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TECHNOLOGICAL AND NATURE-BASED SOLUTIONS TO CLOSE WATER LOOPS:

REPLICABILITY STUDIES WITHIN HORIZON2020 HYDROUSA

Relatore:

Prof. Ing. Francesco Fatone

Laureando:

Nicola Lancioni

Correlatori:

Prof. Ing. Anna Laura Eusebi

Ph.D. Ing. Martina Santinelli

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Summary

ABSTRACT

This thesis is focused on cutting-edge solutions which sustainably address water-related challenges across the Mediterranean region. Water pollution, water scarcity and flooding risk have become concrete issues along coastal areas in recent years, mainly due to the climate change and population increases.

On one hand, nature-based solutions and green infrastructures have been widely proposed to tackle water-related issues in rural and peri-rural areas. HYDROUSA project has developed six regenerative nature-based solutions for water management, to close water loops and to implement circular business models. This thesis would like to deliver a methodology to assess the feasibility of the HYDROUSA solutions in Mediterranean sites and all around the world. Therefore, in the first chapter of this thesis the values of nature-based solutions and of the HYDROUSA solutions are highlighted. In the second chapter, the methodology to evaluate the feasibility of HYDRO solutions in the replication sites is discussed. In the third chapter, the feasibility of HYDROUSA solutions in the Italian replication site is assessed.

On the other hand, the role of the desalination plants as drinking water plants has considerably grown in most Mediterranean areas in order to address water scarcity. Such that the rejected brine from the plants has become an environmental problem. FIT4REUSE project aims to develop sustainable and zero liquid discharge (ZLD) processes for brine treatment. The reported research in this thesis is focused on the assessment of evaporation and chemical precipitation technologies through laboratory and pilot tests, within the FIT4REUSE project. Hence, in the first chapter the most common processes for brine treatment, based on the ZLD approach, are studied. In the second chapter, the materials and methods used for laboratory and pilot tests are shown. In the third chapter, the results and the findings of the trials are discussed.

INTRODUCTION

Water management in the Mediterranean area is currently fragmented and there are several barriers, which need to be overcome in order to close water loops and contribute towards the environmental and economic development of these regions. Specifically, Mediterranean regions face significant challenges in terms of water management and preservation. Water resources are becoming even more scarce, while the high touristic activities during the summer months stress the limited water reserves. To overcome these challenges, a HORIZON 2020 project, HYDROUSA was launched in July 2018 to develop a water resilient economy, mitigate climate change and reform the agro-food system.

HYDROUSA project proposed six nature-based low energy footprint solutions for different water resources management (e.g. rainwater, groundwater, seawater, wastewater) in order to address the water-related challenges across the Mediterranean area.

Whereas the transferability of the HYDROUSA solutions (also called HYDROs) is going to be assessed in 25 cases in Mediterranean coastal areas and islands and at several water-stressed rural or peri-urban non-Mediterranean areas in Europe and even beyond Europe. This thesis would like to provide the proper methodology to carry out replicability studies of the HYDROs in the replicability cases. A multi-criteria decision analysis based (MDCA) method has been adopted for the evaluation of HYDRO solutions replicability. The overall feasibility of the HYDROs in a specific replication site has been divided into social, legislative, technical and economic feasibility. Such aspects might either support or hinder the possible realization of the HYDROUSA solutions in different sites. Finally, the replicability study of the Italian case has been carried out by using the proposed methodology and reported as case example.

Moreover, the use of seawater as drinking water source has recently boosted all around the Mediterranean region, especially along coastal areas, in order to face water scarcity. The most common desalination plants exploit membrane-based technologies, which discharge a considerable amount of brine into the environment. FIT4REUSE, HORIZON 2020 project, aims to provide innovative and sustainable technologies for brine treatment, enabling a wider use of desalination water in agriculture. This thesis focuses on evaluating sustainable processes for brine treatment, based on a zero liquid discharge approach. Evaporation, chemical precipitation and forward osmosis (FO) coupled with reverse osmosis (RO) have been implemented in a pilot plant for brine treatment. Tests have been carried out in laboratory and in pilot plant in order to determine the best set-up of the evaporation and chemical precipitation, before the FO/RO membrane. Water recovery, brine volume minimization, selective recovery of Mg and Ca, avoidance of membrane fouling and scaling have been taken into account to assess evaporation and chemical precipitation technologies.

1. FRAMEWORK AND STATE OF ART

1.1. Sustainable and nature-based solutions to close water loops

Nowadays, both rural and urban context are dramatically threatened by multiple environmental challenges such as flood risks, water pollution and water scarcity, which are going to result in social and economic inequality in the foreseeable future. According to the World Water Development Report (WWRD 2018) 2018 "Nature-based solutions for water" of UNESCO, the global water use has increased by six times over the past 100 years and continues to grow steadily at a rate of about 1% per year due to population growth, economic development and changing consumption patterns. Agriculture accounts for about 70% of global water consumption, while industry and domestic use represent respectively the 20% and 10%. Furthermore, the people living in severely water scarce areas is going to increase from 1.9 billion to 3.2 billion by 2050; and at the same time, the global water cycles is going to intensify due to global warming with wetter regions generally becoming wetter and drier regions becoming even drier. The trends in water availability are coupled with changes in flood and drought risks. The people at risk from floods is going to rise from 1.2 billion to 1.6 billion in 2050 with a growth of over 340% of the economic value of assets at risk. While the population currently affected by desertification is around 1.8 billion people. Regarding the water quality, globally an estimated 80% of discharged wastewater is released to the environment without any proper treatment. The deterioration of water quality is expected to boost over the next decades resulting in threats to human health, environment and sustainable development, especially in developing countries.

Natural-based solutions (NBS) aims to tackle these environmental, social and economic water-related issues in sustainable ways. They are cutting-edge technologies and actions which try to replicate ecosystems and enhance natural processes in order to provide water treatment, water supply and flooding management. If they are adapted to local conditions, they might be energy and resource-efficient, and resilient to change. The applications of NBS are also called "green infrastructures", which refers, for water loops, to natural systems providing water resource management benefits equivalent to conventional water infrastructures (WWRD 2018). These innovative solutions may overcome water-related stresses and achieve water security, by managing utterly water availability, accessibility and quality (WWRD 2019). In addition, green infrastructures have many financial advantages due to their low capital expenditure (CAPEX) and operating expenditure (OPEX). NBS are developed and implemented by taking into account the pillars of the sustainable development: social, environmental and economical dimensions (C. Nesshöver et al., 2016). They are cost-effective solutions than more traditional approaches, thus, their applications have multiple co-benefits for human health, economy, society and environment.

Moreover, there is a clear interconnection between NBS and the circular economy; where waste and emissions are minimized by closing the energy, material and water loops. Although the natural water cycle is already a circular system, the obsolete linear economic system of "make-use-dispose" has hindered the introduction of a sustainable water management in many realities for many years. Applications of NBS might boost the circular economy implementation, by closing water loops and addressing issues of water availability, water quality, ecosystem degradation and managing water-related risks (WWRD 2018). However, the concept of "closing water loop" and its relationship with NBS is still not well addresses within the research community. Currently publications focus mainly on technical performance of green infrastructures and their economic assessment (C.E. Nika et al., 2020). The water circularity aspects with its pros for local communities are not taken into account, thereby the NBS advantages are still underestimated.

However, in recent times, there has been an increasing attention to the natural-based solutions and their potentialities by policy makers. The 2030 Agenda for Sustainable Development, with its Sustainable Development Goals (SDGs), has adopted the Target 6.6 "By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes" to support the achievement of SDG 6 "Ensure availability and sustainable management of water and sanitation for all", in recognition of the role of ecosystems in the achievement of the targets. In 2015, the European Commission started developing an EU research and innovation policy on NBS, within the "Horizon 2020 Framework Program", in order to achieve the position of world leader in this field (Final Report of the Horizon 2020 Expert Group on 'Nature-Based Solutions and Re-Naturing Cities'). Moreover, on 11 December 2019, the European Commission presented the Green Deal, aiming to become "the world's first climate-neutral continent by 2050" by implementing a circular and sustainable economy. The involved areas are clean energy; sustainable industry; building and renovation; sustainable mobility; biodiversity; from fark to fork; eliminating pollution. The NBS might supporting to deliver the European Green Deal, since they may enhance the transition to a green economy by closing the water loops (C.E. Nika et al., 2020).

In 2017, the HYDROUSA project has been funding from "Horizon 2020 Research and Innovation Programme" and it involves 27 highly competent organisations: the National Technical University of Athens (Greek), Brunel University London (UK), Polytechnic University of Marche (Italy), Heliopolis University (Egypt), Aegean University (Greek), Catalan Institute for Water Research

(Spain), Water Europe platform, SEMIDE, and other public stakeholders as well as private companies.

The HYDROUSA main goal is the development of a new circular business model, suitable for Mediterranean and other water-scarce regions in Europe and worldwide. Thus, HYDROUSA aims to provide innovative, regenerative and circular solutions for:

- Nature-based water management of Mediterranean coastal areas, closing water loops
- Nutrient management, boosting the agricultural and energy profile
- Local economies, based on circular value chains

HYDROUSA rejects the current water and wastewater management practices and, provides innovative nature-based solutions for decentralized water scarce areas, which will close water loops and at the same time will boost local agriculture systems and energy savings. Furthermore, it will change the human perspectives by valorising non-conventional water and nutrient resources, which are currently not being exploited. Despite traditional way of managing water in broken loops, HYDROUSA's closed loops sustainably manage water service while creating products and ecosystem services favourable to economy, the environment, and the local community.

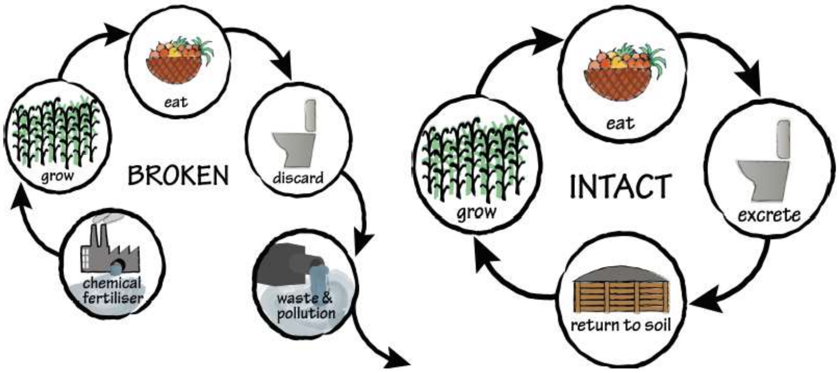


Figure 1.1: Comparison between traditional broken water loop and HYDROUSA intact water loop

HYDROUSA aspires to demonstrate at large scale the feasibility and sustainability of NBS and technologies for low-cost water treatment, recover of fresh water, nutrients and energy from wastewater, salt and fresh water from sea water, and freshwater from atmospheric water vapour. Furthermore, water conservation solutions such as aquifer storage and sustainable agricultural practices including fertigation are applied in the water loops (www.hydrousa.org). HYDROUSA promotes the concept of decentralise on-site water, materials and energy conservation, treatment and reuse as the figure 1.1 reports.

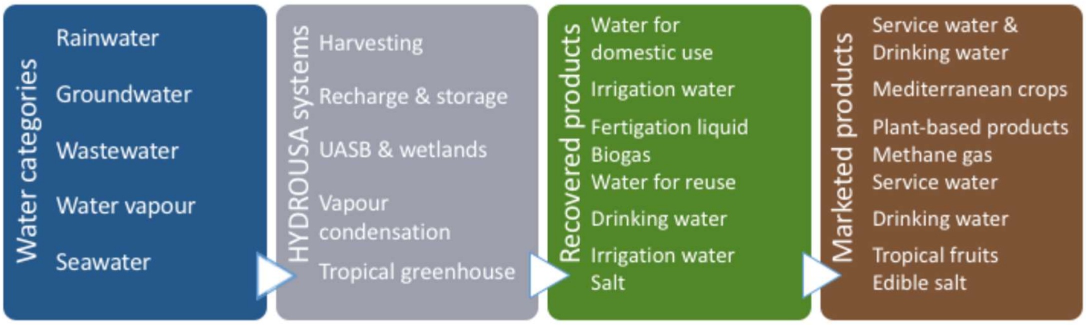


Figure 1.2: HYDROUSA concepts

The HYDROUSA concepts have been become a reality by realizing six demonstration sites at full scale in three Mediterranean islands (Lesvos, Mykonos, and Tinos). These demo scale solutions are called HYDRO 1-6.

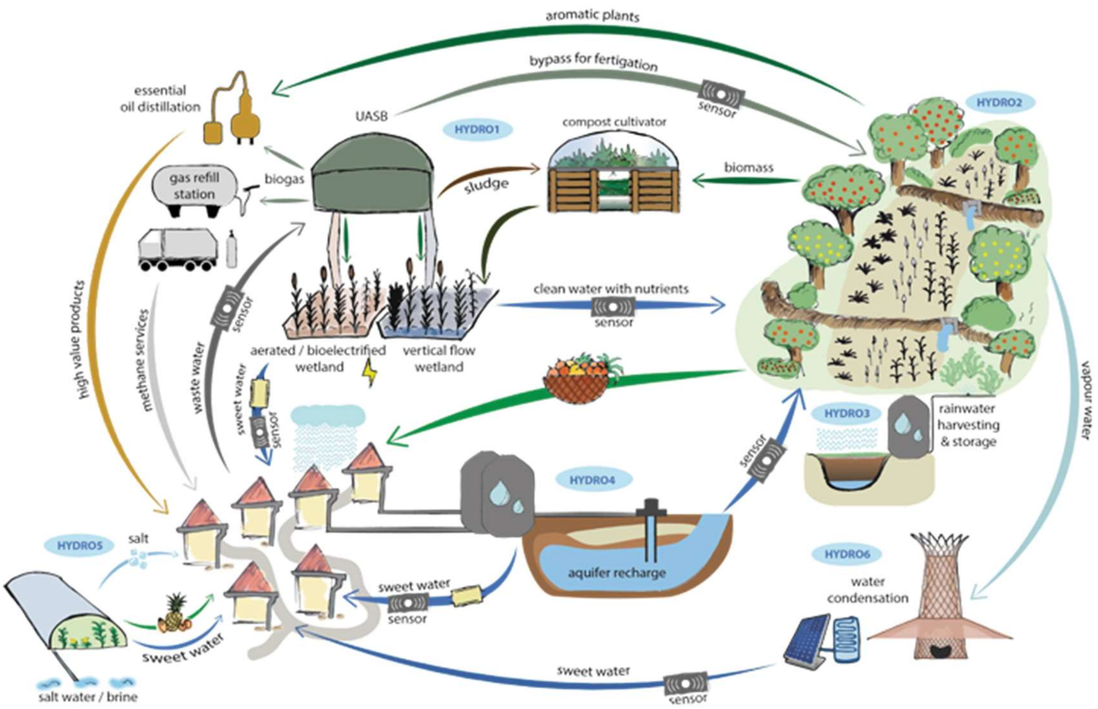


Figure 1.3: Scheme of HYDRO 1-6

HYDRO 1 consists of a sewage treatment system applied in decentralised areas with high seasonal loads in order to recover energy and recycle water and nutrients. The influent domestic wastewater is treated by an upflow anaerobic sludge blanket (UASB) reactor, a series of saturated and unsaturated constructed wetlands, filtration and disinfection. The effluent is suitable to be reused for irrigation purposes. The anaerobic process produces biogas which is either used in a CHP generator or upgraded to methane. The small amount of produced sludge from UASB reactor is reused as fertilizer in agriculture, after composting treatment.

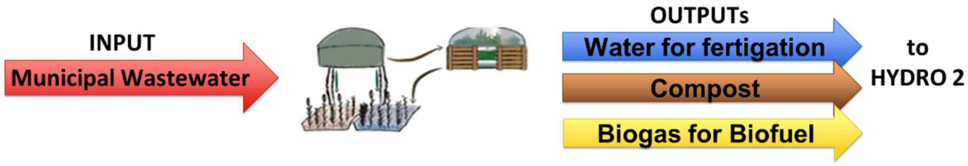


Figure 1.4: Simplified scheme of HYDRO 1

HYDRO 2 involves a cultivate agroforestry system which reuses the nutrient-rich water and compost recovered from HYDRO 1. The agroforestry system is divided in three main groups: (1) forestry trees for fruit and timber production, (2) orchards/bushes; (3) herbs and annual crops. It combines traditional irrigation methods with precision irrigation by adopting drip and channel irrigation.

Figure 1.5: Simplified scheme of HYDRO 2

HYDRO 3 consists of a low-cost and innovative rainwater harvesting system for irrigation in remote areas, where house roofs are not available. A shallow, subsurface water collection system is designed to collect rainwater which is stored in tanks and subsequently reused in agriculture.

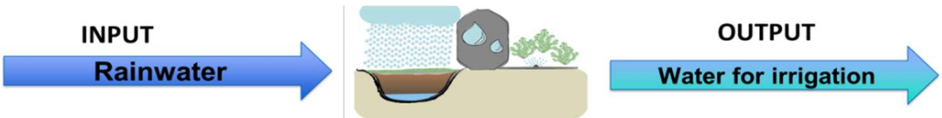


Figure 1.6: Simplified scheme of HYDRO 3

HYDRO 4 is a rainwater harvesting and treatment system for the supply of irrigation water, drinking water and for aquifer recharge. Rainwater is collected by storage tanks on residence roofs: a part of the water is used for domestic non-potable uses and, the remaining part is treated by slow sand filtration in order to produced drinking water. Besides surface runoff is collected using a novel bioswale system, filtered and stored into the aquifer to be used as irrigation water.

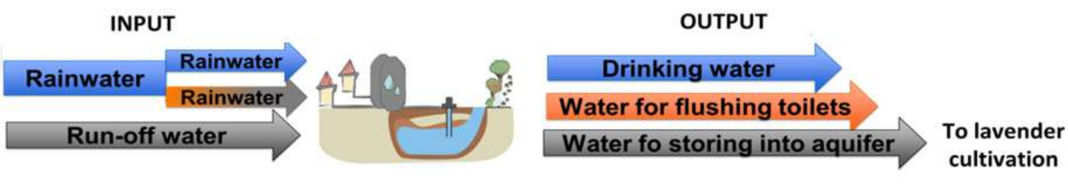


Figure 1.7: Simplified scheme of HYDRO 4

HYDRO 5 consists of a mangrove still desalination system coupled with a saltwater evaporation greenhouse. Seawater and brine (e.g. from the desalination plants) are treated by the Mangrove still process which is composed of a series of interconnected desalination panels where evaporation and condensation occur. The system produces distilled water, which is used in a cultivation greenhouse, and brine that is pumped to the salt factory, where salt is obtained by means of evaporation and ventilation of the brine. In addition, the seawater is also treated by a saltwater evaporation greenhouse, where evaporation and transpiration produce moisture which is subsequently condensed into freshwater.

Figure 1.8: Simplified scheme of HYDRO 5

HYDRO 6 is an eco-tourist resort where water, energy and food self-reliance are demonstrated. It implements rainwater and vapour water recovery systems for drinking purposes as well as wastewater reclamation system for irrigation purposes. Therefore, the grey wastewater from the resort is treated by means of settling tank, reed beds and UV disinfection in order to produce reclaimed water for irrigation. While the main solid fraction of the wastewater is used for the production of compost by means of a composting toilet system. The resort is completely energy autonomous and all activities are powered by PV panels.

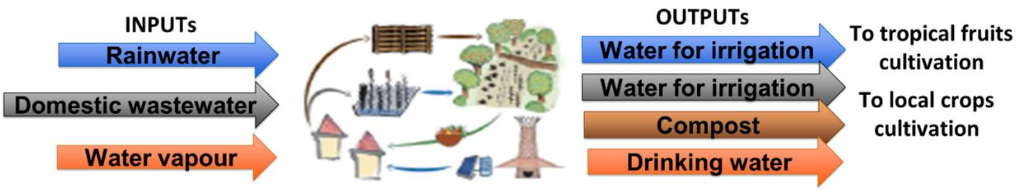


Figure 1.9: Simplified scheme of HYDRO 6

The HYDROUSA solutions are designed in order to close the water loops in a competitive way especially in small and decentralized areas, where water-related services are often disregarded, and investments opportunities are quite scarce. Thus, they may support to deliver a sustainable and circular economy in small contexts, without leaving individual or regions behind and ensuring a fair and inclusive transition. In addition, HYDROUSA solutions will contribute to achieve the SDG 6 “Ensure availability and sustainable management of water and sanitation for all” and “SDG 12 “Ensure sustainable consumption and production patterns” of UN Agenda 2030 in rural and remote areas. Based on the sustainable development pillars, the HYDROs values have been studied taking into account the social, environmental and economic aspects.

Table 1.1: Social, environmental, economic values of HYDRO solutions

HYDROs Values			
HYDRO solution	**Social Value**	**Environmental value**	**Economic value**
HYDRO 1	- Create/maintain jobs - Community awareness & engagement /education - Help societies be water autonomous	- Reduced pollution of groundwater, fresh and sea water - Reduce CO_2 footprint - Increase biodiversity & green areas - Improve soil quality & productivity	- Provide decentralised wastewater treatment system through low-cost, low-energy and green installation services - Recover water, nutrients, energy (biogas) - Generate compost/fertilizers
HYDRO 2	- Create/maintain jobs - Community awareness & engagement /education - Help societies be water autonomous	- Reduced pollution of groundwater, fresh and sea water - Reduce CO_2 footprint - Increase biodiversity & green areas - Improve soil quality & productivity - Improvement of the microclimate	- Produce crops and herbs
HYDRO 3	- Create/maintain jobs: farmers - Community awareness & engagement /education -Help citizens in villages and remote areas be autonomous -Autonomous irrigation system (less irrigation workload)	- Reduce freshwater abstraction - Increase biodiversity & green areas - Reduce CO_2 footprint	- High value cultivated and processed products (e.g. Essential oils) - Money savings thanks to harvesting water and farming improvement
HYDRO 4	- Create/maintain jobs: farmers - Community awareness & engagement /education -Help citizens in villages and remote areas be autonomous - Autonomous irrigation system (less irrigation workload)	- Reduce freshwater abstraction - Increase biodiversity & green areas - Retain water level in the aquifer	- High value cultivated and processed products (e.g. Essential oils, crops) - Money savings thanks to harvesting water and farming improvement
HYDRO 5	- Create/maintain jobs: farmers - Community awareness & engagement /education - Help societies be water autonomous	- Reduce freshwater abstraction - Reduce CO2 footprint - Increase biodiversity & green areas - Halt soil degradation and salt intrusion	- Provide water through desalination, evaporation and condensation - Recover (Edible) salts - Provide topical fruits with high value.

			-Increase yields and improve farming activities - Save energy (passive system)
HYDRO 6	- Create/maintain jobs: farmers, hospitality business - Community awareness & engagement /education - Promote sustainable tourism - Help tourist facilities be autonomous	- Reduce freshwater abstraction - Reduce CO_2 footprint - Increase biodiversity & green areas - Halt soil degradation and salt intrusion	- Recover water and nutrients - Cultivate crops - Generate compost/fertilizers - Offer an agro-tourism structure

Despite the advantages, different constrains for the replicability of HYDROUSA solutions have been detected, they are distinguished in three main categories: (i) socio-economic, (ii) legislative and (iii) technical. The social-cultural and economic constrains include: social acceptance of water re-use in irrigation and domestic uses, lack of awareness on the added value of innovative nature-based solutions and shared collaboration on the community level, cost and availability of financial incentives, and scattered communities without sewerage systems. Also, the legislative aspects should not be underestimated. The national/local legislative framework may hinder either the realization of nature-based solutions or the reuse of HYDRO by-products. While technical constrains of the HYDROs are mainly related to the climate, size/capacity and space since these solutions have been designed developed for small community (< 2000 P.E.) across the Mediterranean region (warm climate).

The HYDRO 1-6 replicability is going to be assessed in other Mediterranean and water stressed places: in 25 transferability sites along coastal areas and islands in Italy, Spain, Cyprus, France, Egypt, Croatia, Israel, Turkey, Palestine, Lebanon, Morocco and Tunisia and at least in 6 water-stressed rural or urban areas from Bulgaria, China, United Arab Emirates, Australia, Mexico, Chile, Malaysia and Argentina. This thesis would like to provide a methodology in order to draw up replicability studies of the HYDROUSA solutions in the sub-mentioned transferability sites.

Therefore, a multi-criteria decision analysis (MCDA) based method has been chosen to assess the replicability of the HYDRO 1-6 in the previous mentioned transferability sites. It is a useful tool for the assessment of multiple criteria affecting the objectives/targets of a project, e.g. the realization of a HYDRO in a site. It involves the assignation of a score to each criterion for the evaluation of specific aspects, which may support or hinder the achievement of the objectives.

Furthermore, a weight is assigned to each criterion based on the importance of the aspects for the achievement of the objectives (Department for Communities and Local Government, UK Government, 2009). Hence, firstly, objectives of a project are identified through the analysis of the context; secondly, criteria affecting the realization of the project based on the objectives are detected. In addition, the criteria may be subdivided into sub-criteria for a more detailed and accurate analysis of the project aspects (Department for Communities and Local Government, UK Government, 2009). Subsequently a scoring scale for the assignation of the scores and the weights of each criterion/sub-criterion are chosen. The key idea is to define scales representing the measurement system as well as to weight the scales for their relative importance and finally to calculate weighted averages across the scales (Department for Communities and Local Government, UK Government, 2009).

In the context of the replicability studies of the HYDROUSA solutions, a literature review has been carried out in order to identify the most common objectives, criteria/sub-criteria, scoring scales and relative weights for water-related projects. The main findings are summarized in the table 1.2.

Table 1.2: Literature review MCDA

REFERENCE			Department of Computer Science, University of Toronto		
OBJECTIVES	**CRITERIA**	**SUB-CRITERIA**	**DESCRIPTION**	**SCORING SCALE**	**WEIGHT**
Evaluation technical feasibility	Technology	-	An assessment of the maturity, availability (or ability to acquire), and desirability of the computer technology needed to support this candidate.	0 -100	30%
	Expertise	-	An assessment to the technical expertise needed to develop, operate, and maintain the candidate system	0 - 100	
Evaluation operational feasibility	Functionality	-	Describes to what degree the alternative would benefit the organization and how well the system would work.	0 - 100	30%
	Political	-	A description of how well received this solution would be from both user management, user, and organization perspective.	0 - 100	
Evaluation economic feasibility	Payback period	-		0 - 100	30%
	NPV	-		0 - 100	

Evaluation schedule feasibility			An assessment of how long the solution will take to design and implement	0 - 100	10%
REFERENCE			[Z. Markov et al., 2017]		
OBJECTIVES	**CRITERIA**	**SUBCRITERIA**	**DESCRIPTION**	**SCORING SCALE**	**WEIGHT**
Selection of the BAT Best Available Technology	General issues	commonly used for the similar capacity		1 poor 3 fair 5 good	0.1
		existing experiences in the country		1 poor 3 fair 5 good	0.2
		construction simplicity		1 poor 3 fair 5 good	0.1
		land requirements		1 poor 3 fair 5 good	0.1
		ease of addition of further process streams or retrofit		1 poor 3 fair 5 good	0.2
		treatment efficiency		1 poor 3 fair 5 good	0.3
		sub-total General issues			1
	Operation and Maintenance (O&M)	simplicity of the operational start-up phase		1 poor 3 fair 5 good	0.1
		ease to operate		1 poor 3 fair 5 good	0.1
		requirement of external expertise		1 poor 3 fair 5 good	0.2
		energy demand		1 poor 3 fair 5 good	0.2
		requirement of spare parts		1 poor 3 fair 5 good	0.2
		grade of automation		1 poor 3 fair 5 good	0.2
		sub-total O&M			1
	Process reliability	effect of plant failure		1 poor 3 fair 5 good	0.3
		ability to adjust processes		1 poor 3 fair 5 good	0.3
		reaction to shock loads		1 poor 3 fair 5 good	0.2
		formation of scum		1 poor 3 fair 5 good	0.1
		formation of bulking scum		1 poor 3 fair 5 good	0.1
		sub-total Process reliability			1
	Sludge handling	quality of sludge produced		1 poor 3 fair 5 good	0.3
		quantity of sludge for disposal		1 poor 3 fair 5 good	0.3

		ability to restart treatment process after inhibition		1 poor 3 fair 5 good	0.2
		Sub-total Sludge handling			0.7
	Non-monetary criteria		sum of the previous subtotals	the highest sum of the subtotals gets 40/40, the score decreases the sum decreases	40% of the total score
	Monetary NPV			The lowest NPV get 60/60, the score decreases as the NPV increases	60% of the total score
REFERENCE			N. Marleni et al., 2020		
OBJECTIVES	**CRITERIA**	**SUBCRITERIA**	**DESCRIPTION**	**SCORING SCALE**	**WEIGHT**
Evaluation best technology	Safety risk		Evaluation of both human and environmental risk, that is, to assess the safety for workers in operating and maintaining the system as well as the agricultural worker that use the effluent of the treated wastewater.	1 non preferred - 5 preferred	10%
	Costs		This criterion contains investment cost to develop a system as well as operating, maintaining, personnel, energy and chemical products cost for every alternative.	1 non preferred - 5 preferred	30%
	O&M simplicity		The selection should take into account the special needs of system operation and maintenance. If the operation needs many people to be involved, it can be a reason for a policy maker to refuse it.	1 non preferred - 5 preferred	10%
	Perception issues		This criterion is about the view of local population affected by the system. The perception could be caused by the	1 non preferred - 5 preferred	10%

			aesthetic impact caused by the presence of the facilities on the landscape, bad smell which can be produced by the open channel to irrigate the water as well as the treatment facilities.		
	Area		The proposed alternatives require a certain land area to install the system and the barrier area which might need very wide area.	1 non preferred - 5 preferred	10%
	Treatment efficiency		Efficiency in reducing pathogenic microorganism and metal concentration. This criterion considers the variability of treatment effectiveness under normal and emergency operation	1 non preferred - 5 preferred	30%
REFERENCE			[A. Meerholz et al., 2013]		
OBJECTIVES	**CRITERIA**	**SUBCRITERIA**	**DESCRIPTION**	**SCORING SCALE**	**WEIGHT**
Technical feasibility	Reliability	long-term performance	Determine the variability of the technology performance and efficiency of treatment under normal and upset conditions	1 bad - 5 good	0.2
		short-term performance		1 bad - 5 good	
		mechanical reliability	Evaluate the probability of mechanical failures, and the impact of failures on effluent quality	1 bad - 5 good	
	Simplicity	ease of plant construction, system installation and start-up	Determine the ease with which construction materials can be sourced, compatibility with existing processes, level of automation	1 bad - 5 good	0.18
		operation and maintance requirement	Determine robustness of equipment, operational familiarity with the process, spares lead time	1 bad - 5 good	
	Efficiency	removal of wastewater constituents	Determine the extent of constituent removal in the wastewater	1 bad - 5 good	0.30

Socio-economic feasibility	Land requirement	size of land requirement	Determine physical footprint of technology	1 bad - 5 good	0.08
		favourable land conditions	Determine extent of site preparation required	1 bad - 5 good	
	Affordability	construction cost	Determine initial construction costs	1 bad - 5 good	0.10
		annual operation and maintenance cost	Determine operational and maintenance expenses over the technology life cycle	1 bad - 5 good	
	Social acceptability	general social acceptability	Determine extent to which technology is accepted by the impacted community	1 bad - 5 good	0.02
		environmental impact/perception		1 bad - 5 good	
Environmental feasibility	Sustainability	continuity of facility provision or operation	Determine ease with which system can be expanded, and whether technology has a life cycle of at least 25 years	1 bad - 5 good	0.12
		possibility of resource recovery	Determine which by-products or wastes are generated that require additional treatment	1 bad - 5 good	
REFERENCE			K. Jóźwiakowski et al., 2016		
OBJECTIVES	**CRITERIA**	**SUBCRITERIA**	**DESCRIPTION**	**SCORING SCALE**	**WEIGHT**
Technology feasibility	Simplicity and ease of use			0 lowest - 10 highest	The candidate with the highest score for more scenarios is chosen.
	Stability of technology			0 lowest - 10 highest	
	Technical realiability			0 lowest - 10 highest	
	Investment costs			0 lowest - 10 highest	
	Operating costs			€	
	Impact on the environment			€	
	Space required			m2	
	Aestethetics			0 lowest - 10 highest	
REFERENCE			G. Bertanza et al., 2014		
OBJECTIVES	**CRITERIA**	**SUBCRITERIA**	**DESCRIPTION**	**SCORING SCALE**	**WEIGHT**

Technical feasibility for upgrading	Technology reliability	Technology reliability (e.g. considering the variability of influent)		red - yellow -green	red = - 1 yellow = 0 green = 1
		Number of full-scale applications in EU		red - yellow -green	
		measured range of process performance variability under typical working conditions		red - yellow -green	
	Complexity and integration with existing facilities	required intervention for integration with existing structures		red - yellow -green high - medium - low	red = - 1 yellow = 0 green = 1
		additional footprint including the whole equipment		red - yellow -green >15% - 5-15% - <5%	
		daily workhours for ordinary operation		red - yellow -green >20% - 10-20% - <10%	
		particular job conditions for personnel		red - green yes - no	
		prescribed safety standards		red - yellow -green	
	Flexibility/ modularity	possibility of modular implementation		red - yellow -green	red = - 1 yellow = 0 green = 1
	Social and authorization aspects	public acceptance		red - yellow -green	red = - 1 yellow = 0 green = 1
		complexity of authorization procedures		red - yellow -green	
	Residues and recovered materials	solid/slurry		red - yellow -green	red = - 1 yellow = 0 green = 1
		liquid		red - yellow -green	
		gaseous		red - yellow -green	
		freshwater		red - yellow -green	

	Consumption of raw materials and reagents	polyelectrolyte		red - yellow -green	red = - 1 yellow = 0 green = 1
		coagulants		red - yellow -green	
		substrate for denitrification		red - yellow -green	
		pure oxygen		red - yellow -green	
		pure methane		red - yellow -green	
		other		red - yellow -green	
	Electric energy consumption	quantity		red - yellow -green	red = - 1 yellow = 0 green = 1
	Thermal energy consumption	quantiy		red - yellow -green	red = - 1 yellow = 0 green = 1
	Electric energy available for external recovery	quantity of heat		red - yellow -green	red = - 1 yellow = 0 green = 1
		type of heat vector		red - yellow -green	
		heat vector temperature		red - yellow -green	
		quantity of electric energy		red - yellow -green	

When comparing literature findings, the most common objective of a project is the technical/technology feasibility, in many cases it results as the only objective. Although the related criteria and sub-criteria may vary significantly depending on the assessed technology, the most representative criteria are reliability, simplicity and efficiency (A. Meerholz et al., 2013). The second most-common objective of a project is the economic feasibility although sometimes the costs of the technologies are included as criteria for the technical feasibility (N. Marleni et al., 2020). The related criteria/sub-criteria of the economic feasibility are usually the payback period and the net present value (NPV) (Department of Computer Science, University of Toronto). Subsequently, the social aspects are taken into account as objectives. For this aspects the related criteria are usually focused on the social awareness and inclusion of the citizen in the project (A. Meerholz et al., 2013). The policy feasibility is not usually assessed in literature cases since it may be quite site-specific. However, in the chapter 2.1 the policy feasibility has been considered to evaluate the feasibility of the HYDROs, since the legislative framework may support or hinder the realization of new innovative technologies such as nature-based solutions (CLEVER cities project, 2019) and decentralized solutions applied to small and/or rural communities.

