of an innovative wastewater treatment pilot plant for nutrients and energy recovery

MEMÒRIA

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1. Abstract

The present work is based on a real project developed by Cetaqua in collaboration with Avecom, a company devoted to steering and optimizing microbial processes.

This work aims to study the feasibility of an innovative layout for a wastewater treatment plant (WWTP). This new point of view pretends to enable the plant to be self-sustainable, by increasing the sludge produced in a Pre-concentration step at the inlet of the WWTP, and therefore increasing the biogas produced in the anaerobic digester.

In order to reach this goal, a revision of the state of art is carried out; furthermore there is a detailed description of methodology, which comprehends the definition, design and start-up of the pilot plant; the new WWTP is under demonstration due to the pilots already are in start-up phase. Economic feasibility is evaluated taking as a starting point the expected results of the project. Finally the most significant conclusions and lessons learned are summarized.

ETSEIB

2. Index

3. Glossary

Abbreviations

AD	Anaerobic Digestion
BAS	Biosorptive Activated Sludge
BAT	Benefit After Tax
BOD	Biological Oxygen Demand
CAPEX	Capital Investment Cost
CAS	Conventional Activated Sludge
ChW1	Chemical Wash Type 1
COD	Chemical Oxygen Demand
CSTR	Continuous Stirred Tank Reactor
DO	Dissolved Oxygen
DS	Dried Solids
EEA	European Environment Agency
GHG	Greenhouse Gas
HRAS	High Rate Activated Sludge
HRT	Hydraulic Retention Time
Hw	Hydraulic Wash
IB	Index Buffer
IRR	Internal Rate Of Return
KPI	Key Performance Indicator
MLSSV	Mixed Liquor Volatile Suspended Solids
N	Nitrogen
NPV	Net Present Value
NTU	Nephelometric Turbidity Unit
P	Phosphorus
PFD	Process Flow Diagram
PID	Proportional Integral Derivative
PLC	Programmable Logic Controller
PMMA	Poly Methyl Methacrylate
PVC	Polyvinyl Chloride
SRT	Sludge Residence Time
SVI	Sludge Volume Index
TPAD	Temperature Phased Anaerobic Digestion
TSS	Total Suspended Solids
UF	Ultra-Filtration
VFA	Volatile Fatty Acids
VS	Volatile Solids
WWTP	Waste Water Treatment Plant

Symbols

A	Weight of dried residue at 105 ºC + dish in grams
B	Weight of dish in grams
C	Weight of evaporated residue at 550 ºC + dish in grams
V_{sample}	Volume of sample employed
$\dot{m}_i$	Volumetric flow of each component, l/h.
$X, NaOH_{vol-UF}$	Volumetric concentration of NaOH in de solution, $\%_{vol}$
$X, NaClO_{vol-UF}$	Volumetric concentration of NaCl in de solution, ppm
Mw_i	Molar weight of each component, g/l
$X, i_{vol-Com}$	Concentration in its commercial package

4. Introduction

4.1. Objectives

This work aims to propose an innovative layout of the wastewater treatment plant, the new designed treatment and also the start-up process is also described. The feasibility of an innovative layout for a wastewater treatment plant (WWTP) is assessed from the economic point of view. It also aims to demonstrate the difficulties encountered when working with a real case, and hence why there is no reliable data yet.

1. The new layout proposed, is tested by means of a prototype composed by three units at pilot scale, which are explained in more detail further in this work. There are three main results expected, one associated to each pilot. Quality objective: cleaning the water in order to meet discharge levels. This is achieved by measuring common parameters such as Chemical Oxygen Demand, solids, pH, temperature…
2. Energetic efficiency: it is expected to measure a higher energy generated by means of Anaerobic Digestion. The energy production is measured by an estimation based on the biogas produced.
3. Environmental objective: aiming to recover the major part of the nitrogen present in water in ammonium form. This results are measured by in-line ammonium sensors at the inlet and outlet of one pilot.

The economic analysis aims to provide data about profitability by assessing the Net Present Value (NPV), the Internal Rate of Return (IRR) and the payback.

5. Theoretical introduction

The present work has been developed in collaboration with Cetaqua, the enterprise where I work at the same time. A brief description of the enterprise is given below.

Cetaqua is a non-profit foundation that integrates, manages and conducts research, technological development and innovation projects in the integral water cycle field. Cetaqua was created to take advantage of the synergies between its three founding partners: Aguas de Barcelona, Spain's biggest water utility (AGBAR Group), the Technical University of Catalonia (UPC) and the Spanish National Research Council (CSIC). Cetaqua benefits from both academia and industry support, which enable the center to be aware of the sector's current and future needs and to effectively transfer and apply the results of its research. Cetaqua's main research areas are: health and the environment (involving advanced water treatment and sludge management); water and energy; water, economy and society; efficient infrastructure management; alternative water resources (such as desalination and water reclamation) and impact of global change (including management of floods and droughts).

Related with nutrient and energy recovery in wastewater treatment plants Cetaqua has an extended experience in wastewater treatment, sludge Anaerobic Digestion and co-digestion with other organic substrates for increasing biogas production, water reclamation and reuse.

5.1. Current situation of wastewater treatment

In the latest years there has been an increase in concern about climate change, and non-renewable resources. This fact has led to stricter thresholds of emission, driving the companies to improve the efficiency of their processes and what's more; start talking about recovery rather than removal to meet discharge requirements [1].

Regarding the wastewater sector, it has been considered a human health concern and environmental hazard for a long time. The actual technologies for wastewater treatment were established in the early 20th century, based on engineering traditions [2].These technologies were designed to cleanse the water by removing the organic pollutants and the nutrients, nitrogen (N) and phosphorous (P), but only to meet discharge requirements hence the WWTPs can't be considered sustainable.

The traditional technologies consist in a biological treatment of the wastewater via Conventional Activated Sludge (CAS) system. Although this system is considered very robust, it is not sustainable due to it is designed to remove organic matter and nutrients. Its major drawback is the energy consumed in aeration of the biological reactors, which in most cases represents the half of the total energy consumed of 0.6 kWh per m^3 by WWTPs [3]. Municipal wastewater has average values of organic matter concentrations (expressed in terms of chemical oxygen demand, COD) of 400-500 mg COD/L that may contain a potential chemical energy of 1.5-1.9 kWh/m^3 of wastewater, which easily overcomes the energy requirements of the CAS system [2]. The main problem of these technologies lies beneath in the degradation of the organic matter via aerobic mineralization to CO_2 released to the atmosphere, thus creating two added problems: the release of a greenhouse gas (GHG) and the consequent loss of the major part of potential chemical energy. Another drawback is that neither phosphorus nor nitrogen is recovered. Nitrogen is removed by biological nitrification/denitrification process and phosphorus is removed by biological or chemical treatments.

The increasing market value of wastewater components, such as ammonia and phosphorus, are acting as key drivers for resource recovery from wastewater. Because phosphorus is mined as a mineral, and thus it is a limited resource; its commercial value will inevitably increase as it is depleted [2]. According to U.S. Geological Survey, the reserves of phosphorus will last 300 years at most, at the actual rate of mine production, this fact besides the climate change has challenged the water sector to optimize the energy use, limit the greenhouse gas emissions and recover nutrients from wastewater [4].These issues have led to a research activity in order to find new wastewater treatments or procedures which enable the WWTPs to move from being energy consumers to energy and nutrient producer sites [5].

A more detailed description of the CAS system is given below.

The WWTPs usually has 2 streamlines.

The **water line** is composed by the following operations:

- Pre-treatment: its aim is to remove the bigger fraction of solid particles; there are many physical methods that can be employed to fulfill this goal, such as screenings, de-sanders or degreasers.

- Primary treatment: in this step the rest of the suspended solids are removed from wastewater. The employed method depends on the nature of matter which will be removed. The main treatments consist in systems of flocculation, settling, flotation or different methods to remove the remaining oil and fat.

- Secondary treatment: this step aims to remove the biodegradable organic matter by means of biological treatments, in which microorganisms oxidize the organic matter and thus reduce the Biochemical Oxygen Demand (BOD) of the effluent.

The water coming from the physical treatments still has a load about 40-60% of suspended solids. The removed fraction corresponds to floating and settleable solids and the remaining one, corresponds to solids which density is similar to the water or even colloidal particles. This fraction cannot be removed by physical treatments.

When selecting a biological treatment it must be taken into account that the biodegradation speed must be enough to have an appropriate removal of pollutants. This speed may vary upon different parameters such as microorganism strain, nutrients, pH, temperature, dissolved oxygen…

This process achieves the removal of the major part of the dissolved organic compounds and part of the colloidal by means of biological adsorption and bio-oxidation.

- Tertiary treatment: focused in eliminate a series of compounds, such as nitrogen and phosphorus based substances or different kinds of organic and inorganic matter. In order to do so, different nutrient removal methods are used. These methods comprehend different processes such as biological, chemical, adsorption or even reverse osmosis. The choice will depend on the later use of the water.

Sludge line description

The main objective of the sludge line is to reduce the volume, the environmental impact and the odor of the sludge produced in the different sewage treatment stages.

The most extended method for sludge stabilization is the Anaerobic Digestion, due to it not only stabilizes the sludge but also produces biogas (mixture of methane, carbon dioxide and other gases) which can be burnt in order to obtain energy, and hence allowing a reduction on the energy demand reduction.

The sludge stabilization is achieved by Anaerobic Digestion (AD) which can be run under different conditions (psychrophilic, mesophilic or thermophilic conditions).

Before AD step, the sludge is usually thickened either by gravity (primary sludge) or by flotation (secondary sludge) to reduce the digester required volume. Digested sludge is dewatered mostly by centrifugation.

The sludge line treats both primary and biological sludge together. However, the thickening of primary and secondary sludge takes place in different thickeners:

- Primary sludge thickening: sludge coming from the primary settling tank is thickened in a gravity thickener.

- Secondary sludge thickening: sludge coming from the secondary settling tanks is thickened in a flotation thickener.

If needed, some coagulant may be added in order to enhance the thickening. The dosage will depend upon the sludge characteristics.

Thickened primary and secondary sludge are mixed in a mixing tank. The mixed sludge undergoes the following operations:

- Anaerobic Digestion: mixed sludge is digested anaerobically at mesophilic conditions (37ºC).

The sludge fed to the digester is mixed by means of a recirculation system, where the digested sludge pass through a series of heat exchangers to maintain isothermal conditions, and returns to the digester at the upper part.

Some chemicals may be added in this step to control the production of dangerous gases, such as hydrogen sulphide.

Once digested, the sludge is stored in a buffer tank until it is dewatered.

- Dewatering: this process is usually carried out by centrifuges. In order to ease the dewatering process, a solution of poly-electrolyte may be dosed to the sludge at the centrifuges entrance. The polymer dose must be adjusted according to the quality of both the dewatered sludge and the reject water. The dewatered sludge is stored in a silo.

Management of side streams

There are mainly three water side streams originated in different points of the sludge treatment: two thickening side streams and a dewatering side stream.

- Thickening side streams: it corresponds to the clarified water from gravity and flotation thickeners, which treat primary and secondary sludge, respectively. Thickening side streams are collected together in a well and pumped together to the inlet of the fine screens (pretreatment) being mixed with the main line.

- Dewatering sidestream: it corresponds to the water extracted from sludge during the dewatering process (centrifuges). Dewatering sidestream is collected in another well. All streams are pumped at the inlet of the plant and they are mixed in the main line.

This sidestream is originated discontinuously and thus the centrifuges does not work 24 h per day.

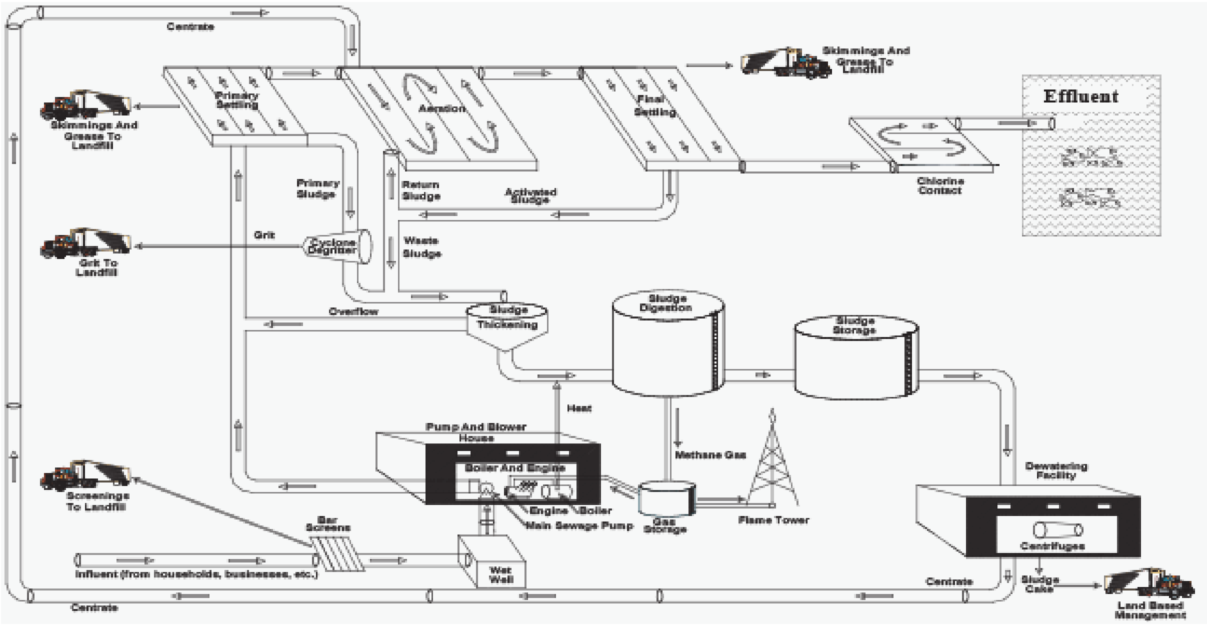


Figure - 1 Current layout of a WWTP (New York City Environmental protection)

5.2. Fundamentals of conventional system

This part of the present work concerns about giving a more detailed view of the two main processes in conventional system (Conventional Activated Sludge system (CAS) and Anaerobic Digestion (AD)), in order to make a further analysis of alternatives.

5.2.1. CAS System

A CAS system is a series of biological treatment steps that degrade the biological materials from the sewage or wastewater. [6]

The first step of a CAS system is the aeration tank, where the wastewater is mixed with air to activate micro-organisms. While digesting the wastewater, the organisms collide with each other, forming larger particles called flocs, which have a larger capacity to degrade the biological components of the wastewater.

Activated sludge system comprehends a mixed culture of microorganisms which oxidize the organic matter according to the following stoichiometry. [7]

Oxidation and synthesis:

$$COHNS + O_2 + nutrients \rightarrow CO_2 \rightarrow +NH_3 + C_5H_7NO_2 + end\ products \qquad \text{[Eq 1]}$$

Endogenous respiration:

$$C_5H_7NO_2 + 5O_2 \rightarrow 5CO_2 + 2H_2O + NH_3 + energy \qquad \text{[Eq 2]}$$

COHNS represents the organic matter in wastewater, which serves as electron donor while the oxygen serves as electron acceptor. Although the equation 2 shows only simple end products, stable organic end products are also formed.

The aeration basin is followed by a secondary clarifier or settling tank. During this step, micro-organisms with their adsorbed organic material settle.

Water from the clarifier is transported to installations for disinfection and final discharge or to other tertiary treatment units for further purification.

It is clear that this process is able to remove the organic matter from wastewater (essentially carbon). However, it is also capable of removing nitrogen from wastewater if appropriate conditions are given.

Biological nitrification in the activated sludge process consists of the removal of oxygen from an aeration tank and its addition to ammonium ions or nitrite ions. Oxygen is added to ammonium ions by the nitrifying bacterium Nitrosomonas, while oxygen is added to nitrite ions by the nitrifying bacterium Nitrobacter.

The quantities of ammonium ions and ammonia in an aeration tank are dependent on the pH and temperature of the activated sludge. In the temperature range of 10 ºC to 20 ºC and pH range of 7 to 8.5, which are typical of most activated sludge processes, about 95% of the reduced form of nitrogen is present as ammonium ions.

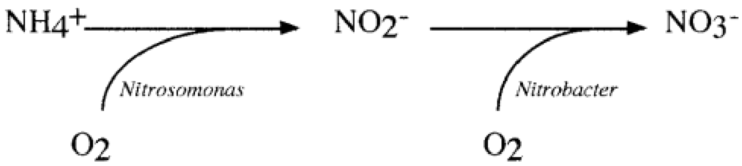


Figure - 2 Nitrification process (Nitrification and Denitrification in the Activated Sludge Process Michael H. Gerardi page 43)

Although activated sludge processes are used for nitrification, these processes are not ideal for nitrification. Due to the large population size and rapid growth of organotrophs in the aeration tank as compared to the small population size and slow growth of nitrifying bacteria, the population size of nitrifying bacteria is gradually diluted, making it difficult to achieve and maintain desired nitrification. Approximately 90% to 97% of the bacteria in the activated sludge process consist of organotrophs, while the remaining 3% to 10% of the bacteria are nitrifiers.

After that, it is clear that there is a huge demand of dissolved oxygen in order to stimulate the microorganism's growth. This oxygen is transferred to water by compressors at full scale WWTPs, leading to an enormous energy demand. Although this is a robust system, the energy requirement is a great drawback. Regarding the paradigm shift occurred in the latest years respect to the energy consumption, new research paths has been opened in order to overcome this problem [3], [8]–[10].

5.2.2. Anaerobic Digestion (AD)

Anaerobic Digestion is a process involving four main stages which is capable of transforming the organic matter into biogas. This biogas can be burnt in order to obtain energy and thus reduces the energetic demand of the WWTP.

Anaerobic Digestion comprehends a set of sequential chemical reactions carried out by microorganisms. These chemical reactions can be grouped into the following four groups.

Hydrolysis

In most cases, biomass is made by large organic polymers. It is necessary to break down this complex chains in order to be assimilable. These monomers, such as sugars, can be employed by other bacteria. This process is called hydrolysis. Through hydrolysis, the complex organic molecules are broken down into simple sugars, amino acids, and fatty acids. [11]

Acetate and hydrogen produced in the first stages can be used directly by methanogens. Other molecules, such as fatty acids with a chain length greater than acetate must be first catabolized into compounds directly usable by methanogens.