Moreover, the scoring scales are either numerical scale (e.g. from 1 to 100) or representative scale (e.g. red, yellow and green). They are usually used to evaluate the consequences of both qualitative and quantitative criteria for the targets in a unique reference scale. For instance, the NPV (€) and the simplicity of a technology (qualitative criteria) may not be compared, if they are not evaluated through the scoring assignation. Finally, higher weights are usually referred to technical and economic criteria while social aspects affect slightly the project realization.

In the chapter 2.1, the MCDA based approach was applied and contextualized in the HYDROUSA Project for the evaluation of HYDROs feasibility. Specifically, the assessment model used is shown and discussed in detail. Within the replicability study, also the values and constraints of HYDRO 1-6 are assessed in the local context. Especially, factors affecting resource recovery from water loops and energy efficient technology development and deployment, value chains, water services, governance and regulations, social perception and financial schemes are considered. In the third chapter, the replicability study for the Italian site is reported, as case study.

1.2. Brine treatment & processes for Zero Liquid Discharge (ZLD)

Many Mediterranean countries suffer from enduring water shortages, especially in the Southern Mediterranean countries where the economies of the rural communities depend directly on the water resources. Along the Mediterranean coastal areas, 180 million inhabitants suffer water stress and have access to less than 1000 m^3/y/capita, and 80 million inhabitants face water scarcity with less than 500 m^3/y/capita. Moreover, in the Mediterranean area it is expected that average precipitation will diminish by 10 to 25 % in summer and by 10 to 60 % in spring by the end of the century due to climate change (EU SWIM-Support Mechanism, 2015).

According to the report "assessment of potential cumulative environmental impacts of desalination plants around the Mediterranean sea" of the EU SWIM-Support Mechanism (2015), sea water desalination is currently a promising option to supply safe drinking water along the Mediterranean coastal, and it has become an economically viable alternative source of freshwater thanks to the newest technological advances. In the Mediterranean region, over 1532 seawater desalination plants had been installed from 1970 to 2013, and the reported installed capacity of these plants has increases by an outstanding 560% from 2000 to 2013. Spain ranked first as the highest producer of desalinated water with an installed capacity of 3.7 million m^3/day (31% of the total Mediterranean capacity), followed by Algeria with a production of 2.4 million m^3/day (20%) and Israel with 2.1 million m^3/day (18%). The nearly 12 million m^3/day of desalinated water, produced around the Mediterranean Sea, is predominantly consumed by municipalities to deliver high quality drinking water (85 % of the total Mediterranean capacity). From a technological point of view, the reverse osmosis (RO) membrane has become the most common desalination technology in use in the Mediterranean region accounting for the 82.3 % of the total installed capacity. The main drawbacks of desalination of sea water are related to its huge energy consumption per m^3 produced and to the brine production.

The brine flowrates are usually quite high, seawater reverse osmosis plants usually have water recovery rate of 40% to 55%, thus the 45% to 60% of feed seawater becomes unwanted brine (A. Panagopoulos et al., 2019). Furthermore, if the water recovery rate increases, the produced brine volume certainly decreases but its salinity rises. If the produced brine is discharged into the sea, there are different badly environmental impacts such as changes of alkalinity, salinity and average temperature of the seawater. Thereby its proper management and disposal are needed even though they may economically limit the use of desalinated water as alternative water resource. Generally, the brine disposal cost varies from 5% to 33% of the total costs (A. Panagopoulos et al., 2019).

The traditional brine disposal methods are surface water discharge, sewer discharge, deep-well injection, evaporation ponds and land application (A. Panagopoulos et al., 2019). The surface water discharge is a brine disposal method that includes the direct discharge into oceans, rivers, bays, lakes and other open water bodies. If the limits are not fulfilled, this method may harm the receiving water body leading to thermal pollution, pH and salinity increase as mentioned previously. The sewer discharge includes the discharge of brine into the nearby wastewater collection system. It is usually adopted by small-scale desalination plants since the high TDS content of the brine can affect badly the receiving wastewater treatment plant (WWTP). The deep-well injection involves the injection of brine into a confined deep underground aquifer, isolated from other aquifers. The main environmental concern is the potential pollution of nearby water aquifers which might be used as drinking water source. Evaporation ponds are basically shallow lined basins in which brine slowly evaporates thanks the solar energy. The remaining part is precipitated salt crystals, which are periodically disposed off-site. The main drawback is the potential pollution of groundwater aquifers in the case of pond seepage. The land application is a brine disposal method that involves spray irrigation of brine on salt-tolerant plants and grasses. The irrigation may have a negative impact on the underlying groundwater aquifer.

The environmental and economical drawbacks of the brine disposal methods and the adaptation of stricter regulations for brine disposal have encouraged the implementation of brine treatments known as Zero Liquid Discharge (ZLD) systems, which aim to completely eliminate the liquid waste (brine) by recovering high-quality freshwater and solid waste. A typical ZLD system consists of three stages: (i) preconcentration, (ii) evaporation and (iii) crystallization (A. Panagopoulos et al., 2019). In the first stage, membrane-based technologies are used for water recovery minimization of brine volumes and as brine concentrator; they are crucial to reduce the flow rate conveyed to the next two stages. In the following stages, thermal-based technologies are exploited for water recovery, minimization of brine volumes and production of solid by-products.

The membrane-based technologies for brine treatment are reverse osmosis (RO) and high-pressure reverse osmosis (HPRO), forward osmosis (FO), osmotically assisted reverse osmosis (OARO), membrane distillation (MD), membrane crystallization (MCr), electrodialysis (ED) and electrodialysis reversal (EDR) and electrodialysis metathesis (EDM) (A. Panagopoulos et al., 2019).

The reverse osmosis is usually used for desalination of seawater, a hydraulic pressure is applied to the feed brine forcing water molecules to move through the membrane in order to get freshwater though concentrated brine is obtained as by-product. The high TDS content of the brine can lead to high energy demand, rapid scaling and fouling therefore RO application is limited to about 55000-70000 mg/L TDS. However, specific membranes and modules can handle pressures above 82 bar, enabling the application of high-pressure RO, defined as RO operating above 82 bar, for the treatment of brine with >70000 mg/L TDS (A. Panagopoulos et al., 2019). These technologies need intensive pre-treatment processes to avoid scaling and fouling issues. The forward osmosis uses osmotic pressure rather than hydraulic pressure, a draw solution is used to produce the osmotic gradient across the membrane, the water molecules are transported from the less concentrated feed brine solution to the draw solution. Subsequently the diluted draw solution is regenerated, concentrated brine is produced as by-product. As the previous membrane technologies, FO needs intensive pre-treatment processes to avoid scaling and fouling problems and its application is limited to about 65000 mg/L TDS (A. Panagopoulos et al., 2019). Recent developments resulted in a new technology called 'osmotically assisted reverse osmosis' (OARO). Similar to the RO, OARO applies hydraulic pressure to transport water molecules across the membrane, but in this case, a lower osmotic pressure sweep solution on the membrane's permeate side is added to decrease the difference in osmotic pressure. Hence, the water flux increases, and a number of consecutive stages are used to increase the inlet TDS concentration limit from which freshwater can be recovered. A typical OARO system includes a series of OARO stages and the final stage of RO, furthermore intensive pre-treatments are needed to avoid scaling and fouling. The membrane distillation is a thermal-driven membrane-based technology, it is based on a vapor pressure gradient that can be produced by the temperature differential across the hydrophobic microporous membrane. The hydrophobic membrane prevents liquid molecules from moving through the pores while allowing vapor molecules to pass through. Thus, separation is achieved by enabling the recovery of a high-purity freshwater, high rejection rate over 99% and extremely high-TDS brine (up to 350,000 mg/L TDS) can be treated without restrictions (A. Panagopoulos et al., 2019). The main drawbacks are the low membrane flux and the poor thermal efficiency, pre-treatments for fouling and scaling are required. The membrane crystallization is an extension of the MD that also obtains valuable solid crystal salts. On the permeate side a distillate is installed, when the volatile compounds pass through the membrane, they condensate. However, this technology is still under research. Electrodialysis and electrodialysis reversal are voltage-driven membrane-based technologies. ED uses an applied electrical voltage gradient to drive cations and anions in opposite directions through semipermeable membranes. The EDR has the same electrochemical principles as the ED, except that a reversal of DC voltage is performed in the EDR to reverse ion transport and minimize scaling/ fouling. The energy costs increase with the TDS of the feed brine. To minimize the scaling problems and improve the performance, an ED modification called 'electrodialysis metathesis' was developed. Except for water recovery, EDM can find application in the synthesis of inorganic salts and ionic liquids.

While the thermal-based technologies for brine treatment are brine concentrator (BC) and brine crystallizers (BCr), multi-stage flash distillation (MSF) and multi effect distillation (MED), spray dryer (SD), eutectic freeze crystallization (EFC) and wind-aided intensified evaporation (WAIV) (A. Panagopoulos et al., 2019).

Brine concentrators and brine crystallizers are the most commonly used brine treatment technologies in a ZLD system since they are the most-coeffective solutions in terms of water and by-products recovery, and costs (A. Panagopoulos et al., 2019). In the BC, the feed brine is supplied to a heat exchanger that elevates brine's temperature at the boiling point and then proceeds to a deaerator that removes non-condensable gases. Brine is then mixed with the recirculating slurry, which is pumped to the concentrator where water evaporation occurs. A portion of brine evaporates and goes to the vapor compressor. Subsequently, vapor from the compressor passes to the outside of the evaporator tubes, where its heat is transferred to the colder brine that falls inside the tubes. As the compressed vapor releases heat, it condenses as freshwater and is pumped through the feed heat exchanger, where its heat is transferred to the incoming brine stream. In the BCr, the brine is initially fed into the crystallizer sump. The incoming brine then mixes with the circulating brine is pumped into a heat exchanger where it is boiled by vapor from the vapor compressor. Since the tubes in the heat exchanger are submerged, the brine is under pressure and does not evaporate. The recirculating brine inserts at an angle into the crystallizer vapor body and swirls in a vortex. A small portion of the brine evaporates, forming crystals. A large amount of the brine is recirculated to the heater while a small stream of the recirculating loop is transferred to a centrifuge or filter to remove the remaining water from the crystals. The vapor is compressed in a vapor compressor and heats the recirculating brine as it condenses on the heat exchanger. Finally, freshwater is collected and dry solid is produced. Multi-stage lash distillation and multi-effect distillation might be the leading thermal-based desalination technologies in the future, they could be appropriate for brine treatment after material upgrades. In the MSF, the feed brine is preheated utilizing condensing vapours from the flash units and conclusively reaches a maximum temperature (up to 110–120 °C) with an external heat source. The hot feed brine is transferred through lower vapor pressure flash units (in series) in which a portion of the feed solution is evaporated and condensed in the feed preheat exchangers. Thus, the condensed water vapor is the freshwater and the concentrated brine is the liquid that exits from the final flash unit. The MED technology is similar to the MSF, except that (i) vapor condensation occurs in heat exchange with the liquid in distillation effect and (ii) the maximum temperature is up to 70–75 °C. Spray dryers are an alternative technology to crystallizers for the concentration of brine, by converting the brine into a dry powder of mixed solid salts. The concentrated brine is diffused into the chamber by a centrifugal atomizer and at the same time, hot air is pulled into the chamber. The bag filter separates the dry powder from the hot air stream. Thus, the powder is collected, while air exits to the environment. Eutectic freeze crystallization is an extension of the freeze crystallization technology that utilizes the different densities between the ice and the salt produced. Thus, pure water and salt can be obtained concurrently from aqueous solutions by EFC at a very high-water recovery. Wind-aided intensified evaporation is a thermal-based technology used for brine volume minimization. Vertical wetted packing towers use wind power to evaporate densely packed wetted surfaces. Specifically, pressurized air is diffused via the distribution pipes and is vertically moved to the surface of the brine.

A. Panagopoulos et al., (2019) have assessed the performance of some processes/units involved in ZLD systems for brine treatment in terms of water recovery and costs, the results are summarized in the figure 1.10.

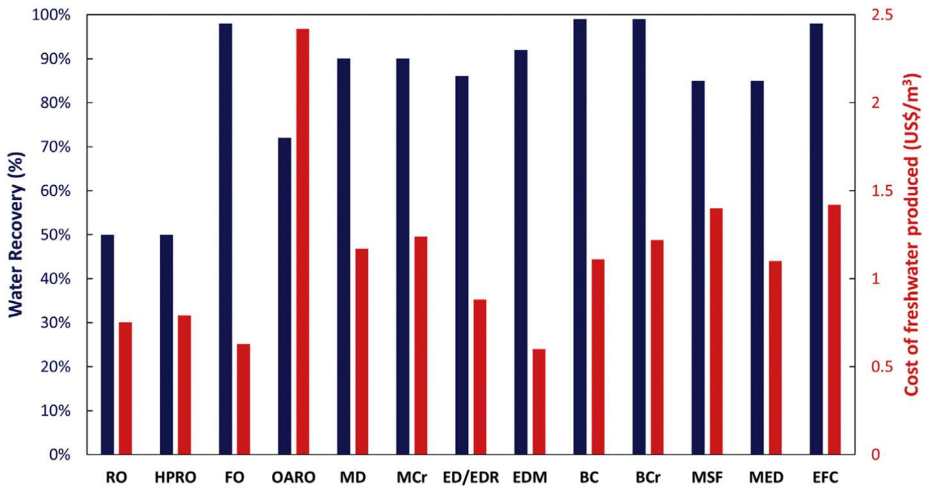


Figure 1.10: Water recovery and cost of freshwater produced from membrane-based and thermal-based technologies

Among the membrane-based technologies, the forward osmosis (FO) is the most-cost effective options with a water recovery around 99% and low costs for freshwater production. While brine concentrator (BC) and brine crystallizers (BCr) are the most cost-effective units, respectively, for brine evaporation and crystallization. Despite the high performance, these technologies consume a large amount of energy contributing to significant emission of greenhouse emissions. RO has a specific energy consumption (SEC) around 0.8-13 kWh/m^3, whereas BC and BCr have, respectively, SEC around 16-26 kWh/m^3 and 52-70 kWh/m^3. Hence, incorporation of low-grade waste heat or renewable energy sources (RES) within the systems are suggested in order to reduce the carbon footprint.

However, in ZLD systems, a high recovery rate is usually difficult to achieve due to the rapid membrane scaling and fouling. Therefore, pre-treatments before membrane-based technologies are needed to protect the membranes and facilitate zero liquid discharge. The goal of pre-treatments is to remove scaling precursor ions and potential organic foulants from the raw brine. The common observed scale-forming compounds are calcium carbonate ($CaCO_3$), calcium sulphate ($CaSO_4$) and silica (SiO_2), which are formed by the abundance of precursor dissolved ions such as Ca^{2+}, Mg^{2+}, Na^+, Cl^-, SO_4^{2-} and silicate anions (G.U. Semblante et al., 2018). The typical concentration of TDS for brine solutions obtained from seawater varies from 50000 mg/L to 80000 mg/L. The main pre-treatment technologies include conventional precipitation, seeded chemical precipitation, chemical coagulation, electrocoagulation, ion exchange, nanofiltration and adsorption on activated carbon (G.U. Semblante et al., 2018).

The conventional precipitation is the most common brine pre-treatment, it consists in the addition of alkaline solutions such as lime ($Ca(OH)_2$), soda ash ($NaHCO_3$) or caustic soda (NaOH). Addition of NaOH to raw brine may result in high removal of Ca^{2+} (> 94%), Ba^{2+} (> 97%) and Sr^{2+} (> 88%), moderate removal of Mg^{2+} (38-80%) and SiO_2 (67-85% if pH > 10) and minor removal of DOC (11-42%). The addition of alkaline solutions increases the pH value (> 10) facilitating the precipitation of calcium carbonate and other scale-forming compounds (G.U. Semblante et al., 2018). Furthermore, to enhance the precipitation process, “seed” materials can be added to provide additional surface area for crystal growth. Potential seed materials are CaCO3, CaSO4 and CaHPO4. Ions removal efficiency improvements are largely dependent on the seed type and brine composition. One drawback of the chemical precipitation process is high operating cost due to chemical usage and sludge disposal. Moreover, inhibition of the chemical precipitation process may occur due to residual antiscalants in brine from upstream RO treatment (G.U. Semblante et al., 2018). Chemical coagulation is a conventional treatment process that involves the addition of coagulant to destabilize colloids and promote floc formation. Typical coagulants are ferric chloride ($FeCl_3$), polyaluminium chloride (PACl) and aluminium chlorohydrate (ACH). Coagulation is effective at removing organic compounds (60-80%). However, the disadvantages of coagulation include poor removal of silica under acidic and neutral pH, badly effects on brine quality and high dosage requirement (e.g. >2000 mg/L) (G.U. Semblante et al., 2018). Clearly, pre-treatment using chemical coagulation alone is not enough thereby coagulation may be combined with other technologies (e.g., chemical precipitation) to create a pre-treatment train. For instance, PACl (dosage = 2-3 g/L) may be combined with either caustic soda, to balance brine conductivity, or anionic polymer, which attracts Ca^{2+} and Mg^{2+} and facilitate the floc formation. Electrocoagulation involves the in-situ generation of coagulants using an electrolytic cell. Its removal efficiencies for Ca^{2+} and Mg^{2+} goes from 40% to 90%, high removal percentages are reached at basic pH values (10-11) of the brine. The silica and organic removal efficiencies typically varies from 40% to 80%. Moreover, less sludge is produced if compared to conventional coagulation and flocculation (G.U. Semblante et al., 2018). Ion exchange involves the replacement of cations in solution with anions associated within a matrix (e.g. resin) or vice versa. Commercial resins have consistent removal efficiency and relatively low cost. The hardness removal efficiency of the ion exchange is high (60-80%) while the silica removal efficiency varies from low to high (up to 80%), depending on the type of ion exchange resin; unfortunately, the organic compounds removal is null (G.U. Semblante et al., 2018). Nanofiltration consists of a membrane-based technology, when it is used as brine pre-treatment, it operates at low water recovery due to the fouling issues. Its removal efficiencies for Ca^{2+}, Mg^{2+} and organic compounds is between 60% to 80%, whereas the silica removal is moderate (40-60%) (G.U. Semblante et al., 2018). Finally, adsorption on activated carbon, typical used in wastewater treatment, may be used to remove organic compounds in brine. However, the removal efficiencies of precursors ions are quite low.

Therefore, a sustainable and optimized ZLD system for brine treatment will include: (i) pre-treatments for removal of precursors ions, (ii) membrane-based technologies for water recovery, volumes minimization and brine concentrating, (iii) evaporation and, (iiii) crystallization for water and solid by-products recovery (T. Tong et al., 2016).

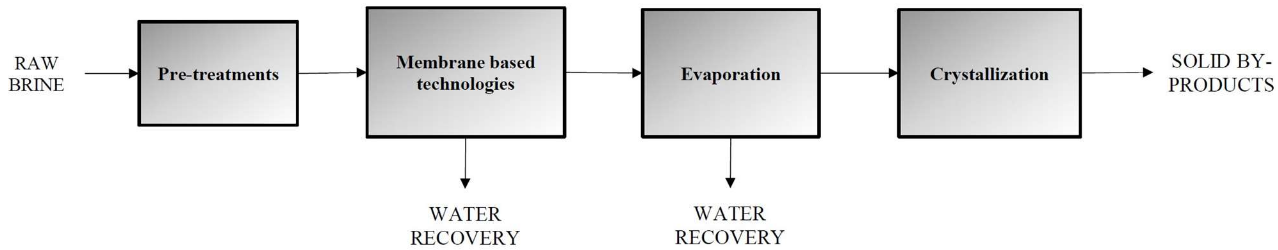


Figure 1.11: Conventional processes for Zero Liquid Discharge (ZLD)

As the nature-based solutions assessed in the first subchapter, ZLD systems perfectly fit in solutions to close water loops across the Mediterranean region. They may support to achieve the SDG 6 "Ensure availability and sustainable management of water and sanitation for all" of UN Agenda 2030 in water scarcity regions around the world. Nevertheless, they may assist the transition to a sustainable and circular economy aiming to close water, energy and material loops within the context of desalinization plants and brine treatments.

In the context of ZLD systems, the FIT4REUSE project has been funding for enabling a wider use of desalted water in agriculture by reducing the costs of desalinisation technologies and providing a sustainable way for brine treatment and disposal. FIT4REUSE is part of the PRIMA Programme, which is supported under Horizon 2020 the European Union's Framework Programme for Research and Innovation. It involves partners such as University of Bologna (Italy), Polytechnic University of Marche (Italy), ISPRA (Italy), National Technical University of Athens (Greek), Higher Institute of Applied Biological Sciences of Tunis (Tunisia), ITUNOVA Technology Transfer Office (Turkey); and also companies: BIOAZUL (Spain), ECOFILAE (France) and Mekorot (Israel). FIT4REUSE aims to provide safe, locally sustainable and accepted ways of water supply for the Mediterranean agricultural sector by exploiting non-conventional water resources, namely treated wastewater and desalted water. The overall concept of FIT4REUSE are identified with the three main pillars of the project:

- innovation of treatment technologies,
- application of non-conventional water resources in simulated/relevant environment
- assessment and regulation

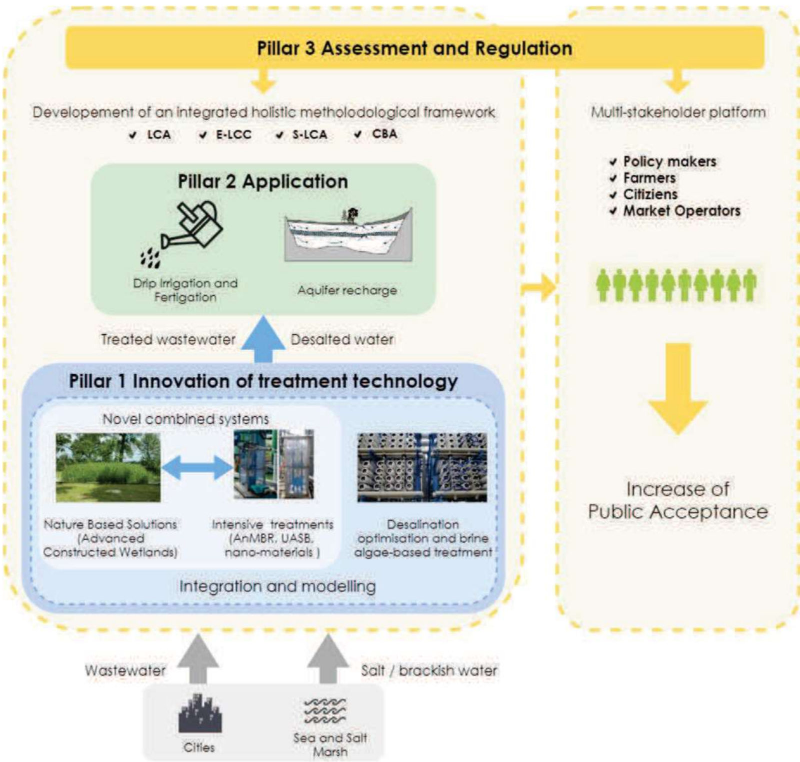


Figure 1.12: FIT4REUSE concepts

The first pillar focuses on the development of innovative, sustainable and low-cost technologies for municipal wastewater treatment for agricultural reuse, desalination and, brine treatment and disposal. The second pillar concentrates its activities on use of treated municipal wastewater and desalted water for irrigation and aquifer recharge. It addresses both direct and indirect use of non-conventional water resources providing effective guidelines. Finally, third pillar performs a holistic assessment of use of non-conventional water resources and improve public and legal acceptance of treated wastewater. It creates a specific methodological framework for impact assessment and multi-stakeholder platform that exploit the results and improve perception of non-conventional water resources (www.fit4reuse.org).

Regarding the brine treatment, different novel technologies are being assessed at the pilot scale across the Mediterranean region. In the pilot plant located in Israel, the brine from desalinization plants is used as substrate to produce microalgae biomass in a closed algal Photo-Bioreactor (PBR). The algae growth reduces the nitrate concentration thus the algae biomass can later be used as raw material for commercial products, such as renewable fuels, fertilisers, animal feedstock, etc.

The Polytechnic University of Marche have been assigned to develop and assess a pilot plant in Italy, where the brine is treated combing existing technologies with thermal evaporation, nutrients recovery by chemical precipitation and forward osmosis. In the preliminary phases, the three units have been tested taking into account energy saving and a ZLD approach in order to provide a sustainable configuration for brine minimization, water and nutrients recovery. Different temperatures and times of evaporation have been studied to concentrate the flow and to recover water without disregarding energy optimization. The effects in terms of chemical recovery rates of calcium and magnesium salts have been analysed. The salts precipitation favours the forward osmosis long terms operation in terms of applied fluxes, fouling and scaling phenomenon; moreover, the recovered salts is used for production of struvite. The water recovery of the forward osmosis at different conditions has been evaluated taking account the specific costs. Moreover, the final minimized and concentrated flows of brine will be tested in order to determine the compatibility with the PBR feeding. Within the Italian pilot plant, this thesis would like to assess preliminary laboratory tests and pilot tests in real environment which have been carried out to evaluate the best configuration for thermal evaporation, chemical precipitation and forward osmosis in order to treat effluent brine from a desalinization plant.

2. MATERIALS AND METHODS

2.1. Replicability study of HYDROUSA solutions: methodology

A feasibility study report template has been drawn up in order to provide guidance methodology for the evaluation of the replicability of HYDROUSA solutions (hereafter HYDRO 1-6) in the previous mentioned transferability sites.

The overall feasibility of HYDROs in the local context is assessed by means of the multi-criteria decision analysis (MCDA) method, which has been exploited within the feasibility study report template. According to the literature review, the MCDA method is a useful tool for the evaluation of multiple complex aspects and alternatives contributing to the achievement of goals and to the implementation of a project. It is useful to handle quantitative and qualitative variables and is especially used for complex decisions where there are trade-offs between competing objectives (A. Meerholz et al., 2013). Basically, the MCDA is applied by following these steps (Department for Communities and Local Government, UK Government, 2009):

1. Establish the decision context (identification of decision makers, other key players and social-economic scenarios).
2. Identify the options to be appraised.
3. Identify objectives and criteria (identification and organization of criteria for options evaluation in a hierarchy e.g. criteria and sub-criteria).
4. Scoring (assess the expected performance of each option against the criteria and then assesses the value associated with the consequence of each option for each criterion).
5. Weighting (assign weights for each of the criterion to reflect their relative importance to the decision).
6. Combine the weights and scores for each option to derive an overall value.
7. Examine the results.
8. Sensitivity analysis (optional to evaluate MCDA accuracy).

Therefore, the MCDA method covers different criteria (scoring) with subjective and objective evaluations about the importance of the evaluation criteria in the decision-making context (weighting) (H. Saarikoski et al., 2017). The main assessment criteria, found in literature for the evaluation of water-related infrastructure and project feasibility (A. Meerholz et al., 2013; N. Marleni et al., 2020), are:

- Social feasibility
- Policy feasibility

- Technical feasibility
- Economic feasibility

For replicability study of HYDROUSA solutions, the sub-mentioned criteria are respectively subdivided into different sub-criteria in order to evaluate the feasibility of the HYDROs in the local context. A numerical score is assigned to each sub-criterion, the evaluation may be either objective or subjective depending on the criterion involved. Subsequently the feasibility score of each assessment criteria (i.e. social, policy, technical, economic feasibility) is calculated applying the Equation 1.

$$S = \sum_{i=1}^{n} s_i \qquad \textit{(Equation 1)}$$

where:

- S = the feasibility score
- i = the sub-criteria of interest, i = 1, …, n
- s_i =the score given for a specific sub-criterion.

Once the scores are obtained for social, policy, technical and economic criteria, a value function (Equation 2) is used to define the overall feasibility score (v(x)) as follows (A. Meerholz et al., 2013):

$$v(x) = \sum_{x=1}^{n} W_i \cdot S_i \qquad \textit{(Equation 2)}$$

where:

- S_i = the score with respect to a criteria i
- n = the number of criteria
- i = the criteria of interest, i = 1, …, n
- W_i = the relative importance (weight) of a criteria i, $W_i > 0$.

According to the literature review in the first chapter, the technical and economic criteria have usually higher weights than other aspects, thereby they are mainly taken into account to evaluate the feasibility of project. However, considering the cutting-edge characteristics of HYDROUSA solutions, attention must also be paid on the analysis of social and policy framework. Both social acceptance and policy support are fundamental for HYDROUSA water loops exploitation in small and decentralized communities. The lack of social awareness and an ad-hoc legislative framework for the application of nature-based solutions as decentralized systems may hinder the replicability of HYDROUSA solutions, especially in small and decentralized contexts where the HYDROs are going to be realized. Applied weights are determined as follows:

- Social feasibility 30%
- Policy feasibility 30%

- Technical feasibility 20%
- Economic feasibility 20%

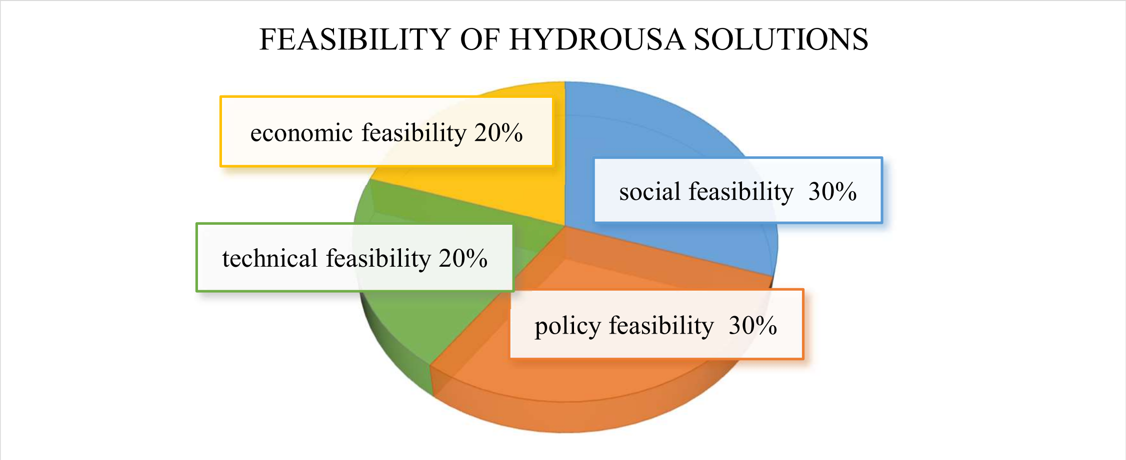


Figure 2.1: Weights of feasibility criteria for HYDROUSA solutions

As explained before, each feasibility criterion has been subdivided into feasibility sub-criteria in order to obtain a deep analysis of the HYDROUSA solutions replicability as well as assign proper scores to each aspect.

According to the literature review (CLEVER cities project, 2019), the type of policy instruments for sustainable urban development/ socially inclusive urban regeneration (i.e. nature-based solutions), mentioned in international policies, EU policies, and EU funding mechanisms, are:

- Regulatory instruments (R)
- Economic instruments (E)
- Information, awareness-raising and public engagement instruments (IAP)
- Monitoring and research instruments (MR)
- Others

The information, awareness-raising and public engagement instruments as well as monitoring and research instruments are assumed as social feasibility sub-criteria since they aim to raise social awareness and acceptability of a project. They include stakeholder and public participation, trainings and qualifications, public information programmes, monitoring systems for green infrastructure (i.e. decentralized systems for HYDROUSA solutions), research projects, assessment of green infrastructure status and ecosystem services. While the regulatory instruments are considered as policy feasibility sub-criteria for the evaluation of the legislative framework. They involve national/regional planning law or regulations, national/regional strategies and action plans, targets (e.g. mandatory or voluntary), standards, bans, permits/quotas, planning/zoning, environmental impact assessments (EIA), public procurement. Moreover, the economic instruments are included within the feasibility study report template in order to identify the funding pathways for the realization of HYDROs. They include pricing (e.g. taxes and charge/fees, reduced taxes/charges, trading of permits, tariffs), payments/subsidies (e.g. payment to landowners, financing target research projects, payment for insurances), voluntary agreements/cooperation (e.g. payments to landowners, financing targeted research projects, payments for insurances, payments to landowners, financing targeted research projects), private sector (e.g. loans, bonds, crowdfunding) and liability schemes.

In the following pages, the feasibility criteria, the respective sub-criteria are assessed and quantified. Regarding the social sphere, the social feasibility aims to provide a framework to analyse, prioritize and incorporate social information and engagement into the design and delivery of projects, while involving a wide range of stakeholders. Furthermore, the assessment of social aspects aims to evaluate the influences that the project might have on the society. This aspect of the feasibility study does not only include the evaluation of possible benefits towards the community, but also the analysis of all information instruments which could create awareness and public engagement. In the context of HYDRO implementation, social feasibility assessment could contribute to provide information about the necessary instruments to arise awareness and to support the dialogue between public and private institutions, key actors and citizens.
Generally, in a local context the different instruments to raise social acceptability may be:

- Low level implemented
- Medium level implemented
- High level developed.

Thus, three score categories from low to high are identified in order to facilitate the assignation of the scores as the table 2.1 shows. The sum of the sub-criteria scores results in the social feasibility score, which may go from 1 to 100.

Table 2.1: Social analysis score attribution sub-criteria

SCORES FOR SOCIAL FEASIBILITY EVALUATION			
Feasibility Sub-Criteria	**LOW (1-6)**	**MEDIUM (7-13)**	**HIGH (14-20)**
Stakeholder and public participation	Low level of social interest (policymakers and stakeholder engagement) (e.g. low Institutions engagement and low citizen interest)	Partial level of social interest and stakeholder engagement (e.g. high Institutions engagement but low citizen interest or vice versa)	High level of social interest and stakeholder engagement (e.g. high Institutions engagement and high citizen interest)
Feasibility Sub-Criteria	**LOW (1-5)**	**MEDIUM (6-10)**	**HIGH (11-16)**

Trainings and qualifications	Low level of training	Medium level of training	High level of training
Public information programs	Low level of information activities	Medium level of information activities	High level of information activities
Monitoring systems for decentralized systems	Low frequency of monitoring activities	Medium frequency of monitoring activities	High frequency of monitoring activities
Research projects	Low interest in research	Medium interest in research	High interest in research
Assessments of decentralized system status/ ecosystem services	Low level of ecosystem mapping	Medium level of ecosystem mapping	High level of ecosystem mapping

While for the policy analysis, regulatory instruments at different institutional level are evaluated regarding the exploitation of the selected HYDROUSA solutions in the replication site, from its implementation to the final-products valorisation at community level.

Generally, the previous mentioned regulations instruments may:

- hinder the implementation of the HYDROs and the use/reuse of its by-products.
- either not be in force or promote only some aspects of the HYDROs and of the use/reuse of its by-products.
- fully support the implementation of the HYDROs and the use/reuse of its by-products.

As for social feasibility sub-criteria, three score categories from low to high are identified for policy instruments as the table 2.2. shows and the sum of the scores results into the policy feasibility score (from 1 to 100). The national/regional planning law or regulations has been considered as more important than other sub-criteria with a higher score scale, since the presence of ad-hoc regulations for small-systems may greatly facilitate the realization of the HYDROs and the exploitation of its outputs. On the contrary, the achievement of the high-quality standards, enforced by national and regional regulations and addressed to big and centralized systems, may hinder the realization of HYDROs and be a challenge to the economic sustainability of the projects.

Table 2.2: Policy analysis score attribution sub-criteria

SCORES FOR POLICY FEASIBILITY EVALUATION			
Feasibility Sub-Criteria	**LOW (1-4)**	**MEDIUM (5-8)**	**HIGH (9-12)**
National/ regional planning law or regulations	No ad-hoc regulation for small-systems are implemented in the	Regulation in the context of HYDRO output are implemented, but ad-hoc	Ad-hoc regulation for small-systems are implemented in the

	context of HYDRO output	regulation for small-systems are not implemented	context of HYDRO output
Feasibility Sub-Criteria	**LOW (1-4)**	**MEDIUM (5-8)**	**HIGH (9-11)**
National/ regional strategies and action plans	No Strategies to promote the management and reuse of HYDRO recoverable resources are implemented	Strategies promote the management and reuse of some HYDRO recoverable resources	Strategies promote the management and reuse of all HYDRO recoverable resources
Planning/ zoning	Bans to HYDRO plants realisation in the chosen replication site	HYDRO plants realisation is subjected to restrictions/prescriptions in the chosen replication site	No restrictions to HYDRO plants realisation in the chosen replication site
Targets	No targets are implemented in the context of HYDRO output	Targets are implemented in the context of some HYDRO outputs	Targets are implemented for all HYDRO outputs
Standards	Clear limits for the reuse of all HYDRO outputs	Limits for the reuse of some HYDRO outputs	Defined standards for the reuse of all HYDRO outputs
Bans	Legal barriers detected for all HYDRO output management/ HYDRO implementation	Legal barriers detected for some HYDRO output management	Legal barriers not detected for HYDRO output management
Permits/ quotas	Simplified procedures to get permits for small HYDRO systems and reuse of recovered resources are not implemented	Simplified procedures to get permits for small HYDRO systems and reuse of recovered resources are implemented just for some aspects of HYDRO management	Simplified procedures to get permits for small HYDRO systems and reuse of recovered resources are implemented and cover all HYDRO management aspects
Environmental impact assessments	Simplified authorization procedure for small HYDRO systems and recovered resources management are not implemented	Simplified authorization procedure for small HYDRO systems and recovered resources management are implemented for some aspects (i.e. Plants realisation but not for by-products reuse)	Simplified authorization procedure for small HYDRO systems and recovered resources management are implemented
Public Procurement	HYDRO system is not in line with objectives of Green Public Procurement (GPP)	HYDRO system is partially in line with objectives of (GPP)	HYDRO system is fully in line with objectives of (GPP)

Although social and policy framework analysis involves different instruments at different levels, the evaluation through the scoring method may mainly depends on the involved replicability case study.

Thereby, a deep careful analysis of social and policy instruments is fundamental in order to take into account and evaluate all social and legislative aspects involved into HYDROs realization and exploitation.

Regarding the technical feasibility, key performance indicators (KPIs) are identified for each HYDRO and assumed as technical sub-criteria in order to evaluate the technological aspects in the local context. Therefore, the preliminary design of the chosen HYDRO in the replication site is carried out together with mass balance, energy balance and graphic schemes. Subsequently, the KPIs are calculated, evaluated (i.e. low, medium and high efficiency) and a scores is assigned as table 2.3 illustrates. Then, the technical feasibility score is calculated by averaging the grades involved. The KPIs mainly considers the amount of reused final-product from HYDROs and they are obtained from the results of Greek demo scale studies in Lesvos, Mykonos, and Tinos.

Table 2.3: Technical analysis score attribution sub-criteria

SCORES FOR TECHNICAL ANALYSIS EVALUATION					
HYDRO	**Feasibility Sub-Criteria**	**Definition of Sub-Criteria**	**LOW (1-33)**	**MEDIUM (34-66)**	**HIGH (67-100)**
1+2	Efficiency	Reuse wastewater with high nutrient content ($m^3\ y^{-1}$)	<5000	5000<x<10000	≥10000
		Compost production (tons y^{-1})	<5	5<x<10	≥10
		Recovered energy from Biogas (MWh y^{-1})	<5	5<x<10	≥10
3	Efficiency	Rainwater harvested ($m^3\ y^{-1}$)	<25	25<x<50	≥50
4	Efficiency	Rainwater and run-off collected ($m^3\ y^{-1}$)	<125	125<x<250	≥250
		Water stored in the aquifer (m^3)	<250	250<x<500	≥500
		Drinking water production ($m^3\ y^{-1}$)	<5	5<x<10	≥10
5	Efficiency	Harvested rainwater ($m^3\ y^{-1}$)	<37.5	37.5<x<75	≥75
		Freshwater produced (L d^{-1})	<100	100<x<200	≥200
		Salt produced (kg d^{-1})	<1	1<x<2	≥2
6	Efficiency	Water recovered from atmospheric vapor ($m^3\ y^{-1}$)	<15	15<x<30	≥30
		Harvested rainwater ($m^3\ y^{-1}$)	<25	25<x<50	≥50
		Reclaimed water ($m^3\ y^{-1}$)	<15	15<x<30	≥30

Considering the economic aspects, though the previous mentioned economic instruments are taken into account for the identification of financing pathways of the HYDROs, the payback period (PP) indicator is used as economic feasibility sub-criteria (table 2.4). It is calculated by estimating the Capital Expenditure (CAPEX), the yearly Operational Expenditure (OPEX) and the yearly revenues of the HYDROs as shown in Equation 3.

$$PP = \frac{CAPEX}{yearly\ incomes - yearly\ OPEX} \qquad (years) \qquad \textit{(Equation 3)}$$

The CAPEX includes the initial costs for purchase and installation of technologies, land purchase, legal affairs, product certification, quality monitoring; while OPEX involves yearly costs for electricity, maintenance and staff. The yearly incomes consider the revenues from the selling of HYDROs outputs (e.g. reclaimed water, fertilizers, etc.) and tariffs for HYDROs service (e.g. water tariff).

Table 2.4: Economic analysis score attribution sub-criteria

SCORES FOR ECONOMIC FEASIBILITY EVALUATION			
Feasibility Sub-Criteria	**LOW (1-33)**	**MEDIUM (34-66)**	**HIGH (67-100)**
Payback Period (PP)	PP ≥ 9 years	9 years < PP ≤ 5 years	PP < 5 years

According to HYDROUSA project targets, the figure 2.1 shows the expected payback periods of HYDROs 1-6. The PP indicates how long it will take for the original investments to be repaid considering revue streams and operational costs. This method does not consider the time value of money (e.g. as for the Net Present Value) though it gives a clear and simple idea about the economic advantages of nature-based solutions respect traditional grey infrastructures, which have usually higher payback periods.

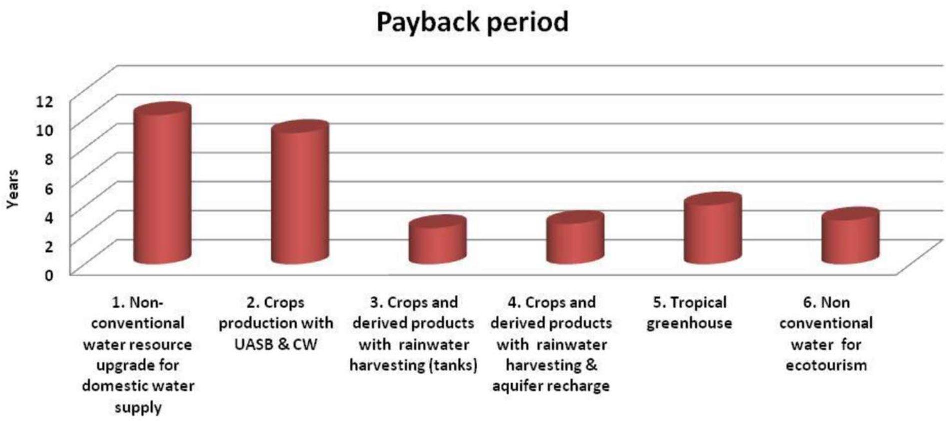


Figure 2.2: Expected payback periods of HYDROUSA solutions

Despite the social and policy feasibility analysis, the technical and economic evaluations are quite objectives analysis whose grades are obtained from mass balances, energy balances and market values evaluations.

Finally, as the matrix of feasibility study (table 2.5) highlights, the feasibility scores of the criteria are weighted in order to obtain the overall feasibility score of the HYDRO in the replication site.

Table 2.5: Matrix of the feasibility study

FINAL RESULTS			
Feasibility Criteria	Main Feasibility Sub-Criteria	Weight	Score
Social Feasibility	Stakeholder and public participation, Social Benefits, Social Acceptance	30%	
Legal Feasibility	Strategies and Action plans, Targets and Quality standards, Permitting Pathway	30%	
Technical Feasibility	Efficiency	20%	
Economic Feasibility	Financial pathway, Payback Period	20%	
OVERALL FEASIBILITY	-	**100%**	**SCORE from 1 to 100**

The feasibility study matrix summarizes the findings of the replicability study report and provides a numerical score of the HYDROs feasibility within a replication site. Thereby it can be exploited to compare either the feasibility of different HYDROs in a replication site or even the replicability of a HYDROUSA solution within different transferability sites. The criteria assessment is also supporting the evaluation of the HYDROs circularity in terms of water, energy and material loops, in the context of small and decentralized communities.

In the following pages, the feasibility study report template for HYDROUSA solutions is described at a glance, in order to illustrate its structure and its goals. The feasibility study report template summary is reported below.

1. Project Strategic Context
   - 1.1. Scenarios analysis and related benefits
2. Characterization of the replication site
   - 2.1. Description of the area
   - 2.2. Environmental constraints
3. Social analysis and final end-users' identification
4. Policy analysis and institutional framework
   - 4.1. Regulatory Instruments for decentralized community systems
   - 4.2. National/Regional Strategies and Action plans
   - 4.3. National/Regional Legislations and quality standards/Targets
   - 4.4. Identification of the permitting pathway
   - 4.5. Results of policy analysis

5. Stakeholders and policymaker’s identification
6. Technical analysis
   6.1. HYDRO scheme implementation
   6.2. Design Data and Sizing Criteria for HYDRO replicability
   6.3. Graphic design (e.g. plan, block flow diagram)
   6.4. Results of technical analysis
7. Economic analysis
   7.1. Identification of the financing pathway
   7.2. Cost estimation for HYDRO implementation (CAPEX)
   7.3. Cost estimation for HYDRO maintenance (OPEX)
   7.4. Revenue & costs saving streams
   7.5. Results of economic analysis
8. Conclusion

In the first chapter of the feasibility study report template, once one or more HYDROUSA solutions are chosen to be realized into the replication site, an overview of the project and the relevant data of the local context need to be analysed. The replication site is usually chosen based on its different criticalities such as water scarcity, seasonal pressure due to the touristic seasonal, presence of rural and isolated communities, lack of water loops or even of water resources. Hence, the nature-based solutions of HYDROUSA are going to overcome these criticalities of the replication site. In this regard, the local social and environmental conditions and constraints should be generally summarized. Specifically, the water and water-related resources availability, local needs of the community, social and/or economic challenges to be faced should be clarified. So, the demand estimation for a specific resource recovery and reuse and benefit that could be derived from the project should be quantitatively reported. The importance of the HYDRO implementation in local water and water-related resources management for the closure of the water loop in the local decentralized replication site should be discussed.

While in the second chapter, the transferability site is identified and described indicating extension of the area, orographic and hydro-geological characteristics, climatic conditions, nearby existing infrastructures (if it is relevant to the project) and close end-users of the HYDRO. Relevant geographic/ environmental indicators/ information related to the local environmental conditions and sensitivity/ constrains should be stated in order to highlight possible “environmental fragilities” in terms of water, soil, flora and/or fauna, and any potential risks connected to the project. Moreover, the reasons, for which the other HYDROUSA solutions are discarded, should be justified.

Once the HYDRO project is broadly contextualized by considering also the small and decentralized community needs and expectations, the feasibility assessment is carried out by means of MCDA method considering the social, legislative, technical and economic criteria as mentioned in the previous pages.

Hence, in the third chapter of the feasibility study report template, the social aspects are assessed in order to evaluate the social feasibility of the project. Thereby, possible benefits towards the local community as well as the information instruments which could create awareness and public engagement are investigated.

In the fourth chapter, the policy and institutional framework is studied considering regulatory instruments at different levels (from local up to national) to exploit the HYDRO in the replication site, from its practical implementation to its final-products valorisation. Since, the fragmentation of the regulatory framework and/or the lack of specific legislative instruments for water-related infrastructures in small communities may affect the project realization as well as the use of the final-products. Once, the institutional framework is clearly identified, the regulatory instruments are evaluated in order to assign a score to the policy feasibility of the project.

In the fifth chapter, the main stakeholders and policymakers involved into the HYDRO implementation are identified and classified into three categories: (i) primary for direct beneficiaries and direct related person, (ii) secondary such as intermediaries in the process of delivering aid to primary stakeholders, (iii) external stakeholders such as decision and policymakers. The needs and the expectations of these “actors” from the HYDRO realization should be reported.

In the sixth chapter of the feasibility study report template, the technical feasibility of the HYDRO is assessed. Specifically, the local design criteria for HYDRO flows and loads are defined in order to size and preliminary draw the best available HYDRO layout. Preliminary mass and energy balances are carried out in order to obtain the key performance indicators (KPIs) of the HYDRO and determine the technical feasibility of the project.

In the seventh chapter of the feasibility study report template, the financing pathways with the possible economic instruments for the HYDRO implementation are analysed. An evaluation of the costs associated to the project and local market analysis of the recoverable resources from the HYDRO is reported. Thus, the CAPEX, yearly OPEX and revenues are estimated in order to calculate the payback period and determine the economic feasibility of the project.

Finally, in the conclusion chapter, the matrix of the feasibility study with the overall score is reported summarizing the findings of the report. Furthermore, critic comments and suggestions should be made in order to improve the overall feasibility of the HYDROs in the replication site.

2.2. Brine treatment:

The best configurations for the evaporation and chemical precipitation of the brine from desalinization plants have been investigated, firstly at laboratory scale and finally at pilot scale in real environment. The assessed criteria for the evaluation of the configurations are:

- Water recovery.
- Brine volume minimization.
- Magnesium and calcium salts recovery.
- Matrix carried to the forward osmosis (FO) membrane in order to avoid scaling and fouling.

The brine of the desalinization plant of Capraia island (Tuscany Archipelago, Italy) have been used for laboratory and pilot tests. For the evaluation of the assessed criteria, the pH, conductivity, total suspended solids (TSS), total dissolved solids (TDS), total solids in percentage (TS%), cations in the dissolved phase, and percentages of magnesium and calcium in the solids have been measured in different matrixes, in laboratory. The applied methodologies of these laboratory tests are reported in the Annex 2 “Laboratory tests” for the sack of clarity.

2.2.1. Preliminary laboratory tests

At laboratory scale, firstly the evaporation and the chemical precipitation have been separately investigated; subsequently they have been combined in order to evaluate the best integrated treatment configuration.

2.2.1.1 Evaporation tests

The evaporation of the brine is one of the processes typically included into a ZLD system for brine treatment and usually aims to water recovery and brine volume minimization (A. Panagopoulos et al., 2019). It involves essentially the heat transfer to a boiling liquid with the purpose of concentrating a non-volatile solute from a solvent (e.g. water) by boiling off the solvent, which is subsequently condensed for recovery (C. Charisiadis, 2018). Thereby the initial brine is split into two flows: (i) the concentrated brine, which has higher concentrations of dissolved ions due to the evaporation, and (ii) the distillate, which has low dissolved ions concentrations. The evaporation process normally stops just before the solute begins to precipitate, otherwise it is considered as crystallization (C. Charisiadis, 2018). The main factors affecting the brine evaporation are (L. F. Petrik et al., 2015; I. S. Al-Mutaz et al., 2014):

- Salinity of the brine (mg TDS/L)
- Evaporation temperature (˚C)
- Evaporation pressure (mbar)

As salinity increases, the evaporation rate decreases and the boiling point of the brine increases. This is due to the reduction in the water vapour pressure at the water surface (L. F. Petrik et al., 2015). From Raoult's Law, it is stated that the partial pressure of a solute (i.e. salts) in a solution is equal to the vapour pressure of solvent (i.e. water) times the mole fraction of the solute in solution. So, the law dictates that vapour pressure lowering is proportional to the mole fraction of the solute in the solution. Moreover, the evaporation rate increases with the evaporation temperature, which is the primary driver of the evaporation process (L. F. Petrik et al., 2015). Finally, the evaporation rate increases and the boiling point of the brine decreases, as the evaporation pressure decreases. Hence, a vacuum condition allows the brine to boil at a lower temperature and a faster evaporation, improving energy efficiency (I. S. Al-Mutaz et al., 2014).

Therefore, the 500 mL of initial brine has been evaporated for 30 minutes with a vacuum of -0.55 bar to facilitate the evaporation, at different temperatures: (i) 60 ˚C and (ii) 100 ˚C. The brine has been tested at its initial pH (7,5) and at different pH: (i) 8, (ii) 9 and (iii) 10, which have been reached through the addition of NaOH. Subsequently, the dissolved cations and anions, the TDS of the concentrated brine and of the distillate have been measured in order to evaluate the concentrations of magnesium and calcium in the concentrated matrixes and possible drawbacks at different pH and temperature.

At laboratory scale, a rotary evaporator (figure 2.3) has been used to carried out the evaporations under vacuum conditions. It is composed of: (i) a motor unit, that rotates the evaporation flask containing the sample; (ii) a vapor duct, that is the axis for sample rotation and a conduit for the vapour being drawn off the flask; (iii) a vacuum system, to reduce the pressure in the system; (iv) a heated fluid bath, to heat the sample; (v) a condenser with a collecting flask at the bottom, to catch the distillate solvent; (vi) a structure, to lift or dip the evaporation flask into the heating bath.

Figure 2.3: Laboratory Rotavapor "Buchi"

2.2.1.2. Chemical precipitation tests

The chemical precipitation is usually used as pre-treatment in ZLD systems for brine treatment in order to remove precursors ions avoiding scaling and fouling of the membrane-based technologies (A. Panagopoulos et al., 2019). At laboratory scale, the chemical precipitation has been investigated by the addition of sodium hydroxide (NaOH) to the raw brine in order to remove scaling precursors ions as well as for a selective recovery of magnesium and calcium, in solid phase.

The NaOH utilization has been preferred rather than lime and/or soda ash, since it may achieve higher recovery percentages of magnesium and calcium, according to the literature review (H. Dong et al., 2017).

The formation of magnesium hydroxide ($Mg(OH)_2$) occurs thanks to the reaction between the Mg^{2+} in the brine and OH^- provided by addition of NaOH. The sodium hydroxide converts also the HCO_3^- in the brine to CO_3^{2-}, which reacts with Ca^{2+} and results in the precipitation of a small amount of calcium carbonate ($CaCO_3$) (H. Dong et al., 2017). Moreover, the dissolved OH^- reacts directly with Ca^{2+} forming calcium hydroxide ($Ca(OH)_2$) (N. Um et al., 2014).

The reaction paths during the chemical precipitation are shown in equations 3-7 below.

$$NaOH \rightarrow Na^+ + OH^- \qquad \textit{(Equation 3)}$$

$$Mg^{2+}_{(l)} + 2OH^- \leftrightarrow Mg(OH)_{2\,(s)} \qquad \textit{(Equation 4)}$$

$$NaOH + HCO_3^- \leftrightarrow CO_3^{2-} + Na^+ + H_2O \qquad \textit{(Equation 5)}$$

$$Ca^{2+}_{(l)} + CO_3^{2-} \leftrightarrow CaCO_{3\,(s)} \qquad \textit{(Equation 6)}$$

$$Ca^{2+}_{(l)} + 2OH^- \leftrightarrow Ca(OH)_{2\,(s)} \qquad \textit{(Equation 7)}$$

Magnesium hydroxide, calcium carbonate and calcium hydroxide precipitate when their respective reactions reach the equilibrium state. These reactions are reversible, and the equilibrium is mainly affected by the temperature, the pH and the initial concentrations of dissolved Mg^{2+} and Ca^{2+} in the brine (N. Um et al., 2014).

At laboratory scale, the chemical precipitation has been experimented by means of jar tests (figure 2.4). Beakers with the raw brine have been prepared, subsequently different concentrations (ml NaOH/L brine) of NaOH (30% v/v) have been added to the batches. The conditioned brine has been rapidly stirred for 2 minutes and then the settling in the beakers has been monitored at least for 9.5 hours. Hence, from the raw brine two matrixes are obtained: the precipitate and the supernatant. The pH and the conductivity before, after the addition of NaOH and after the settling have been monitored; since they may significantly vary throughout the test. Finally, the settling velocity of the precipitate, magnesium and calcium recovery in the precipitate have been evaluated.

The settling velocity has been obtained by monitoring the level of the precipitate respect the total level of the solution through the time. The percentages of magnesium and calcium in solid phase have been calculated by means of mass balances. The initial dissolved concentrations of Mg and Ca in the raw brine represent all the available magnesium and calcium. Thereby the concentrations in the liquid phase (both in the supernatant and in the precipitate) are subtracted in order to obtain the amount of Mg and Ca precipitated in the solid phase. Moreover, the percentage of magnesium and calcium in the TSS of the precipitate have been measured by means of Scanning Electron Microscope (SEM), as explained in the annex 2, to validate the calculated data.

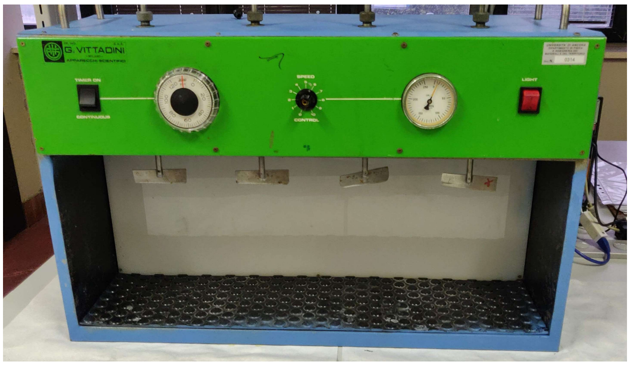


Figure 2.4: Jar test apparatus with 4 places

Reviewing the literature, the precipitation of $Mg(OH)_2$ and $Ca(OH)_2$ usually occurs at pH higher than 9 (R. Ordònez et al., 2012). Indeed, according to the Pourbaix Diagram for magnesium in the figure 2.5, at a neutral redox potential, the formation of magnesium hydroxide occurs at pH higher than 9.2.

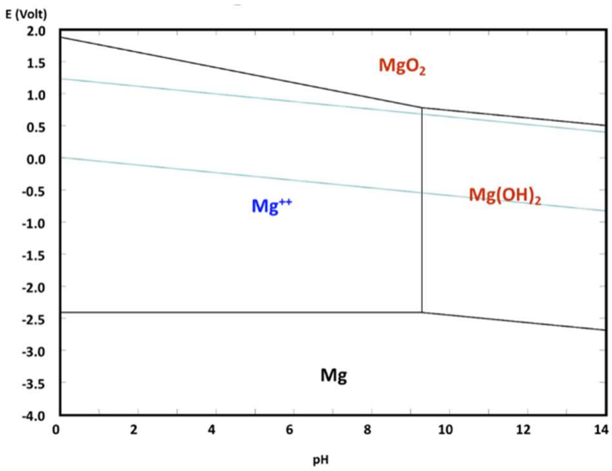


Figure 2.5: Pourbaix diagram for magnesium

Therefore, at the beginning of the experimental phase, a final pH of 9.3 has been obtained adding (i) 4.5 mL of NaOH per L of raw brine. Subsequently, dosage of (ii) 9, (iii) 13.5 and (iv) 18 mL of NaOH per L of brine has been experimented in order to evaluate the best dosages for the settling and, the magnesium and calcium recovery.

Furthermore, the combination of the chemical precipitation with the coagulation and flocculation has been experimented in order to improve the settling velocity, to reduce the volume of the precipitate as well as to evaluate the recovery of magnesium and calcium in solid phase.

Coagulation is a process for combing small particles into larger aggregates (coagula), it involves the reaction between coagulant chemicals and the surface of particles (precipitate). The coagulation mechanism involves either charge neutralization or precipitation by positively charged coagulant, or enmeshment in or adsorption on the surfaces of precipitated floc particles (Q. Yang et al., 2007). Whereas, flocculation refers to the aggregation phenomenon of coagula to form bigger particles (flocs) by addition of flocculation agents (flocculants) (R. Ordònez et al., 2012).

Firstly, the effects of the coagulation plus flocculation on the precipitation have been studied by means of jar tests (figure 2.4); aluminium sulphate ($Al_2(SO_4)_3$) and anionic polymer (APAM) have been respectively assessed as coagulant and flocculant. The use of an anionic flocculant has been preferred rather than a cationic one; according to the literature, its negative charges might balance the positive charges of the coagulant based on Al, resulting in low turbidity and more stable flocs (L. D. Xavier et al., 2020). According to the literature review, the typical dosage of $Al_2(SO_4)_3$ is about 3-4 g L^{-1} (O. P. Sahu et al., 2013) and the dosage of anionic polymer may range from 1 to 7 mg L^{-1} (G.U. Semblante et al., 2018). Therefore the performances of aluminium sulphate and anionic polymer has been investigated setting, respectively, a dosage of 3 g L^{-1} and 7 mg L^{-1}, and varying the dosage of the caustic soda: (i) 9, (ii) 13.5, and (iii) 18 mL of NaOH per L of brine. Afterwards, the effects of the anionic polymer have been investigated by setting the dosage of $Al_2(SO_4)_3$ at 3 g L^{-1} and of NaOH at 18 mL L^{-1}, and varying the dosage of APAM: (i) 0, (ii) 7, (iii) 14 and (iv) 21 mg L^{-1}.

Subsequently, through a jar test (figure 2.4), the performance of two coagulants have been compared: aluminium sulphate ($Al_2(SO_4)_3$) and polyaluminium chloride (PACl). A sodium hydroxide dosage at 18 mL L^{-1}, APAM at 7 mg L^{-1} have been set for two beakers: (i) one with $Al_2(SO_4)_3$ at 3 g L^{-1} and (ii) the other one with PACl at 3 g L^{-1}. Polyaluminium chloride (PACl) is similar to aluminium sulphate except it contains high charge polymeric aluminium species and consumes less alkalinity (O. P. Sahu et al., 2013). Furthermore, the PACl is widely investigated in literature and, throughout the trials, its use has been results in improvements of the magnesium recovery. Thereby it has been preferred rather than the aluminium sulphate.

According to literature review, the typical dosages of PAC are various, they may range from 2-3 g L^{-1} (G.U. Semblante et al., 2018) to 15 g L^{-1} (R. Ordònez et al., 2012). Thus, also a PAC dosage of 15 g L^{-1} has been tested with a NaOH dosage of 4.5 mL L^{-1} (i) without APAM and (ii) with APAM at 7 mg L^{-1}; afterwards they have been also compared to the another case with the same NaOH dosage but without PAC addition.

At laboratory scale, the chemical precipitation with coagulation and with coagulation plus flocculation have been investigated thanks to jar tests as previously mentioned. Regarding chemical precipitation and coagulation, beakers with the raw brine have been prepared, then different concentrations (ml NaOH per L brine) of NaOH (30% v/v) have been added to the beakers. The conditioned brine has been rapidly stirred for 2 minutes before the coagulant has been added. Subsequently, the solution has been stirred rapidly for 2 minutes and slowly for 15 minutes. After the stirring phases, the settling of the precipitate in the beakers have been monitored at least for 9.5 hours. While for chemical precipitation with coagulation plus flocculation, the previous procedure has been followed; but after the initial 15 minutes of slow stirring, the flocculant has been added and the solution has been slowly stirred for other 15 minutes, before the settling phase. The pH and the conductivity have been monitored before, after the addition of NaOH, after coagulant addition, after the flocculant dosage and finally after the settling. All the chemical precipitation trials have been carried out at ambient temperature, around 25 ˚C.

Based on the volume of raw brine, the $Al_2(SO_4)_3$ coagulant has been previously prepared by dissolving an amount (g) of powder $Al_2(SO_4)_3 \bullet 16H_2O$ in a certain volume (mL) of distillate water in order to obtain the required concentrations (i.e. 3 g L^{-1}). While the used PAC coagulant is already diluted at 17% w/w and is ready-made for the use. The anionic flocculant (APAM) has been prepared by dissolving 0.5 g of powder medium molecular weight (MMW) anionic polymer in 1 litre of tap water and stirring the solution for 1 hour.