Acidogenesis

The biological process of acidogenesis results in further breakdown of the remaining components by acidogenic (fermentative) bacteria. Here, Volatile Fatty Acids (VFAs) are created, along with ammonia, carbon dioxide, and hydrogen sulfide, as well as other byproducts.

Acetogenesis

The third stage of Anaerobic Digestion is acetogenesis. Here, simple molecules created through the acidogenesis phase are further digested by acetogens to produce largely acetic acid, as well as carbon dioxide and hydrogen.

Methanogenesis

The final stage of Anaerobic Digestion is the biological process of methanogenesis. Here, methanogens use the intermediate products of the previous stages and convert them into methane, carbon dioxide, and water. These components make up the majority of the biogas emitted from the system. Methanogenesis is sensitive to both high and low pH and occurs between pH 6.5 and pH 8 [12]. The remaining, indigestible material the microbes cannot use and any dead bacterial remains constitute the digestate.

It must be taken into account that since VFAs are created along the process, they must be consumed at enough rate in order to avoid acidification. Hence the measure of VFAs constitute a performance indicator which must be measured along with other parameters which will be further discussed.

Regarding the operation temperature, anaerobic digesters can either work under mesophilic or thermophilic conditions. It will depend on the type of microorganisms present in the sludge.

The biogas produced is a mixture mainly compound by methane and carbon dioxide as well as other gases in minor fractions. Table - 1 shows a generic composition for biogas.

Table - 1 Composition of biogas depending on its source (biogas-renewable-energy)

Components	Household waste	Wastewater treatment plants sludge	Agricultural wastes	Waste of agrifood industry
CH_4 % vol	50-60	60-75	60-75	68
CO_2 % vol	38-34	33-19	33-19	26
N_2 % vol	5-0	1-0	1-0	-
O_2 % vol	1-0	< 0,5	< 0,5	-
H_2O % vol	6 (40 ° C)	6 (40 ° C)	6 (40 ° C)	6 (40 ° C)
Total % vol	100	100	100	100
H_2S mg/m3	100 - 900	1000 - 4000	3000 – 10 000	400
NH_3 mg/m3	-	-	50 - 100	-
Aromatic mg/m3	0 - 200	-	-	-
Organochlorinated or organofluorated mg/m3	100-800	-	-	

5.3. Study of alternatives

It has been already mentioned that the recently shift paradigm in nutrient and energy recovery, has led to new research paths in order to recover energy and start recovering nutrients in WWTPs. Hereby this part of the present work aims to provide a brief description of the emergent technologies which also aim to substitute or at least enhance the conventional system.

5.3.1. Alternatives to CAS System

There are not many alternatives to the CAS system reported in the bibliography in a similar way of NECOVERY project because it is a quite rather innovative idea. There is also no bibliography about a process which substitutes both the primary settling and biological treatment.

Nevertheless according to G. Mezohegyi et al. [13] COD can be also concentrated by submerged aerated or vibrated membranes. This experiment tried to fulfil the requirements of a sequential anaerobic treatment by producing sewage concentrate in a certain amount and concentration (15–20 L/day and 3–5000 mg/L of COD, respectively) that could be used as continuous feed for a volatile fatty acid (VFA) reactor (installed at Waterleau's pilot plant, in Wespelaar, Belgium).

Figure - 3 shows a schematic overview of the two compared systems.

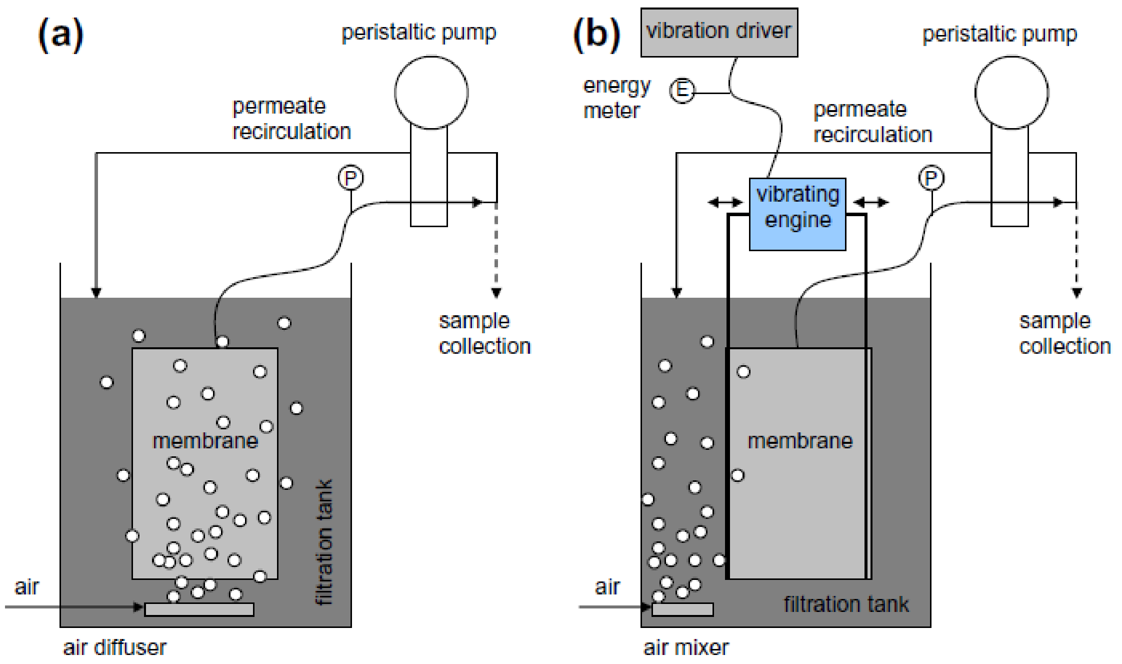


Figure - 3 Experimental lab-scale set-up for performance comparison of (a) aerated and (b) vibrated membrane filtration

Authors concluded that both methods where valid to concentrate organic matter but they proved that under their operating conditions, vibrated membranes were a better method considering fouling factors and energy usage factors (Figure - 4). These results are consistent with the earlier findings of the authors; (magnetic) membrane vibration is an effective fouling control mechanism in wastewater treatment due to the enhanced shear rate generated at the liquid-membrane interface [14] .

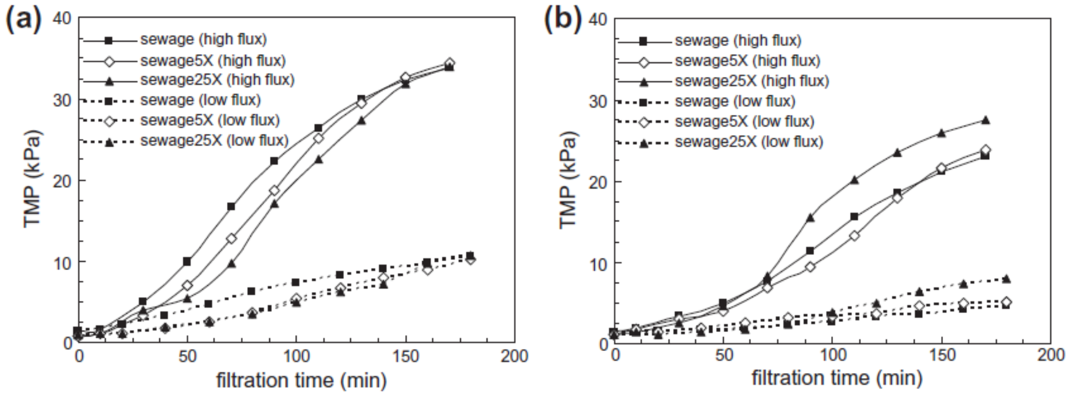


Figure - 4 TMP evolution during the flux stepping method for the three different feeds

On the other hand Diamantis et al. [15] propose a process of biosorption as Pre-concentration process. In this case they used a Biosorptive activated sludge system (BAS system) as pretreatment of an Ultrafiltration (UF) unit. This way COD can be removed to apply a subsequent waste-to-energy strategy (Anaerobic Digestion of the concentrated organic sludge). They propose the following montage.

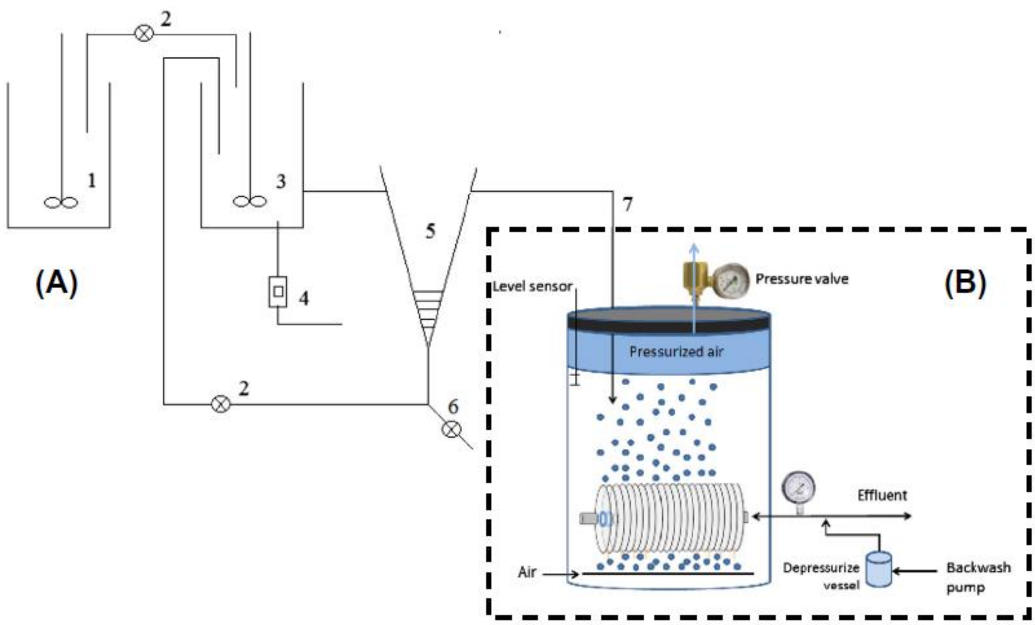


Figure - 5 Schematic representation of the (A) BAS and (B) membrane filtration experimental setup (1. Raw wastewater tank, 2. Peristaltic pump (feeding and recycle), 3. Aeration tank, 4. Air supply, 5. Sedimentation tank, 6. Sludge wastage, 7. BAS effluent)

The most significant characteristic of this process is its low HRT (Eg. HRT=1 h against HRT= 8 h for a CAS system) and hence the equipment size can be drastically reduced in order to reduce the space requirements and also Capital Investment Costs (CAPEX) and even the operational costs due to an aeration requirement reduction.

They made a set of three experiments: direct filtering of sewage, BAS previous to UF without iron salts and BAS previous to UF adding iron salts. The removal efficiency results obtained are sum up in the Table - 2.

Table - 2 Influent and effluent wastewater characteristics, and percentage removal efficiency during ultrafiltration of raw sewage and Biosorptive activated sludge effluent, with and without iron supplementation (concentrations in mg L-1, numbers in par

	CODtot	CODpart	CODsol	TKN	NH_4-N	NO_2-N	NO_3-N	PO_4-P
Raw sewage								
Influent	424 (±52)	304 (±57)	121 (±13)	59 (±1)	41 (±2)	<0,5	<0,5	7.3 (±0.1)
Effluent	49 (±4)	0	49 (±4)	43 (±2)	34 (±1)	<0,5	<0,5	5.0 (±0.6)
Removal	88.4%	100%	59.5%	27.1%	17.1%	n/a	n/a	31.5%
BAS without iron								
Influent	105 (±12)	36 (±18)	72 (±2)	53 (±3)	38 (±4)	<0,5	<0,5	3.4 (±0.2)
Effluent	54 (±2)	0	54 (±2)	49 (±3)	31 (±4)	<0,5	<0,5	3.0 (±0.5)
Removal	48.6%	100%	25.0%	7.5%	18.4%	n/a	n/a	11.8%
BAS with iron								
Influent	101 (±11)	38 (±12)	63 (±2)	53 (±1)	43 (±3)	<0,5	<0,5	n/d
Effluent	52 (±3)	0	52 (±3)	49 (±2)	40 (±1)	<0,5	<0,5	0.3 (±0.1)
Removal	48.5%	100%	17.5%	7.5%	7.0%	n/a	n/a	n/d

Furthermore the Figure - 6 shows how using BAS systems significantly improves the ultrafiltration membranes performance.

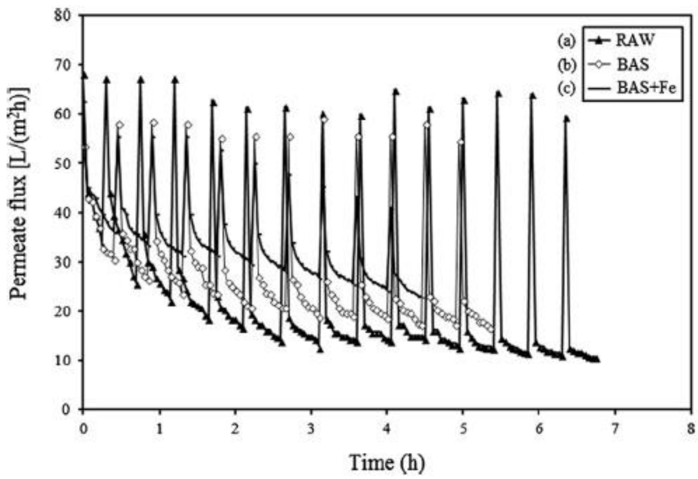


Figure - 6 Permeate flux during sewage filtration: (a) without pre-treatment, (b) with BAS and (c) with BAS and iron addition

5.3.2. Alternatives to Anaerobic Digestion

The Anaerobic Digestion is the most employed method. Not only because it stabilizes the sludge but also because of the inherent energy production associated to the biogas burning.

Nevertheless, according to the European Environment Agency (EEA) there are many alternatives which are described below.

Direct disposal

It can be given an agricultural use by disposing the sludge directly to the soil. This process is not as coarse as it may sound because the sludge must be pre-treated before its disposal. Pretreatment must reduce the water content, the amount of pathogens, the heavy metals and it also must control de pH and dry solids.

The main advantage is that this method leverages the nutrients (nitrogen and phosphorus) redirecting them to the soil. It is also a really cheap method put it provides no any form of energy.

5.3.2.1. Composting

Sludge composting aims at biologically stabilizing sludge while controlling pollution risks in order to develop agriculture or other end use outlets exploiting the nutrient or organic value of sludge. It can be applied either to non-digested sludge (e.g. Italy, France) or to digested sludge (e.g. the Netherlands). Composting involves aerobic degradation of organic matter, as well as a potential decrease of the sludge water content, the efficiency of which depends on the composting process.

Structuring composting conditions and mixture ratios naturally depend on the types of wastes to be treated as well as the quality specifications set for the resulting compost. For example, the processing of organic materials would be different if the goal was to incinerate the end product, thus demanding that the water content of sludge should be reduced, than if the goal of the composting process was to produce a soil improver, as defined by a particular agricultural outlet, which would therefore require that specific nutritional and structural properties should be present in the end product.

5.3.2.2. Gasification-Wet Oxidation

Gasification is a thermal process whereby a feedstock containing combustible material is converted with air (sometimes oxygen and/ or steam) to an inflammable gas.

The first stage is to remove most of the remaining water by thermal drying. The dry solid (DS) content output from the drier is 85-93% DS, depending on the type of gasifier installed.

Now the sludge is prepared for gasification, i.e. ‘incineration’ with sub-stoichiometric oxygen input. The various components in the sludge are partly, and some of them completely, oxidized.

A large number of reactions take place in the reduction zone of the gasifier. However, the overall process can be described by the following three main gasification reactions:

$$C + CO_2 \rightarrow 2CO \qquad [Eq\ 3]$$

$$C + H_2O \rightarrow CO + H_2 \qquad [Eq\ 4]$$

$$CO + 3H_2 \rightarrow CH_4 + H_2O \qquad [Eq\ 5]$$

The input is mechanically dewatered sludge, digested or undigested. Since the composition of the sludge varies greatly, the composition of the exit gas from the gasification process will also vary to a great extent.

Either composting or direct disposal are cheap alternatives but they are more interesting from a waste management point of view. This two techniques do not fit to the WWTP of the new era, although they recover nutrients in any way, these methods don’t produce energy and thus cannot lead to a zero energy WWTP. On the other hand gasification must be further studied in order to achieve reliable data.

5.3.2.3. Temperature Phased Anaerobic Digestion (TPAD)

This technique has been developed during last years as an enhancement of conventional Anaerobic Digestion [16]. It combines both temperatures (thermophilic and mesophilic) in the same process and therefore bringing together the advantages of both systems: it improves the reduction of solids and the production rate of biogas by enhancing the digestion rate limiting step, i.e., the hydrolysis of organic matter [17]. It also provides other advantages such as further stabilization of the sludge due to the VFA generated under thermophilic conditions are degraded in the mesophilic reactor and thus avoiding acidification. On the other hand thermophilic conditions allow inactivating and reducing the pathogens which cannot live under these conditions.

It is certain that there are studies testing both possibilities, first a mesophilic stage followed by a thermophilic stage and vice versa. Nevertheless the configuration most studied is the one setting a thermophilic stage in first place.

Table - 3 displays results for different tests of Continuous Stirred Tank Reactor (CSTR) AD and TPAD.

Table - 3 Results of lab tests carried out by Lab MET

Reactor type	HRT=SRT (Days)	COD conversion (%)	VS (conversion)
CSTR Meso	30	68	66
CSTR Meso (long-term-test)	20	60	60
CSTR Thermo	30	64	61
CSTR Meso	15	59	55
CSTR Thermo	15	47	46
TPAD without pH correction	19	63	62
TPAD with pH correction	19	70	68

6. Methodology and materials

6.1. Project description

The LIFE programme is the EU's funding instrument for the environment and climate action. The general objective of LIFE is to contribute to the implementation, updating and development of EU environmental and climate policy and legislation by co-financing projects with European added value.

The LIFE NECOVERY project aims to demonstrate, by means of a prototype, the feasibility of an innovative WWTP flowsheet based on a Pre-concentration step at the inlet of the WWTP and focused on the recovery of nutrients and energy. It will evaluate the impact of this cradle to cradle approach on the overall WWTP process, compared to the conventional flowsheet (Figure - 1). In Europe the main large WWTPs are built and it is important to aim towards the market of existing plants requiring refurbishing or extension, and focusing on the main following targets:

- **High sludge and energy production**: The innovative and crucial step is the Pre-concentration (biosorption) which will produce an upper effluent with very low solids and a bottom effluent with high quantity of solids leading to a higher biogas production.