Finally, the settling velocity, the magnesium and calcium recovery in the precipitate have been elaborated, as explained before.

2.2.1.3. Integrated systems

After the evaporation and chemical precipitation with or without coagulation and flocculation have been assessed. Three integrated systems have been studied, at laboratory scale, in order to provide the best configuration before the final forward osmosis/reverse osmosis (FO/RO) treatment:

1. E + C system (figure 2.6), which involves firstly evaporation (E) and then chemical precipitation with settling (C).
2. C + E_C system (figure 2.7), composed of chemical precipitation with settling (C) and evaporation (E) with the concentrated flow (_C) going to the FO/RO.
3. C + E_D system (figure 2.8), which is equal to the system C + E_C though the distillate flow (_D) goes to the FO/RO in order to reduce the probabilities of scaling/fouling.

The following parameters are considered for the assessment of the systems:

- Water recovery from evaporation (i.e. distillate volume over the initial volume).
- Mg and Ca recovery from chemical precipitation, compared with initial concentration of Mg and Ca in the raw brine.
- Settling efficiency of the precipitate (i.e. supernatant volume over the total volume).
- Avoidance of the membrane fouling/scaling, taking into account concentrations of TS, TDS and relative volumes going to the FO/RO.

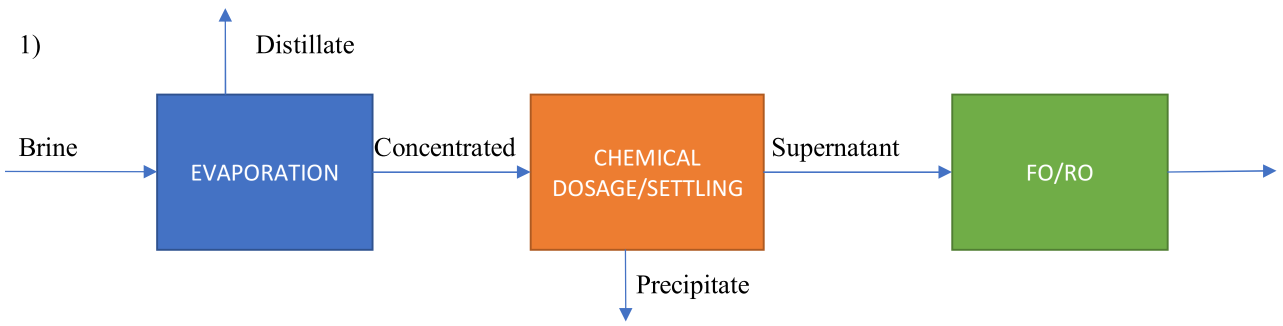


Figure 2.6: Integrated system E + C

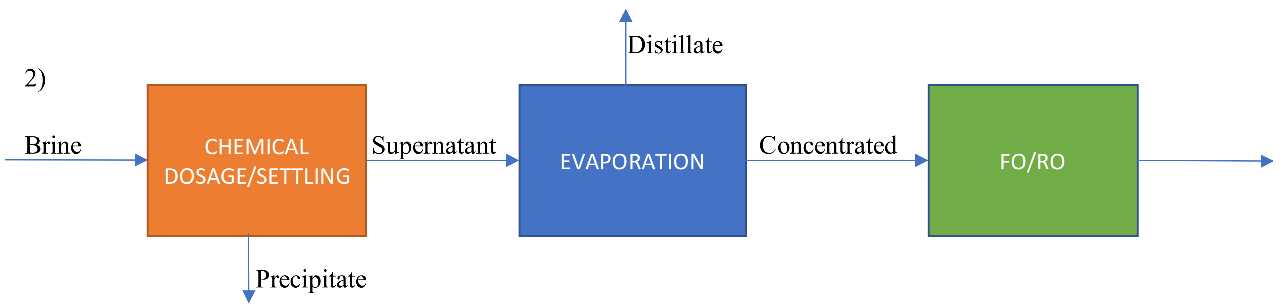


Figure 2.7: Integrated system C + E_C

3)

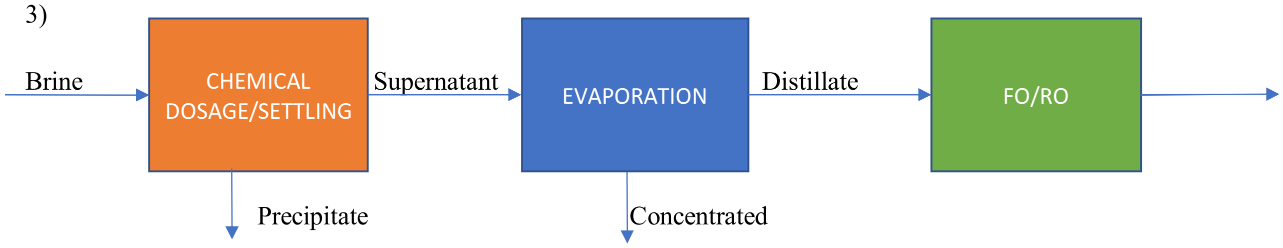


Figure 2.8: Integrated system C + E_D

Regarding the first system, different tests have been carried out: 17 mL/L of sodium hydroxide have been dosed (i) before and (ii) after 30 minutes of evaporation (at 100˚C and -0.55 bar) in order to evaluate the best place where the brine may be conditioned; in both cases, PAC at 15 g/L has been added before1 hour of settling. Moreover, the test with dosage of NaOH after the evaporation and PAC at 15 g/L has been compared with another test with dosage of NaOH after the evaporation but PAC at 3 g/L.

While the second and the third system have been assessed through a single test, where chemical precipitation has been carried out with NaOH at 18 mL/L and PAC at 3 g/L, settling of 3 hours and finally evaporation of the supernatant flow for 30 minutes, at 100˚C and -0.55 bar.

In the chapter 3, these systems have been compared in terms of solid magnesium and calcium recovery and of total dissolved solids (TDS) going to the forward osmosis. Although the application of FO is limited by a concentration of 65000 mg/L TDS (A. Panagopoulos et al., 2019), some of these flows with concentrations of TDS between 4-5 g/L may easily lead to the scaling and fouling of the membrane.

The followed lab procedures for the implementation of the evaporation and chemical precipitation are, respectively, the same reported in the previous evaporation and chemical precipitation subchapters.

2.2.2. Pilot tests in real environment

After the preliminary phase in laboratory, tests have been carried out at pilot scale in real environment. The pilot plant is situated in Falconara Marittima (Italy), it has been made by the UNIVPM for the study of the brine treatment within the FIT4REUSE project. The pilot plant works in a batch configuration and is composed of:

- Evaporator with a vacuum system
- Precipitation tank
- Forward osmosis (FO) membrane
- Reverse osmosis (RO) membrane

The P&Id of the pilot plant (without RO) is shown in the figure 2.13. The raw brine may be pre-treated by evaporation or chemical precipitation. Afterwards, either the supernatant or the distillate goes to the forward osmosis membrane, where the influent flow is concentrated while the draw solution is diluted throughout the process. Subsequently, the diluted draw solution is treated by the reserve osmosis membrane in order to recover freshwater and to concentrate the diluted draw solution, which is then recirculated back to the FO membrane.

The evaporator (figure 2.9) is mainly composed of an electrical resistance, an oil chamber, a tank equipped with a stirrer, a cooling system for the collection of the distillate. The electrical resistance warms the thermodynamic oil in the chamber which in turn warms the tank containing the raw brine. Although the temperature of the thermodynamic oil may reach 200˚C, it can be set through the thermostat. Throughout the evaporation the temperature of the brine inside the tank cannot be measured, so in the trials the indicated temperatures are referred to the temperature of the thermodynamic oil. In the evaporation tank, maximum allowed volume is about 30 L. The evaporator is powered by electrical energy with an installed power of 5 kW.

Figure 2.9: Industrial evaporator "FORMECO"

While the vacuum system of the evaporator is mainly composed of a vessel of 15 L equipped with a pressure gauge (figure 2.10) and connected to a vacuum pump (figure 2.11). Initially, the vessel is connected to the evaporator through the condensation system and is filled with tap water. Subsequently, the water is withdrawn by the pump and a vacuum environment is created. The negative pressure value may be monitored through the pressure gauge and may be set through the pump and a valve. However, the maximum reachable negative pressure is about -0.5 bar and the evaporator should be at a constant temperature during the operation. Otherwise the variation of the temperature in the evaporator may lead to variation of the vacuum in the system.

Throughout the evaporation the distillate is accumulated in the empty vessel, each 1,5 hour it is withdrawn by the vacuum pump in order to hold constant the negative pressure. The volume of the distillate throughout the time has been monitored in order to evaluate the evaporation rate.

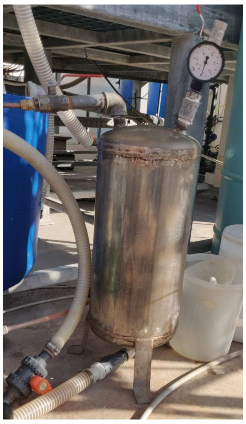


Figure 2.10: Vessel with a pressure gauge

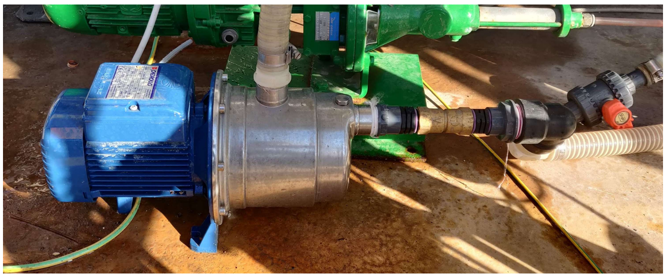


Figure 2.11: Vacuum pump

The precipitation tank (figure 2.12) of the pilot plant is equipped with a vertical axis mixer and a peristaltic pump. It has a rectangular footprint about 1200 cm^2 and may contain up to 100 L of raw brine. The mixer is used to stir the solution after the dosage of caustic soda for 30 minutes, subsequently the settling of the precipitate is carried out by gravity in the tank. The peristaltic pump withdraws the supernatant after the sedimentation, the precipitate flow is removed by opening the tap on the bottom.

Figure 2.12: Precipitation tank

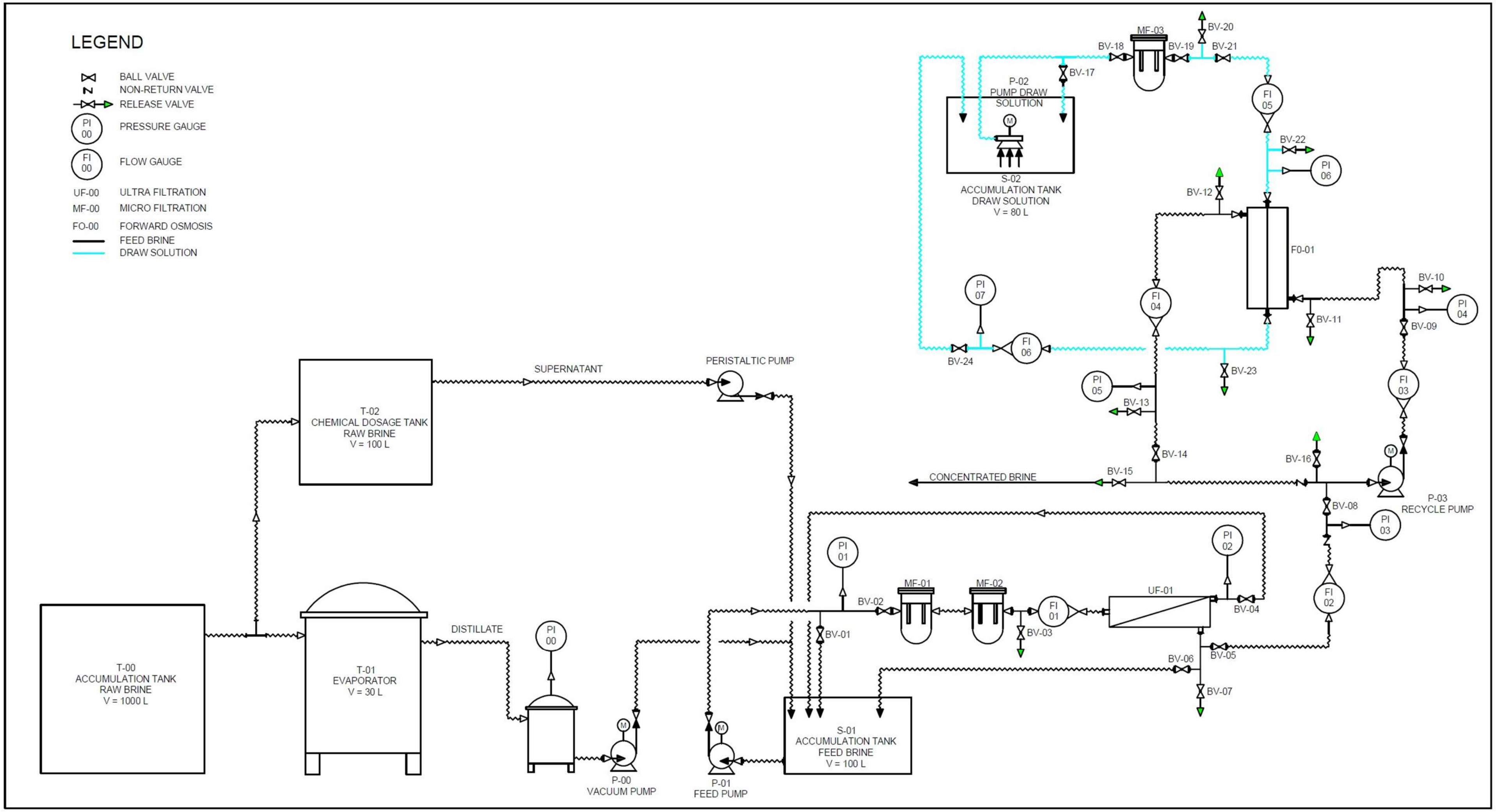


Figure 2.13: P&Id pilot plant

As the P&Id shows, either the supernatant flow or distillate are carried to the FO membrane (figure 2.14), whose system is composed of two circuits: the feed brine and the draw solution one.
The first is composed of an accumulation tank of 100 L for the feed brine, which is withdrawn by the feed pump and undergoes pre-treatments of microfiltration (MF) and ultrafiltration (UF), before it is carried to membrane. The latter is composed of an accumulation tank of 80 L for the draw solution, which is withdrawn by a submerged pump and undergoes a microfiltration before the membrane.
The feed brine enters the membrane from the bottom while the draw solution enters the membrane from the top (i.e. counter current configuration). The molecules of the water in the feed brine pass through the membrane towards the draw solution, thanks to the osmotic gradient given by the salinity of the draw solution. Thereby the feed brine is concentrated and is continuously recirculated in the membrane, while the draw solution is diluted and is discharged in the accumulation tank.
The plant is equipped with an electrical panel for general electric supply, automatized systems are not present; each operation is managed by hand.

Figure 2.14: RO membrane

Figure 2.15: FO membrane

The FO membrane is coupled with the RO membrane (figure 2.15) as the layout in figure 2.16 shows. The electrical conductivity of the draw solution is measured in the accumulation tank. The salinity of the solution decreases with the conductivity. When the draw solution reaches a low NaCl concentration, for which the osmotic pressure is too low to carry out the forward osmosis, the RO membrane is activated. Therefore, the diluted draw solution undergoes microfiltration and then RO, finally obtaining a concentrated draw solution for the operation of the FO, and freshwater. The plant is equipped with an electrical panel for general electric supply, automatized systems are not present; each operation is managed by hand.

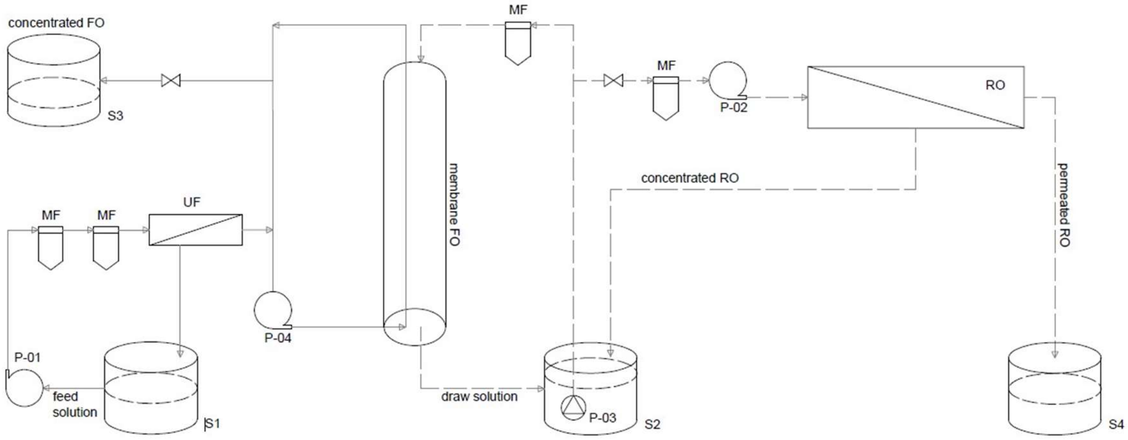


Figure 2.16: Layout of FO/RO

In this thesis, the tests have been focused on the pre-treatment processes before the FO/RO. Firstly, the performances of industrial evaporator of the pilot plant have been tested using raw brine. Secondly, some pre-treatment trains have been studied in pilot plant in order to provide the most cost-effective configuration before the FO/RO.

2.2.2.1. Evaporation tests

In the pilot plant, the evaporation of 15 L raw brine at different temperatures and pressures has been tested by means of the industrial evaporator and the vacuum system. The main scopes are the evaluation of the brine evaporation rate and the assessment of the optimal operational conditions.
Therefore, the trials have been carried out at different temperature (T) and pressure (P) values: (i) 150˚C and atmospheric pressure, (ii) 150˚C and -0.3 bar, (iii) 150˚C and -0.4 bar, and (iv) 110˚C and -0.4 bar. The tests have lasted until all 15 L of raw brine was evaporated.
Furthermore, the instantaneous electrical consumptions of the evaporator have been monitored throughout the tests in order to assess the energy performances at different conditions. The measurements have been carried out by means of a current clamp.

2.2.2.2. Integrated systems

After the data elaboration of the laboratory tests, the following integrated systems have been chosen and investigated in order to determine the best pre-treatment technologies before the FO/RO:

- Scenario 1 (figure 2.17), involves the chemical precipitation of the raw brine and the treatment of the supernatant flow by the FO/RO.

- Scenario 2 (figure 2.18), total evaporation of the raw brine with the distillate flow going to the FO/RO.
- Scenario 3 (figure 2.19), combination of raw brine evaporation and chemical precipitation of the distillate flow before the FO/RO.

The scenarios have been tested using an initial volume of 15 L of raw brine. The FO/RO membrane involve forward osmosis, in order to concentrate the influent flow, and reverse osmosis for the regeneration of the diluted draw solution and recovery of freshwater.
The main scopes of the following pre-treatment lines are:

- Ca and Mg recovery in liquid and solid phase.
- Avoidance of the membrane fouling and scaling, taking into account the TS concentrations and volumes going to the FO/RO.
- Energy optimization.

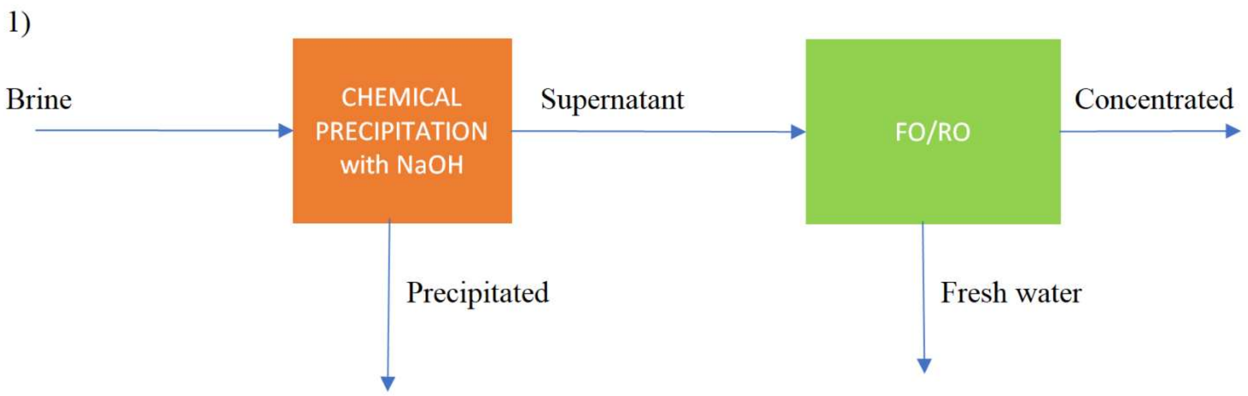


Figure 2.17: Scenario 1

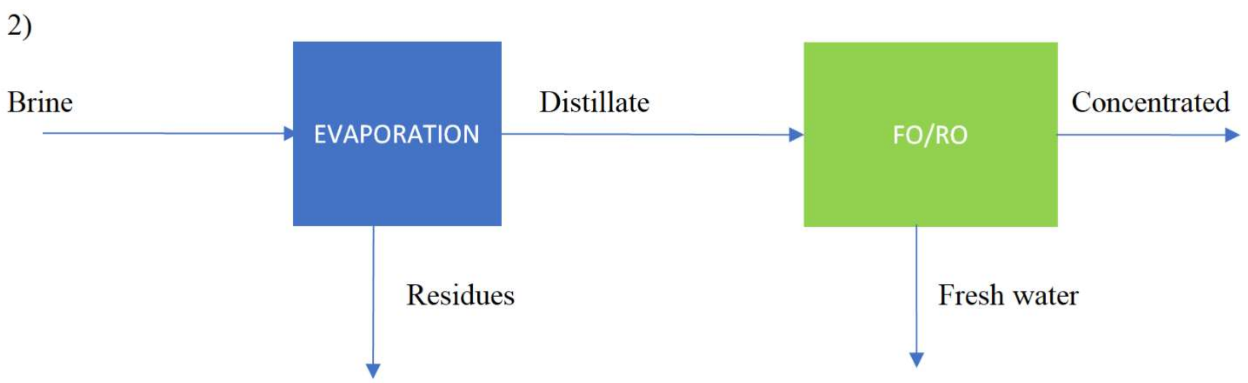


Figure 2.18: Scenario 2

3)

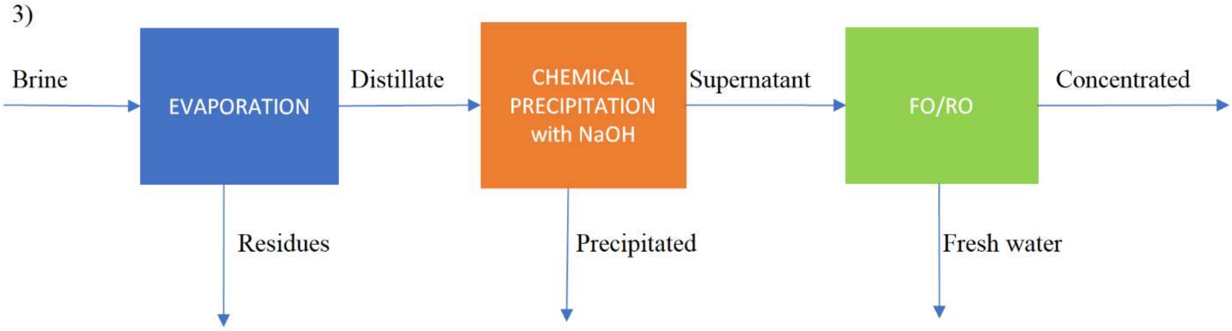


Figure 2.19: Scenario 3

3. RESULTS AND DISCUSSION

3.1. Replicability study of HYDROUSA solutions: Italian case study

The replication study methodology for HYDROUSA solutions, as explained in the chapter 2.1, has been applied in order to draw up the feasibility study report of the Italian case study, which involves the realization of the solutions HYDRO 1 and HYDRO 2 in Gorgona, a small island in the Mediterranean sea.

In this chapter the main findings and results of the feasibility report of the Italian case study are reported, while the whole feasibility study report is included in the annex for the sake of clarity.

The Italian replication site is situated in Gorgona, the smallest island of the Tuscany Archipelago in the Tyrrhenian sea and it is part of the Livorno municipality, which is 36 km away, in Tuscany region. The island is characterized by a typical Mediterranean vegetation and a rural landscape, the climate is usually temperate, and the precipitations are generally scarce. It hosts the last island penal colony in Europe, thereby the population is about 150 people and is composed of correctional facility inmates, guards and the local population. Gorgona territory has not got an own water source and the freshwater comes from the desalinization plant of the nearby island of Capraria, which has been installed to solve the water scarcity issue in the Tuscany Archipelago. The water is mainly exploited for domestic uses and for irrigation of the agricultural areas.

HYDRO 1 and HYDRO 2 have been chosen to be replicated on the island, thereby the final products from HYDRO 1 (e.g. reclaimed water, fertilizer) could be reused in site into HYDRO 2. The proposed project is the revamping of the existing wastewater treatment plant into HYDRO 1 while the agriculture areas on island are supposed to be the HYDRO 2. The main water-related challenges of Gorgona island are: (i) water scarcity, (ii) preservation of the natural resources from pollution, (iii) proper sludge management and (iv) lack of water loops and a circular management of the natural resources. The nature-based solutions of HYDROUSA could tackle these water-related issues and furthermore it might implement a circular business model for the decentralized community on the island. Thus, the main direct benefits of the HYDRO 1&2 for Gorgona island could be:

- Reduce the water scarcity
- Reclaim of nutrient-rich effluent wastewater for irrigation purposes
- Optimization of sludge management and reuse on site
- Reduce water pollution and use of natural resources
- Promote an alternative green economy to support social inclusion and well-being.

Therefore, such HYDROs aims to close the water and material loops on Gorgona, enhance the self-reliance of the island and of its inhabitants and, support a business model which might include all the population (i.e. inmates, etc.), without leaving no one behind.

Despite all the direct advantages of HYDROUSA solutions, the feasibility study report has been carried out to evaluate the social, legislative, technical, economic feasibility and all related aspects of possible HYDROs implementation in the replication site of Gorgona.

Starting from the social aspects, the HYDRO 1 could treat mainly the wastewater from the local penitentiary and the inmates could manage the HYDROs and be the final end-users of HYDRO 2 products. Thus, the realization of the project has become an opportunity to socially reinclude the inmates into the society, providing a service and creating business opportunities. The instruments to raise social awareness of the project in Gorgona are analysed and evaluated in the table 3.1 as explained into table 2.1. They are essential tools to inform the local population about the benefits of HYDROUSA nature-based solutions and support the social acceptability of them.

Table 3.1: Social feasibility evaluation

Feasibility Criteria	**SOCIAL FEASIBILITY**	
Type of instrument	**Example**	**SCORE**
Trainings and qualifications	Training and qualifications (obtaining certificates or proof of qualification) related to sustainable urban development, (socially inclusive) urban regeneration, closing loop infrastructure, nature-based solutions planning. Design, implementation and maintenance.	16 The HYDROs could be managed by inmates of the local penitentiary, who will be trained by the water utility for the purpose. The specification in the special tender specifications could establish that before an autonomous management, a "management on behalf" (in this case) of the UASB is envisaged, specifying that during this management the staff will be properly trained. The formation could be continuous, starting before the implementation of the HYDROs and going on also after the processes start-up. Personnel could be qualified for the specific maintenance roles.
Public information programs	A series of activities geared toward raising the amount of information available and people's awareness about sustainable urban development, (socially inclusive) urban regeneration, green and blue infrastructure, nature-based solutions etc. and its benefits (brochure,	16 The water utility and the water authority could arrange public gatherings to inform citizens (e.g. inmates, local population on island) about HYDROUSA and HYDROs projects.

	factsheets, events, campaigns, videos..)	
Stakeholder and public participation	Decision-making processes or knowledge-building consultations by policy makers which involve stakeholders with a direct interest in or practical knowledge of the issue being discussed, e.g. Townhall meetings, citizen councils, workshops for stakeholders, stakeholder advisory groups, multi-criteria analysis, household surveys	20 The water utility, the water authority and the local government authorities could be part of the HYDROs project, and they could actively contribute to it.
Monitoring systems for decentralized systems	Manual or automatic system (technological or by hand) which collects data about activities, products used, timing, etc. Monitoring and reporting of infrastructure areas Monitoring and mapping of activities relevant to sustainable urban development, (socially inclusive) urban regeneration, green and blue infrastructure	8 The monitoring activities for green infrastructure and ecosystems on Gorgona island is actually medium. Data about the HYDRO management could be firstly collected manually, like other reports related to the HYDROs monitoring.
Research projects	Research related solutions for sustainable urban development, (socially inclusive) urban regeneration, green and blue infrastructure, including development of more efficient solutions (e.g. green roofs and facades)	16 The involved stakeholders might be interested into the HYDROUSA project, which solutions might lead to social, environmental and economic advantages for Gorgona. These aspects could be monitored in detail once the HYDROs will be operative, with the collaboration of research centres or universities (i.e. UNIVPM and UNIFI). Other research projects in addition to Hydro have and will be implemented: (1) in April 2020, pilot Israeli water collection devices were installed; (2) an international "Summer" school in ecology and conservation will be organized next September 2021.
Assessments of decentralized system status/ ecosystem services	E.g. national overviews on the status of sustainable urban development, (socially inclusive) urban regeneration, green and blue infrastructure and related ecosystem services including mapping (e.g. Mapping and Assessment of Ecosystem Services - MAES)	15 At national level, green infrastructure mapping is quite scarce for Toscana region. However, the natural ecosystems on the island are classified and mapped. This HYDRO solution might represent a pioneer project for decentralized and regenerative treatment and business models and can be considered as a first case-study to

		implement decentralized solutions in rural contexts. Moreover, an accordance between the water utility and the Tuscany region is present for the mapping of the Tuscany archipelago green infrastructures in the foreseeable future.
OVERALL SCORE	**From 1 to 100**	**91**

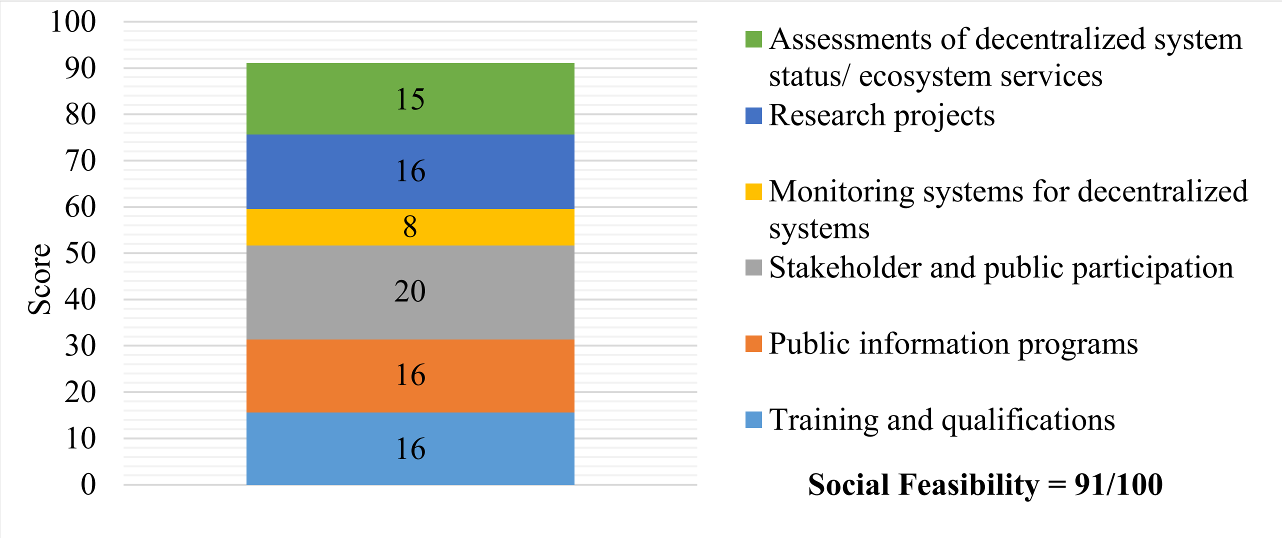


Figure 3.1: Comparison of the social sub-criteria

At national and local level, the assessment and monitoring of green infrastructures are medium. However, the public interest of the stakeholders and policymakers for the implementation of the innovative HYDROUSA solutions is high and relevant. Since HYDRO 1&2 is going to address the water-related criticalities of the island and implement a circular business model which includes the inmates of the local penitentiary and the local population. Thus, the feasibility of the project from a social point of view (i.e. awareness and acceptability) results satisfying and may support the realization of the HYDROs. Moreover, the project might represent a pioneer solution for small, decentralized systems and be an example to other realities in the Tuscany archipelago and Mediterranean Sea.

Regarding the policy framework, the plans/strategies involving Gorgona island and its water-related issues and targets at different institutional levels are assessed in the table 3.2. Indeed, they may either support or hinder the realization of the HYDROs on the replication site.

Table 3.2: Plan/strategies analysis

PLAN	LEVEL	DESCRIPTION	TARGETS AND CONSTRAINS FOR GORGONA ISLAND	EVALUATION
Structural Plan (Piano Strutturale Comune di Livorno)	Livorno municipality	The Gorgona island is known as Elementary Organic Local Unit-UTOE 22 and it is within the rural territory. The category of intervention is “conservation”.	Some of targets of the UTOE 22 are the preservation of the water resource and the protection of the natural resources from pollution.	The construction of the HYDROs is in line with the targets and constrains of the Structural Plan. However, the urbanistic classification should be modified from rural to technical service.
Urbanistic regulation (Regolamento Urbanistico Comune di Livorno)	Livorno municipality	The Gorgona island is part of the area "hilly and environmental system".	The environmental redevelopment plan rules the works on the territory and on the buildings.	Destination uses are not clear for Gorgona island.
Acoustic Classification plan (Piano di Classificazione Acustica Comune di Livorno)	Livorno municipality	The island is subdivided in homogenous classes: I (area particularly protected), II (area with residential destination), III (mix areas).	The replication site is situated in area II, thereby acoustic emissions levels should be observed.	Through the construction and management phase, some precautions could be adopted, to respect the acoustic limits of the area. Moreover, the noise impact document (DO.IM.A.) is needed for the building permission.
Water Protection Plan (Piano Tutela delle Acque (PTA))	basin "Coast Tuscany"	Gorgona is part of the “Tuscany coast” basin- Tuscany Archipelago.	The quality target for the Tuscany Archipelago is “1-HIGH”. Besides, the reuse of reclaimed water is advised in order to tackle the water related issues of the Tuscany Archipelago.	The HYDROs realisation is compatible with the water protection plan.
Territorial Direction Plan (Piano di Indirizzo Territoriale (PIT) con valenza di piano paesaggistico)	Tuscany region	The island is part of the area “n. 8 Piana Livorno-Pisa-Pontedera”.	The whole island is submitted to landscape constraint (G.U. n. 150 of the 1971). One of the plan targets for the island is the requalification of the rural landscape.	The project aim is in line with the preservation targets and constrains of the plan. However, ordinary permissions to evaluate the project and work impacts could be needed.

Plan of the National Park (Piano del parco nazionale dell'Arcipelago toscano)	National park of Tuscany archipelago	The plan subdivides the island in two areas: zone B “natural reserve” and zone C “extensive protection.	The replication site is situated within the zone C. One of the plan target for the island is the requalification of the rural landscape.	The project is in line with the preservation targets and constrains of the plan. Moreover, the permission of the National Park could be needed to realize the project.
Network Natura 2000 (Siti rete natura 2000)	Tuscany region	The island and the nearby marine areas are included into the network Natura 2000 under the Birds directive and Habitats directive.	The island and the nearby marine areas are classified as special area of conservation (SAC) and as special protection area (SPA).	The implementation of the HYDROs must be evaluated through an impact assessment (VINCA) in order to analysis the possible effects on the Network 2000 sites.
Plan of Management Flooding Risk (Piano di gestione rischio alluvioni (PGRA))	basin "Coast Tuscany"	The hydraulic hazard map of the plan identifies two areas on the island: one with high probability of flooding P3 and another with moderate probability of flooding P2.	The replication site is situated close to an area which has a high probability of flooding P3 with a return period between 20 and 50 years.	The HYDRO 1 could be carefully developed outside the zone P3 for safety reasons.
Territorial Plan of Provincial Coordinament (Piano territoriale di coordinamento provinciale (PTCP))	Livorno province	Gorgona is included into the system 4) “island landscape” and into landscape area (Adp) “24 Gorgona”.	The anthropological works should meet the circular economy, which has been implemented by the prison activities.	The HYDROs realisation is compatible with the territorial plan.

The main products of the HYDRO 1 are reclaimed water for irrigation purposes and sludge/compost for agriculture areas. There is not a unique legislative instrument that regulate the reuse of them. Different national/regional legislations may be applied requiring different quality standards, monitoring frequencies, bans, reuse modalities and authorisations, which may lead to an economical either advantageous or disadvantageous implementation of the HYDROs. Therefore, four policy instruments and relative scenarios have been identified for the reuse of reclaimed and three scenarios for the use of sludge/compost in agriculture. They are, respectively, analysed in table 3.3 and 3.4.

Table 3.3: Legislative instruments for the reuse of reclaimed water from HYDRO 1

REUSE RECLAIMED WATER				
	SCENARIO 1	**SCENARIO 2**	**SCENARIO 3**	**SCENARIO 4**
LEGISLATIVE INSTRUMENT	D.M. n. 185/2003	D. lgs n. 152/2006	DPGR n. 46/R 2008	Regulation EU n. 741/2020
DESCRIPTION	The reclaimed water has to fulfil the technical rules of the Decree for its reuse in agriculture.	The reuse of reclaimed water is set as discharge on soil and it has to fulfil the relative limits.	The reclaimed water is set as “agri-food wastewater” for fertigation purposes and it has to fulfil the relative limits. (Art. 101 com.7 D. Lgs. 152/2006, e annex 2 of DPGR n. 46/R/2008).	The Regulation summarizes the minimum requirements for water reuse depending on the vegetative species and their final use on the market. The introduction of these quality standards results in a more economically feasible reuse of reclaimed wastewater for irrigation purposes, even for small and decentralized water systems.
QUALITY STANDARDS	Quality standards are listed in the table within the annex and in the note 4 of the annex.	Quality standards are listed in the table 4 of the annex 5 of the third part. In addition, according to the com. 1, the region may define their own quality standards taking into account of the maximum admissible loads and of the best available technologies.	The use of "agri-food wastewater" for irrigation purposes is allowed if the following conditions are fulfilled: a) preservation of the water bodies reaching their quality targets, b) the fertilising effects on soil and on crops are provided depending on the quantitative and temporal demands, c) hygienic, environmental and urbanistic regulations are observed (art. 28).	annex I table 2, quality levels B and C.

MONITORING FREQUENCY	The plants for the treatment of wastewater is subject to the monitoring by competent authority (art. 7). The monitoring may be carried out by the owner of the plant (art. 6).	4 monitoring per year (annex 5 third part).		Annex I table 3 routine monitoring frequency, annex I table 4 monitoring frequency for validation.
REUSE MODALITIES	The reuse should assure water saving and not exceed the water demand of crops and green areas. In addition, the reuse for irrigation purposes has to fulfil the "Code of good agricultural practice" (D.M. n. 86/1999) according to the article 10 of the D.M. n. 185/2003. A fertilization plan should be drafted.	The reuse modalities are not reported.	The reuse modalities are stated in the art. 28 of DPGR.	annex I table 1 the irrigation methods are identified. The reclamation plant operator shall not be responsible for the quality of reclaimed water after the point of compliance.
BANS		In the annex 5, part third, the substances, whose discharge is banned, are reported. However, according to the art. 100 com. 2 the water utility may authorize the treatment of liquid waste, which are compatible with the processes/units of the WWTP, for particular needs.	Bans are listed in the article 24 bis.	In the annex I table 1 the allowed crop categories are stated.

AUTHORISAT.	Environmental authorisation (AUA Autorizzazione Unica Ambientale) to the SUAP of municipality.	Environmental authorisation (AUA Autorizzazione Unica Ambientale) to the SUAP of municipality.	Simplified communication reported in the annex 4, cap. 5, com. 3 of the DPGR to the SUAP of municipality (art.29).	Any production and supply of reclaimed water destined for a use agricultural irrigation as specified in section 1 of Annex I, shall be subject to a permit or authorisation.
EVALUATION	Restrictive limits and demanding monitoring frequency.	Low sampling frequency, restrictive limits and the irrigation use is not mentioned	Moderate limits, irrigation use is mentioned but not clear information about quality monitoring	The Regulation shall be enforced by June 2023. The adoption of this legislative instruments may be economically advantageous for the implementation of decentralized solutions as HYDRO 1&2.

The Regulation EU n. 741/2020 has been approved by the European parliament and council in date 25 May 2020, it shall be enforced after 3 years of its approval. Therefore, in the foreseeable future this legislative instrument might be adopted for a cost-effective implementation of the HYDROs on Gorgona island.

Table 3.4: Legislative instruments for the use of compost from HYDRO 1

REUSE COMPOST FROM TREATED SLUDGE			
	SCENARIO 1	**SCENARIO 2**	**SCENARIO 3**
LEGISLATIVE INSTRUMENT	D. lgs. n. 99/1992	D.M. n. 266/2016	D. lgs. n. 75/2010 and the following updates by the D. lgs. n. 218/2013
DESCRIPTION	The Decree governs the direct reuse of the sludge on soil	Realization of a composting system managed by the small community on the island. The composting activity is carried out according to the rules of annex 4, part A and part B.	The treated sludge is labelled as "compost from sludge".

QUALITY STANDARDS	In the annex IA maximum quality standards for soils are listed. In the annex IB maximum quality standards for sludge are reported. Art. 3, com. 4 other limits are stated.	The allowed materials and wastes for the composting system managed by small community are listed in the annex 3: treated sludge is not mentioned.	The compost should fulfil the limits of the category "compost from sludge" of the D. lgs. n. 218/2013, attachment 2.
MONITORING FREQUENCY	At least 1 analysis of the soil each 3 years (art 10). At least 1 analysis of the sludge each year or each time the characterization of the treated wastewater largely changes (art. 11).	The monitoring is performed by the regional environmental agency and the municipality (art. 9).	The monitoring is performed by environmental agencies according to article 6 of the D. lgs. n. 75/2010.
REUSE MODALITIES	According to article 12 com. 6, the stabilized sludge may be reused following the rules of the DM n. 86/1999 “Code of good agricultural practice".	For the reuse in agriculture, the compost has to fulfil the characteristics of the categories "mix compost" and "green compost" according to the D. lgs. n. 75/2010 and following updates (art.6 com. 2).	Before the use, the compost must be labelled, and specific features reported (part I of the D. lgs. n. 75/2010).
BANS	In the article 4 bans for reuse are reported.		
AUTHORISAT.	Environmental authorisation (AUA Autorizzazione Unica Ambientale) to the SUAP of municipality.	Simplified procedure submitted to the municipality (art. 3).	Once the compost is labelled, it can be used/sold.
EVALUATION	Restrictive limits, demanding monitoring frequency and labelling is necessary.	Labelling is necessary. The sludge is not mentioned for community composting systems.	Restrictive limits, demanding monitoring frequency and labelling is necessary.

Furthermore, at the national level, the decree law n. 109/2018 (“Genova decree”) in the art. 41 tries to address the topic of the sludge management, which have come up during the recent years. It reinforces the D. lgs. n. 99/1992 and establish a more restrictive quality standard for the hydrocarbons in the sludge (i.e. 1000 mg/kg as-is). Therefore, the three legislative instruments in table 3.4 are present at national level for the direct reuse of the sludge in agriculture or for its use as compost. However, the Tuscany region has been denying the authorizations for the direct reuse of the sludge in agriculture since 2016; especially for organic farming, imposing unfeasible restrictive limits.

Indeed, the Tuscany region is stalling and is waiting for the promised rearrangement of the relative legislation at the national level. Hence, regarding the Gorgogna case study, the most likely pathway for the use of the treated sludge in agriculture is the D. lgs. n. 75/2010 (updates by the D. lgs. n. 218/2013). The treated sludge of the HYDRO 1 has to be labelled as "compost" before its reuse in the HYDRO 2.

While the construction of HYDRO 1 is regulated by the regional law L.R. 65/2014, it may be considered as primary urbanization work thereby its realization is subjected to the building permission, which is free of charge for water-related infrastructure. The building permission is submitted to the office for productive activities (SUAP) of Livorno Municipality and it involves three regional standard paperwork: parties involved attachment (in Italian "Allegato soggetti coinvolti"), form for building permission (in Italian "Richiesta di permesso a costruire") and asseveration report (in Italian "relazione tecnica di asseverazione"). Moreover, the following attachments are needed with the asseveration report.

Table 3.5: Attachments of the asseveration report

Attachment	Why?
Technical elaboration of the actual situation, project and descriptive relation	Routine
Photographic documentation of the actual situation	Routine
Structural document (Deposito stutturale ex-Genio Civile)	Routine
Ordinary permission (Autorizzazione paesaggistica rilasciata con procedimento ordinario)	The whole island is submitted to landscape constraint (G.U. n. 150 of the 1971), so the ordinary permission to evaluate landscape impacts is needed according to the D.P.R n. 31/2017
Authorization of the National Park (Nulla osta Ente parco nazionale)	Gorgona is part of the National Park of the Tuscany archipelago which authorise the realisation of "HYDRO 1" according to the National Law n. 394/1991
Impact assessment (VINCA: Valutazione d'incidenza)	The island and the nearby marine areas are special area of conservation (SAC) and special protection area (SPA) of the Network Natura 2000. Therefore, an impact assessment is needed according to the Regional Law 30/2015.
Noise impact document (DO.IM.A.: Documentazione di Impatto acustico)	According to the technical rules of the acoustic classification plan of Livorno municipality, the realisation of the works needs the noise impact document

The art. 158 bis of the D. lgs n. 152/2006 imposes a simpler procedure for the construction of a wastewater treatment plant with the presentation of the authorisation to the water authority. However, the Gorgona territory is out of the integrated water service perimeter, so the building permission is necessary for HYDRO 1 realisation as previously explained.
Moreover, a combined heat and power (HCP) generator unit could be installed in order to reuse the biogas from the UASB for the heating of the reactor itself. According to the Legislative Decree n. 387/2003, the realization and the management is not subjected to authorization since the nominal power of the generator is below 3 MW thermal. The realization of the HYDRO 2 is not subjected to authorisations, since the existing agriculture areas of the island are supposed to be exploited.

The broad analysis of the policy framework may be quite time-consuming though it might support the assignation of objective scores for replicability evaluation. Once the plans/strategies, the legislation framework affecting the reuse of the HYDRO 1 by-products and the permitting pathways for the construction of the HYDROs are deeply analysed, at different levels. The policy feasibility analysis may be carried out assigning a score to each policy-sub criterion as table 3.6 illustrates based on the table 2.2.

Table 3.6: Policy feasibility evaluation

Feasibility Criteria	**POLICY FEASIBILITY**	
Type of instrument	**Example**	**SCORE**
National/ regional planning law or regulations	Spatial planning law, environmental regulation and/or law, directives focusing on water cycle.	8 The realization of the HYDROs could be supported by the policy framework. Different regulations implement the use of by-products (reclaimed water and stabilized sludge) in agriculture. However, regulations for small systems are not clearly stated in the regulatory framework. The final by-products use/reuse may not be economically viable if the regulations for big systems are applied.
National/ regional strategies and action plans	National strategies for sustainable development, water cycle wastewater treatments, green and blue infrastructure etc.	8 The regional and local strategies might promote the use of reclaimed water from WWTP in order to tackle the scarcity of fresh water and water pollution in the Tuscany Archipelago. However, the use of stabilized sludge in agriculture and the recovery of biogas are not mentioned. A specific regulation could be implemented

		at national and regional level for small decentralised system.
Planning/ zoning	Comprehensive planning of the different uses to be conducted in areas of an urban settlement designated by certain categories	8 The replication site is situated on the Gorgona island, which is subjected to different environmental constrains due to its value. Therefore, different precaution actions should be taken into account for the realization of the HYDROs.
Targets	Targets focused on decentralised systems, water loop cycle, recovery resource, sustainable urban development, urban regeneration, green and blue infrastructure etc. Targets focused on these could be part of sustainable development strategies or action plans, strategies or similar	8 The regional and local targets are essentially the preservation of the agricultural landscape and to tackle the water scarcity and water pollution on the island, which are in line with HYDROs. The sludge management and the biogas recover are not specifically listed as main objectives.
Standards	Legal or regulatory requirements for all persons or businesses to whom it applies to maintain a certain level of environmental quality confine actions to a certain type of practice or limit, or to rehabilitate resources. E.g. in a certain area the effluent from WWTP should satisfy certain limits, by-products (fertilizer) for reuse should have certain characteristics, etc. Legal or regulatory requirement for the utility to maintain a certain level of environmental quality, limits, or to rehabilitate resources. e.g. **Mandatory:** Environmental standards by law, directives, plans, etc. **Voluntary:** Agreements between private citizens and Municipality regarding the management and reuse of the HYDRO by-products.	9 The regulatory instruments define precise standard quality for the reuse of reclaimed water and stabilized sludge in agriculture. However, as they refer mainly to centralised plants, the application to small decentralised systems, managed at community level, could be too onerous.
Bans	A legal or regulatory prohibition of a certain type of activity or use of a material/ product.	11 There are no clear bans to the HYDROs implementation: all by-products of the HYDRO 1 could be used in HYDRO 2 according the regulatory framework, once the quality standards are fulfilled.
Permits / quotas	A license or authorization issued by a competent Authority allowing the utility to perform certain activity or to have a certain portion / amount of a product. Requirements such as maintenance of pre-development	6 Different permissions could be needed to obtain the authorisation for HYDRO realisation, due to required works and to the environmental constraints on the replication site. Moreover, as actual policy

	hydrology or pollutant loading reduction requirements are tied to stormwater permits.	framework refers mainly to centralised plants, the application to small decentralised systems, managed at community level, might be too onerous.
Environmental impact assessments	Legal or regulatory process which an individual or business must undergo before application for approval to perform a certain action. Environmental Impact Assessment (EIA), audits, inspections	11 Considering the small scale of the HYDROs, the EIA procedures could be simplified and not obstructive for the project implementation
Public Procurement	Green Public Procurement (GPP)	11 The GPP can be easily applied while applying the required procedures for public or private tenders
OVERALL SCORE	**From 1 to 100**	**80**

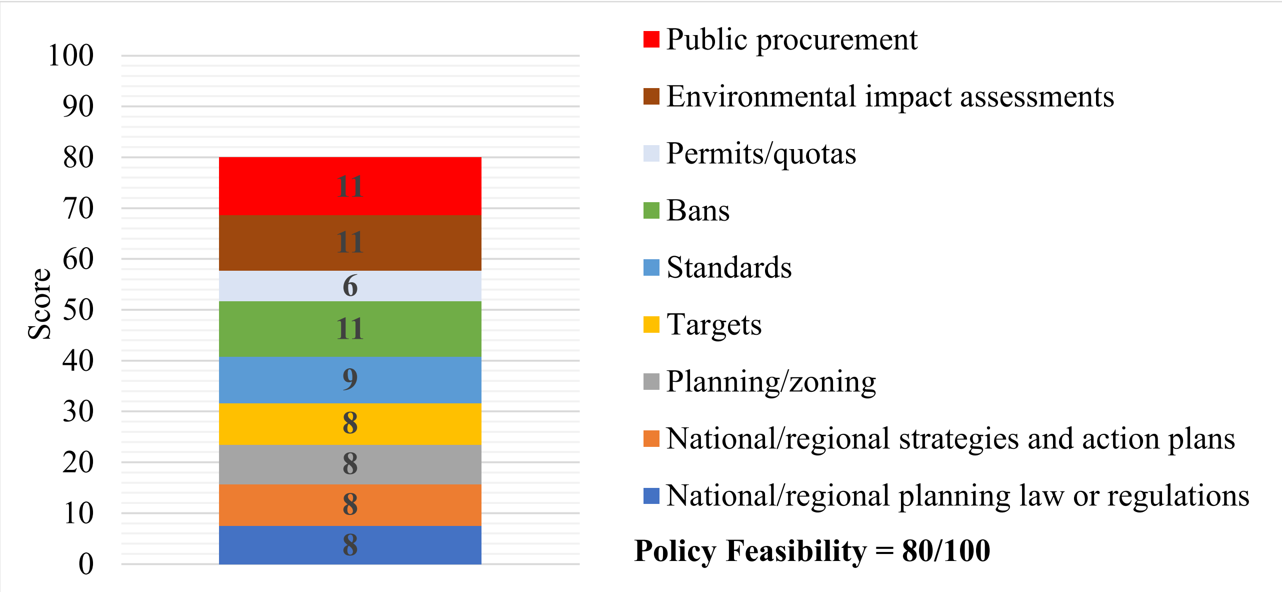


Figure 3.2: Comparison of the policy sub-criteria

An ad-hoc legislation instruments to support small, decentralized water-related service as well as for the implementation of regenerated close loops is not present. Furthermore, the fulfilling of high-quality standards for reclaimed water and sludge, enforced by some regulations, may hamper the economic sustainability of the project. Despite these possible barriers, the policy feasibility of HYDRO 1&2 in Gorgona may be considered satisfying, with a score of 80/100. A collaborative discussion between the water utility and policymakers may support the application of legislative instruments, which result in an economic viability of the project. In addition, no general barriers that completely prevent the application of HYDRO 1&2 and of its final products have been found in the Italian and regional regulatory framework.

While for the technical feasibility, a possible layout of the HYDRO 1 has been proposed to be integrated with the existing WWTP nearby the local penitentiary, in order to reduce the consume of the soil and save costs. Hence, the HYDRO 1 could be composed of:

- N. 1 Existing screening for the removal of inert materials and a pumping station
- N. 1 Upflow Anaerobic Sludge Blanket (UASB) reactor
- N. 1 Combine heat and power (CHP) unit in order to generate heat
- N. 1 Existing Imhoff tank, which could be used as pumping station for vertical flow (VF) constructed wetland
- N. 2 VF constructed wetlands (two lines in parallel)
- N. 2 Existing horizontal flow (HF) constructed wetlands (two lines in parallel)
- N. 1 Sand Filtration (tertiary treatment)
- N. 1 UV disinfection (tertiary treatment)
- N. 1 Sludge Drying Reed Bed (SDRB) for the treatment of the excess sludge

The capacity of the plant would be about 220 PE during the summer and 150 PE during the winter, treating a flowrate of 62 m^3d^{-1}. The block flow diagram of the proposed HYDRO 1 for Gorgona island is reported below in the figure 3.3. The influent wastewater could be pre-treated through screening and then go to the UASB reactor which could have a footprint of 3.7 m^2 and an excess sludge about 0.062 kg d^{-1}. The biogas produced was preliminary estimated about 60 m^3d^{-1} with an energy content of 47.6 kWh d^{-1}; it could go to the CHP unit in order to be converted into heat for the heating of the UASB reactor, the reused energy was estimated about 28 kWh d^{-1}. The UASB reactor operates under anaerobic conditions, hence for modest flow rate it is able to treat the influent organic load while produces biogas and low excess sludge. The wastewater effluent from UASB reactor is supposed to be divided into two identical lines of constructed wetlands, each line could be composed of a new vertical flow (VF) constructed wetland and the existing horizontal flow (HF) constructed wetland. The total area of VF constructed wetlands should be about 380 m^2 (190 m^2 for each line), whereas the total area of the existing HF constructed wetlands is 1000 m^2 (500 m^2 for each line). The first ones are under aerobic conditions while the second ones are anaerobic, hence they are able to carry out nitrification and denitrification. Subsequently the effluent could go to the tertiary treatments, which could be composed of sand filtration and UV disinfection. Both units are necessary to meet the quality standards of different legislative instruments for reclaimed water. The sand filtration could have an area of 0.4 m^2, a part of its effluent could be used for backwashing and then goes back to the UASB reactor. The UV disinfection could involve the use of one lamp in order to break down the pathogenic load.

The produced sludge from the UASB reactor is supposed to be carried to the sludge drying reed bed for the stabilization treatment, the SDRB allows a safe reuse of the sludge in agriculture as compost. The implementation of the SDRB could avoid the costs for the disposal of the sludge, which may be quite expensive due to the maritime transportation.

If the treated sludge from SDRB could not have the quality characteristics to be labelled as “compost from sludge”, a composting system will be needed in order to meet the quality standard of the D. lgs. n. 75/2010 and following updates by the D. lgs. n. 218/2013. This technology may be able to treat the organic waste of the whole island.

The design of the HYDRO 2 is not carried out since the existing agricultural areas nearby HYDRO 1 could be used.

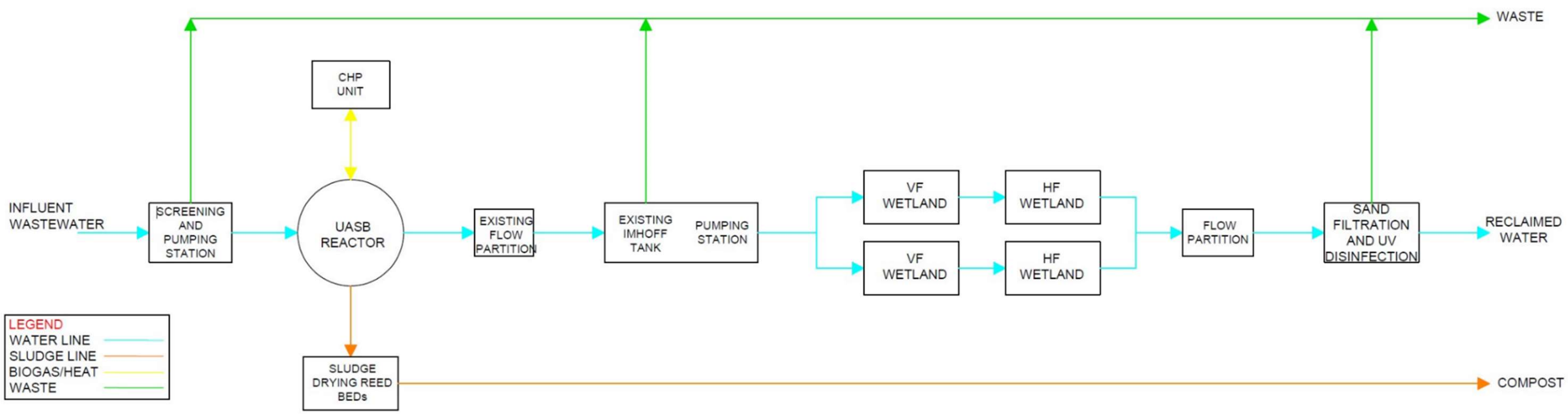


Figure 3.3: Block flow diagram of the proposed HYDRO 1

In the following figures (figure 3.4, 3.5, 3.6), preliminary and expected mass and energy balances of the units/processes involved in the HYDRO 1 proposal are reported in order to evaluate the technical KPIs.

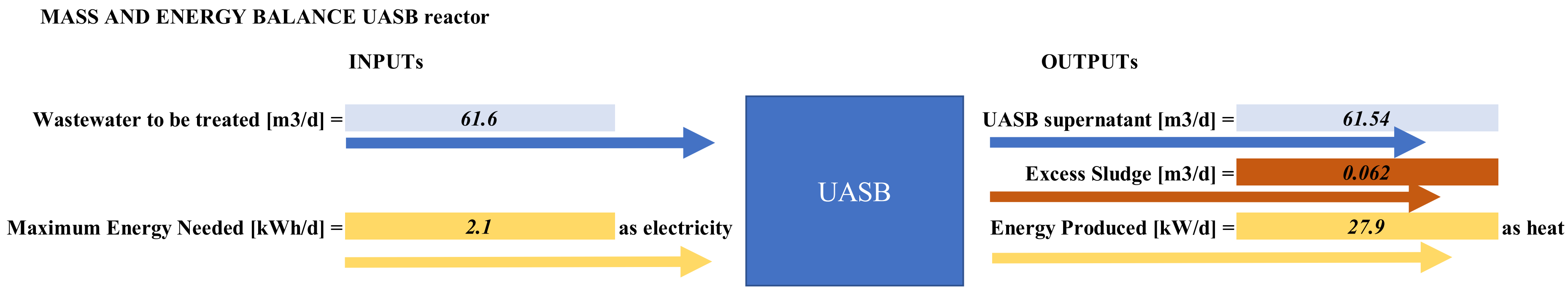


Figure 3.4: Preliminary mass and energy balance of the UASB reactor

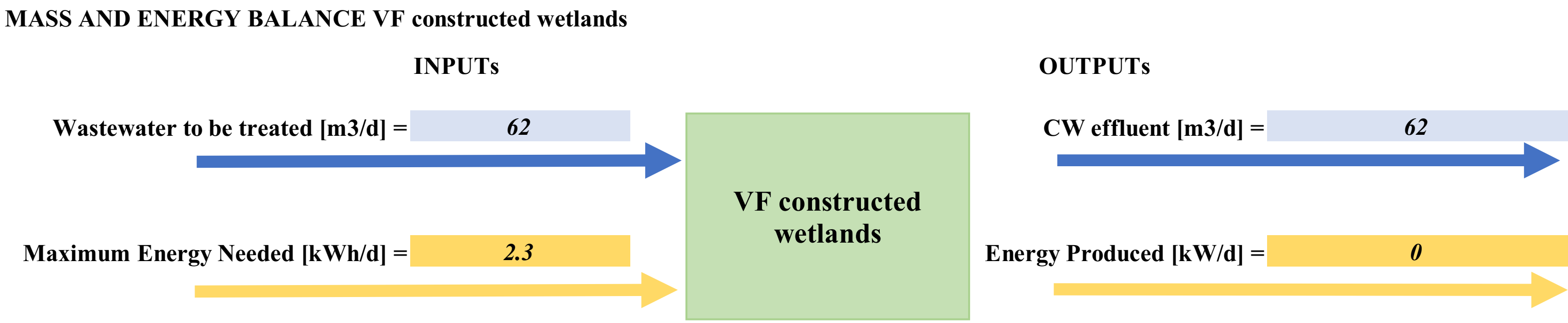


Figure 3.5: Preliminary mass and energy balance of VF constructed wetlands

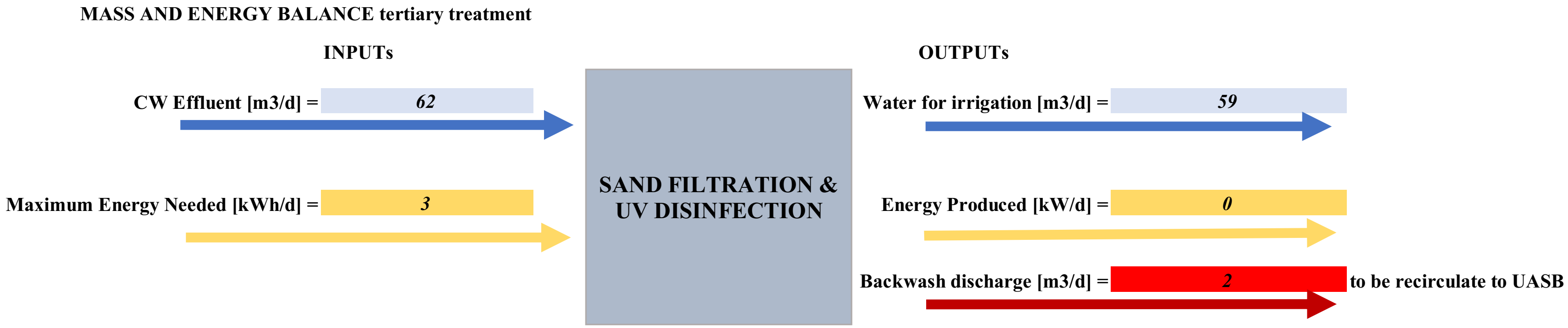


Figure 3.6: Preliminary mass and energy balance of sand filtration & UV disinfection

Once the proposed layout, the planimetry and preliminary designs of the main units/ processes have been carried out, the KPIs of the HYDROs may be calculated in order to evaluate the technical feasibility of the project as explained in table 2.3.

Table 3.7: Technical feasibility evaluation

TECHNICAL FEASIBILITY				
HYDRO	**Feasibility Sub-Criteria**	**Definition of Sub-Criteria**	**Expected Value**	**SCORE**
1+2	Efficiency	Reuse wastewater with high nutrient content (m^3/y)	21,703.00	90 The amount of reclaimed wastewater might be enough for water supply of the HYDRO 2.
		Recovered energy from Biogas (MWh/y)	10.22	90 The amount of recovered energy might be enough for the heating of the UASB reactor.
OVERALL SCORE		**From 1 to 100**		**90**

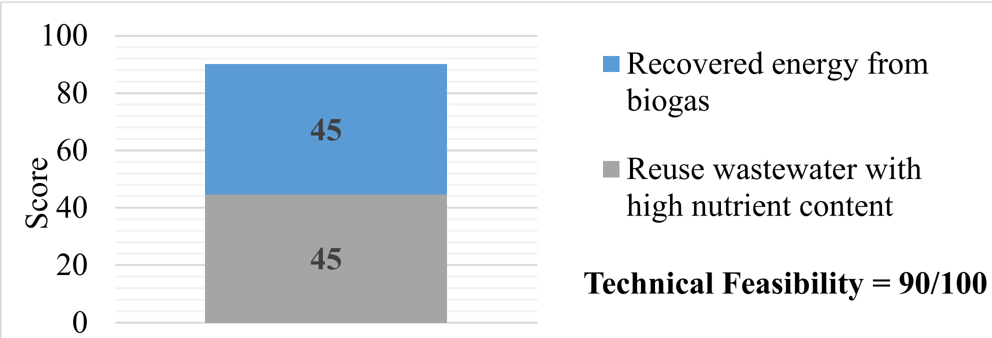


Figure 3.7: Comparison of technical sub-criteria

The technical feasibility of the project is evaluated to be about 90/100, the recovered energy from biogas and the reclaimed water are enough, relatively, for the heating of the UASB reactor and for water supply of the HYDRO 2. The amount of the compost from the composting systems was not considered in the technical feasibility as table 2.3 shows. Since at this stage of analysis no data are available to estimate the organic waste load in the island, for the compost production, compost was not considered as potential revenue stream.