- **Resource recovery**: The downstream process steps then focus on handling the 2 streams from the Pre-concentration step, in order to maximize energy and nutrient recovery. The upper diluted stream will be treated in a zeolite adsorption unit in order to recover the nitrogen; the lower stream (enriched sludge) is treated in a conventional Anaerobic Digestion unit in order to obtain energy from the biogas formed.

Figure - 7 compares the traditional layout of a WWTP and the proposed layout implementing the high sludge production system and the resource recovery units.

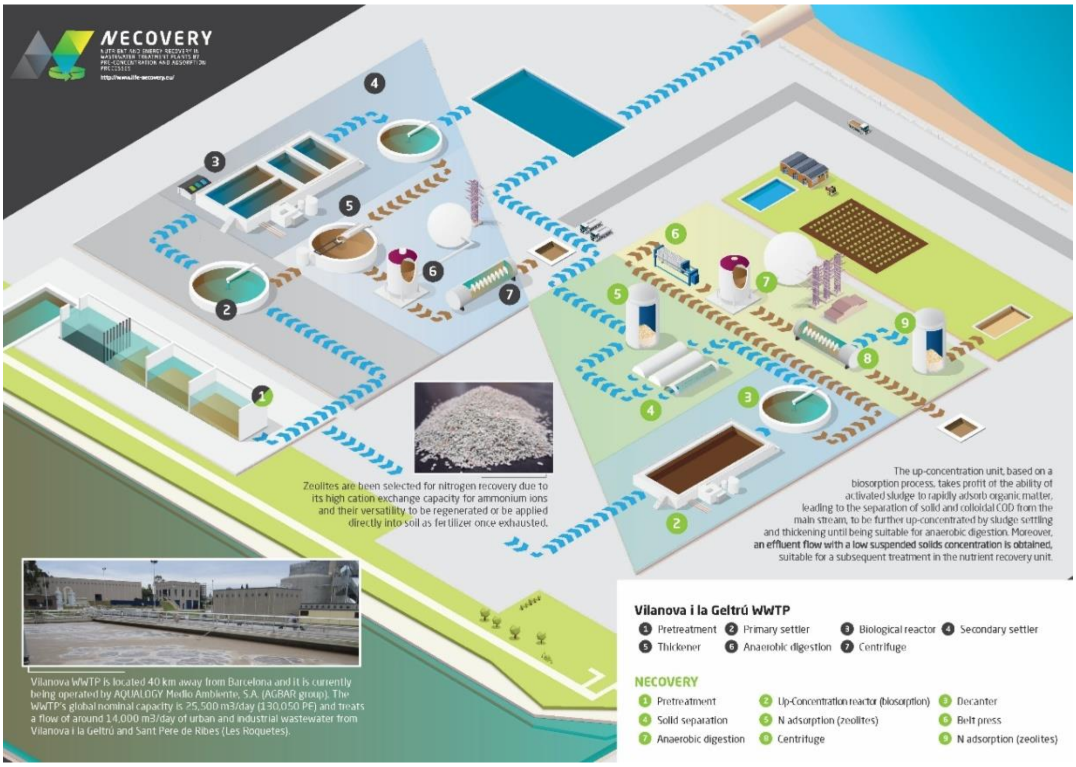


Figure - 7 Life NECOVERY brochure

By far the most common treatment currently in use is the conventional activated sludge system (CAS), in which suspended bacterial biomass anabolizes part of the organic compounds, mineralizes another part of it into CO through aerobic respiration, oxidizes ammonium to nitrate (nitrification), and it is able to incorporate phosphorus and adsorb or complexate metals. In the best case, the excess biomass (sludge) which is created in the process can be anaerobically digested to recover some of the energy in the form of methane-rich biogas, but nutrients are mostly not recovered (some phosphorus from incinerated sludge, but this is not widely practiced), nor is the effluent suitable for reuse without further tertiary treatment.

Over the years, the CAS system has grown more complex and also intrinsically more energy intensive. In addition, the more recent developments towards nitrogen removal as well as the desire to minimize the excess sludge production have led to systems which employ more extended aeration (relatively high sludge ages and low sludge loading rates). From the energy consumption point of view it has the following two consequences: (1) it requires more aeration and thus more energy consumption and (2) it leads to the creation of less and worse digestible sludge, which leads to an unfavorable energy recovery.

The unfavorable energy recovery through sludge digestion of CAS sludge means that typically a minimum of 20% of the electricity consumption of the plant can be recovered [18]. (Mller & Kobel, 2004), Wett et al. (2007) and Senter Novem (2006) reported the energy consumption of the conventional activated sludge system to be in the order of 33 kWhel/(IE.y) in Western Europe of which typically 20-35% can be recovered through AD of the sludge.[18][19][20]

Within the LIFE NECOVERY project, this problem will be overcome by applying this target to the wastewater sector, focusing on an innovative cradle-to-cradle approach.

The project is expected to deliver the following results:

- New concept of WWTP: the WWTP of the future must be self-sustainable, which means to be capable to be energy zero and to recover as much of the resource present in wastewater as possible. Therefore the increase in energy recovery and the implementation of nutrient recovery in the main line are going in this direction.

The ultimate target for this new flowsheet is to obtain the following achievements for the WWTP.

- 60% energetic self-sufficiency with higher sludge recovered in Pre-concentration process (without external substrates)
- 70% nutrient recovery by implementing N&P recovery in the main line
- 80% by-products return to land by reusing the sludge produced in Anaerobic Digestion
- 30% carbon footprint reduction by the implementation of the new flow-sheet
- An innovative product: the prototype of the system developed, implemented on a wastewater treatment plant will be a key result of the project. The innovation as it is said is the integration of existing technologies in a new concept of recovery resources (energy and nutrients).

Besides, in Table - 4, the general situation in current WWTPs (based on the average values of CAS systems) is compared with the LIFE NECOVERY targets (according to the experience in the privately funded project).

Table - 4 Comparison of the Life NECOVERY targets against the conventional systems

Target	Current situation (CAS system)	LIFE NECOVERY expectations/targets
Energy self-Sufficiency (electricity requirements)	35%	60%
Nutrient recovery	0%	70%
By-products returned to land	40%	80%
Carbon footprint reduction	-	30%

As it has been already said the project will be assessed by means of a prototype. It is compound by three pilot or units, each of which has its own purpose. Each pilot is identified by a code according to the corresponding designing action required by the European commission. Pre-concentration pilot is known as B, Anaerobic Digestion is known as B2 and nutrient recovery pilot is known as B3.

Figure - 8 aims to give a brief idea about what happens with carbon (mainly organic matter) and nitrogen.

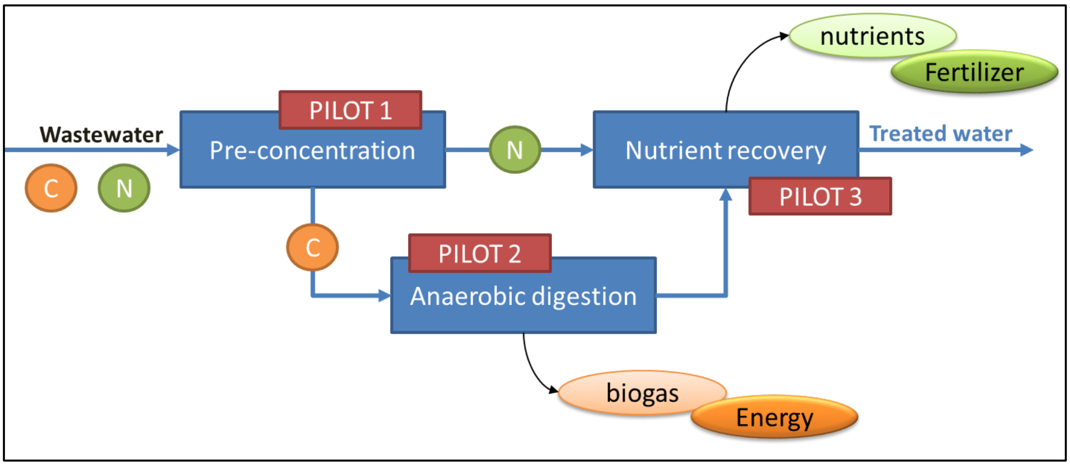


Figure - 8 Block diagram of the NECOVERY pilot plant

6.2. Pilot B1

The main objective of the Pre-concentration step is to maximize COD and Total Suspended Solids (TSS) removal and to minimize the nitrogen removal [21], [22]. The latter can be obtained by a specific combination of the process parameters sludge retention time (SRT), sludge concentration and Hydraulic Retention Time (HRT), which promotes biosorption, minimizes bio-oxidation and guaranteeing good effluent quality. Moreover nitrification can be avoided by applying a short SRT and low Dissolved Oxygen (DO) levels.

The objective is still producing clean water, meeting discharge requirements. In order to achieve this goal, it must be produced an upper diluted effluent and a bottom effluent with higher quantity of solids. This is achieved by means of a Pre-concentration step (based on biosorption) at the inlet of the WWTPs.

The selected Pre-concentration process consists of a High Rate Activated Sludge System (HRAS) of sequential design, followed by a decanter for separation of sludge and treated water [23], [24]. The sludge effluent is sent to the pilot B2 (Anaerobic Digestion) to produce energy by means of biogas production. The settler's liquid effluent is further treated in a nutrient recovery step (pilot B3) to recover nitrogen. Due to there is no intermediate process to remove COD, BOD_5 and TSS from the liquid effluent, there must be taken into account that this stream must meet discharge requirements.

The equipment employed in this process is rather similar to the used in the conventional system. The innovation lies beneath in the modification of key parameters. Conventional systems usually works with HRT= 8 hours while the HRAS which will be tested, will have an HRT lower than 2 hours. This way the microorganism community will be conform a young sludge able to adsorpt organic matter to its cellular wall rather than degrade it, as it happens in the conventional system. Furthermore, given this residence time, nitrifier organisms cannot grow, this way nitrogen is not removed so it can be latter recovered.

Figure - 9 displays the process flow diagram of the Pre-concentration pilot.

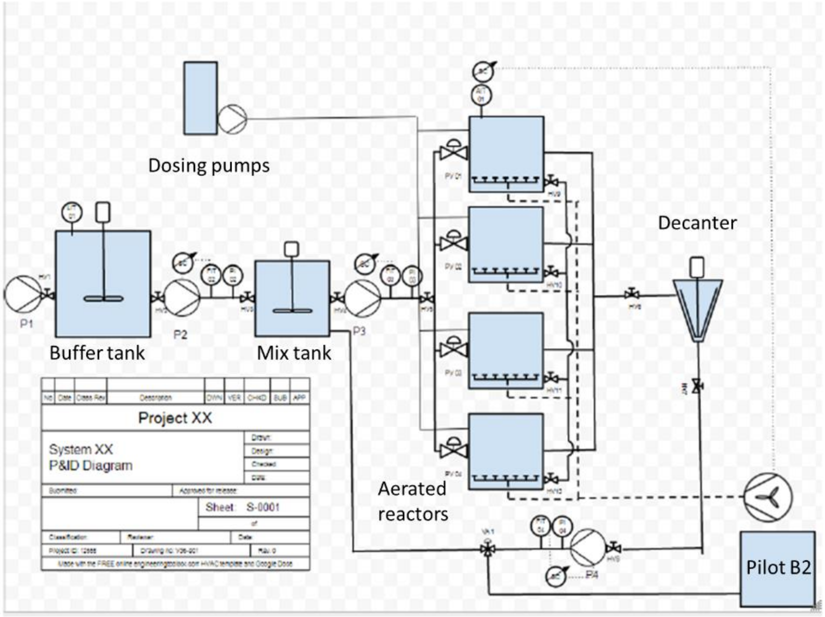


Figure - 9 Process Flow Diagram of Pre-concentration pilot

The equipment of the pilot is flowing described.

6.2.1. Buffer tank (T1)

The waste water is pumped from the outlet of Vilanova's WWTP pretreatment directly to the pilot. It is collected in buffer tank T1, where it is continuously mixed by means of a mechanical mixer (M1). This mixer has no frequency driver so it's always connected at its max speed. This tank has two buoys. The upper one controls the feed pump P1, switching it on or off depending on the height of the liquid; currently it is set up to switch off the bomb when water reaches 1 m height. The second one (lower) is designed for safety purposes. When the liquid level is too low it stops the pilot in order to protect the pump from running without liquid.

The wastewater is pumped from the buffer tank to mixing tank T2 by pump P2. This pump has a frequency driver in order to adjust flow to desired levels. The flow is continuously measured and can be read either on the flow meter screen or on the PLC.

The buffer tank can be drained off by opening a manual valve in the rear part of the pilot. There is also another manual valve which enables to open an overflow from here to the settler. Both options are also available for the rest of the tanks.

The feed tank has a small gutter to collect possible overflow or foam.

Table - 5 Buffer tank dimensions

Width	1	m
Total height	1.2	m
Height floater	1	m
Active volume	1	m³
Flow P2	0-2	m³/h

6.2.2. Mixing tank (T2)

This tank is filled either with fresh waste water from buffer tank T1 by means of pump P2, and moreover with returned settled sludge from the settler S1 by means of the recirculation pump P4. The ratio fresh waste water / returned sludge can be set via the PLC. Both pumps P2 and P4 are frequency driven.

There is a continuous display of the liquid level in the tank and it can be set in the PLC the desired level.

Mixer M2 homogenizes the mix between raw water and the recirculated sludge from settler S1. It works exactly as the mixer M1 due to it has no frequency driver.

There are also other variables controlled during the operation in this tank, such as pH and temperature which can be read either in a screen located into the pilot or via remote control at the PLC program.

The mixing tank has a small gutter to collect possible overflow or foam.

Table - 6 Mixing tank dimensions

Width	1	m
Total height	1.2	m
Active volume	1	m³
Flow P3	0-2	m³/h

6.2.3. Aerated tanks T3 – T6

Pump P3 transports the mixed liquor from the mixing tank to the aeration tanks from T3 to T6. This pump is frequency driven and can be controlled with the PLC. The flow is measured continuously and can be either read on the screen of the flow meter or on the PLC.

These tanks are designed in a way that they can be operated independently. It means that by opening and closing manual valves you can activate or bypass each tank. This way you can work with one, two, three or even 4 aerated tanks. There are also many valves which allows to work under two operating regimes, either series or parallel (Figure - 10).

- **Series**: working in this mode requires opening the feeding valve to T3 (or the corresponding one) and closing the feeding valves to the rest of the tanks. It is also necessary to open the connection valves between tanks and finally to open the overflow gutter to the settler of the last tank used. The movement of the fluid from one tank to another is carried out by gravity. This way of operation resembles a plug-flow reactor.
- **Parallel**: if all the feed valves are open, and so are all the overflow valves and moreover all the connection valves are closed, then the tanks from T3 to T6 are in parallel mode.

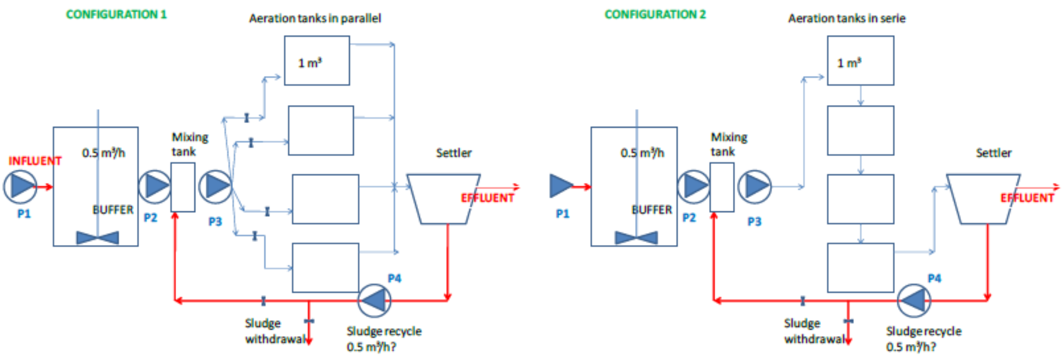


Figure - 10 Configurations either in parallel or series

The tank level is controlled in two ways:

Each tank has a spillway to drive the overflow to the settler S1, each of which is controlled by a manual valve. These valves are the small ones at the top of the reactors.

The other way is by means of the connection valve which allows passing the liquor from one tank to another by gravity but this is not meant exactly for level control purposes.

This way it can be clear that a lot of different set-ups can be tested just by switching the manual feeding valves, the overflow valves and the connection valves. It must be taken into account that the blower is controlled by DO-measurement in tank T3, therefore it is mandatory to at least use always tank T3 in each experiment.

There are a few parameters which are continuously measured and displayed in the tank T3 such as pH, temperature and dissolved oxygen. The values associated to this measures can be read either on the screen or remotely on the PLC.

From tank T3 to T6 there is an aeration disc at the bottom part which distributes the air among the tanks. The air stream is generated by a frequency driven blower which is capable of controlling the air flow supplied in order to control de DO level in the tank T. The aeration of tanks T4-T5-T6 can be shut down by means of manual valves installed at the entrance of each one. This is not possible for the tank T3 for safety means due to it must not be possible to close all the outlets when the blower is turned on. This way the blower remains protected.

Table - 7 Aerated tank dimensions (for each one)

Width	1	m
Total height	1.2	m
Active volume	1	m^3

6.2.4. Settler S1

As it has been previously mentioned, every tank (including buffer and mixing tanks) has a spillway which can be manually activated by means of a manual valve. This spillway drives the water directly to the settler. It should not have to be mentioned that during normal operation, manual valves of T1 and T2 are always closed.

Is expected that the settler must be able to split the sludge from the water; providing clarified water at the top part and sludge at the bottom. The clarified can be sampled by means of another manual valve outside the pilot. This clarified water is sent to the pilot B3 in order to remove the nitrogen from water. Regarding the sludge, it is pumped by a frequency driven pump (P4). A part of it is recirculated to the mixing tank in order to maintain a certain concentration of microorganisms and the other fraction is purged from the system and sent to a sewer. At this moment the purge works with manual valves but it is deemed the possibility of installing electrical valves and this is already considered in the PLC.

Table - 8 Settler dimensions

Diameter	1	m
Active volume	0.5	m^3
ºFlow P4	0-2	m^3/h

6.2.5. Dosing skid

A dosing station for two products is forecasted. The product is pumped in the reactors by positive displacement pumps. It is possible to dose the desired product in tanks from T3 to T6 by means of manual valves. The positive displacement pumps are placed in a closed environment to prevent projections.