Regarding the economic feasibility, the CAPEX, yearly OPEX and revenues are estimated comparing the data from the demo case studies in Greek and using literature values. The Capital Expenditure was estimated about 355,735.00 € including costs for legal affairs/ staff training/ product certification, unit supply and installation; the land purchase is not present since the existing WWTP and agriculture areas could be used. An investment grant representing the 40% of the CAPEX is assumed to be funded by the Livorno municipality, due to the fact that the HYDROs cloud close the water loop on the island (i.e. wastewater treatment, water for irrigation purpose) solving water-related criticalities. Moreover, a sort of "research centre of the circular economy", which is one of the municipality targets for

Gorgona, could be implemented thanks to the HYDROs. So, the CAPEX might go down to 142,294.00 €. The estimated partition of the investment costs is reported in the figure 3.9.
The highest expenditure is estimated for the UASB reactor, the costs for constructed wetlands are supposed to be reduced thanks to the revamping of the two existing beds and the exploiting of the remaining existing two beds. The HYDRO 2 costs could be negligible since the existing areas in Gorgona might be exploited.

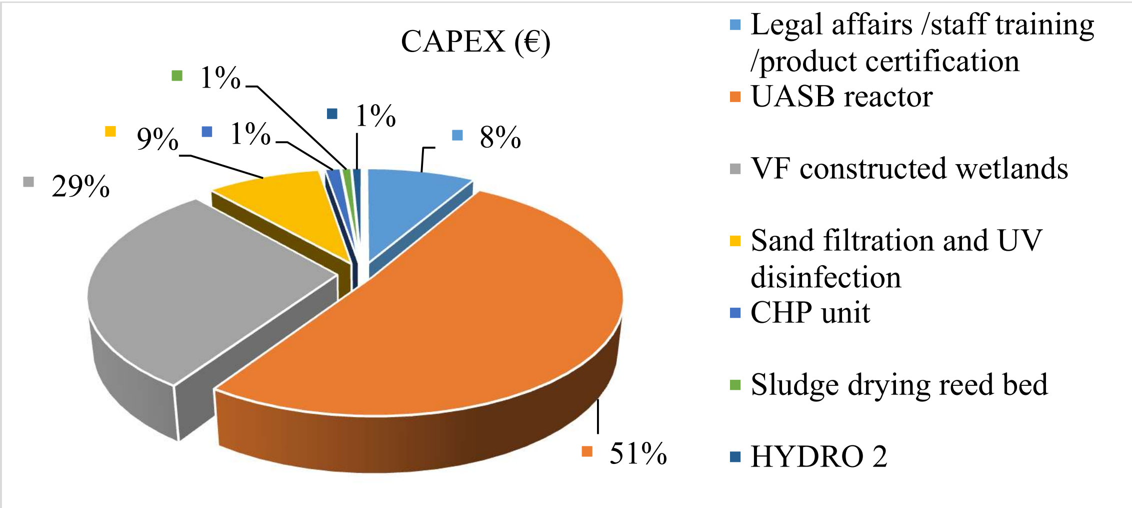


Figure 3.8: CAPEX distribution

The estimated yearly OPEX might be about 13,244.00 € per year including costs for energy, staff and maintenance as figure 3.10 highlights. Although the highest OPEX could be related to staff costs, they are supposed to be destinated to the inmates who manage the HYDROs.

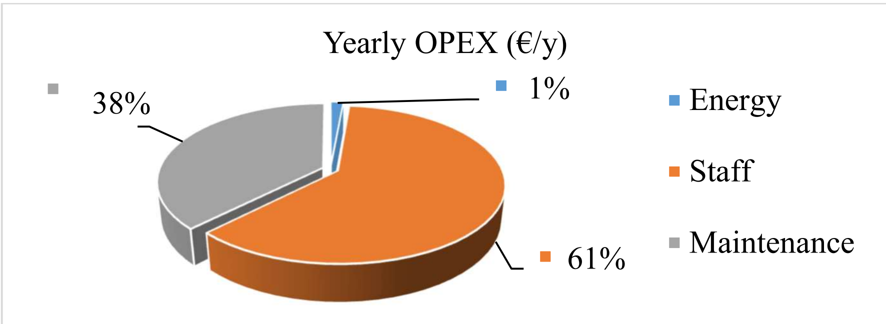


Figure 3.9: Yearly OPEX distribution

The yearly revenues were estimated about 39,152.00 € including the selling of reclaimed water and water tariff for the treatment service, allocated as figure 3.11 shows. The highest profit was detected to be related to the water tariff and the incomes from reuse of treated wastewater for irrigation are supposed to be reduced by a 50% since the half of the reclaimed water is supposed to be reused into

HYDRO 2. According to the proposal, the produced biogas and compost will be not sold and will be, respectively, reused in site and into HYDRO 2. Furthermore, the revenues from the sale of vegetable and fruits produced into HYDRO 2 could be completely given to the inmates of the local penitentiary.

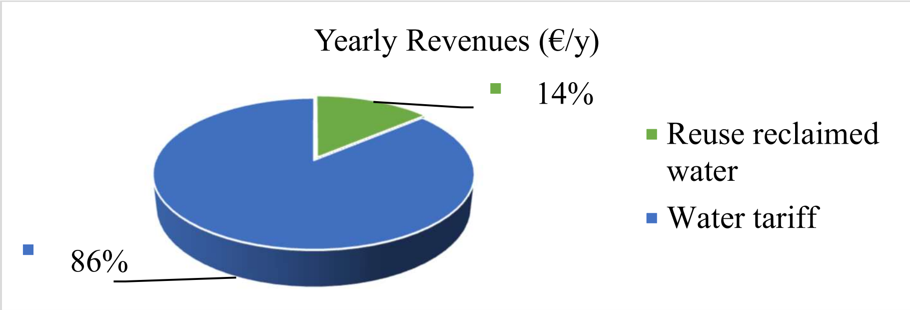


Figure 3.10: Yearly revenues distribution

Considering the previous CAPEX, yearly OPEX and yearly revenues, the payback period may be estimated and should be about 5.5 years, the possible timeline of HYDROs costs and revenues is reported in the figure 3.12.

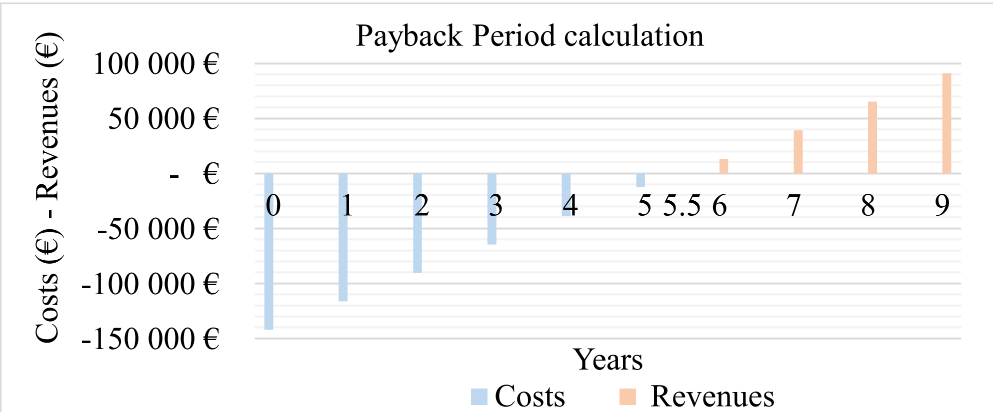


Figure 3.11: Costs & Revenues timeline

Hence, the economic feasibility score of the project is obtained according to the table 2.4.

Table 3.8: Economic feasibility evaluation

ECONOMIC FEASIBILITY		
Feasibility Criteria	Feasibility Sub-Criteria	Score
Economic Feasibility	Payback Period of 5.5 years	65
OVERALL SCORE	**From 1 to 100**	**65**

The economic feasibility score may result modest because the reclaimed water and the fertilizer from HYDRO 1 reused into HYDRO 2 are assumed to be completely granted on voluntary basis. Moreover, the revenues from the sale of vegetable and fruits produced into HYDRO 2 are supposed to be completely provided to the inmates of the local penitentiary. This financial policy may result in a higher payback period though the inmates could take advantages of priceless benefits such as social inclusion, labour market integration and honest incomes. Therefore, the well-being and the rehabilitation of the prisoners into the society would be preferred rather than the economic profits of the water utility.

Finally, the overall feasibility matrix of the HYDROs in the Gorgona site is drawn up as explained in the table 2.5.

Table 3.9: Feasibility matrix of Gorgona HYDRO 1&2

FINAL RESULTS			
Feasibility Criteria	Main Feasibility Sub-Criteria	Weight	Score
Social Feasibility	Stakeholder and public participation, Social Benefits, Social Acceptance	30%	91
Legal Feasibility	Strategies and Action plans, Targets and Quality standards, Permitting Pathway	30%	80
Technical Feasibility	Efficiency	20%	90
Economic Feasibility	Financial pathway, Payback Period	20%	65
OVERALL FEASIBILITY	-	**100%**	**82**

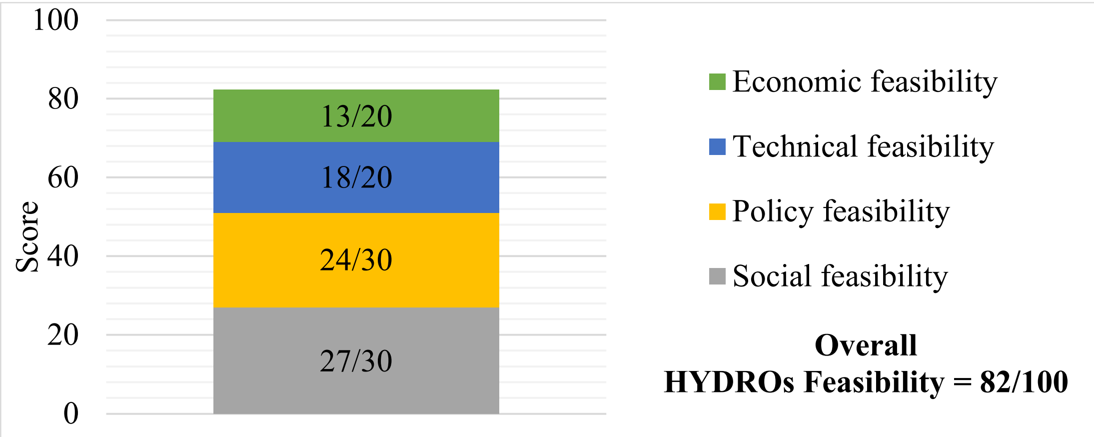


Figure 3.12: Comparison of the HYDROs feasibility criteria

Analysing the results of the study, the replicability of HYDRO 1 and HYDRO 2 on Gorgona island could be socially, legally, technically, and economically feasible. By the way, the overall score is about 82/100 and there are still ways for improvement. For instance, the policy feasibility for HYDROs realization and exploitation of their products may be improved by implementing a collaborative debate between stakeholders and policymakers about the benefits of the nature-based solutions: how NBS might contribute to tackle water-related challenges in small and decentralized communities, contributing also to develop locally a circular business model. The economic and social

feasibility may be enhanced by implementing a touristic business, where the circularity of the HYDROs, their social benefits for local inmates and the integration with the surrounding landscape are highlighted.
Although there are wide margins of improvement for Gorgona case study, it is a pioneer project for decentralized and small communities and may be an inspiration for other similar realities, which are threatened by water-related challenges in the foreseeable future and often “left behind” from policymakers, without local development and investment strategies.

Finally, the main issues detected for the social, legal, technical and economic feasibility of the project are reported in table 3.10 together with the possible solutions for improving the replicability.

Table 3.10: Issues detected and possible solutions

<table>
<tr><th colspan="4">FINAL RESULTS</th></tr>
<tr><th>Feasibility Criteria</th><th>Score</th><th>Issues Detected</th><th>Possible suggestions for improving feasibility</th></tr>
<tr><td rowspan="3">Social Feasibility</td><td rowspan="3">91</td><td>Monitoring and mapping Green Infrastructures</td><td>Creation/update of a Regional database for GI monitoring</td></tr>
<tr><td>Monitoring systems for decentralized systems</td><td rowspan="2">So far, the absence of a Regulatory Body at community level suggests the need to define a whole policy process for implementing the management of decentralized system by local communities.</td></tr>
<tr><td>Assessments of decentralized system status/ecosystem service</td></tr>
<tr><td rowspan="2">Legal Feasibility</td><td rowspan="2">80</td><td>Lack of ad hoc regulations for small and decentralized systems</td><td rowspan="2">Implementation of regulations based on the community composting approach and application of quality standards based on the cultivated crops (for irrigation purposes)</td></tr>
<tr><td>lack of regional legislative instruments for sludge spreading for agricultural uses.</td></tr>
<tr><td>Technical Feasibility</td><td>90</td><td>No major issues are detected</td><td>No major issues are detected</td></tr>
<tr><td>Economic Feasibility</td><td>65</td><td>No major issues are detected</td><td>No major issues are detected</td></tr>
<tr><td>OVERALL FEASIBILITY</td><td>82</td><td></td><td></td></tr>
</table>

3.2. Brine treatment and recovery compounds:

3.2.1. Preliminary laboratory tests

The results of the laboratory tests are reported in the following chapters, firstly analysing the evaporation tests, secondly the chemical precipitation (coagulation and flocculation) and finally the main findings of the tested integrated systems are reported.

3.2.1.1. Evaporation tests

The following evaporation tests have been carried out on the raw brine in order to evaluate the concentrations of anions and cations dissolved in the distillate and in the concentrated flow, as explained in the chapter 2.2.1.1. In the following tables only the concentrations of the main anions (i.e. Cl^-, SO_4^{2-}) and cations (i.e. Na^+, K^+, Mg^{2+}, Ca^{2+}) found in the brine are listed and discussed. Firstly, the brine has been evaporated for 30 minutes at a temperature of 60˚C and with a vacuum of -0.55 bar. The trials have been performed on the raw brine at:

1. pH = 7.5 (pH of the raw brine)
2. pH = 8
3. pH = 9
4. pH = 10

Table 3.11: Result of the evaporation test 1 (60˚C and -0.55 bar)

EVAPORATION TEST 1							
OPERATIVE CONDITIONS							
Parameter		**M.U.**		**Value**			
Raw brine volume		mL		500			
Evaporation time		min		30			
Temperature		˚C		60			
Pressure		bar		-0.55			
ANIONS AND CATIONS							
Sample	**pH**	**Cl^-**	**SO_4^{2-}**	**Na^+**	**K^+**	**Mg^{2+}**	**Ca^{2+}**
Raw brine	7.5	26193	2793	14800	730	1800	800
Concen. 1	7.5	66925	16023	35277	1927	4053	1304
Distill. 1	7.5	20	193	3	1	4	38
Concen. 2	8	54971	5818	41485	2162	4421	1523
Distill. 2	8	8	69	3	0	10	62
Concen. 3	9	82379	8949	38336	2958	3876	1259
Distill. 3	9	2	0	n.a.	n.a.	n.a.	n.a.
Concen. 4	10	95886	10089	45147	2290	2612	1668
Distill. 4	10	16	84	n.a.	n.a.	n.a.	n.a.

Regarding the distillate flows, the dissolved concentrations of anions and cations are low in all the cases. Whereas, the anions and cations concentrations in the concentrated flows varies at different pH. The following graphs are plotted in order to assess the data in function of the pH.

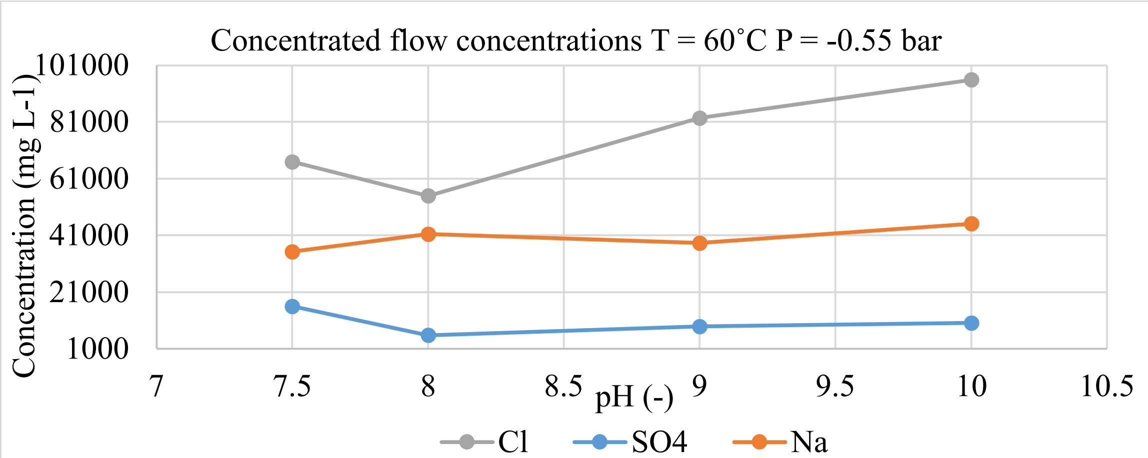


Figure 3.13: Concentrated flow trends of the evaporation test 1 (first part)

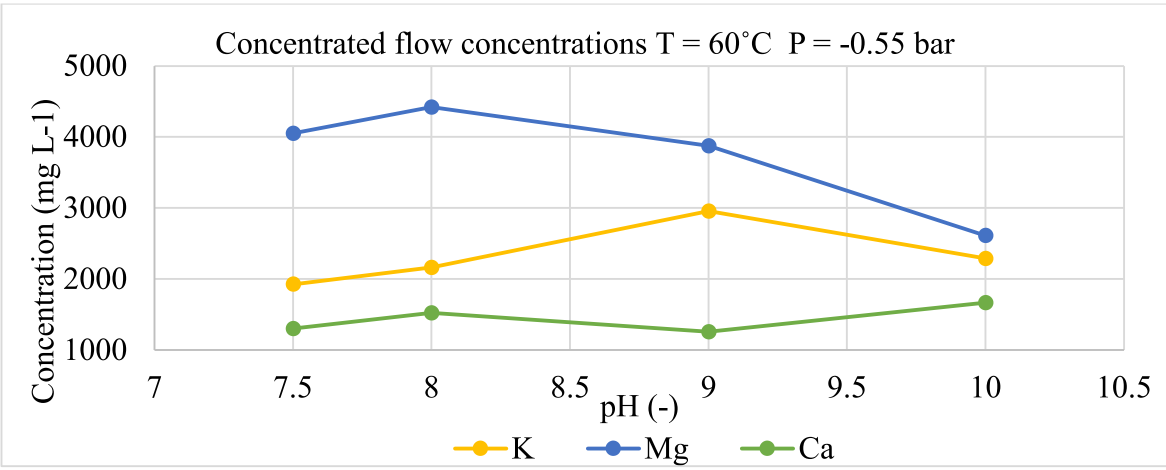


Figure 3.14: Concentrated flows trends of the evaporation test 1 (second part)

Although, no significant variations have been found for SO_4^{2-}, Na^+, K^+ and Ca^{2+}, the concentrations of Cl^- and Mg^{2+} highlight a trend. When the pH increases, the chloride rises as well as the magnesium decreases. The magnesium drops at pH higher than 9 mainly due to the precipitation of the dissolved ions, thereby the Mg^{2+} reacts with OH^- present by addition of NaOH and generate magnesium hydroxide, which is in solid phase.

Secondly, the brine has been evaporated for 30 minutes at a temperature of 100˚C and with a vacuum of -0.55 bar. The tests have been performed on the raw brine at pH equal to (1) 9 and (2) 10, since, as the previous test highlights, the main variations of the anion/cation concentrations have been noticed at pH between 9 and 10.

Table 3.12: Results of the evaporation test 2 (100°C and -0.55 bar)

EVAPORATION TEST 2							
OPERATIVE CONDITIONS							
Parameter		**M.U.**		**Value**			
Raw brine volume		mL		500			
Evaporation time		min		30			
Temperature		°C		100			
Pressure		bar		-0.55			
ANIONS AND CATIONS							
Sample	**pH**	**Cl^-**	**SO_4^{2-}**	**Na^+**	**K^+**	**Mg^{2+}**	**Ca^{2+}**
Raw brine	7.5	26193	2793	14800	730	1800	800
Concen. 1	9	140493	15552	32627	1504	3800	1305
Distill. 1	9	32	205	3	1	6	59
Concen. 2	10	155040	17227	32777	1637	3838	1125
Distill. 2	10	53	172	2	1	10	69

As the previous tests, the distillate presents very low dissolved anions and cations. Therefore, the concentrated flows of these tests and of the previous ones have been considered for the following discussion.

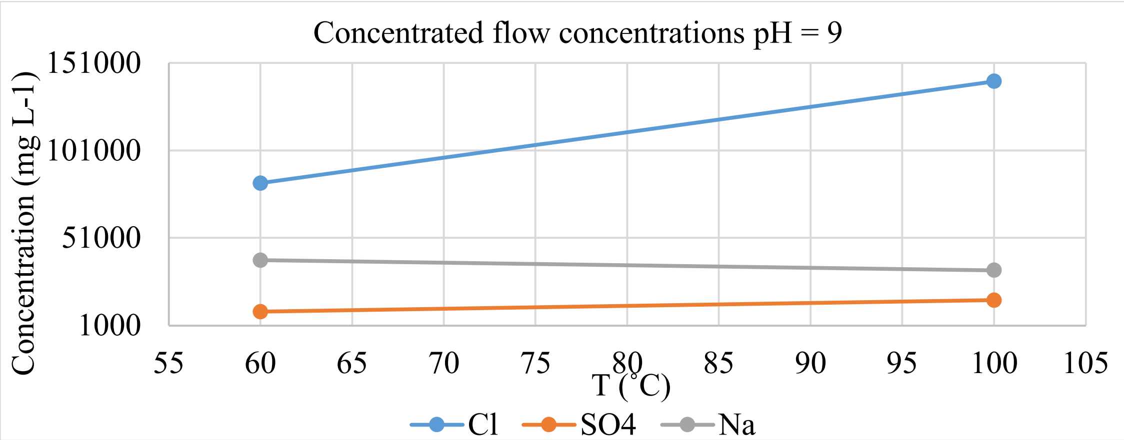


Figure 3.15: Concentrated flow trends of the evaporation test 2 (first part)

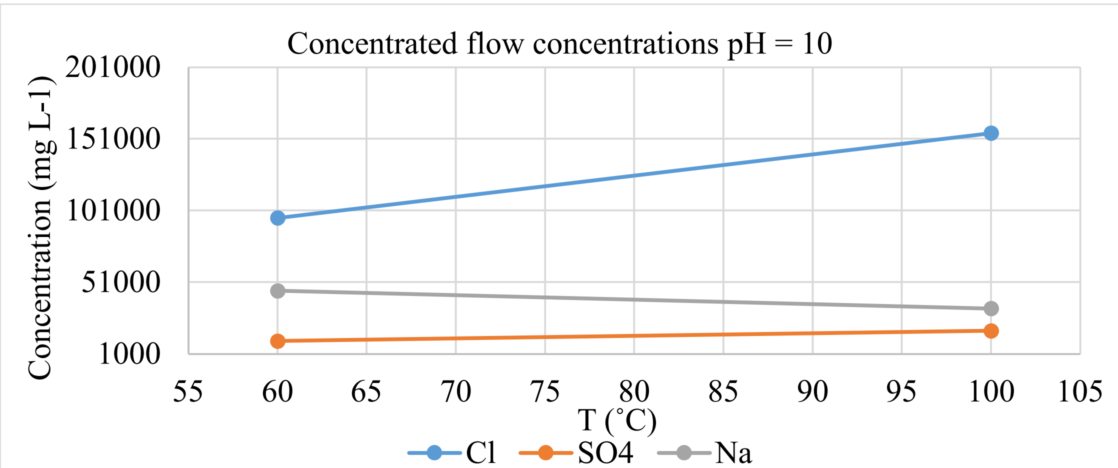


Figure 3.16: Concentrated flow trends of the evaporation test 2 (second part)

The above reported graphs show the same trend at pH between 9 and 10. The increase of chloride ions with the temperature is due to the evaporation and the high presence of Cl^- in the raw brine. Although the evaporation involves the reduction of the raw brine volume, the ions remains dissolved and their concentrations raise in function of the evaporation rate (e.g. litres of distillate per hour), which is mainly driven by the temperature in this case. Moreover, the chloride represents the highest concentrations of ions in the brine, so its increase is more significant and detectable as figure 3.15 and 3.16 highlight.

Finally, the concentrations of anions and cations in the concentrated flows are compared in function of the temperature for pH equal to 9 and equal to 10.

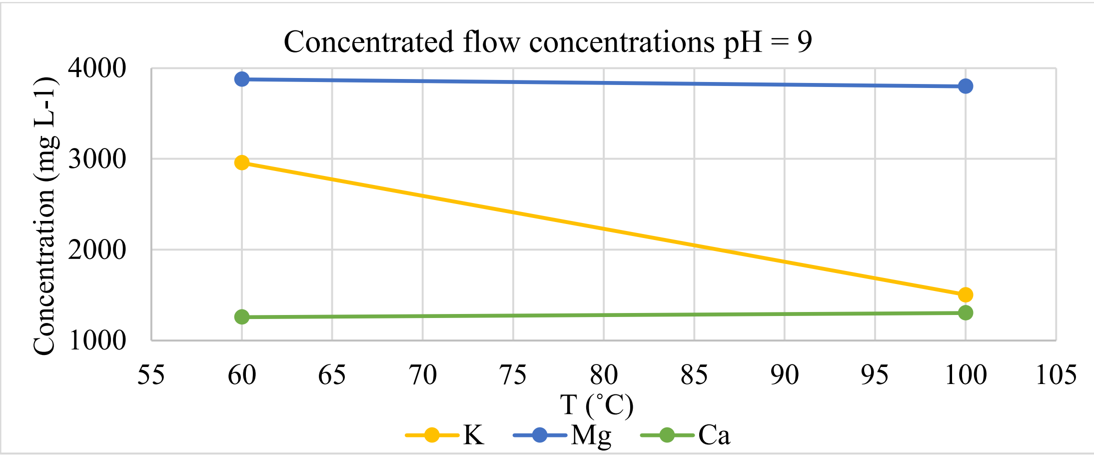


Figure 3.17: Comparison concentrated flow trends at pH = 9 in function of the temperature

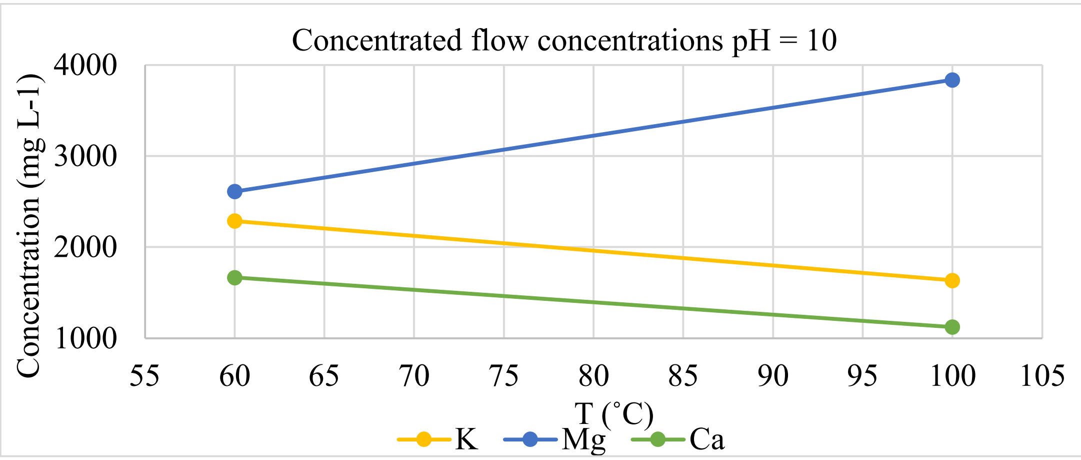


Figure 3.18: : Comparison concentrated flow trends at pH = 10 in function of the temperature

As the chloride trend, the magnesium concentration increases thanks to the evaporation temperature, especially at pH equal to 10. This behaviour may be due to the fact that at pH equal to 9, the OH^- are the limiting reagent for the formation of magnesium hydroxide. The Mg^{2+} reacts as soon as the NaOH is dosed; so, the concentration increases due to the evaporation and it is balanced by the precipitation.

Instead, at pH equal to 10, the reaction may be at the equilibrium and the Mg^{2+} has been already precipitated, so at this point its concentration increases in function of the evaporation rate (i.e. temperature). In support of this hypothesis, at the evaporation temperature of 60˚C, the magnesium concentration is higher in the case of pH = 9, since less dissolved Mg^{2+} may be precipitated in the solid phase.
The evaporation tests at laboratory scale have contributed to preliminary evaluate the evaporation yields in terms of anions and cations concentrations in the raw and processed brine.

3.2.1.2. Chemical precipitation tests

The chemical precipitation of the brine coupled with or without coagulation and flocculation and the subsequent precipitate settling have been evaluated by means of jar tests, as follow:

- Jar test 1, four beakers with different dosage of NaOH (i.e. 4.5, 9, 13.5, 18 mL L^{-1})
- Jar test 2, three beakers with the same addition of 3 g L^{-1} of aluminium sulphate, 7 mg L^{-1} of anionic flocculant and with different dosage of NaOH (i.e. 9, 13.5, 18 mL L^{-1})
- Jar test 3, four beakers with the same addition of 18 ml L^{-1} of caustic soda, 3 g L^{-1} of aluminium sulphate and with different dosage of APAM (i.e. 0, 7, 14, 21 mg L^{-1})
- Jar test 4, two beakers with the same addition of 18 ml L^{-1} of caustic soda, 7 mg L^{-1} of anionic flocculant and 3 g L^{-1} of coagulant. However, $Al_2(SO_4)_3$ and PAC were dosed, respectively, in one beaker and in the other one.
- Jar test 5, three beakers with the same addition of 4.5 ml L^{-1} of sodium hydroxide. Specifically, the first sample without coagulant/flocculant, the second one with addition of 15 g L^{-1} of PAC and, the third one with addition of 15 g L^{-1} of PAC and 7 mg L^{-1} of APAM.

The results of the jar tests are reported in the following table. Also, the measurements of the pH over the time are reported, they may be a useful parameter to understand the kinetics of the process and to predict the precipitation. It has been noticed that after the addition of sodium hydroxide, the initial pH of the brine increases (e.g. > 10) thanks to the dissolution of OH^- in the brine and it represents the available hydroxide ions for the precipitation reactions. The initial increase is proportional to the amount of NaOH added. After a while, the pH is starting to decrease, since the OH- reacts with Mg_2^+ and Ca_2^+ for the formation, respectively, of magnesium hydroxide and calcium hydroxide, until the reaction reaches the equilibrium condition. The final pH of the brine is still higher than the initial one and it is still proportional to the NaOH addition. However, the pH does not represent an accurate parameter to compare chemical precipitation performances due to the fact that it significantly varies throughout the time.

Hence, the settling curves including maximum sedimentation velocity lines, the magnesium and calcium recovery have been assessed in function of the caustic soda dosage.

Thereafter the different tests are compared evaluating the %SED (= volume of supernatant over the total volume) at 9.5 hours, the maximum sedimentation velocity (%SED per hour), the Mg and Ca recovery percentages in terms of solid compounds in the precipitate with respect to the initial concentrations in the raw brine. Jar test 1 results are showed in the table below.

Table 3.13: Results of the jar test 1

CHEMICAL PRECIPITATION & SETTLING - JAR TEST 1					
Parameter	**M.U.**	**Beaker 1**	**Beaker 2**	**Beaker 3**	**Beaker 4**
OPERATIVE CONDITIONS					
Volume raw brine	mL	900	900	900	900
NaOH dosage	mL L^{-1}	4.5	9	13.5	18
RAW BRINE CHARACTERIZATION					
pH	-	7.10	7.15	7.16	7.15
Conductivity	ms cm^{-1}	50.5	50.3	50.7	51
Mg	mg L^{-1}	2742	2742	2742	2742
	mg	2468	2468	2468	2468
Ca	mg L^{-1}	2352	2352	2352	2352
	mg	2117	2117	2117	2117
BRINE AFTER NaOH DOSAGE					
pH	-	10.0	10.2	10.5	11.4
Conductivity	ms cm^{-1}	50.4	50.3	50.7	51
BRINE AFTER STIRRING					
pH	-	10.1	10.2	10.6	11.5
Conductivity	ms cm^{-1}	42.	43.2	44.1	46.2
SETTLING					
Volume precipitate at:					
3 h	mL	281	675	750	728
9.5 h	mL	248	465	593	450
24 h	mL	225	405	488	338
BRINE AFTER SETTLING					
pH	-	9.3	9.7	10.1	10.9
Conductivity	ms cm^{-1}	52.4	53.1	57.6	59.3
SUPERNATANT CHARACTERIZATION					
TSS	mg L^{-1}	223	97.5	137.5	132.5
	mg	145	42	42	60
TDS	mg L^{-1}	91300	54350	53930	53220
TS%	mg L^{-1}	9452	54430	54600	55880
Mg	mg L^{-1}	2570	1071	347	45
	mg	1677	466	107	20
Ca	mg L^{-1}	2063	1324	1196	1340
	mg	1346	576	368	603
PRECIPITATE CHARACTERIZATION					
TSS	mg L^{-1}	8355	28950	28150	31175
	g	5	13	17	14
TDS	mg L^{-1}	95480	51600	51900	54200

TS%	mg L^{-1}	121790	62700	61100	70500
Mg in liquid	mg L^{-1}	2544	912	455	101
	mg	598	383	228	34
Ca in liquid	mg L^{-1}	2145	834	1432	684
	mg	504	350	716	227
Mg in solids	mg	193	1619	2134	2414
	%	28.3%	24.8%	24.2%	26.7%
Ca in solids	mg	266	1191	1033	1287
	%	5.3%	2.6%	2.2%	3.5%

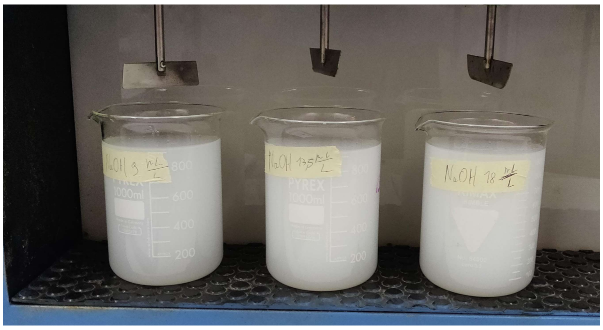


Figure 3.19: Samples after 9 hours of settling

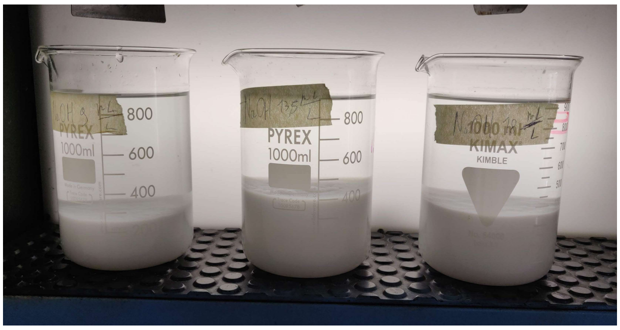


Figure 3.20: Samples after addition of NaOH and stirring

Throughout the jar tests, the %SED has been monitored for each beaker obtain the settling curves, as follow.

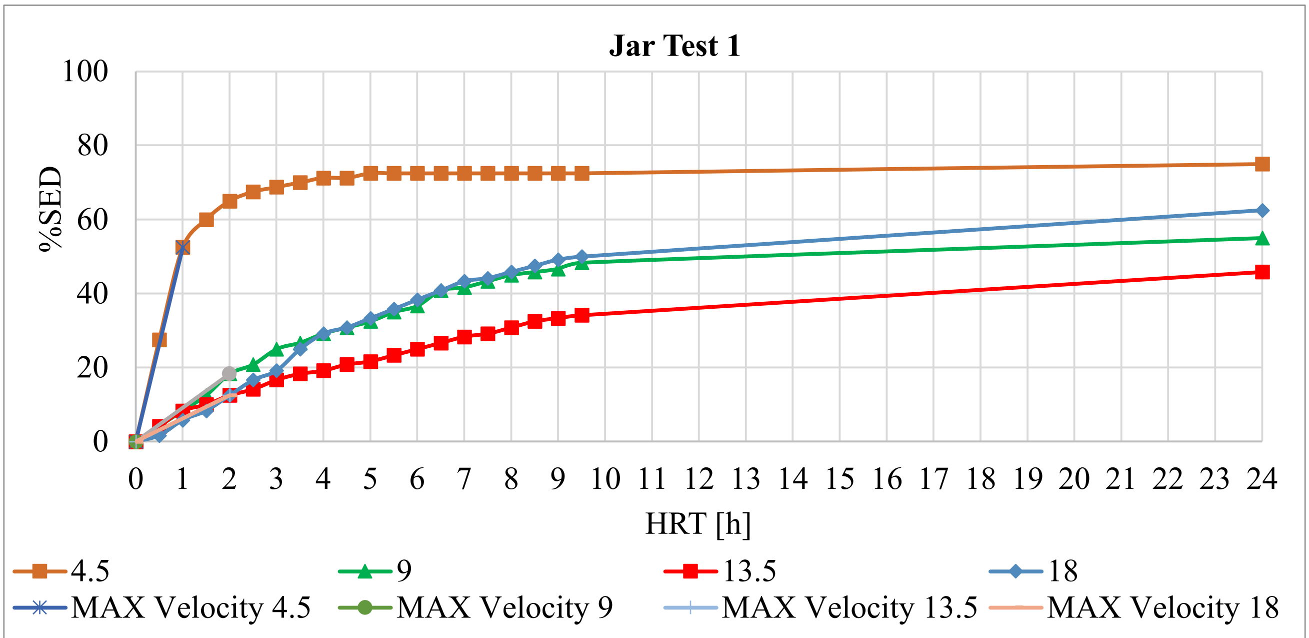


Figure 3.21: Settling curves of the jar test 1

When comparing the milligrams of Mg and Ca in the precipitate in solid phase, the recoveries are quite low for 4.5 mL L^{-1} of sodium hydroxide. Whereas, the milligrams of Mg and Ca in the precipitate increases, if the NaOH dosage increase (from 4.5 to 18 mL L^{-1}).

By analysing the sedimentation curve of jar test 1, the NaOH dosage of 4.5 mL L^{-1} implies the fastest precipitation reaching 53% of %SED after 1 hour and the plateau conditions after 5 hours, it involves the maximum %SED after 24 hours. While the trends of the other dosages are similar, the maximum sedimentation velocity occurs until 2 hours reaching about the 15% of %SED. The plateau conditions are reached after 9 hours and the maximum %SED after 24 hours are ranging from 40% to 60%. Taking into account the yields of clarification, as the sodium hydroxide increases, the load of TSS in the supernatant increases. Such behaviour is likely due to the increase of precipitate compounds with the NaOH dosage.

Furthermore, jar test 2 results are showed in the table below.

Table 3.14: Results of the jar test 2

CHEMICAL PRECIPITATION + COAGULATION + FLOCCULATION & SETTLING - JAR TEST 2				
Parameter	**M.U.**	**Beaker 5**	**Beaker 6**	**Beaker 7**
OPERATIVE CONDITIONS				
Volume raw brine	mL	900	900	900
NaOH dosage	mL L-1	9	13.5	18
$Al_2(SO_4)_3$ dosage	g L^{-1}	3	3	3
APAM dosage	mg L^{-1}	7	7	7
RAW BRINE CHARACTERIZATION				
pH	-	7.5	7.5	7.4
Conductivity	ms cm^{-1}	47.6	43.7	46.1
Mg	mg L^{-1}	2742	2742	2742
	mg	2468	2468	2468
Ca	mg L^{-1}	2352	2352	2352
	mg	2117	2117	2117
BRINE AFTER NaOH DOSAGE				
pH	-	10.2	10.5	11.4
Conductivity	ms cm^{-1}	49.1	52.5	55.8
BRINE AFTER $Al_2(SO_4)_3$ DOSAGE				
pH	-	8.7	8.8	9.0
Conductivity	ms cm^{-1}	43.2	44.6	45.8
BRINE AFTER APAM DOSAGE				
pH	-	8.5	8.6	8.8
Conductivity	ms cm^{-1}	45.8	46.7	48.1
SETTLING				
Volume precipitate at:				
3 h	mL	285	428	375
9.5 h	mL	263	413	360
24 h	mL	263	413	360
BRINE AFTER SETTLING				
pH	-	8.5	9.1	8.8
Conductivity	ms cm^{-1}	46.5	45.5	50.2
SUPERNATANT CHARACTERIZATION				
TSS	mg L^{-1}	225	400	400

	mg	143	195	216
TDS	mg L^{-1}	53100	52400	50100
TS%	mg L^{-1}	57200	54000	51900
Mg	mg L^{-1}	1644	912	508
	mg	1048	444	274
Ca	mg L^{-1}	1928	1888	2013
	mg	1229	920	1087
PRECIPITATE CHARACTERIZATION				
TSS	mg L^{-1}	13050	12725	29750
	g	3	5	11
TDS	mg L^{-1}	57100	53000	51200
TS%	mg L^{-1}	62900	61400	65600
Mg in liquid	mg L^{-1}	1855	1125	535
	mg	390	383	154
Ca in liquid	mg L^{-1}	2147	2044	2310
	mg	451	695	665
Mg in solids	mg	1030	1641	2040
	%	24.5%	25.9%	24.8%
Ca in solids	mg	436	501	364
	%	1.0%	0.7%	0.8%

After the settling, the coagula formation (figure 3.22) has been noticed for jar test 2.

Figure 3.22: Formation of coagula

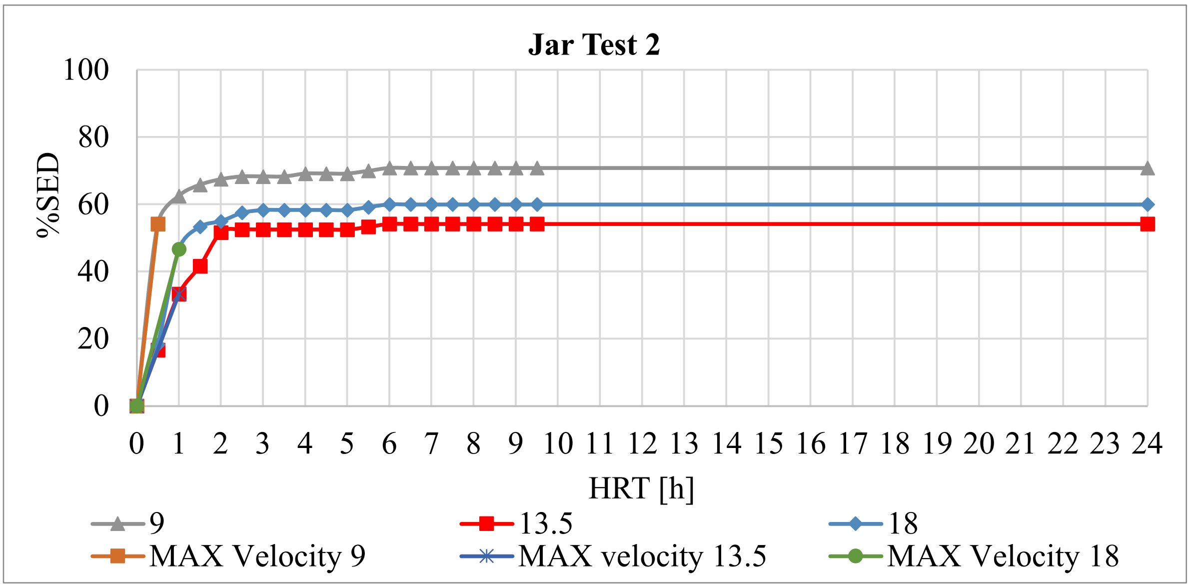


Figure 3.23: Settling curves of the jar test 2

As in the jar test 1, the milligrams of Mg and Ca in the precipitate and the TSS load in the supernatant boost, if the NaOH dosage increase from 9 to 18 mL L^{-1}.

Regarding the sedimentation curves of the jar test 2, although the trends in function of the soda dosage are similar to the ones of jar test 1, the maximum velocity lines are steeper such that after 1 hours the %SED are 63%, 33% and 47%, respectively, for beakers 1, 2 and 3. The plateaus conditions are reached after 3 hours for all three beakers and the maximum %SED after 24 hours are varying between 50% and 70%. The dosage of 13.5 mL L^{-1} of NaOH results in the worst sedimentation efficiency (%SED) over the time.

Jar test 3 results are showed in the table below.

Table 3.15: Results of the jar test 3

CHEMICAL PRECIPITATION + COAGULATION + FLOCCULATION & SETTLING - JAR TEST 3					
Parameter	**M.U.**	**Beaker 8**	**Beaker 7**	**Beaker 9**	**Beaker 10**
OPERATIVE CONDITIONS					
Volume raw brine	mL	900	900	900	900
NaOH dosage	mL L^{-1}	18	18	18	18
$Al_2(SO_4)_3$ dosage	g L^{-1}	3	3	3	3
APAM dosage	mg L^{-1}	0	7	14	21
RAW BRINE CHARACTERIZATION					
pH	-	7.7	7.4	7.8	7.8
Conductivity	ms cm^{-1}	47.6	46.1	47.9	48.1
Mg	mg L^{-1}	2742	2742	2742	2742
	mg	2468	2468	2468	2468
Ca	mg L^{-1}	2352	2352	2352	2352
	mg	2117	2117	2117	2117
BRINE AFTER NaOH DOSAGE					
pH	-	11.5	11.4	11.6	11.5
Conductivity	ms cm^{-1}	50.2	55.8	52.5	53.8
BRINE AFTER $Al_2(SO_4)_3$ DOSAGE					
pH	-	9.0	9.0	9.1	9.1
Conductivity	ms cm^{-1}	46.7	45.8	46.2	45.2
BRINE AFTER APAM DOSAGE					
pH	-	8.9	8.8	9.0	9.1
Conductivity	ms cm^{-1}	49.2	48.1	49.0	49.4
SETTLING					
Volume precipitate at:					
3 h	mL	353	375	360	360
9.5 h	mL	345	360	353	345
24 h	mL	345	360	353	345
BRINE AFTER SETTLING					
pH	-	9.01	8.8	9.1	9.4
Conductivity	ms cm^{-1}	49.6	50.2	49.7	49.9
SUPERNATANT CHARACTERIZATION					
TSS	mg L^{-1}	250	400	100	250

	mg	139	216	205	139
TDS	mg L^{-1}	50300	50100	50700	51900
TS%	mg L^{-1}	50900	51900	51200	55700
Mg	mg L^{-1}	409	508	412	363
	mg	227	274	225	201
Ca	mg L^{-1}	2206	2013	2376	2040
	mg	1225	1087	1301	1132
PRECIPITATE CHARACTERIZATION					
TSS	mg L^{-1}	19375	29750	18525	15925
	g	7	11	7	6
TDS	mg L^{-1}	51450	51200	50800	51600
TS%	mg L^{-1}	64200	65600	63700	68800
Mg in liquid	mg L^{-1}	405	535	374	427
	mg	115	154	106	125
Ca in liquid	mg L^{-1}	2213	2310	2240	2139
	mg	630	665	632	627
Mg in solids	mg	2126	2040	2137	2142
	%	-	24.8%	-	-
Ca in solids	mg	262	364	184	357
	%	-	0.8%	-	-

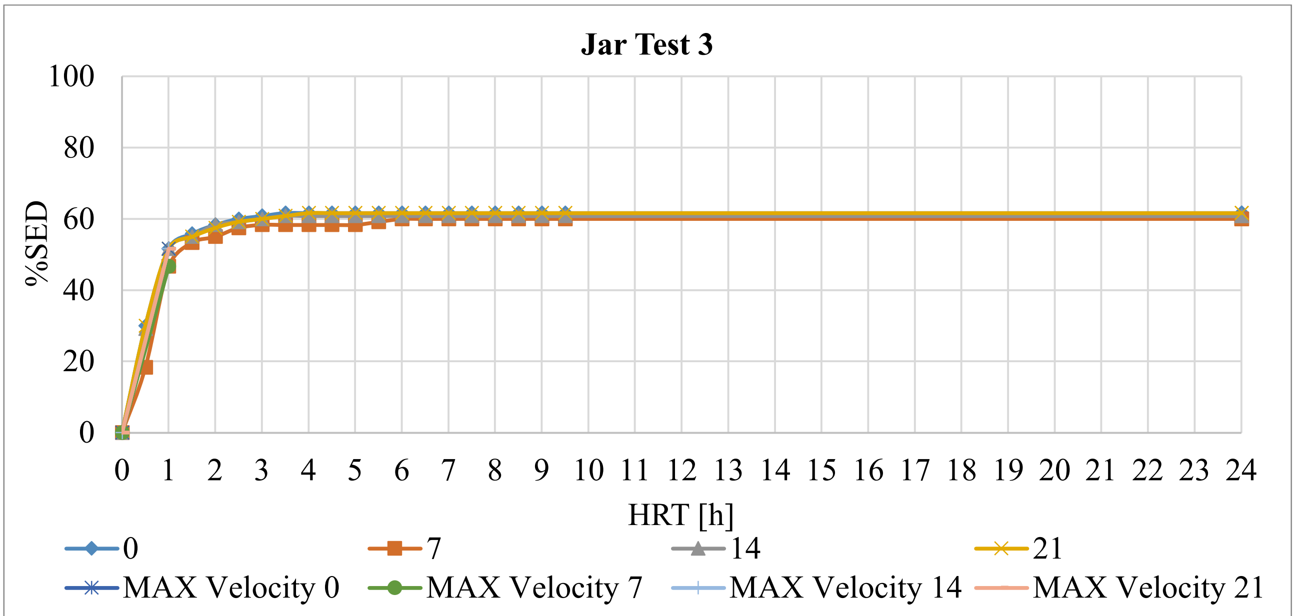


Figure 3.24: Settling curves of the jar test 3

When comparing the sedimentation curves of the jar test 3, as the anionic flocculant dosage increases, the sedimentation efficiencies and velocity throughout the time remain constant. The maximum velocity is about 50% of SED% per hour and the plateau condition is reached after 3 hours. In addition, the milligrams of Mg and Ca in the precipitate and TSS loads in the supernatant are not affected by the flocculant dosages.

Jar test 4 results are showed in the table below.

Table 3.16: Results of the jar test 4

CHEMICAL PRECIPITATION + COAGULATION + FLOCCULATION & SETTLING - JAR TEST 4			
Parameter	**M.U.**	**Beaker 7**	**Beaker 11**
OPERATIVE CONDITIONS			
Volume raw brine	mL	900	900
NaOH dosage	mL L-1	18	18
$Al_2(SO_4)_3$ dosage	g L^{-1}	3	0
PAC dosage	g L^{-1}	0	3
APAM dosage	mg L^{-1}	7	7
RAW BRINE CHARACTERIZATION			
pH	-	7.4	7.5
Conductivity	ms cm^{-1}	46.1	48.5
Mg	mg L^{-1}	2742	2742
	mg	2468	2468
Ca	mg L^{-1}	2352	2352
	mg	2117	2117
BRINE AFTER NaOH DOSAGE			
pH	-	11.4	11.4
Conductivity	ms cm^{-1}	55.8	49.2
BRINE AFTER $Al_2(SO_4)_3$ / PAC DOSAGE			
pH	-	9.0	9.1
Conductivity	ms cm^{-1}	45.8	41.3
BRINE AFTER APAM DOSAGE			
pH	-	8.8	9.1
Conductivity	ms cm-1	48.1	50.6
SETTLING			
Volume precipitate at:			
3 h	mL	375	398
9.5 h	mL	360	383
24 h	mL	360	383
BRINE AFTER SETTLING			
pH	-	8.8	9.5
Conductivity	ms cm^{-1}	50.2	51.7
SUPERNATANT CHARACTERIZATION			
TSS	mg L^{-1}	400	100
	mg	216	52
TDS	mg L^{-1}	50100	51900
TS%	mg L^{-1}	51900	52100
Mg	mg L^{-1}	508	278
	mg	274	144
Ca	mg L^{-1}	2013	2140
	mg	1087	1107
PRECIPITATE CHARACTERIZATION			
TSS	mg L^{-1}	29750	13950
	g	11	5
TDS	mg L^{-1}	51200	5200
TS%	mg L^{-1}	65600	63700
Mg in liquid	mg L^{-1}	535	299

	mg	154	97
Ca in liquid	mg L^{-1}	2310	2220
	mg	665	722
Mg in solids	mg	2040	2227
	%	24.8%	-
Ca in solids	mg	364	287
	%	0.8%	-

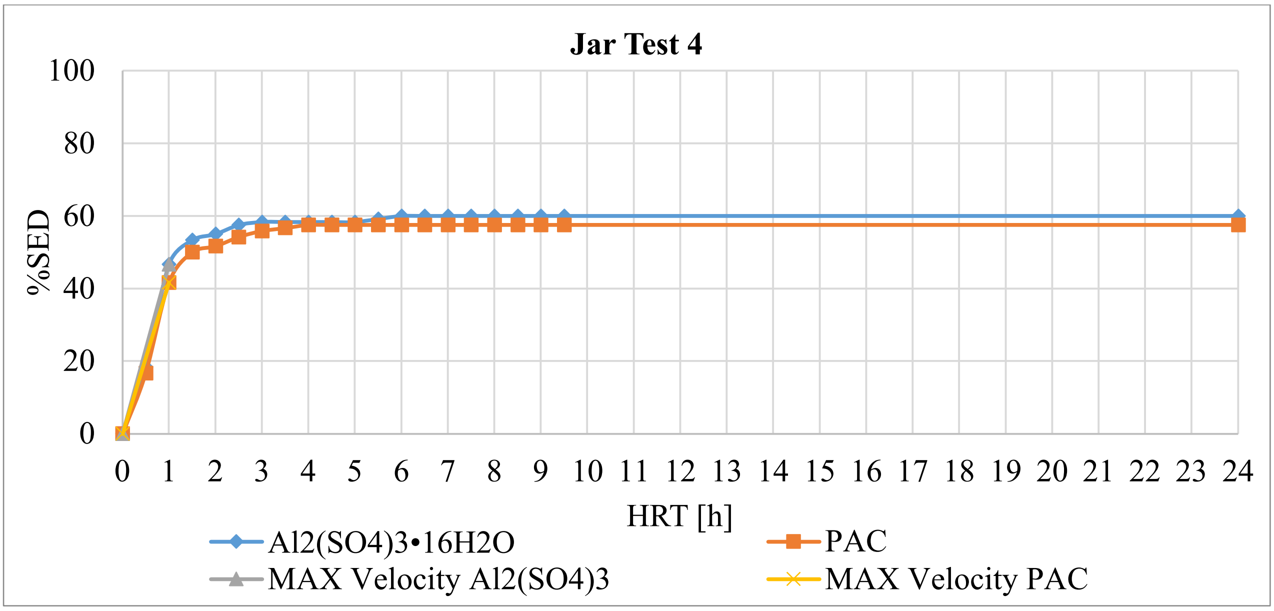


Figure 3.25: Settling curves of the jar test 4

By analysing the milligrams of Mg and Ca in the precipitate in solid phase, the PAC addition involves a higher magnesium recovery while the $Al_2(SO_4)_3$ dosage implies a higher Ca recovery. However, the load of TSS in the supernatant is lower in the case of PAC addition, providing a better clarified supernatant. When comparing the settling performances, the sedimentation curves are quite similar reaching the plateau conditions after 3 hours, the %SED are about 60% after 24 hours and the maximum settling velocity occurs until 1 hour achieving about 45% of %SED.

Jar test 5 results are showed in the table below.

Table 3.17: Results of the jar test 5

CHEMICAL PRECIPITATION + COAGULATION + FLOCCULATION & SETTLING - JAR TEST 5				
Parameter	**M.U.**	**Beaker 12**	**Beaker 13**	**Beaker 14**
OPERATIVE CONDITIONS				
Volume raw brine	mL	2000	2000	2000
NaOH dosage	mL L-1	4.5	4.5	4.5
PAC dosage	g L^{-1}	0	15	15
APAM dosage	mg L^{-1}	0	0	7
RAW BRINE CHARACTERIZATION				
pH	-	7.0	7.2	7.1

Conductivity	ms cm^{-1}	48.7	48.6	40.7
Mg	mg L^{-1}	2742	2742	2742
	mg	5485	5485	5485
Ca	mg L^{-1}	2352	2352	2352
	mg	4704	4704	4704
BRINE AFTER NaOH DOSAGE				
pH	-	10.0	10.0	10.0
Conductivity	ms cm^{-1}	56.5	49.9	54.4
BRINE AFTER PAC DOSAGE				
pH	-	-	3.94	4.1
Conductivity	ms cm^{-1}	-	58.2	56.9
BRINE AFTER APAM DOSAGE				
pH	-	-	-	4.0
Conductivity	ms cm-1	-	-	49.0
SETTLING				
Volume precipitate at:				
3 h	mL	625	1100	1050
9.5 h	mL	525	900	850
24 h	mL	500	750	750
BRINE AFTER SETTLING				
pH	-	9.3	3.8	4.3
Conductivity	ms cm^{-1}	64.1	57.8	56.9
SUPERNATANT CHARACTERIZATION				
TSS	mg L^{-1}	223	183	100
	mg	323	228	125
TDS	mg L^{-1}	56500	57840	58200
TS%	mg L^{-1}	57200	61073	61460
Mg	mg L^{-1}	2570	2166	1882
	mg	3726	2708	2352
Ca	mg L^{-1}	2063	1447	838
	mg	2991	1809	1047
PRECIPITATE CHARACTERIZATION				
TSS	mg L^{-1}	8355	13788	13575
	mg	4595	10341	10181
TDS	mg L^{-1}	57500	59820	59500
TS%	mg L^{-1}	62231	72310	73240
Mg in liquid	mg L^{-1}	2544	2061	1990
	mg	1399	1546	1492
Ca in liquid	mg L^{-1}	2145	1292	859
	mg	1180	969	645
Mg in solids	mg	1300	155	268
	%	28%	1.5%	2.7%
Ca in solids	mg	1825	76	183
	%	5%	0.7%	0.3%

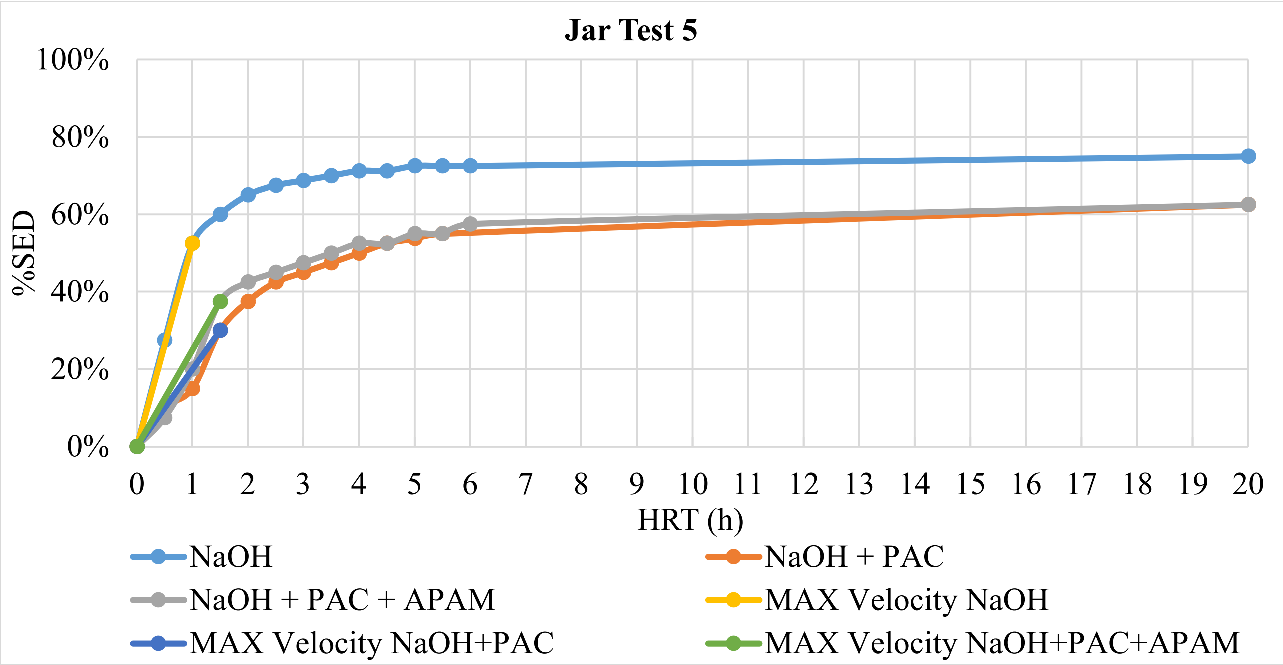


Figure 3.26: Settling curves of the jar test 5

By analysing the previous table, the amount of Mg and Ca in the precipitate in solid phase drop dramatically after the addition of 15 g L^{-1} of PAC and slightly rise after the addition of the anionic flocculant.

Taking into account the sedimentation curves of the jar test 5, the addition of 15 g L^{-1} worsens the sedimentation of the precipitate throughout the time. Such that the maximum velocity is lowered to 30-38% of %SED and the %SED after 20 hours goes down to 60%. However, the plateau conditions are achieved after 4 hours of settling for all three cases.

Finally, the different tests are compared in terms of dosages, settling velocity, %SED, and recovery of solid Mg and Ca in the precipitate.

Table 3.18: Comparison jar test 1 and 2

COMPARISON CHEMICAL PRECIPITATION WITH/WITHOUT COAGULANT AND FLOCCULANT								
Parameter	**M.U.**	**Beaker 1**	**Beaker 2**	**Beaker 3**	**Beaker 4**	**Beaker 5**	**Beaker 6**	**Beaker 7**
DOSAGE								
NaOH dosage	mL L^{-1}	4.5	9	13.5	18	9	13.5	18
$Al_2(SO_4)_3$ dosage	g L^{-1}	0	0	0	0	3	3	3
APAM dosage	mg L^{-1}	0	0	0	0	7	7	7
SETTLING - PERFORMANCES								
Max. settling velocity	% h^{-1}	14.5	5.2	3.7	5.5	27.3	21.0	19.4
Max. settling velocity until time	h	5	9	9	9	2.5	2.5	3
Settling at 7 h (%SED)	%	73%	42%	28%	43%	71%	54%	60%
SOLID COMPOUNDS RECOVERY - PERFORMANCES								
Mg	%	8%	66%	86%	98%	42%	66%	83%
Ca	%	13%	56%	49%	61%	21%	24%	17%

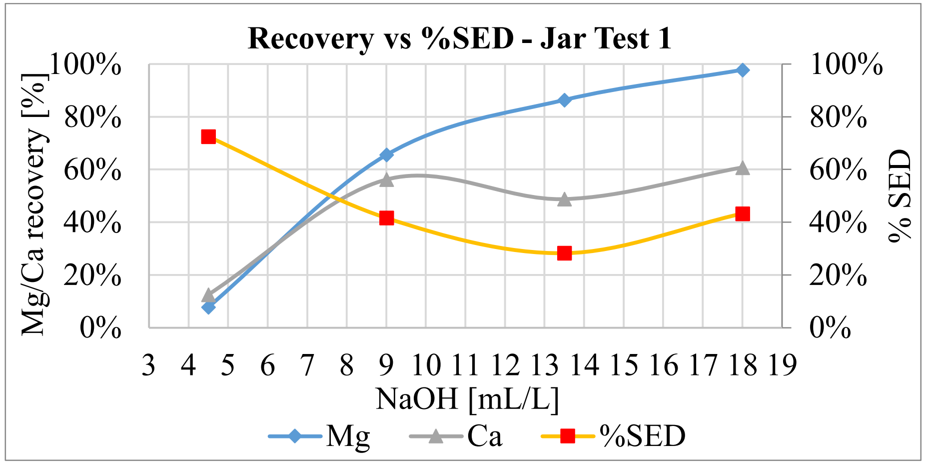


Figure 3.27: Results of the jar test 1

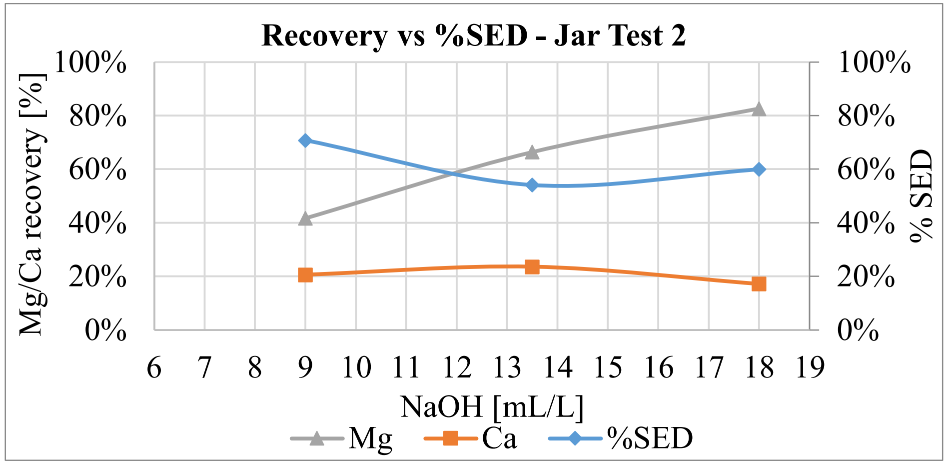


Figure 3.28: Results of the jar test 2

When analysing the jar test 1 and 2 (beakers from 1 to 7), the use of the coagulant (aluminium sulphate) and flocculant (anionic polymer) improves the sedimentation of the precipitate for all soda dosages. However, if the recovery of magnesium and calcium are compared, the percentages are lowered by the coagulant and flocculant addition, especially the Ca recovery. The possible explanation is that the Mg and Ca in the solid phase come back to the liquid phase due to the consumption of alkalinity by the aluminium sulphate. Since their precipitation occurs when the reactions (equations 4 and 7 of the chapter 2.2.1.2.) are at the equilibrium. So, if the dissolved concentration of OH^- decreases, the magnesium and calcium are dissolved as ions in order to re-establish the equilibrium.