The pulse-time and pause-time can be set in the PLC. It is possible to manually alter the volume of each pulse with a controller on the pump itself.

The vessels containing the dosed product can be placed underneath the pumps in a sink, which can be drained off by opening a manual valve at the outside of the container.

Figure - 11, 12 and 13 show some pictures of the inside of pilot B1, where the different elements described above can be observed.

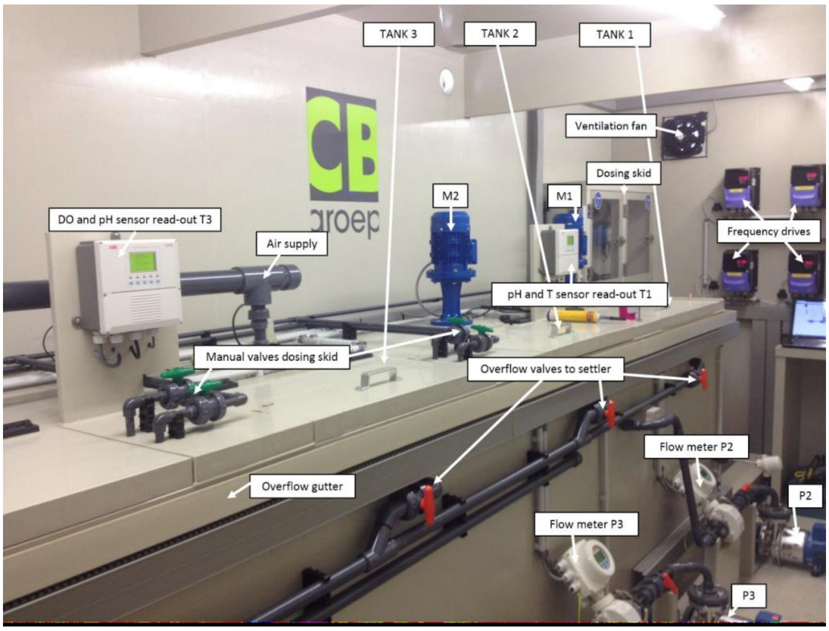


Figure - 11 Inside the Pre-concentration unit (I)

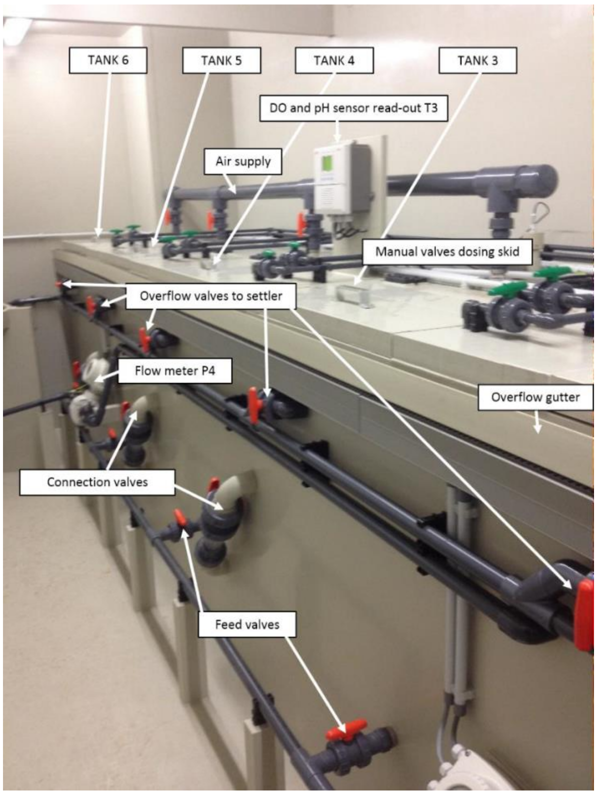


Figure - 12 Inside the Pre-concentration unit (II)

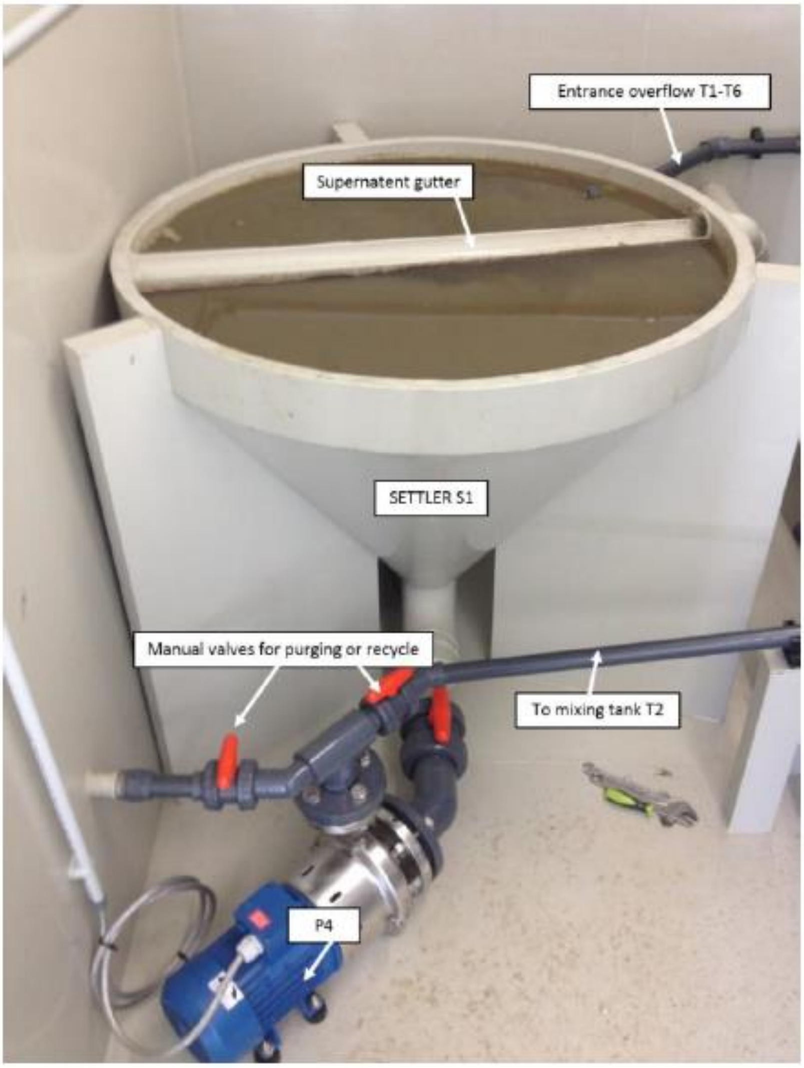


Figure - 13 Inside the Pre-concentration unit (III)

6.2.6. PLC description

Once all the parameterization is established the pilot can be either ran in manual or automatic mode, but it is not possible to run the pilot without the PLC; even the manual mode is set trough the PLC.

There is an emergency stop button on the electrical cupboard and another outside near the door. If this button is pressed, the pilot will automatically be stopped. In case of starting the normal operation again is necessary to press twice the restart button located on the electric cupboard.

The PLC has been programmed with PID algorithms which take into account the differences between the measured value and de set point. In case of the pumps the set point is a certain flow and regarding the blower the set point is the dissolved oxygen in the tank T3. As it has been previously mentioned there are 4 frequency drivers; three associated to the pumps P2, P3 and P4 in order to regulate the flow provided by each pump and there is another frequency driver associated to the blower which allows controlling the dissolved oxygen in the tank T3.

Figure - 14 displays the main screen of the PLC. It allows knowing if everything is working properly at a simple glance. Moreover it allows switching on/off the automatic mode or turning on/off each device in manual mode.

It can be seen the recirculation and purge valves which has been taken into account in the design although they have not been installed yet and so is the dosing station.

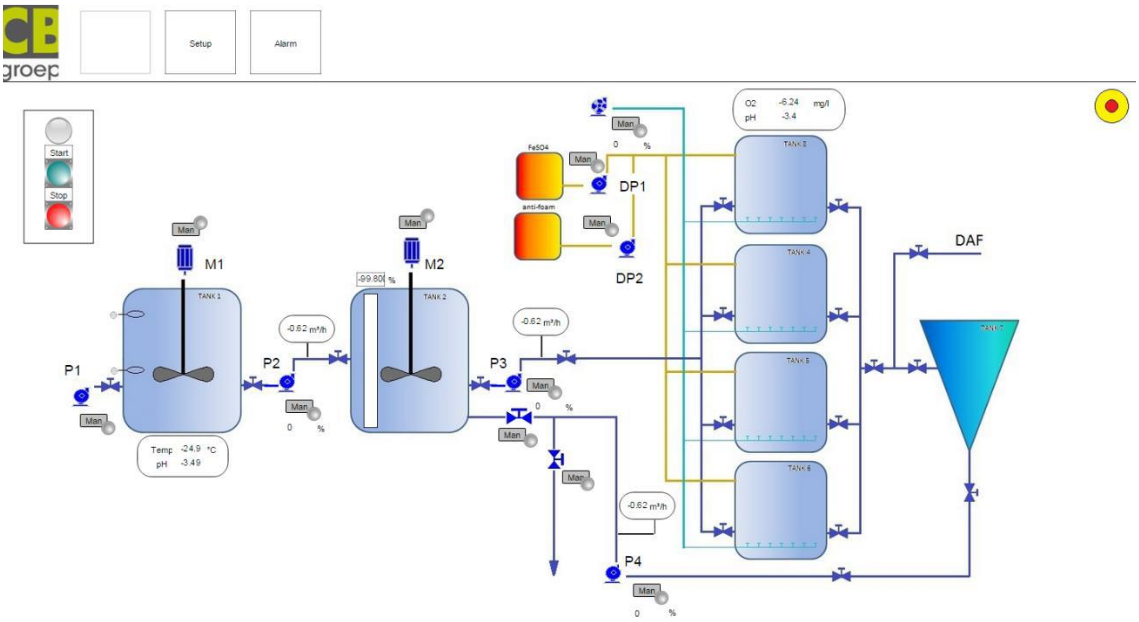


Figure - 14 PLC Home screen

The most important functions of the PLC are:

- Measure of the dissolved oxygen in the first aerated reactor and further control of blower's power to maintain an oxygen dissolved level of 0.5 ppm.
- Regulate the dosage of $FeCl_3$ and polymer in order to achieve good settling properties.
- Regulate the amount of purged sludge.
- Protecting all the pumps from running in void.

6.3. Pilot B2

The main objective of the anaerobic pilot is to maximize the biogas production and to separate the digestate into a solid fraction to be used as natural stable fertilizer and a liquid fraction [25].

The Anaerobic Digestion (AD) pilot was designed as a CSTR that can be operated under mesophilic or thermophilic temperature conditions. During the design of this pilot it was decided to discard TPAD system because of practical considerations (relatively small sludge volumes to be treated), it was concluded that the extra equipment required for this configuration (extra vessel, mixing device, pH and temperature controllers, etc.) would not compensate for the slightly higher COD-to-biogas conversion (about 5%).

The CSTR AD pilot has an active volume of 0.7m³ and is designed to manage a flow of at least 35L/day, at a HRT (hydraulic retention time) over 20 days. The CSTR's digestate can be collected in a separate tank for further batch-wise testing (dewatering and nutrient recovery).

Figure - 15 displays PFD of this pilot.

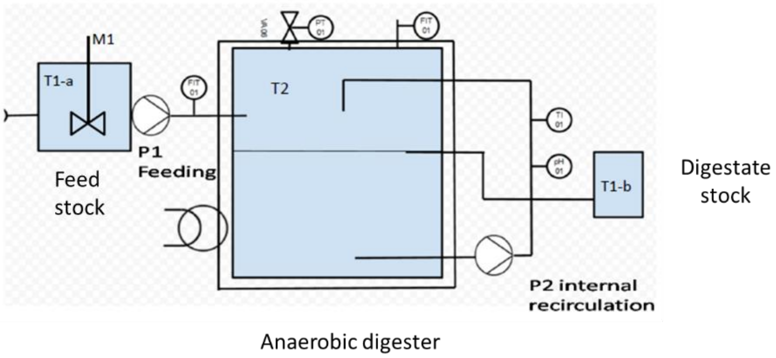


Figure - 15 Schematics of Anaerobic Digestion unit

The equipment of this pilot is explained below.

6.3.1. Sludge influent and/or storage tank (T1)

This tank is split into two different compartments. The thickened sludge from the Pre-concentration unit will be pumped to the first compartment of tank T1 (T1-a). The second compartment will be used for digested sludge storage before dewatering (T1-b).

Mixer M1 is set to homogenize sludge in tank T1-a. It has a frequency driver and it can also be controlled on the electric panel or on the PLC.

This tank can be drained off in a similar way to pilot B1, by means of a manual valve placed in the rear of the pilot. The tank has a small gutter to collect and drain off possible overflow or foam.

Dimensions:

Active volume: 0.4 m^3 each compartment

6.3.2. Anaerobic Digestion tank (T2)

Pump P1 feeds the sludge from the storage tank T1 to the Anaerobic Digestion tank T2. The pump mixer is frequency driven and can be controlled by the PLC. The flow is measured continuously and can either be read on the screen of the flow meter or on the PLC. The flow meter has also a totalizer by means of which total flow can be read either on the screen of the flow meter or on the PLC.

The anaerobic digester is built in stainless steel. It has a removable cover to allow its inoculation. It also has an opening to allow biogas gathering. The tank is isolated with glasswool in order to maintain a constant temperature. The gas outlet must be sealed with a waterlock to prevent air from entering into the digester; nevertheless it must not be much restrictive in order to avoid pressure growth inside the tank. Furthermore a gas meter is forecasted in order to measure the biogas produced.

There is a spillway to remove the exceeding sludge form the reactor. This spillway has another waterlock to prevent air from entering the tank. There are sampling points at the entrances and at the outlet of the digester.

There is a pump (P2) which continuously recycles the content of the tank in order to keep the organic matter suspended. In the recycle loop there are temperature and pH sensors to check the correct behavior of the tank. Furthermore the temperature is maintained by means of an electrical resistances wrapped around the recycle loop.

Table - 9 Anaerobic Digestion tank dimensions

Height	1	m
Active volume	700	m³
Flow P1	0-2	m³/h
Flow P2	2	m³/h

Figure - 16 and 17 show some pictures of the inside of pilot B1, where the different elements described above can be observed.

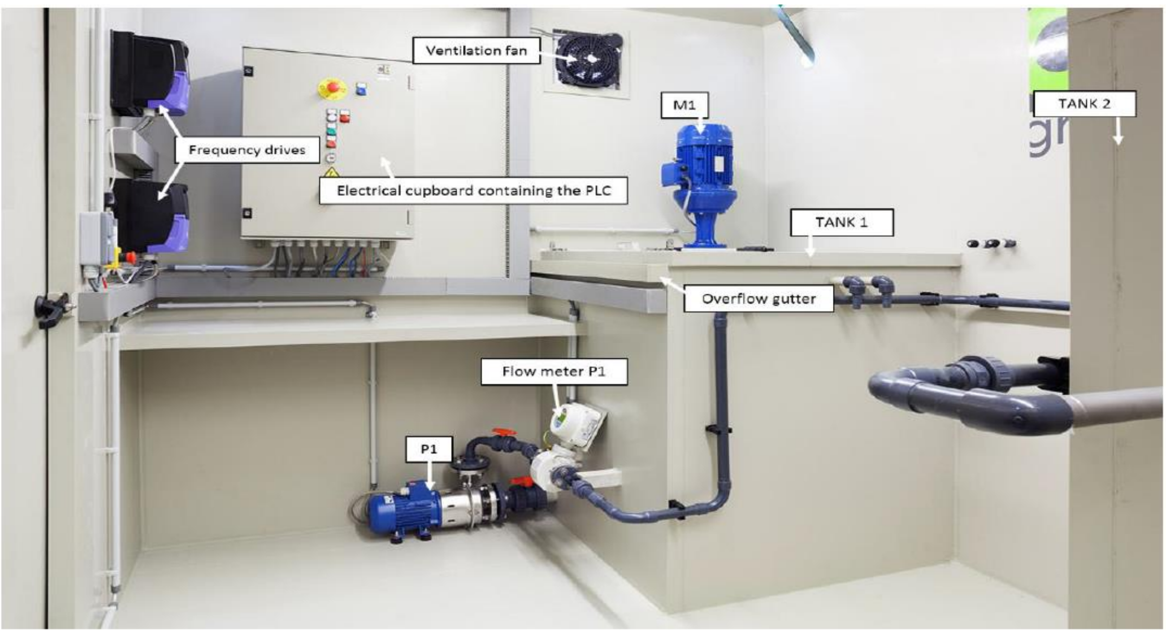


Figure - 16 Inside the Anaerobic Digestion unit (I)

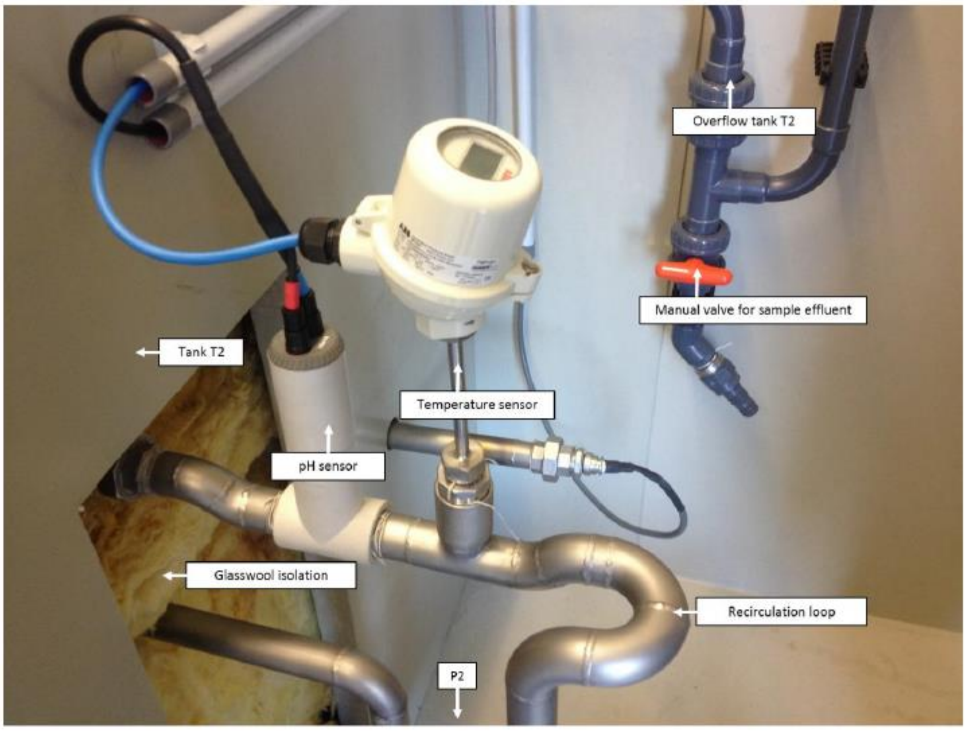


Figure - 17 Inside the Anaerobic Digestion unit (II)

6.3.3. PLC description

Since everything in pilots B1 and B2 has been designed by the same company, the PLC is very similar to the previous one, explained in section **5.5.6** and thus it only will be explained the differences.

Figure - 18 displays the main screen of the PLC.

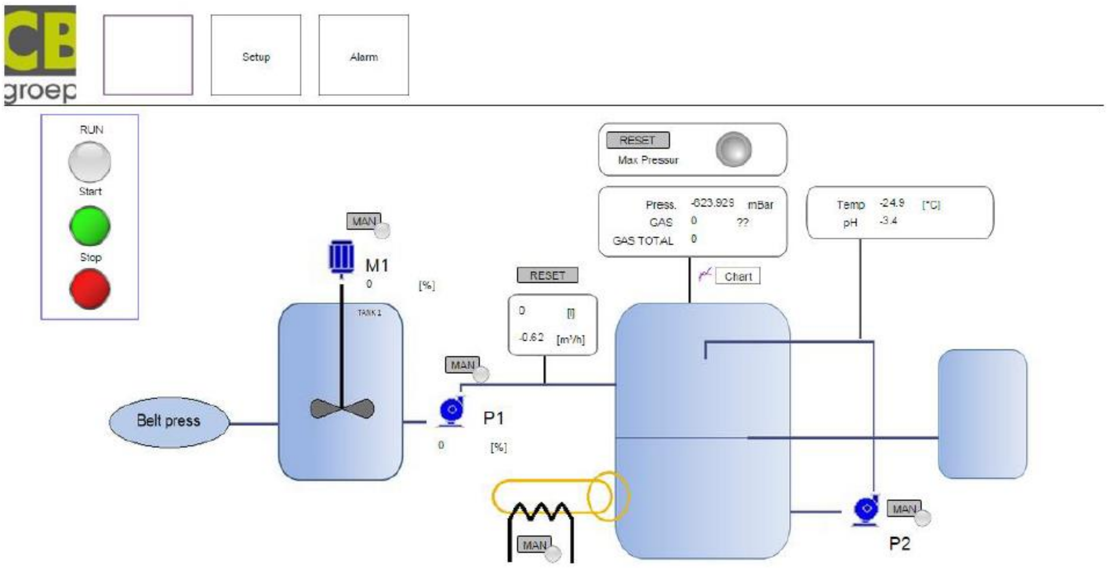


Figure - 18 PLC Home screen

The most important themes controlled by the PLC are:

- Switching on and off the resistance to maintain the temperature at 38ºC
- Controlling the inner pressure of the AD
- Measuring accumulated volume of sludge fed and biogas produced
- Control de level of sludge in the feedstock tank

6.4. Pilot B3

The main o objective of this pilot is nutrient recovery. In this case the nutrient of interest is nitrogen which will be removed from water by means of adsorption with Na-activated natural zeolites [26].

There are any kinds of zeolites. Based on lab-scale experiments, the selected one is clinoptilolite. It provides many advantages such as low acquisition cost (<0.2 €/kg compared to 3-25€/kg of organic resins) which allows to be competitive with other adsorption techniques (cation exchange resins) and high selectivity towards ammonium. Other advantages are that this technology allows cheap and simple maintenance at full-scale applications. The main disadvantage is that zeolites are very sensitive to solids, easily suffering from clogging. In order to prevent zeolites from clogging and poisoning a pretreatment process has been forecasted. The pretreatment is compound by a glass filter to remove the major part of the solids and moreover five UF modules to remove the remaining solids.

The pilot is designed to test the viability of the zeolites at bigger scale. At full scale, the zeolite would be charged with ammonium and after that, it would be sold as solid fertilizer. For practical reasons, zeolites are not removed once they are charged at pilot scale. Once this happens, zeolites are chemically regenerated in order to start the process once again and asses its performance. Notwithstanding, other option would consist in removing the ammonium as ammonium sulphate from the chemical stream. This is carried out by means of stripping or membrane contactors. This way, ammonium sulphate would be also sold as solid fertilizer.

Figure - 19 shows a depiction of the process flow diagram.

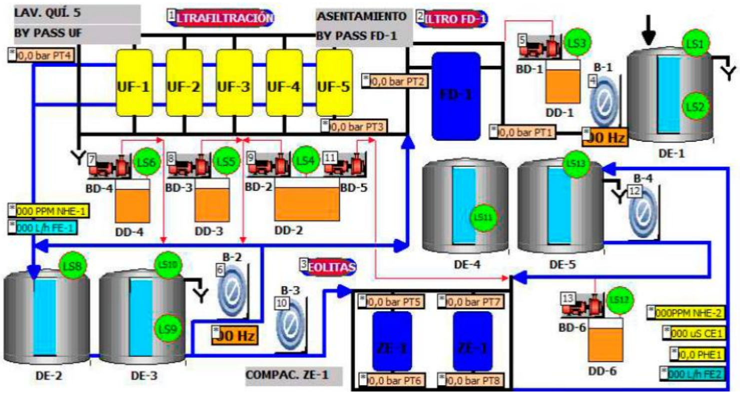


Figure - 19 Schematic representation of the process

Further information of each unit is provided below.

6.4.1. Buffer tank (DE-1)

This tank guarantees a continuous flow to the process. The feeding water is expected to be the clarified obtained in B1's settler. This is not yet the treated water because it is forecasted working each pilot alone before having them all connected and thus the treated water is the outlet water of Vilanova's WWTP.

Pump P1 provides water from this tank to the filter. It has a frequency driver in order to regulate the flow produced by the ultra-filtration system.

6.4.2. Glass filter (FD-1)

It is a simple glass filter whose aim is to remove the major part of suspended solids.

It is designed to be filtering during a period of time after which a counter wash phase is started.

6.4.3. Ultrafiltration (UF-1-5)

It works in a similar way to filter nevertheless its productive time is much less than filtration due to the fast increase in the feeding pressure. It is because of this that UF membranes must not work more than 20 minutes.

In this case there is not only one washing phase. The designed washing system is as follows.

<u>Hydraulic wash</u>

The membranes are cleaned only with ultra-filtered water in a three-phase program in order to clean them not only from the inside but also from the outside.

<u>Chemical Wash type 1</u>

Cleaning only with water is not possible due to water is not pure and the more time the membranes work the more they clog. After a while, microorganism may grow as biofilm an over the membrane and thus increasing the feed pressure.

This kind of cleaning is set to occur once after ‘X’ hydraulic washes have taken place. This ‘X’ value is modifiable in the PLC and is very important to optimize it in order to decrease wasted chemical products.

The chemicals involved in this process are alkaline, in this case a mix of sodium hypochlorite and sodium hydroxide are the chosen ones.

<u>Chemical Wash type 2</u>

This kind of cleaning is set to occur once after ‘X’ type 1chemical washes have taken place. This ‘X’ value is modifiable in the PLC and is very important to optimize it in order to decrease wasted chemical products.

In this case the chemical employed is a strong acid. At the beginning it was thought to use hydrochloric acid but it was later rejected due to ventilation problems in the pilot. The main issues using hydrochloric acid are vapor clouds formation and metal corrosion.

Pump P2 is in charge of the different cleaning phases. It is more powerful than P1, P2 and P3 because of the higher flow requirements in washing phases. Ultra-filtered water is stored in tanks DE-2 and DE-3

6.4.4. Zeolites

There are two zeolites sizes to be tested. The smallest goes from an average particle diameter of 0.5-1 mm and the other goes from 1-1.5 mm. It is forecasted to achieve better results with the smallest ones but it has been taken into account that there could be clogging problems. That is why there is a size a little bigger, just in case the other zeolites collapse too fast.

Zeolites are contained in two columns which allow working in every single possible case.

<u>Service</u>

- Series
- Parallel
- Only one

<u>Regeneration</u>

- Co-current
- Countercurrent

Pump P3 sends ultra-filtered water from tanks DE-2 and DE-3 to the zeolite columns.

Due to zeolites have their surface activated with sodium, the regenerants must be sodium based. In this case sodium hydroxide and brine are the chosen ones.

All the chemical products are stored into their own tanks and are pumped by diaphragm pumps and directly diluted into the corresponding stream.

Finally water without ammonium is stored in tanks DE-4 and DE-5. There are two NH_4 sensors, one at the entrance of ultra-filtered water storage tanks and another at the entrance of the storage tanks of water without ammonium. This way it can be measured the percentage of ammonium absorbed by zeolites. There are also conductivity and pH sensors at the outlet of zeolites in order to verify that all the chemicals have been removed from the columns after the washing process.

6.4.5. PLC description

This pilot is expected to be autonomous due to it is highly automated. That is why a correct parameterization is needed.

There is an emergency stop button on the electrical cupboard and another outside near the door. If this button is pressed, the pilot will automatically be stopped. In case of starting the normal operation again is necessary to press the restart button located on the screen.

Figure - 20 shows the main screen of the PLC where you can select other directories to display.

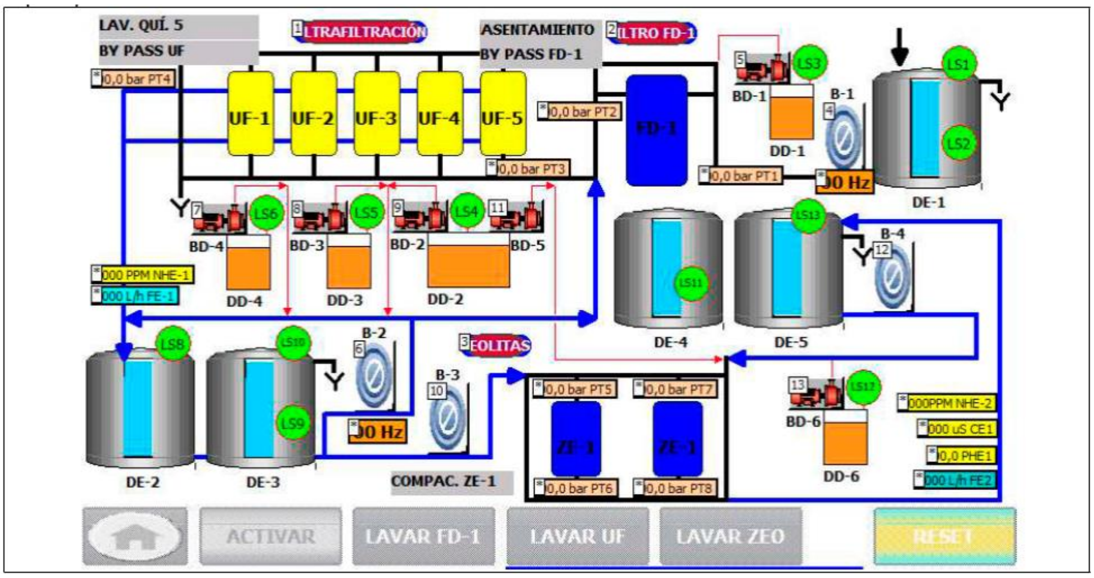


Figure - 20 Zeolites PLC main screen

The PLC allows to set values for a wide rank of parameters, such as:

- Measurement rank for all sensors
- Alarms for all the parameters (flow rates, pH, conductivity pressure…)
- Needed time to trigger an alarm
- Frequency drivers set points
- Select bypass for filter, UF or zeolites
- Dosing time for chemicals
- Maximum differential pressure to trigger a washing step
- Maximum service time to trigger a washing step
- Duration of each washing step
- Maximum number of washing steps triggered by pressure
- Number of hydraulic washes to trigger a type 1 chemical wash
- Number of type 1 chemical wash washes to trigger a type 2 chemical wash

- Ammonium set point at the outlet to trigger a washing phase at zeolites
- Maximum number of washing steps triggered by ammonium at the outlet

The start-up process of this pilot consists in modify these values given by the designer until an optimum is find.

6.5. Analytical procedure

There are many analyses that had been carrying out during the commissioning and start-up of each pilot. This part of the work aims to explain which parameters are measured and analyzed and what is analytical procedure [27].

6.5.1. Common parameters

6.5.1.1. COD

It is one of the key indicators of pollution in industrial wastewater. It is a measure of the oxygen equivalent necessary to oxidize substances in the waste water. It is expressed in ppm of O_2. It indicates the content of oxidizable organic materials and other reducing substances, such as Fe^{+2}, NH_4.

This is the most important parameter since it is mandatory to produce a diluted effluent with low quantity of solids and COD, in order to meet discharge requirements. On the other hand, to fulfill the purpose of the project, a COD rich sludge effluent has to be produced in the settler. For these reasons the COD is measured at the entrance, at the reactor and at both outlets of the settler (clarified and sludge).

Not only total COD is studied, but also settleable and soluble. The differences are explained below.

Total

Its name is auto-explanatory and corresponds to definition given before.

Soluble

It corresponds to the COD measured from a sample of wastewater filtered with a 45 μm filter.

Settleable

It corresponds to de COD measured from the clarified of a sample settled during 30 minutes.

The process is quite simple since we use kits Hach Lange LCK 514 or 314 depending on the expected range.

The procedure is transcribed below.

1. Stir the sediment to remain in suspension
2. Pipette 2.0 mL sample carefully
3. Close cuvette, thoroughly clean the outside
4. Invest
5. Heat in the thermostat at 148 ° C for 2 hours
6. Remove the hot cell and Invest carefully
7. Cool to room temperature in the cooling rack
8. Clean the outside of the cuvette and evaluate

6.5.1.2. Solids

Previous to the analysis here are some common definitions used in this field. Figure - 21 shows a brief classification of solids.

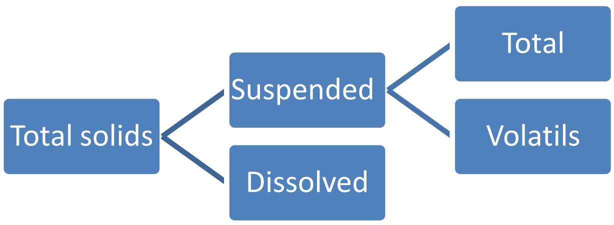


Figure - 21 Classification of solids

Total solids: is the term applied to the material residue left in the vessel after evaporation of a sample and its subsequent drying in an oven at a defined temperature. Total solids includes ‘‘total suspended solids,’’ the portion of total solids retained by a filter, and ‘‘total dissolved solids,’’ the portion that passes through the filter.

Fixed solids: is the term applied to the residue of total, suspended, or dissolved solids after heating to dryness for a specified time at a specified temperature. The weight loss on ignition is called ‘‘volatile solids.’’ Determinations of fixed and volatile solids do not distinguish precisely between inorganic and organic matter because the loss on ignition is not confined to organic matter. It includes losses due to decomposition or volatilization of some mineral salts.

Settleable solids: is the term applied to the material settling out of suspension within a defined period.

Procedure

A well-mixed sample is evaporated in a weighed dish and dried to constant weight in an oven at 103 to 105°C. The increase in weight over that of the empty dish represents the total solids.

It must be taken into account that residues dried at 103 to 105°C may retain not only water of crystallization but also some mechanically occluded water. Loss of CO2 will result in conversion of bicarbonate to carbonate. Loss of organic matter by volatilization usually will be very slight. Because removal of occluded water is marginal at this temperature, attainment of constant weight may be very slow.

If volatile solids are to be measured ignite clean evaporating dish at 550°C for 1 h in a muffle furnace.

Total solids can be measured as follows:

$$Total\ solids\ [g/L] = \frac{(A-B)}{V_{Sample}} \qquad \text{[Eq 6]}$$

$$Volatil\ solids\ [g/L] = \frac{(A-C)}{V_{Sample}} \qquad \text{[Eq 7]}$$

Where:

- A = weight of dried residue at 105 ºC + dish in grams
- B = weight of dish in grams
- C = weight of evaporated residue at 550 ºC + dish in grams
- Vsample =volume of sample employed

The procedure to calculate either total or volatile solids from the suspended fraction, is the same but filtering the sample with a glass filter in order to retain this fraction.

Both COD and solids are the most important parameters because it constitute a *KPI* for each unit for different reasons (explained below). This *KPI* along with others are following explained.

6.5.2. Analysis of KPIs

Pre-concentration unit

COD: it is a quality parameter, since it allows to see at a simple glance whether the efficiency of the process is correct and if discharge requirements are met in the clarified effluent. Total-$COD_{efluent}$ should take values of less than 125 mg/l.

Solids: It allows to know whether the microorganism community is in a correct stage of growth. Total solids inside the reactor must have a value around 3 g/L and 6 g/l at the recycle.

DO: it must be around 0.5 ppm in order to avoid growth of nitrifies

SRT & HRT: both hydraulic and sludge retention time allows to control the growth of microorganism community. In order to have a young adsorptive non-oxidizing and non-nitrogen removing microorganism community, SRT must be around 2 hours and SRT between 6 and 24 hours.

$V30_{30}$ & SVI: The 30-minute settling test (also known as V_{30}) is used to determine the settled sludge volume of mixed liquor samples in activated sludge systems. It is useful in the routine monitoring of biological processes. A thirty-minute settled sludge volume (SSV30) can be used to determine the returned-sludge flow rate and when to waste the sludge. It is also used to calculate sludge volume index (SVI), which helps determine the health of the flock as well as the severity of poor settling (bulking) episodes. The sludge volume index is calculated using the sludge volume and the mixed liquor suspended solids value as follows. [28]

$$SVI = SSV30/\left(\frac{MLSSV\ mg/L}{1000}\right) \qquad \text{[Eq 8]}$$

In order to have a good control of the community, the SVI must take values around 30-50 ml/mg MLSSV.

Anaerobic Digestion unit

COD: measure of the sludge stability. Fresh sludge (digester's feed) may have an average total COD of 40000 ppm and the outlet (stabilized sludge) an average of 20000 ppm.

Solids: It allows to know whether the microorganism community is in a correct stage of growth

Temperature: anaerobic digester works under mesophilic conditions thus maintain a temperature around 39 ºC is critical for the microorganisms.

Alkalinity Index: Alkalinity is the quantitative capacity of an aqueous solution to neutralize an acid. It is usually measured in mg/L of $CaCO_3$. Employing different titration methods it can be obtained different alkalinities, such as total, associated to HCO_3^- or associated to VFAs (volatile fatty acids).

- **Index Buffer (IB)**: It corresponds to the relation between the alkalinity due to VFAs and total. Values around 0.2-0.4 indicates that at least the 60 % of alkalinity is due to HCO_3^-. Values under 0.2 indicates sub-feeding and over 0.35 indicates acidification.
- **Index alpha**: It corresponds to the relation between the alkalinity due to HCO_3^- and total. Values around 0.7 indicates a stable operation.
- **Index AI/AP**: it corresponds to the relation between alkalinity due to VFAs and alkalinity due to HCO_3^-. Values under 0.3 indicates disturbances in the reactor

Nitrogen recovery unit

Solids: it is important to have the lowest amount of solids as possible because it cause severe problems of clogging in the zeolites. That is why the filter FD1 and UF-1-5 are set to protect zeolites.

Washing step due to pressure: either at the filter or the UF module is a direct measure of a correct performance. If this value is higher than 3 washing steps triggered by pressure per hour, then the membranes are not recovering correctly and adjusts must be made.

Washing due to ammonium at the outlet: is a direct measure of a correct performance. If this value is higher than 3 washing steps triggered by pressure per hour, then the membranes are not recovering correctly and adjusts must be made.

ΔP/t: The membranes works at constant flux. This means that when the time goes by, the differential pressure trough the membrane increases. For safety reasons this differential pressure must not overcome a value of 0.8. For this reason a plot of the differential pressure over time is useful to see at a simple glance the evolution of the pressure and when necessary to apply a hydraulic or chemical wash is. Figure - 22 shows how a graphic of this kind is. Do bear in mind that every cycle comprehends a period of 15 minutes filtering and 2 minutes of hydraulic washing.

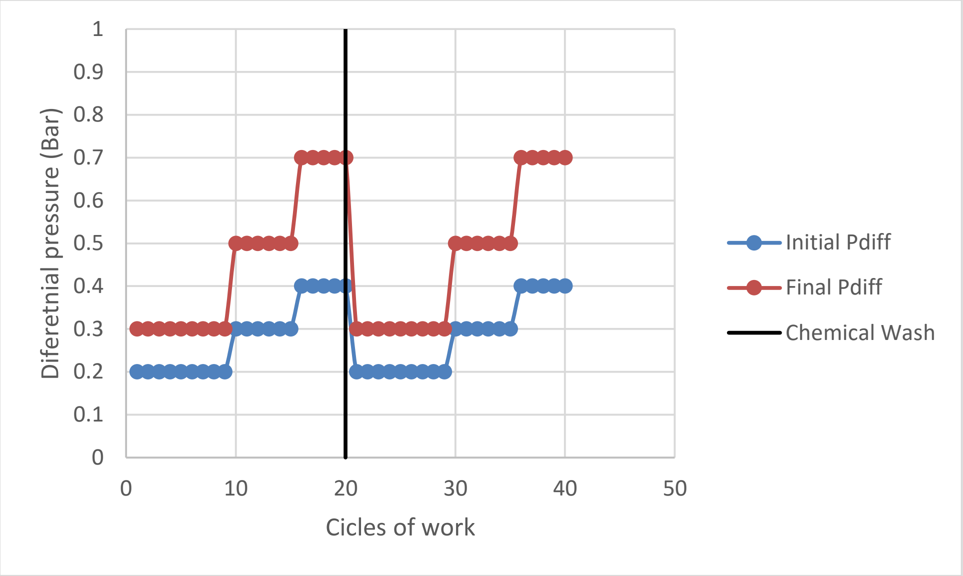


Figure - 22 Variation of pressure with cycles of work.

NTU: the number of turbidity units allows to have another performance indicator for the ultrafiltration membranes. These membranes removes the microscopic suspended solids and hence the turbidity. A good performance of the membranes comprehends a NTU value at the inlet around 30 and at the outlet less than 5.

Ammonium recovered: this is an obvious KPI because is the main purpose of this unit. Measuring the ammonium at the entrance and at the outlet it can be measured the percentage recovered. This parameter measures the effectiveness of the pilot.

Ammonium fraction: this is the percentage of $N\text{-}NH_4$ over the total nitrogen. This is also important because we can only recover nitrogen in the ammonium form, the other fractions (organically bonded, nitrite and nitrate) are wasted. This parameter measures overall effectiveness.

7. Start-up of the pilots

The construction and start-up of Pre-concentration (pilot B1) and Anaerobic Digestion (pilot 2) units were completed in April 2015. At this moment, the pilots were started up in Vilanova WWTP. During the first weeks, some hydraulic tests were carried out to validate the proper operation of the unit after transport. The result of this validation was positive and it was decided to inoculate the Pre-concentration unit with activated sludge from the WWTP and the anaerobic digester with digested sludge from the full-scale digester.

During the first months of operation (May-December 2015), many operational problems have occurred. The efforts of the personnel during these first months of operation have been focused on the solution of these problems. Unfortunately stable operation and reliable results have not been yet obtained. Following main problems are summarized, the actions carried out to solve them, the results of these actions and some pictures related with the problem or solution implemented.

7.1. General issues for Pre-concentration and Anaerobic Digestion pilots

1. Security drain: The overflow gutter doesn't retain the liquor in case of overflow due to the slope of the site.

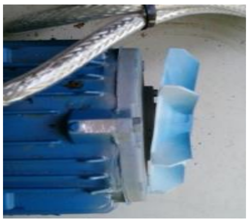
ACTION	RESULT
Pipes system at certain height to drain the liquor	Safety operation of the pilot ☺
	

7.2. Pre-concentration pilot (pilot B1)

1. Clogging of the flow meters. The flow meters installed by manufacturer are electromagnetic with a reduction of diameter. The diameter inside the flow meter is about half inch. That is why they get easily clogged.

ACTION	RESULT
1. Installation of a cartridge Filter (25 μm)	Filter clogged after some minutes ☹
2. Installation of a cartridge Filter (75 μm)	Filter clogged after some hours ☹
3. Installation of a bag Filter (3,7 L; 800 μm)	Filter clogged after some hours ☹
4. Installation of a bag Filter (28 L; 800 μm)	Filter clogged after some days (OK) ☺
5. Installation of a control loop (ΔP = 2.5 bar) in the filter, which stops the influent pump in case of P increases	Safety operation of the pilot ☺
	

2. Pumps damaged due to the operation at a low frequency. The pumps where over dimensioned. The flow required by the pilot, made pumps work at low revs, making them burn.

ACTION	**RESULT**
Replacement of broken motors for low voltage motors (with forced ventilation)	Successful operation of the pumps at low flowrates ☺
	

3. Bad settling properties of the sludge from Vilanova WWTP used to inoculate the Pre-concentration unit.

ACTION	**RESULT**
Evaluation of the sludge volume index of activated sludge from different WWTP, in order to select the sludge with better settling properties to inoculate the process	Better performance of the settler ☺
	

4. Clogging of the influent pump submerged in the WWTP manhole.

ACTION	RESULT
Replacement of the pump by a centrifugal one, with high resistance to solids	Still clogged by wipes
	

5. The pump has not enough autonomy

ACTION	RESULT
As a temporary solution, another pump was installed at the outlet of WWTP primary settling	Possibility to operate but with a water which altered characteristics

6. The treated water is not the correct. The project aims to treat water directly coming out from the pretreatment, not from the primary settling.

ACTION	RESULT
To buy a lobular pump plus a rotating screen. This action took a few months due to the rotating screen is an expensive device, and thus a few alternatives had to be considered	Still waiting for the rotating screen

7. The ducts from the blower to the diffusers are made of PVC. The air inside moves at a high temperature (higher than 60 ºC). This ended decaying the PVC creating a deformation on the connections and generating great leakage points. Resulting in a full stop due to aeration is the core of biological treatments.

ACTION	RESULT
Replacement of the corresponding piece for a new one made of metal	Air reaches again the bioreactors

Currently this pilot is stopped due to we are waiting for the piece to arrive. Once it is installed the pilot will be started once more. At this point, we are aware that we will face new challenges which will have to be overcome. By now we are working to improve the settleability of the sludge because it is forecasted that it will be bad. In order to find the optimum conditions of settleability a Jar test is being carried out. On the other hand, until now, the purge of the settler have never worked. This is the next step which we will approach once the settleability of the sludge is correct.

7.3. Anaerobic Digestion pilot (pilot B2)

1. Overheating of the resistance to heat the digester.

ACTION	RESULT
Replacement of the electrical resistance by an electrical tracing in the recirculation loop	The new resistance was not enough to maintain the digester temperature at 35ºC ☹ → next problem
	

2. Electrical tracing not enough to heat the digester.

ACTION	RESULT
Modification of the position of the electrical tracing to improve the heating	Not enough to reach and maintain 35ºC ☹ → Action 2
Installation of a submerged electrical resistance in a separate water tank	Galvanic corrosion in the external tank (hot water tank) ☹ → next problem
  	

3. Galvanic corrosion in the external tank (hot water tank).

ACTION	RESULT
Installation of a sacrifice anode and coating of the equipment	Avoidance of galvanic corrosion ☺
	

4. Sludge recirculation pump installed provided too high flow rate (turnover of the digester was only few hours).

ACTION	RESULT
Replacement of the recirculation pump for a smaller one	Turnover around 15 hours ☺
	

5. Mixing system in the feeding tank not enough to maintain a satisfactory mixing

ACTION	RESULT
Replacement of the propeller for a bigger one	Successful mixing of the influent sludge ☺
	

9. Impossibility to visually control the behavior of the digester (foams)

ACTION	RESULT
Installation of a sight glass in the digester	Possible to visually control the digester behavior ☺
	

10. No signal given by the temperature sensor

ACTION	RESULT
Reparation of the sensor (3 months were required)	Correct measurement of the T ☺

ETSEIB

11. Delay on the arrival of the biogas flow meter

ACTION	RESULT
Installation of the biogas flow meter (August 2015)	Possibility to measure the biogas production ☺
	

12. Difficult to feed the digester with the sludge from the WWTP (during the first months of operation), due to the large distance between the full-scale digester and the pilot plant

ACTION	RESULT
Installation of a temporized pump and a direct connection between the full-scale digester and the feeding tank in the pilot (200 m of pipe). Installation of a sensor level in the tank as a safety measure to avoid overflow	Possibility to automatically feed the pilot digester ☺
  	

13. Settling of biomass. Recirculation loop is not enough to keep the biomass suspended inside the anaerobic digester.

ACTION	RESULT
Installation of a mixer inside the digester. Several weeks of lab tests and trials were needed to get to this solution	Biomass is correctly re-suspended

14. No biogas detected by the gasometer.

ACTION	RESULT
Still making trials. It is thought that the root cause can be an over dimensioned gasometer or a gas leakage through a connection	No biogas is detected

Currently this pilot is working correctly but still no gas is measured. Apart from this, the lab results of the corresponding parameters are within the limits. That’s why it is thought that there must be gas inside of the digester but it is list at some point.

7.4. Nutrient recovery (Pilot B3)

1. Mechanical failure of the zeolite column ZE-1. It has been concluded that it was due to an incorrect design. The columns were created for us under the requirement of being transparent. The new ones are opaque and can bear 10 bar while the other could only 4.

ACTION	RESULT
Substitution of the old columns for new ones more resistant. But with six weeks of delay.	Safety operation
	

2. Huge leakages (NaOH and brine) trough connections. Creating an unsafety environment.

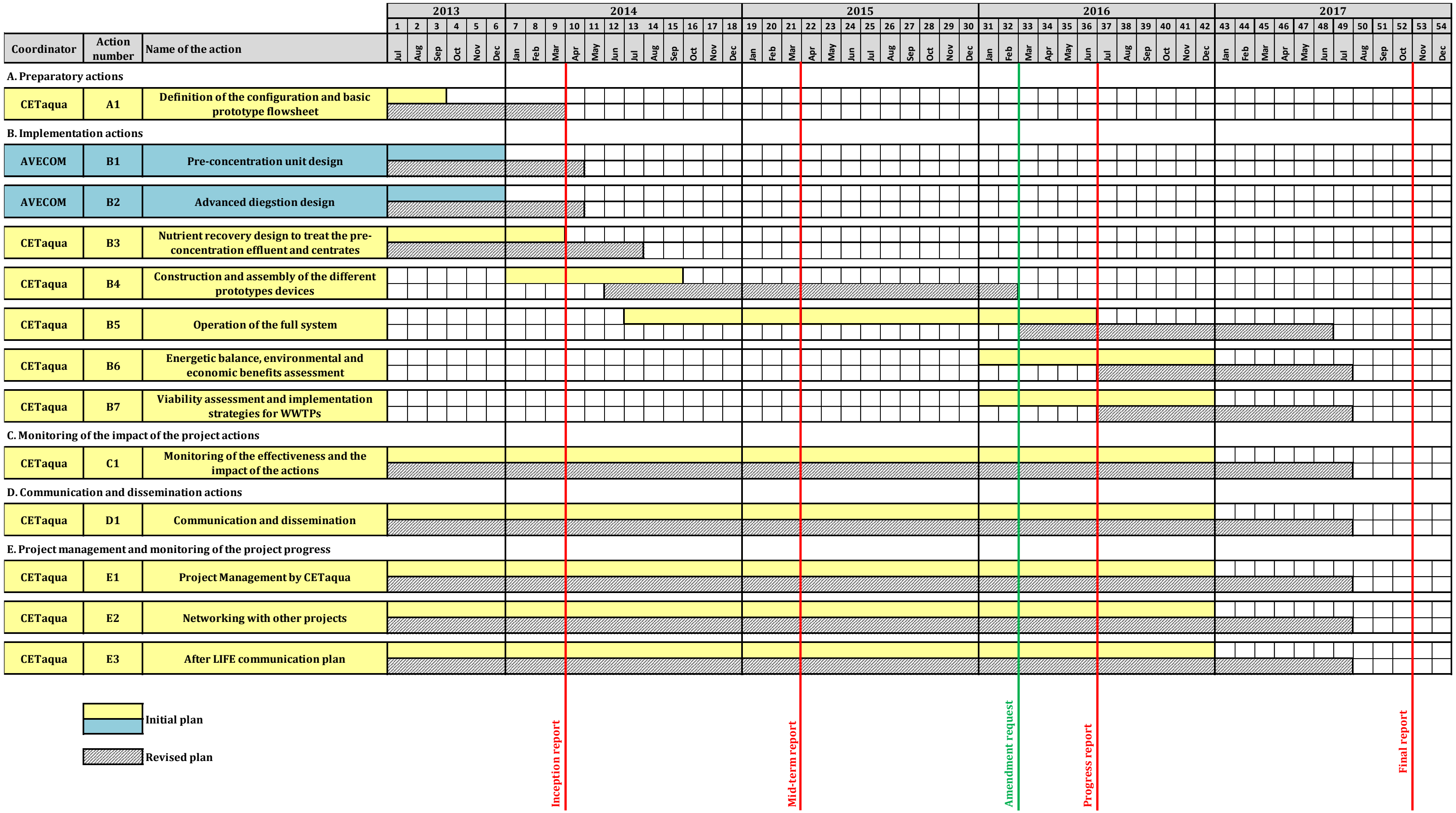
ACTION	RESULT
Get in touch with the designer and wait the technician to come and fix it.	The first time he came, he could not fix all the leakages and he had to come back, turning in more weeks of delay.

Currently this pilot is operating 1 hour per day with the columns of zeolites set in bypass. This way the pilot is only producing ultra-filtered water. This is necessary to maintain the membranes as well as the ammonium sensors wet which avoids its decay.

As it can be seen, most part of the problem lies beneath a wrong design. It has been previously mentioned that pilot design was carried out by Avecom (In case of pilot 1 and 2) and by Hydrowater in case of pilot 3. Nevertheless the problem with the zeolite columns was not Hydrowater's fault because these columns were created by other company. Hydrowater only provides opaque equips. It was thought that it could be helpful to build the zeolite columns in crystal clear material in order to watch what is happening inside. The result was columns built in poly methyl methacrylate (PMMA) with an admissible pressure of 4 bars. When mechanical failure happened it was working at 3 bar. That is why a wrong design is assumed in this case.

All these problems have caused a huge delay in the project and hence that is why there is no reliable performance data. It is expected to start-up again the three pilots during July, 2016. Once this happens the three pilots will be working on their own way for a while before connect them all, just in in order to assure that everything works as it should.

All this problems has led to the forecast of non-having enough time to have results to present to the European commission and hence a proposal of amendment has been presented to the commission to extend the project 7 months. In the next page there is the Gant diagram considering the initial proposal and the revised considering the required extra time for each action to be done by Cetaqua or Avecom.


2013
2014
2015
2016
2017
Coordinator
Action number
Name of the action
Jul Aug Sep Oct Nov Dec
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
A. Preparatory actions
CETaqua A1 Definition of the configuration and basic prototype flowsheet
B. Implementation actions
AVECOM B1 Pre-concentration unit design
AVECOM B2 Advanced diegstion design
CETaqua B3 Nutrient recovery design to treat the pre-concentration effluent and centrates
CETaqua B4 Construction and assembly of the different prototypes devices
CETaqua B5 Operation of the full system
CETaqua B6 Energetic balance, environmental and economic benefits assessment
CETaqua B7 Viability assessment and implementation strategies for WWTPs
C. Monitoring of the impact of the project actions
CETaqua C1 Monitoring of the effectiveness and the impact of the actions
D. Communication and dissemination actions
CETaqua D1 Communication and dissemination
E. Project management and monitoring of the project progress
CETaqua E1 Project Management by CETaqua
CETaqua E2 Networking with other projects
CETaqua E3 After LIFE communication plan
Initial plan
Revised plan
Inception report
Mid-term report
Amendment request
Progress report
Final report

8. Optimization of the Nutrient recovery unit

By the moment I was hired by Cetaqua, the Pre-concentration and digestion units were already installed. Nevertheless the nutrient recovery unit was in construction step. Two months after my arrival I was made responsible for the new pilot. This fact meant that I would be in charge of planning the analysis, make its start-up and everything related to its management.

The pilot arrived the last week of May, 2016. It was constructed by Hidrowater. The contract also includes a start-up period in which a person of this company would come to the pilot to make the start-up process and I would be with him learning how it works.

Two weeks after, the start-up process finished and I started to make some trials employing the base values established by the Hidrowater's technician. After five days of experiments, the pilot ran out of NaOH. This was certainly unexpected because each day the pilot wasn't turned on more than one or two hours, and the NaOH consumption ascended for over 150 L. This fact encouraged me to search for the root cause and attempt to optimize the nutrient recovery unit, starting for the type 1 chemical wash of the ultrafiltration module.

The first step I took was to get in touch with the designer of Hidrowater to gather data. After that he stated the following:

- To achieve a correct cleanse of the membranes, they must be washed with a solution with at least 2.6 % to 6 % in NaOH and from 100 to 500 ppm of NaClO.
- Chemicals are diluted into a stream of 2000l/h which is modifiable in order to attain the concentrations previously mentioned.
- 25 liters of this solution must pass by each membrane (a total of 125 l for the 5 membranes)

Table - 10 displays the star values set by Hidrowater's technician.

Table - 10 Parameters established at the star-up process

Start-up base parameters	
NaOH flow (l/h)	40
NaClO (l/h)	18
Flow of solution (l/h)	2000
Hydraulic wash per chemical wash	5
Chemical dosing time (min)	2

Based on this data I designed a spread sheet in order to verify the conditions given by de pilot's designer.

The results obtained are sown in Table - 11

Table - 11 Results obtained for the initial value

Results obtained	
Concentration of NaOH (%vol)	0.97
Concentration of NaClO (ppm)	626
Volume of solution passed by the membranes (l)	68.6

As it can be seen none of the objective are achieved. Based on these data I decided to program a couple of macros capable of calculating a middle point of operation E.g. 3.5 $\%_{vol}$ of NaOH and 250 ppm of NaClO as follows.

Objective functions:

- $X,NaOH_{vol-UF} = \frac{\dot{m}_{NaOH} \cdot X,NaOH_{vol-Com}}{\dot{m}_{Wash}+\dot{m}_{NaOH}+\dot{m}_{NaClO}} = 3.5\ \%$
- $X,NaClO_{vol-UF} = \frac{\dot{m}_{NaClO} \cdot X,NaClO_{vol-Com} \cdot 10^{6} \cdot Mw_{Cl^-}/Mw_{NaClO}}{\dot{m}_{Wash}+\dot{m}_{NaOH}+\dot{m}_{NaClO}} = 250\ ppm\ of\ Cl^-$

Constrains:

- Pump capacity: $\dot{m}_{NaOH}$<80 l/h
- Pump capacity: $\dot{m}_{NaClO}$<18 l/h
- Flow requirements: $\dot{m}_{Wash}$>1000 l/h in order to assure enough dragging

Where:

- $\dot{m}_i$: is the volumetric flow of each component, l/h.
- $X,NaOH_{vol-UF}$: is the volumetric concentration of NaOH in de solution, $\%_{vol}$.
- $X,NaClO_{vol-UF}$: is the volumetric concentration of NaClO in de solution, ppm
- Mw_i : is the molar weight of each component, g/l.
- $X,i_{vol-Com}$: is the concentration in its commercial package.

Fixed variables:

There are many variables which I have to establish in order to solve this calculations, such as:

- Commercial concentration of chemicals, NaOH is a solution of 50%$_{vol}$ and NaClO is a solution of 5%

Results obtained:

Based on the result of this program I proposed a new point of operation which complies with the concentration objectives inside the membranes. This data (displayed in Table - 12) has been discussed with the designer of the pilot and finally validated.

Table - 12 New point of operation proposed

New point of operation	
NaOH flow (l/h)	80.00
NaClO (l/h)	11.98
Flow of solution (l/h)	1050.88
Hydraulic wash per chemical wash	20
Chemical dosing time (min)	6.56
Results obtained	
Concentration of NaOH (%vol)	3.50
Concentration of NaClO (ppm)	250
Volume of solution passed by the membranes (l)	125.0

As it can be seen, the concentration objectives are now complied at expenses of operating the NaOH pump at its max capacity and reducing the dilution stream close to the constrain of 1000 l/h.

It must be taken into account that the dosing time of chemicals vary from one case to the other due to the necessity of filling each membrane module with 25 l of solution.

Finally I taught that it would be helpful to know the consumption of each chemical and considering its price the weekly cost. Table - 13 and 14 show these data for the two cases already discussed.

Base data	
NaOH consumption (l/h of plant working)	1.07
NaClO consumption (l/h of plant working)	0.48
Weekly cost (€/w)	87.4

Table - 13 Economic results for the proposed point of operation

Data for the new operating point	
NaOH consumption (l/h of plant working)	1.76
NaClO consumption (l/h of plant working)	0.26
Weekly cost (€/w)	122.7

Table - 14 Economic results for the start-up parameters

As it can be seen the proposed point of operation is more expansive than the first case, but this has been approved due to it at least comply with the concentrations inside the membrane modules.

Important

It must be kept in mind that the most important parameter is the number of hydraulic washing steps per type 1 chemical washing step (Hw/ChW1). This parameter determines the frequency of the chemical wash and it cannot be iterated by the program because is an experimental parameter. During a few weeks I have been running tests with the membranes, carrying them to their limit. This means not to make any chemical wash, only hydraulic washes. Therefore the membranes cannot recover their initial state through the time, and hence they collapse by an increase of the pressure. This fact triggers an emergency stop when 3 washes are triggered by pressure (see section 7.4).

Making this experiment I found out that the membranes can work with an Hw/ChW1=slightly higher than 25. In order to protect the membranes and to avoid mechanical stress I decided to operate with an Hw/ChW1=20. This fact justifies the cost of the proposed experiment. In case of not having made this correction and hence operate the plant the new proposal but with Hw/ChW1=5 as it was proposed by Hydrowater, the weekly cost would have raised to **490 €/w**, something intolerable.

Finally I decided to implement an economizer in the program which directly minimizes the weekly cost. Previous to its implementation it was necessary a reflection about the expected values.

It must be taken into account that constrains and the objectives have not changed (concentrations, volumes, pump capacities…), is expectable that the chemical flows fall to its lower limit. This means, the flow that achieves a concentration of NaOH of 2.6% and NaClO of 100 ppm. And this is exactly what happened. Table - 15 and 16 display the correspondent results.

Economized point of operation	
NaOH flow (l/h)	80.00
NaClO (l/h)	6.45
Flow of solution (l/h)	1452.01
Hydraulic wash per chemical wash	20
Chemical dosing time (min)	4.88
Results obtained	
Concentration of NaOH (%vol)	2.60
Concentration of NaClO (ppm)	100
Volume of solution passed through the membranes (l)	125.0

Table - 15 results for the economized point of operation

Data for the economized operating point	
NaOH consumption (l/h of plant working)	1.30
NaClO consumption (l/h of plant working)	0.10
Weekly cost (€/w)	87.2

Table - 16 Costs associated to the economized point of operation

<u>Conclusions</u>

- The starting point of operation was wrong. Although it was economic it cannot be considered as valid.
- Two points of operation has been proposed and validated.
    - One with a higher chemical consumption and hence better performance and higher costs of operation.
    - Second, an optimized one which is the most economic point of operation achievable under the conditions previously mentioned.
- Trials must be carried out in order to know if it is possible operating under the economized conditions along the months.

9. Economic analysis

Although there is no available results yet, it has been elaborated an economic analysis in order to assess the economic viability of the project.

The economic analysis aims to provide data about profitability by assessing the Net Present Value (NPV), the Internal Rate of Return (IRR) and the payback

The analysis has been focused from a product point of view. In this way, there are two possible products to analyze.

- Energy saved derived from the utilization of the HRAS system. Considering both, less energy required by the aeration system and extra energy generated through Anaerobic Digestion.
- The sale of the zeolites as raw material for the ammonium based fertilizers industry.

Regarding these two analysis, 3 scenarios has been proposed and studied, one regarding the sale of zeolites and the other two connected with the energy saving. It will be studied the improvements involving the use of the NECOVERY layout respect to the conventional WWTP plant. Splitting the study between the implementation of the nutrient recovery unit and the HRAS system to produce more energy. These scenarios are explained below.

9.1. Sale of the zeolites as raw material for the ammonium based fertilizers industry (scenario A)

The main objective of this analysis is to calculate the minimum sale prize for the final product. The decision of making this kind of analysis is based on there is no consolidated market for the zeolites. Although in the latest years there has been an increase in the research of the capabilities of this products, there are no specific niche market. It is believed that, in a not so far future, companies will buy ammonium charged zeolites, in order to elute the nitrogen from the zeolites and to prepare ammonium concentrated liquid mixtures.

In order to overcome the lack of availability of data, many assumptions has been made. Furthermore the study is designed in the way that it require the minimum possible data.

They are listed below.

1. The whole production is absorbed by market
2. It is assumed that the results obtained for this scenario, are representative in relation to the required investment.
3. A market study for zeolites is not the point of this study. It is assumed that there exist a market capable of absorbing our production.
4. The scope of the analysis comprehends **20 years**.
5. Taking into account the data gathered from the pilot, the estimated production of zeolites is about **120 kg/h**.
6. The necessary capital investment is about **70,000 €**.
7. The cost of raw zeolites, including transport is **150 €/ton**.
8. The NPV is calculated at a rate of return of **6%.**
9. Employing the recovery unit allows to save **90% of $FeCl_3$** employed by a conventional WWTP. This is due to $FeCl_3$ was employed to remove nutrients, something which has no places within the NECOVERY frame.
10. General expenses comprehend **variable costs** (electricity and chemicals employed per cubic meter of treated water) and **fix costs** (involving chemical analysis which does not depend on the treated flow. E.g. lab analysis.
11. Amortization is lineal.
12. Personnel cost grows at a rate of **1% per year**.
13. Zeolite sales, raw zeolite cost and general expenses grow at a rate of **2% per year**.
14. A common WWTP (medium size) treats an annual volume of raw water **1000 times** higher. This would require one extra operator. In order to make this cost representative, the imputed cost is **0.1 %** of the cost of an operator (**18620 €/y**).
15. The corporation tax is **35%**.
16. The sell prize for zeolites is calculated by iteration (programmed with macros) to find a **NPV=0**.
17. The amortization only takes into account the initial capital investment but not the replacement of equipment during these **20 years**. This is due to I have no aces to the cost and lifetime of each device.

The economic structure of the analysis is divided into income and expenses. Each of which considers the following topics.

<u>Income</u>

1. Sales of zeolite
2. Saving in chemicals

<u>Expenses</u>

1. Raw zeolite cost
2. General expenses. Comprehends the cost of operation (electricity, chemicals…)
3. Amortization
4. Personnel

Taking into account all these data, the profit of this activity has been calculated year by year for the whole period. Table - 18 displays these data for the first year. The calculations for the remaining 19 years are the same and thus are not displayed.

Table - 17 Economic structure of scenario A

	1
Income	**183312.18**
Zeolite sales	179667.18
Saving of chemicals	3645.0
Expenses	**-163535.8**
Raw zeolite cost	-157680.0
General expenses	-2337.2
Amortization	-3500.0
Personnel	-18.6
Benefit	**19776.39**
Taxes	6921.74
BAT	12854.65
Cash flow	16354.65

As it was expected, the NPV is equal to 0, and thus the **IRR=6%**. Furthermore the payback of the investment is about **11.5 years** (Figure - 23).

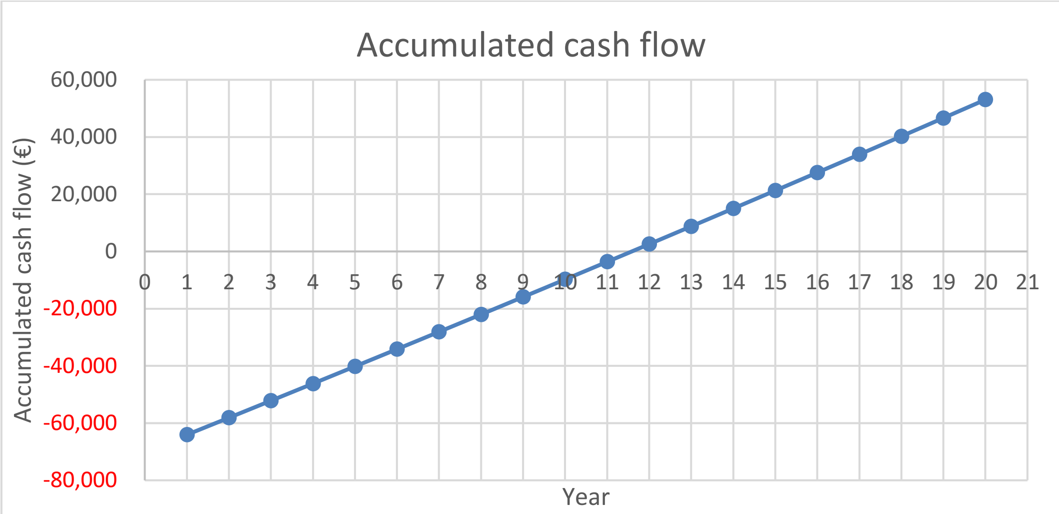


Figure - 23 Payback of scenario A

The result of this study is the required prize for the zeolites, corresponding to **155.4 €/ton**. This value seems to be not so farfetched because it is close to the cost of the raw zeolites.

Taking into account the uncertainty associated to the market of zeolites, it has been decided to make a sensitivity analysis based. This analysis aims to assess the NPV the IRR and the payback for different sale prices. These prices vary from **-5%** to **+10%**. The numeric results are displayed in Table - 18 (base case in blue).

Table - 18 Numeric results of the sensitivity analysis for scenario A

Price (€)	Percentage of variation	NPV (€)	IRR (%)	Payback (years)
147.61	-5%	-71221.4	-	-
149.16	-4%	-56977.1	-10.75%	-
150.72	-3%	-42732.8	-3.71%	-
152.27	-2%	-28488.6	0.32%	19.2
153.82	-1%	-14244.3	3.40%	14.5
155.38	0%	0	6.00%	12.5
156.93	1.00%	14244.3	8.31%	10
163.15	5.00%	71221.4	16.12%	6
170.92	10.00%	142442.8	24.55%	4

In case of selling zeolites at **5%** les price (**147.6 €**), there is no **IRR** due to the dimension of the project is higher than the investment cost. On the other hand there is no payback for the cases where the IRR is negative.

Figure - 24, 25 and 26 display the results of Table - 18

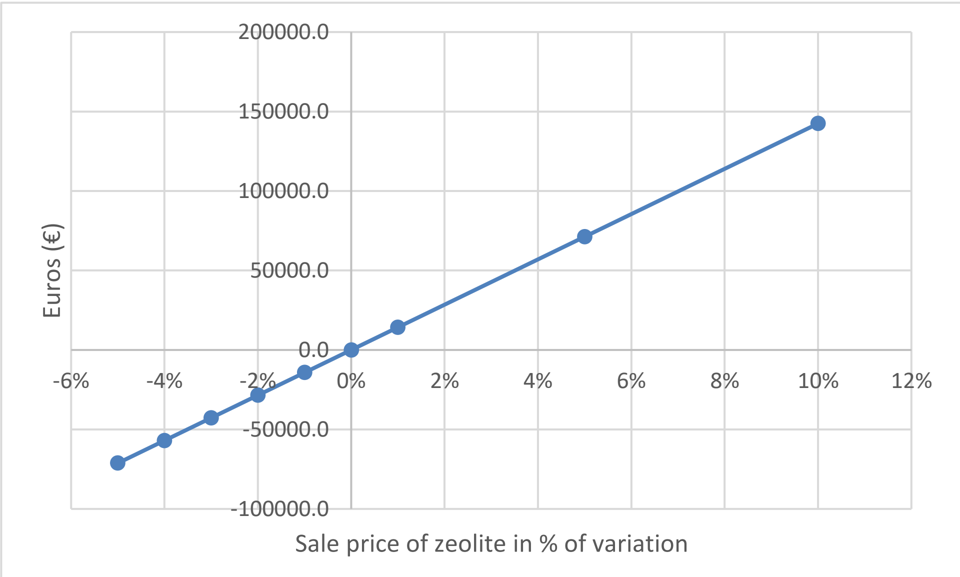


Figure - 24 Sensitivity of the NPV for scenario A

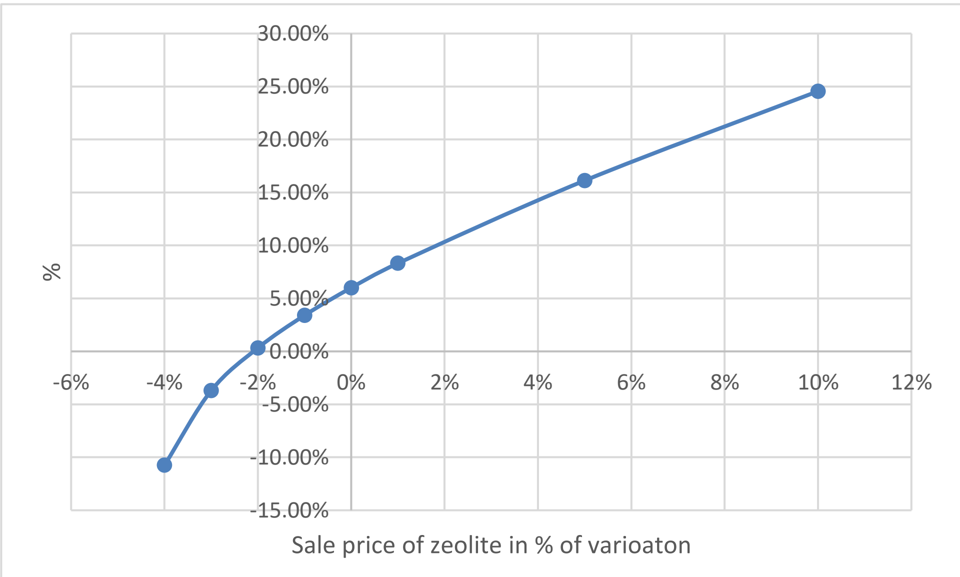


Figure - 25 Sensitivity of IRR for scenario A

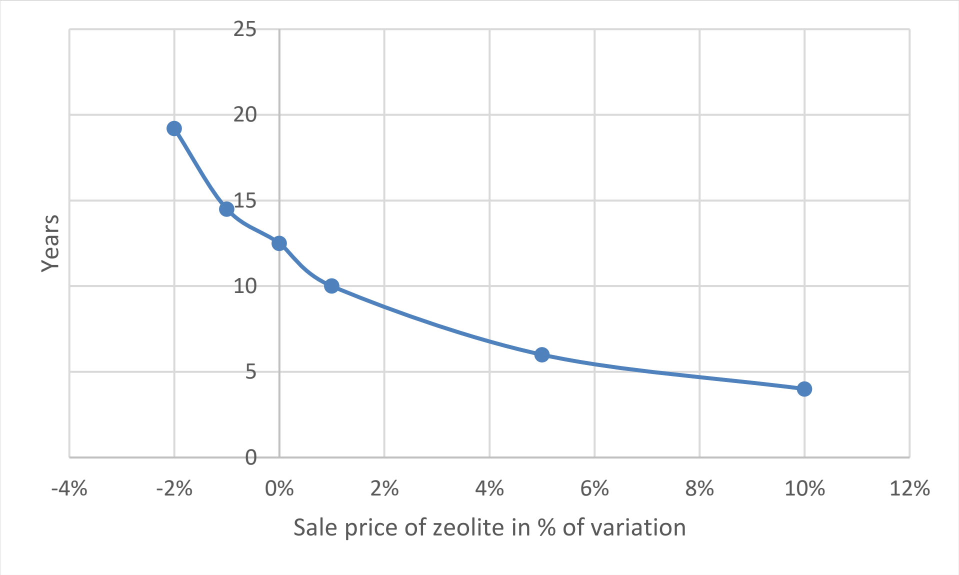


Figure - 26 Sensitivity of Payback for scenario A

It can be seen that the project is very sensitive to the price of the zeolite. The **IRR** vary really fast for little variations of the sale price, comprehending values from **-10%** to **25%**. Moreover the **NPV** vary in a linear way increasing as the sale price rise. On the other hand, payback also shows sensitivity for little variations in the sale price, ranging from **5** to almost **20 years**.

9.2. Energy saved derived from the utilization of the HRAS system (sub-scenarios B and C)

The main objective of this analysis is to study the viability of implementing a HRAS system. In order to do so, two sub-scenarios will be studied.

1. Study of the economic benefits produced by using a HRAS system, against a conventional WWTPS, which has no energy integration (sub-scenario B)
2. Study of the economic benefits produced by using a HRAS system, against a conventional WWTPS, which has energy integration by means of a cogeneration engine (sub-scenario C)

Both scenarios are focused in imputing the economic saving as an income. The main difference between them is the consideration of cogeneration at the WWTP. Therefore, the case A is expected to be more profitable. This study is focused on the possibility of creating a new WWTP but using the HRAS system.

The main assumptions of this model are:

1. The pilot scale data are expected to be representative to full scale ones.
2. Is expected that the construction of a WWTP with this system is slightly higher than a conventional system. It is forecasted a **1%** (of the investment cost of pilots B1 and B2 being equal to **1400€ at pilot scale**) higher due to the main changes are on the operation mode and thus the equipment is almost the same.
3. General expenses grow at a rate of **2%**.
4. Employing a HRAS system **does not require extra personnel and does not generate extra process expenses**.
5. The cost of electricity is **0.12 €/kwh**
6. Amortization is lineal.
7. The corporation tax is **35%**.
8. There would be no extra expensed due to this system.
9. HRAS + AD system allows to reach an energy self-sufficiency of 60%.
10. For scenario A, it is considered that a conventional WWTP has no self-sufficiency.
11. For scenario B, it is considered that a conventional WWTP has over 50% of energy self-sufficiency.

The economic structure of the analysis is divided into income and expenses. Each of which considers the following topics.

Income

1. Energy saving

Expenses

1. Raw zeolite cost
2. General expenses. Comprehends the cost of operation (electricity, chemicals…)
3. Amortization

Taking into account all these data, the profit of this activity has been calculated year by year for the whole period. Table - 19 and 20 display these data for the first year. The calculations for the remaining 19 years are the same and thus are not displayed.

Table - 19 Operating profit for the first year in scenario B

	1
Income	**423.04**
Energy saving	**423.04**
Expenses	**-70.0**
General expenses	0.0
Amortization	-70.0
Personnel	0.0
Profit	**353.04**
Taxes	123.56
BAT	229.48
Cash Flow	299.48

Table - 20 Operating profit for the first year in scenario C

	1
Income	**630.31**
Energy saving	**630.31**
Expenses	**-70.0**
General expenses	0.0
Amortization	-70.0
Personnel	0.0
Profit	**560.31**
Taxes	196.11
BAT	364.20
Cash Flow	434.20

Taking into account these data during 20 years, it has been calculated the NPV, the IRR and the payback. These data are displayed below (Table - 21).

Table - 21 Comparison between scenarios B and C

Scenario B (50% energy self-sufficiency)		Scenario C (0% energy self-sufficiency)	
NPV	2034.96 €	NPV	3580.22 €
IRR	20.91%	IRR	30.87%
Payback	5 years	Payback	4 years

Figure - 27 and 28 display the evolution of the accumulated cash flow for each scenario in order to assess the payback.

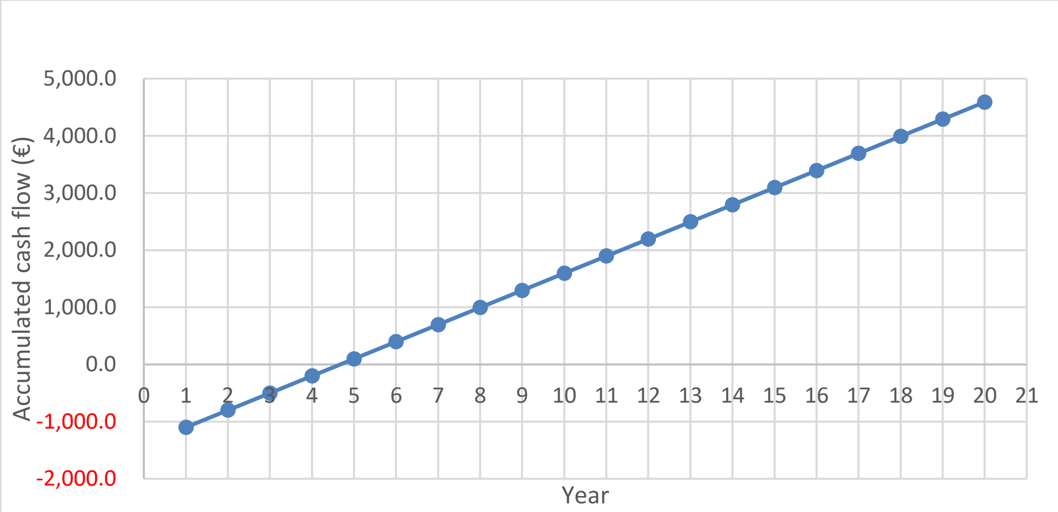


Figure - 27 Accumulated cash flow for scenario B

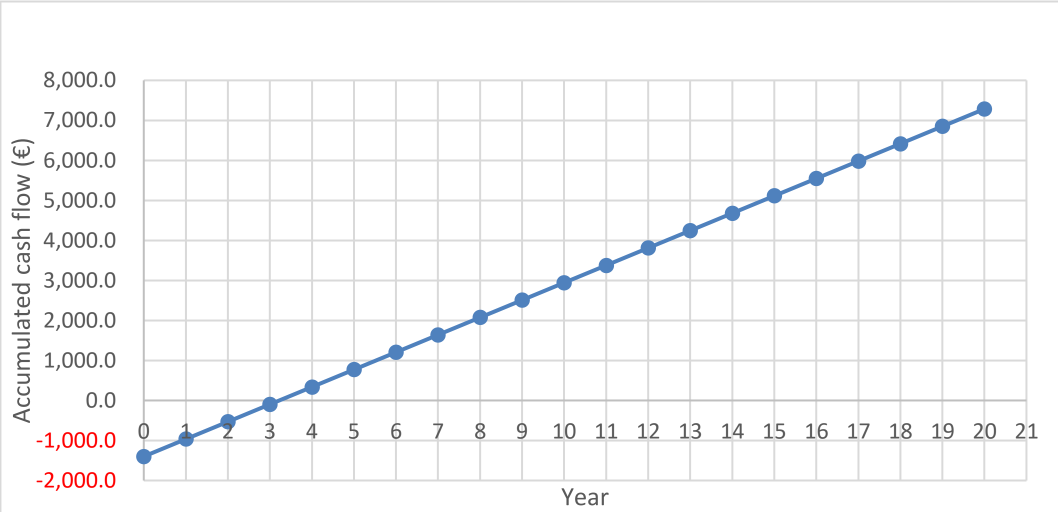


Figure - 28 Accumulated cash flow for scenario C

As it was expected, scenario C is more profitable than the scenario B. Nevertheless it must be taken into account that this study highly depends on the 2nd hypothesis stablished "*Is expected that the construction of a WWTP with this system is slightly higher than a conventional system. It is forecasted a **1%** (of the investment cost of pilots B1 and B2 being equal to **1400€ at pilot scale**) higher due to the main changes are on the operation mode and thus the equipment is almost the same*". An inversion cost slightly higher would make this this investment unprofitable. In the same way, the construction of HRAS system could even be cheaper t and thus having a positive value at time zero, which would make the investment automatically profitable. In order to asses this variability, a sensitivity analysis has been made. This analysis vary the investment cost of the HRAS system from +5% to -10 % of investment cost; evaluating the NPV, the IRR and the payback for both scenarios.

Table - 22 and 23 display the numeric results for the scenario B and C (base case in blue)

Table - 22 Numeric results for scenario B (50% energy self-sufficiency)

Investment cost	Percentage of investment cost	NPV	IRR	Payback (years)
-7000	5%	-2440.99	1.24%	18
-5600	4%	-1322.00	2.90%	15
-4200	3%	-203.02	5.40%	12
-2800	2%	915.97	9.78%	9
-1400	1%	2034.96	20.91%	5
0	0%	3153.94	-	0
1400	-1.0%	4272.93	-	0
7000	-5.0%	8748.88	-	0
14000	-10.0%	14343.81	-	0

Table - 23 Numeric results for scenario C (no energy self-sufficiency)

Investment cost	Percentage of investment cost	NPV	IRR	Payback (years)
-7000	5%	-895.73	4.37%	13
-5600	4%	223.26	6.49%	11
-4200	3%	1342.25	9.70%	9
-2800	2%	2461.24	15.46%	7
-1400	1%	3580.22	30.87%	4.0
0	0%	4699.21	-	0
1400	-1.0%	5818.20	-	0
7000	-5.0%	10294.14	-	0
14000	-10.0%	15889.08	-	0

In case of achieving to have a lack of necessity of invest capital, there would be no IRR due to the project would automatically be profitable; it is the same case for payback.

Figure - 29, 30 and 31 display the comparison of NPV, IRR and payback respectively for cases B and C.

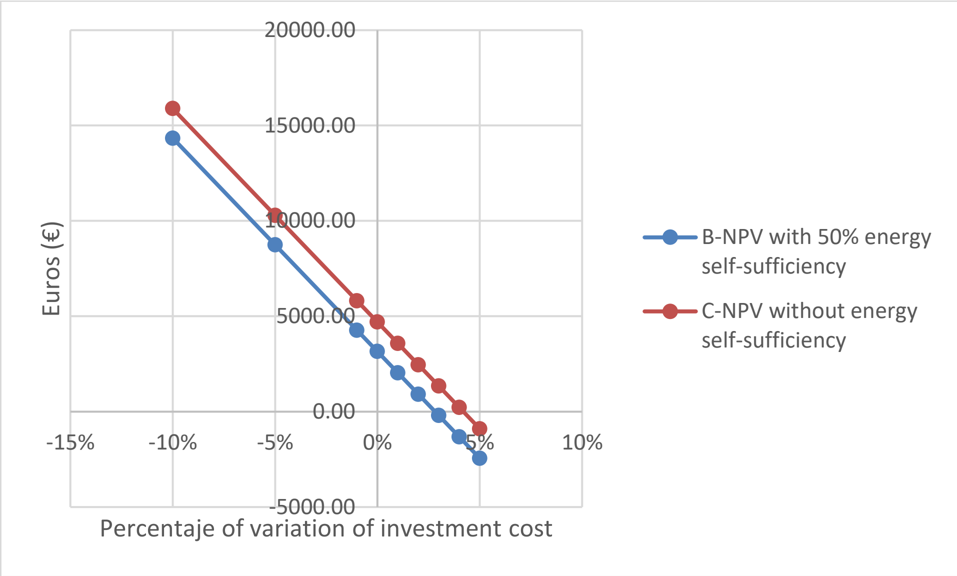


Figure - 29 Comparison of NPV for cases B and C

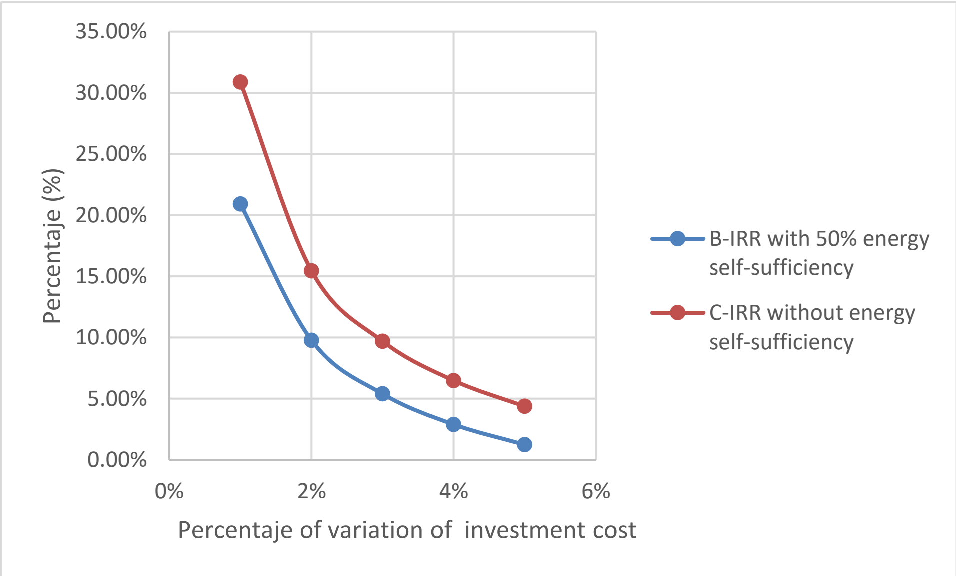


Figure - 30 Comparison of IRR for cases B and C

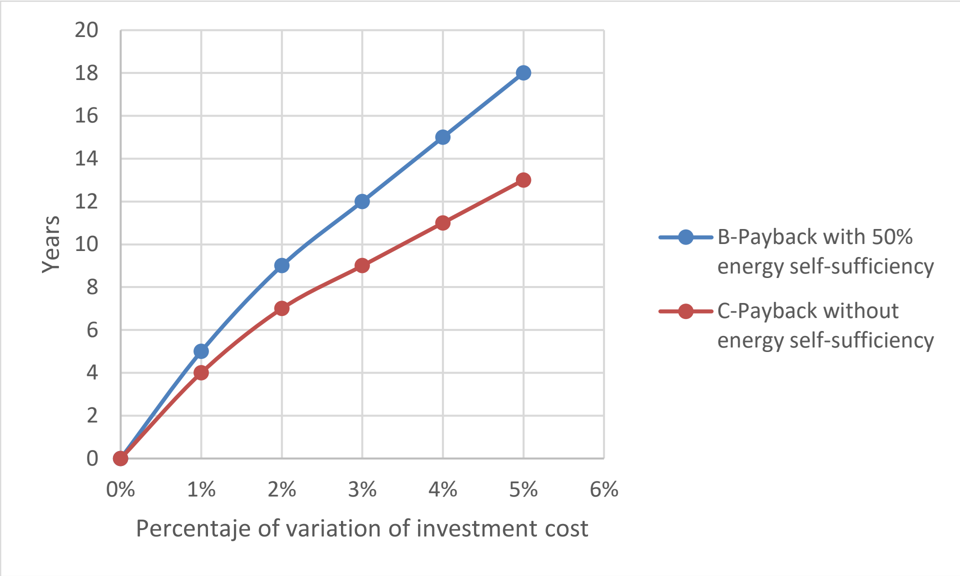


Figure - 31 Comparison of payback for cases B and C

As it was expected, case B (50% self-sufficiency energy) is more restrictive than case C (no energy self-sufficiency) and hence the parameters studied are in accordance. The NPV still grows in a linear way being higher for case C. The IRR can vary from approximately **20%** to **30%** for scenarios B and C in the base case. In the worst case the difference of IRR is reduced to **1.24%** to **4.37%**. Furthermore the payback presents a difference of **5 years** between case B and C for an increase in the investment cost of just 5 %.

10. Conclusions

The start-up of a pilot plant is a long and complex process. It is due to the process of start-up comes with lots of technical issues which must be solved. Most part of these problems are electrical (electric shut downs, over voltage burned devices…) or mechanical (pumps running in void, corrosion of equipment, mechanical failure…); all of them must be solved by electricians, mechanicals or even to send the equipment to the nearest workshop. Sometimes they must be sent to the provider. Since the NECOVERY is a European project with international partners and providers and hence sending them each device may incur a delay from weeks to months.

Despite these inconvenient, the pilots are starting to run now. And it is expected to present some results in coming weeks.

From the environmental point of view this is a huge step regarding the current status of the WWTPS. Conventional WWTPS are energy consuming sites which does not recover any nutrient, while the proposed layout proposed within the NECOVERY frame presents the WWTPS as an evolution capable of not wasting energy and recovering great amounts of non-renewable nutrients.

From the economic point of view, there are high uncertainty in zeolites market. It is probably that in a not so far future, the legislation becomes more restrictive, compelling companies to recover nutrients. When this happens, a market for zeolites will appear. Taking into account that the estimated sale price for the zeolite is close to the cost of the raw materials, it is not so farfetched to think that its sale will be possible. On the other hand the energy saving must be thoroughly revised, because the cost of investment will definitely decide whether it is viable or not. As it has been demonstrated in section 9 little variations in the sale price of zeolite or in the investment cost of the new system proposed (HRAS) has a huge impact in the profit index (NPV, IRR and payback). Moreover it is clear that if it's possible to construct a HRAS system with a low investment cost, it would be highly profitable, achieving IRRs relatively high (**20%** for case B and **30%** for case C with a **1%** increase in the investment cost).

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