Moreover, the calcium recovery is lower than magnesium recovery in percentages for both tests. According to the literature review (www.chem.libretexts.org), the solubility product constant (K_{sp}) is 5.61×10^{-12} and 5.02×10^{-6}, respectively, for magnesium hydroxide and calcium hydroxide. It represents the solubility tendency of a compound, as K_{sp} increases the solubility rises. Therefore, the precipitation of the magnesium hydroxide is easier than the precipitation of the calcium hydroxide, as the laboratory test results highlight.

In addition, for the two tests, the recovery of magnesium and calcium have the same trends in function of the NaOH dosage. The magnesium recovery rises, if the soda dosage increases; while the calcium recovery remains almost constant for dosage between 9- and 18-mL L^{-1} of NaOH. Therefore, higher dosages of NaOH may provide more dissolved ions hydroxide, which are used for $Mg(OH)_2$ precipitation; though the $Ca(OH)_2$ precipitation is affected only at low soda dosages (< 9).

Finally, taking into account the jar test 1, the optimal dosage of NaOH for salt recovery and settling could be around 8 mL L^{-1}, which leads to a modest %SED and middle recoveries of Mg and Ca (figure 3.27). While in the jar test 2, the optimal dosage of NaOH could be around 12 mL L^{-1}, which implies a high %SED and middle recovery of Mg (figure 3.28). However, the main scope of the chemical precipitation is the Mg and Ca recovery despite the settling performances. Thus, higher sodium hydroxide dosages are preferred in order to enhance the salt recovery.

Subsequently, the jar test 3 is taken into account in order to evaluate the performances of the anionic polymer as flocculant.

Table 3.19: Anionic flocculant performances

EVALUATION FLOCCULANT PERFORMANCES					
Parameter	**M.U.**	**Beaker 8**	**Beaker 7**	**Beaker 9**	**Beaker 10**
DOSAGE					
NaOH dosage	mL L^{-1}	18	18	18	18
$Al_2(SO_4)_3$ dosage	g L^{-1}	3	3	3	3
APAM dosage	mg L^{-1}	0	7	14	21
SETTLING - PERFORMANCES					

Max. settling velocity	% h^{-1}	20.3	19.4	20.0	20.0
Max. settling velocity until time	h	3	3	3	3
Settling at 7 h (%SED)	%	62%	60%	61%	62%
SOLID COMPOUNDS RECOVERY - PERFORMANCES					
Mg	%	86%	83%	87%	87%
Ca	%	12%	17%	9%	17%

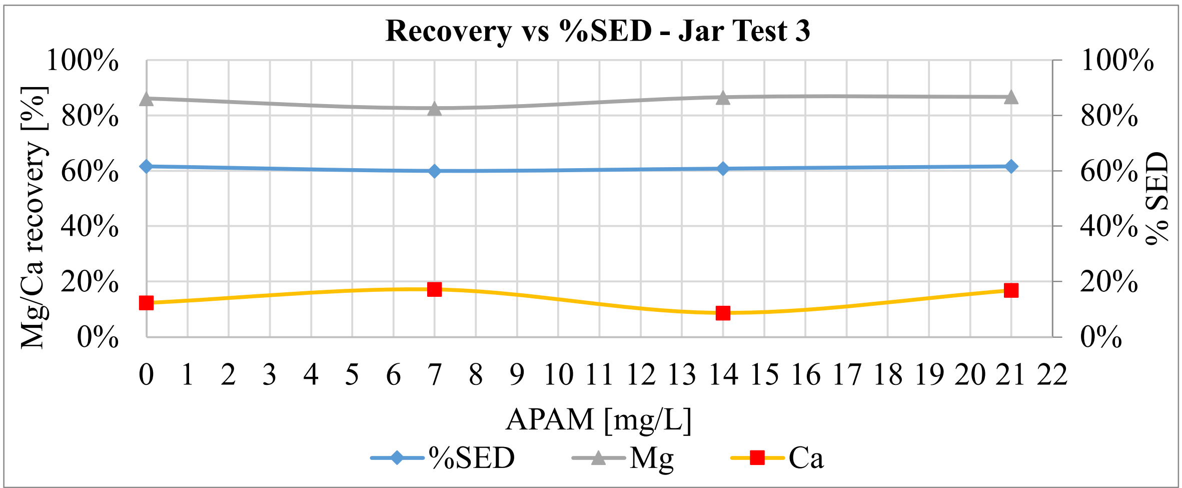


Figure 3.29: Results of the jar test 3

Looking at the graph 3.29, even though the APAM dosage increases significantly, the recovery of Mg and Ca, the sedimentation efficiency (%SED) remains constant. Thus, the anionic polymer does not provide any relevant improvements to the chemical precipitation.

Afterwards the performances of the aluminium sulphate and the PAC have been studied in terms of sedimentation, magnesium and calcium recovery when data of the jar test 4 (i.e. same dosage but different coagulant) are analysed.

Table 3.20: Comparison of coagulants performances

COMPARISON $Al_2(SO_4)_3 \cdot 16H_2O$ VS PAC PERFORMANCES			
Parameter	**M.U.**	**Beaker 7**	**Beaker 11**
DOSAGE			
NaOH dosage	mL L^{-1}	18	18
$Al_2(SO_4)_3$ dosage	g L^{-1}	3	0
PAC dosage	g L^{-1}	0	3
APAM dosage	mg L^{-1}	7	7
SETTLING - PERFORMANCES			
Max. settling velocity	% h^{-1}	19.4	18.6
Max. settling velocity until time	h	3	3
Settling at 7 h (%SED)	%	60%	58%
SOLID COMPOUNDS RECOVERY - PERFORMANCES			

Mg	%	83%	90%
Ca	%	17%	14%

By analysing the results, the maximum settling velocity and the %SED are quite similar. Also, the calcium recovery results alike. However, the Mg recovery using PAC is 7% percentage higher of the recovery using $Al_2(SO_4)_3$. The reason is that the PAC consumes less alkalinity of the aluminum sulphate leading to a higher recovery, as explained before. Indeed, the final pH are 9.5 and 8.8, respectively, for polyaluminum chloride and aluminum sulphate.

According to the literature review, the PAC dosage may be quite variable, the typical dosages are about 3 g L^{-1} (G.U. Semblante et al., 2018) and 15 g L^{-1} (R. Ordònez et al., 2012). Hence, the maximum dosage of 15 g L^{-1} of polyaluminum chloride has been tested with and without flocculant and then compared to the beaker 12, where only NaOH has been dosed. The following performances have been obtained.

Table 3.21: Polyaluminum chloride performances

EVALUATION PAC PERFORMANCES				
Parameter	**M.U.**	**Beaker 12**	**Beaker 13**	**Beaker 14**
DOSAGE				
NaOH dosage	mL L^{-1}	4.5	4.5	4.5
PAC dosage	g L^{-1}	0	15	15
APAM dosage	mg L^{-1}	0	0	7
SETTLING - PERFORMANCES				
Max. settling velocity	% h^{-1}	17.8	12.5	13.1
Max. settling velocity until time	h	4	4	4
Settling at 7 h (%SED)	%	73%	55%	58%
SOLID COMPOUNDS RECOVERY - PERFORMANCES				
Mg	%	24%	2.8%	10%
Ca	%	39%	1.6%	8%

Comparing the PAC performances, the flocculant addition has not given any enhancements, as in the previous cases. Moreover, the recovery of magnesium and calcium have vastly dropped after coagulant addition, since the PAC consumes a lot of alkalinity solubilizing the precipitated Mg and Ca, as discussed before. Indeed, the final pH of the beakers 12 is about 9.3, while the final pH of the beakers 13 and 14 are, respectively, 3.8 and 4.3.

To summarize all the experimental results, the anionic flocculant does not provide any improvements in any test. The use of aluminum sulphate and polyaluminum chloride as coagulants improve the sedimentation velocities and the %SED even though the Mg and Ca recoveries slightly decrease. In particular, the dosage of 3 g L^{-1} of PAC results in a better recovery of magnesium with respect to the same dosage of $Al_2(SO_4)_3$. If the PAC dosage exceeds 3 g L^{-1}, the performances worsen: the sedimentation results slower and %SED is lower, the recovery of magnesium and calcium decreases considerably due to the consumption of alkalinity.

Although the dosage of 3 g L^{-1} of PAC enhances the settling, its application has been discarded since it decreases the recovery of compounds, which is the main target of the chemical precipitation.

Finally, from the jar tests, the best NaOH dosages result to be 9- and 18-mL L^{-1}, since their %SED are satisfying (about 40%), Mg and Ca recoveries are quite high. However, the magnesium recoveries are about 66% and 98%, respectively, for dosage of 9 and 18 mL of soda per L of brine; such recovery trend might not justify the double dosage.

Thereby, a life cycle assessment comparing these two dosages may be useful to choose the most cost-effective operational conditions of the chemical precipitation. The addition of 9- and 18-mL L^{-1} of NaOH should be assessed through a life cycle approach taking into account reagent costs, environmental impacts, energy consumptions, precipitate settling and solid compounds recovery.

3.2.1.3. Integrated systems

At laboratory scale, the three integrated systems (showed in chapter 2.2.1.3.) have been studied by means of the following four experimental tests:

- E + C system test N. 1, which involves raw brine conditioning with 17 mL L^{-1} of NaOH, then evaporation (E) of the conditioned brine (30 mins at 100 ˚C and -0.55 bar), addition of 15 g L^{-1} of PAC to the concentrated flow and final settling of one hour (C);
- E + C system test N. 2, which includes raw brine evaporation (E) (30 mins at 100 ˚C and -0.55 bar), then addition of 17 mL L^{-1} of NaOH and 15 g L^{-1} of PAC to the concentrated flow and final settling of one hour (C);
- E + C system test N. 3, which involves raw brine evaporation (E) (30 mins at 100 ˚C and -0.55 bar), addition of 18 mL L^{-1} of NaOH and 3 g L^{-1} of PAC to the concentrated flow and final settling of seven hours (C);
- C + E system test N. 4, which includes chemical precipitation (C) of the raw brine with dosage of 18 mL L^{-1} of NaOH and 3 g L^{-1} of PAC, subsequently 7 hours of settling and finally evaporation (E) of the supernatant (30 mins at 100 ˚C and -0.55 bar).

All the flow characterizations and the specific operational conditions of the processes for each test are reported in the following tables.

The first and the second tests have been assessed in order to compare the addition of NaOH before and after the evaporation within the E + C system.

Table 3.22: Results of the E + C system test N.1

1- CONDITIONING, EVAPORATION, COAGULATION AND SETTLING		
RAW BRINE CHARACTERIZATION		
Parameter	*Unit*	*Value*
Volume	mL	500
Parameter	*Concentration (mg L^{-1})*	*Load (mg)*
Mg	2742	1371
Ca	2352	1176
TSS	76	38
TDS	51540	25770
TS	58487	29243
CONDITIONING		
Parameter	*Unit*	*Value*
NaOH dosage	mL L^{-1}	17
EVAPORATION		
Temperature	˚C	100
Pressure	bar	-0.55
Time	min	30
Efficiency	%	25%
DISTILLATE CHARACTERIZATION		
Parameter	*Unit*	*Value*
Volume	mL	125
Parameter	*Concentration (mg L^{-1})*	*Load (mg)*
Mg	140	18
Ca	1462	183
CONCENTRATED CHARACTERIZATION		
Parameter	*Unit*	*Value*
Volume	mL	375
Parameter	*Concentration (mg L^{-1})*	*Load (mg)*
Mg	429	161
Ca	2033	762
COAGULATION AND SETTLING		
Parameter	*Unit*	*Value*
PAC dosage	g L^{-1}	15
Settling time	h	1
%SED	%	8%
SUPERNATANT CHARACTERIZATION		
Parameter	*Unit*	*Value*
Volume	mL	30
Parameter	*Concentration (mg L^{-1})*	*Load (mg)*
Mg	1496	45
Ca	2003	60
PRECIPITATE CHARACTERIZATION		
Parameter	*Unit*	*Value*
Volume	mL	345
Parameter	*Concentration (mg L^{-1})*	*Load (mg)*
Dissolved Mg	1496	516
Dissolved Ca	2003	691

Suspended Mg		793
Suspended Ca		242
Parameter	*M.U.*	*Value*
Mg recovery	%	58%
Ca recovery	%	21%

Table 3.23: Results of the E + C system test N.2

2- EVAPORATION, CONDITIONING, COAGULATION AND SETTLING		
RAW BRINE CHARACTERIZATION		
Parameter	*Unit*	*Value*
Volume	mL	500
Parameter	*Concentration (mg L^{-1})*	*Load (mg)*
Mg	2742	1371
Ca	2352	1176
TSS	76	38
TDS	51540	25770
TS	58487	29243
EVAPORATION		
Temperature	°C	100
Pressure	bar	-0.55
Time	min	30
Efficiency	%	26%
DISTILLATE CHARACTERIZATION		
Parameter	*Unit*	*Value*
Volume	mL	130
Parameter	*Concentration (mg L^{-1})*	*Load (mg)*
Mg	206	27
Ca	494	64
CONCENTRATED CHARACTERIZATION		
Parameter	*Unit*	*Value*
Volume	mL	370
Parameter	*Concentration (mg L^{-1})*	*Load (mg)*
Mg	2370	878
Ca	2303	853
CONDITIONING, COAGULATION AND SETTLING		
Parameter	*Unit*	*Value*
NaOH dosage	mL L^{-1}	17
PAC dosage	g L^{-1}	15
Settling	h	1
%SED	%	20%
SUPERNATANT CHARACTERIZATION		
Parameter	*Unit*	*Value*
Volume	mL	72
Parameter	*Concentration (mg L^{-1})*	*Load (mg)*
Mg	1961	142
Ca	1717	124
PRECIPITATE CHARACTERIZATION		
Parameter	*Unit*	*Value*

Volume	mL	298
Parameter	*Concentration (mg L^{-1})*	*Load (mg)*
Dissolved Mg	1961	584
Dissolved Ca	1717	512
Suspended Mg		618
Suspended Ca		476
Parameter	*M.U.*	*Value*
Mg recovery	%	45%
Ca recovery	%	40%

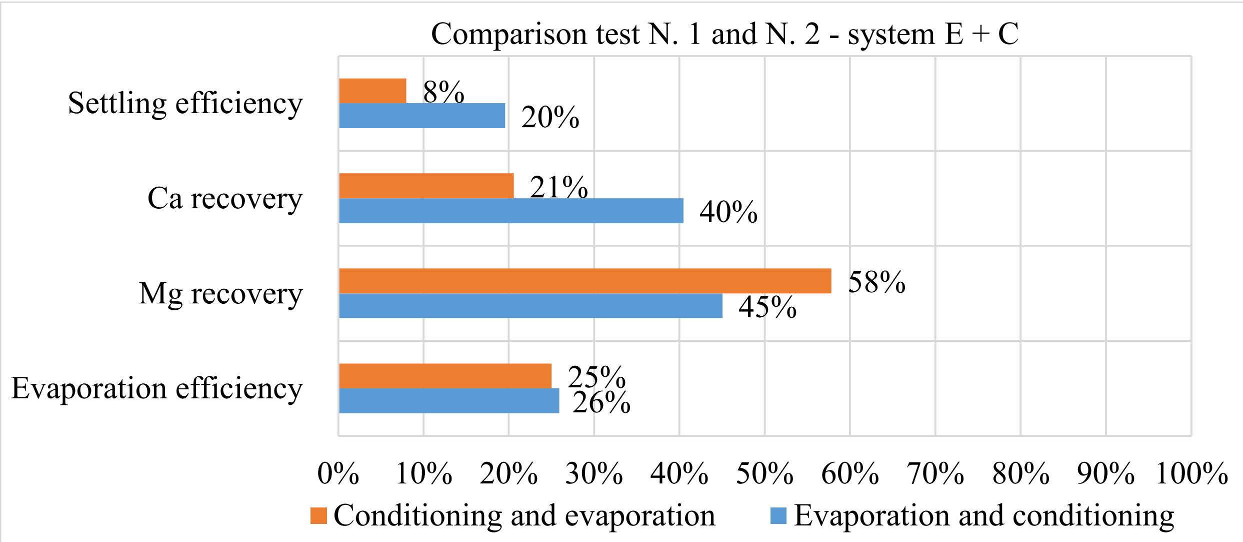


Figure 3.30: Performances evaluation of the system 1

Analysing the tests N. 1 and N. 2, the Mg and Ca recovery are not completely satisfying due to the dosage of 15 g L^{-1}, which consumes an elevate amount of alkalinity, as explained in the chemical precipitation subchapter. However, as the conditioning and evaporation has a higher magnesium recovery, it has also a lower calcium recovery. Regarding the settling efficiency (volume of supernatant over the total volume), the conditioning before the evaporation seems to affect negatively the settling of the precipitate. While the evaporation efficiencies (volume of distillate over the total volume) are not affected by the dosage of NaOH. Moreover, comparing the consumptions of NaOH, if the same dosages (mL L^{-1}) are carried out on the raw brine and on the concentrated brine, about a 25% in less of NaOH is needed for the concentrated brine with respect to the raw brine, thanks to the volume reduction by evaporation. Therefore, in the third test, the conditioning of NaOH after the evaporation has been preferred.

The third test has been carried out to evaluate the E + C system with the optimal dosage of PAC of 3 g L^{-1}.

Table 3.24: Results of the E + C system test N.3

3- EVAPORATION, CONDITIONING, COAGULATION AND SETTLING		
RAW BRINE CHARACTERIZATION		
Parameter	*Unit*	*Value*
Volume	mL	1000
Parameter	*Concentration (mg L^{-1})*	*Load (mg)*
Mg	2742	2194
Ca	2352	1881
TSS	93	93
TDS	55490	55490
TS	56170	56170
EVAPORATION		
Parameter	*Concentration (mg L-1)*	*Load (mg)*
Temperature	˚C	100
Pressure	bar	-0.55
Time	min	30
Efficiency	%	15%
DISTILLATE CHARACTERIZATION		
Parameter	*Unit*	*Value*
Volume	mL	145
Parameter	*Concentration (mg L^{-1})*	*Load (mg)*
Mg	254	37
Ca	1958	284
TSS	75	11
TDS	300	44
TS	300	44
CONCENTRATED CHARACTERIZATION		
Parameter	*Unit*	*Value*
Volume	mL	855
Parameter	*Concentration (mg L^{-1})*	*Load (mg)*
Mg	2712	2170
Ca	2322	1857
TSS	300	257
TDS	59400	50787
TS	63200	54036
CONDITIONING, COAGULATION AND SETTLING		
Parameter	*Unit*	*Value*
NaOH dosage	mL L^{-1}	17
PAC dosage	g L^{-1}	3
Settling time	h	7
%SED	%	45%
SUPERNATANT CHARACTERIZATION		
Parameter	*Unit*	*Value*
Volume	mL	367
Parameter	*Concentration (mg L^{-1})*	*Load (mg)*
Mg	423	155
Ca	1920	705
TSS	500	183

TDS	59700	21908
TS	60400	22165
PRECIPITATE CHARACTERIZATION		
Parameter	*Unit*	*Value*
Volume	mL	433
Parameter	*Concentration (mg L^{-1})*	*Load (mg)*
Dissolved Mg	454	162
Dissolved Ca	2150	768
Suspended Mg	-	1871
Suspended Ca	-	
TSS	21325	9234
TDS	57900	25072
TS	68500	29662
Parameter	*Unit*	*Value*
Mg recovery	%	68%
Ca recovery	%	16%

While, the C + E system test N.4 has been used for the assessment of the system C + E_C and C + E_D, the two systems are essential the same. Although in the first system the contracted flow goes to the FO/RO, in the second system the distillate flow is conveyed to the FO/RO.

Table 3.25: Results of C + E system test N.4

4- CONDITIONING, COAGULATION, SETTLING AND EVAPORATION		
RAW BRINE CHARACTERIZATION		
Parameter	*Unit*	*Value*
Volume	L	900
Parameter	*Concentration (mg L^{-1})*	*Load (mg)*
Mg	2742	2468
Ca	2352	2117
TSS	93	84
TDS	55490	49941
TS	56170	50553
CONDITIONING, COAGULATION AND SETTLING		
Parameter	*M.U.*	*Value*
NaOH dosage	mL L^{-1}	18
PAC dosage	g L^{-1}	3
Settling time	h	7
%SED	%	58%
SUPERNATANT CHARACTERIZATION		
Parameter	*Unit*	*Value*
Volume	L	520
Parameter	*Concentration (mg L^{-1})*	*Load (mg)*
Mg	278	145
Ca	2140	1113
TSS	51900	26988
TDS	100	52
TS	52100	27092
PRECIPITATE CHARACTERIZATION		

Parameter	*Unit*	*Value*
Volume	L	380
Parameter	*Concentration (mg L^{-1})*	*Load (mg)*
Dissolved Mg	299	97
Dissolved Ca	2220	721
Suspended Mg	-	2227
Suspended Ca	-	287
TSS	52000	19864
TDS	13950	5329
TS	63700	24333
Parameter	*M.U.*	*Value*
Mg recovery	%	90%
Ca recovery	%	14%
EVAPORATION		
Parameter	*Unit*	*Value*
Temperature	˚C	100
Pressure	bar	-0.55
Time	min	30
Efficiency	%	20
CONCENTRATED CHARACTERIZATION		
Parameter	*Unit*	*Value*
Volume	L	416
Parameter	*Concentration (mg L^{-1})*	*Load (mg)*
Mg	120	50
Ca	735	306
TSS	60500	25168
TDS	400	166
TS	67200	27955
DISTILLATE CHARACTERIZATION		
Parameter	*Unit*	*Value*
Volume	L	104
Parameter	*Concentration (mg L^{-1})*	*Load (mg)*
Mg	151	16
Ca	1616	168
TSS	500	52
TDS	75	8
TS	1400	146

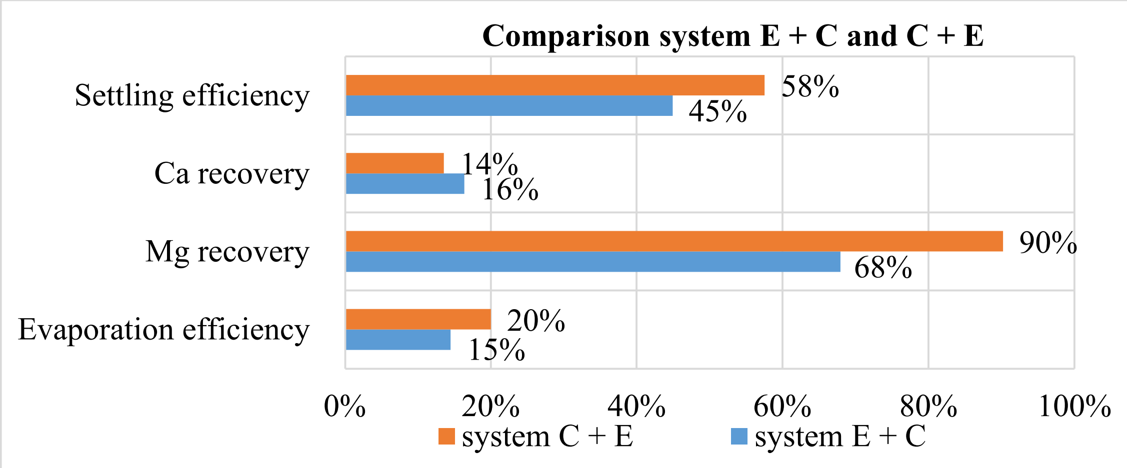


Figure 3.31: Performances comparison of the system E + C and C + E

When analysing the data related to system E + C and C + E, the chemical precipitation before the evaporation lead to a higher recover of magnesium in the precipitate though the calcium recovery does not vary. The settling efficiency of the system C + E is better than one of system E + C, probably due to the fact that the chemical precipitation in the systems C + E is carried out on the raw brine. Instead in the systems E + C the precipitation is performed on a concentrated brine, which has a higher concentration of TSS with respect to the raw brine. Thus, the PAC effect may be not enough for the coagulation and settling of the mass in the precipitate. Furthermore, the evaporation efficiency is better in the case of the systems C + E. Since, in the system E + C, the evaporation has been carried out on the raw brine; while, in the system C + E the evaporation has been performed on the supernatant flow having a lower salinity than the raw brine, such condition improves the evaporation rate (L. F. Petrik et al., 2015).

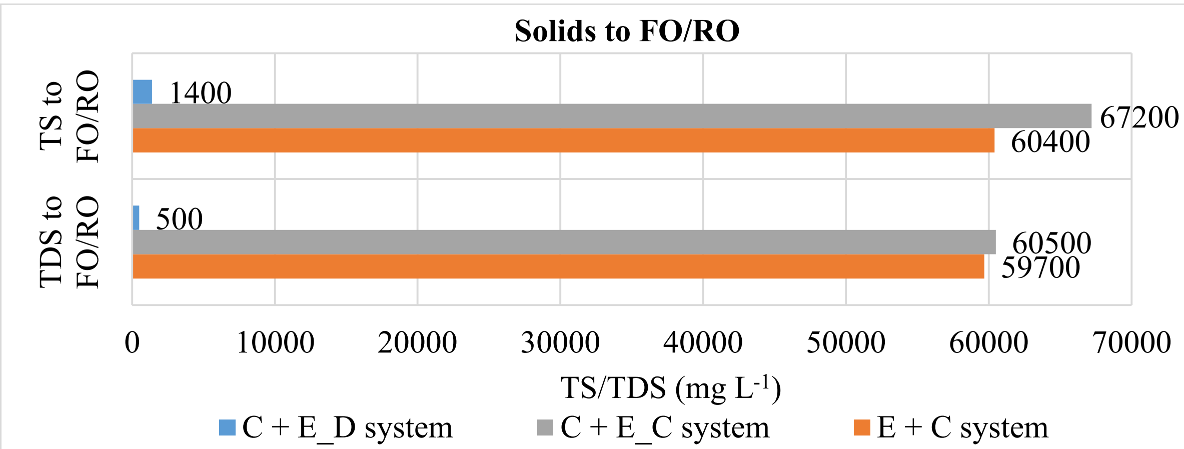


Figure 3.32: Concentrations of solids going to the FO/RO membrane

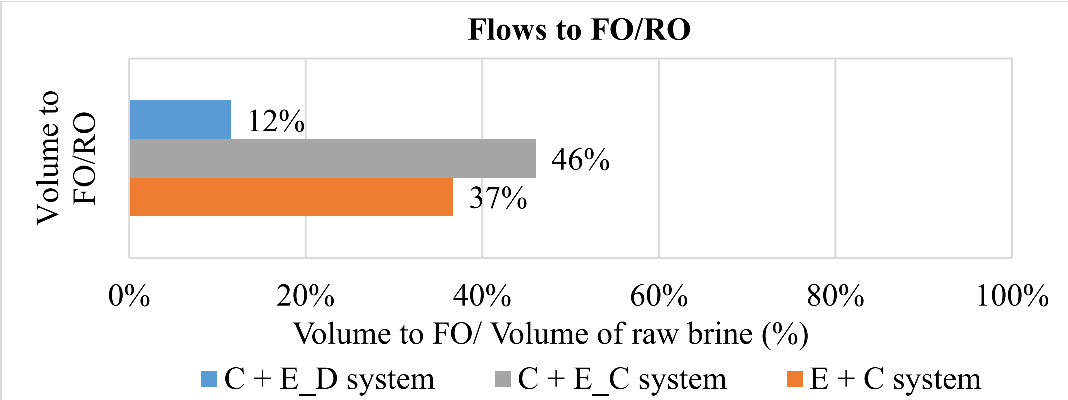


Figure 3.33: Volumes going to the FO/RO membrane

Finally, the systems are compared in terms of solids and volumes which are carried to the FO/RO membranes in order to avoid the rapid fouling and scaling of the membranes.

Regarding the system E + C, the 37% of the initial volume is supposed to go to FO/RO with a TS concentration of 60400 mg L^{-1}, such flow may easily lead to the scaling of the membranes.

By comparing the system C + E_C and C + E_D, in the first case the concentrations of TDS and TS are quite high and may drive the membrane to the scaling. In the system C + E_D, although the flow is poor of TS and the membrane scaling will be quite rare, only the 12% of the initial volume is headed to the FO/RO while the 46% of the initial volume becomes concentrated brine, which needs proper treatments. Therefore, the evaporation should be kept until all the initial volume is evaporated in order to reduce the concentrated flow. This proposal may be a solution though the energy consumptions of the evaporation should be also taken into account in order to determine the most cost-effective solution.

To sum up, the system E + C has generally lower performance of the system C + E, thereby its implementation in the pilot plant has been discharged. Considering the system C + E_C and C + E_D, the results of the chemical precipitation are quite satisfying, the Mg recovery as well as the settling efficiency are important. For avoidance of the membrane scaling, the total evaporation of the brine may be feasible depending on the energy performances of the evaporator.

Moreover, the system C + E has been compared with two previous laboratory tests: (i) chemical precipitation only with NaOH dosage at 18 mL L^{-1}, (ii) total evaporation of the raw brine at 110°C and -0.3 bar. Specifically, the figure below shows the comparison of the Mg and Ca removals obtained by the different treatments.

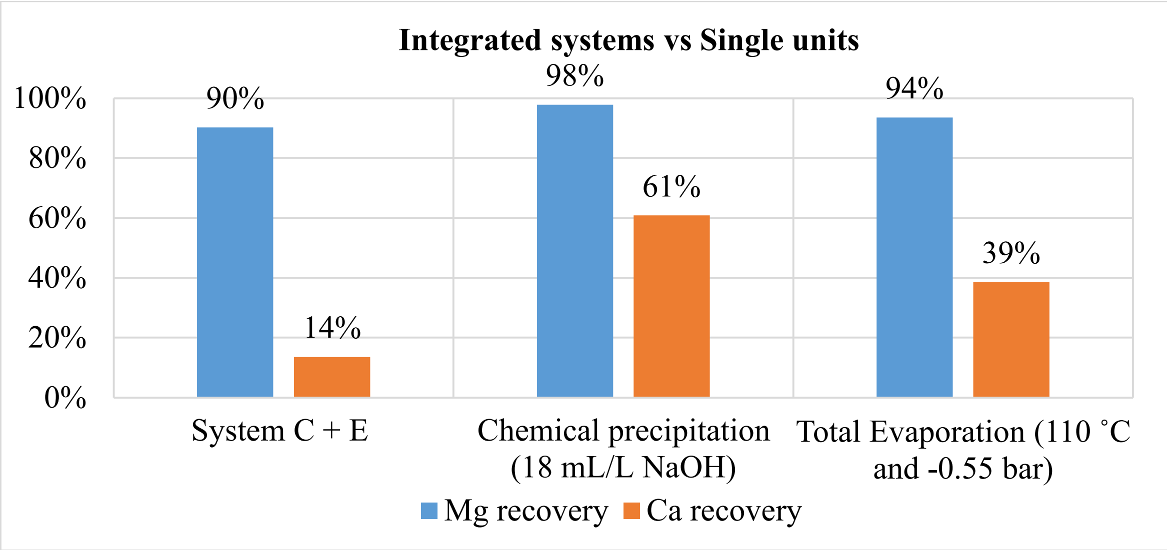


Figure 3.34: Comparison integrated systems and single units

The above graph highlighted that the combination of chemical precipitation with addition of NaOH, PAC and the evaporation does not imply improvements in Mg and Ca salt recovery, while the chemical precipitation of the raw brine with the only addition of NaOH and the total raw brine evaporation provide similar results.

Therefore, the chemical precipitation and the evaporation have been separately evaluated in the pilot plant in order to set up the most cost-effective pre-treatment train before the FO/RO.

3.2.2. Pilot tests in real environment

3.2.2.1. Evaporation tests

At the pilot scale, the evaporation rate of the raw brine has been evaluated at different operational conditions (i.e. temperature and pressure) by means of the industrial evaporator. Hence, four evaporation trials have been carried out on 15 L of raw brine, as follow:

- Evaporation test 1, at 150 ˚C and atmospheric pressure.
- Evaporation test 2, at 150 ˚C and -0.3 bar.
- Evaporation test 3, at 150 ˚C and -0.4 bar.
- Evaporation test 4, at 110 ˚C and -0.4 bar.

Table 3.26: Results of the evaporation 1

<table>
<tr><th colspan="5">EVAPORATION TEST 1</th></tr>
<tr><th colspan="5">OPERATIONAL CONDITIONS</th></tr>
<tr><th colspan="2">Parameter</th><th>M.U.</th><th colspan="2">Value</th></tr>
<tr><td colspan="2">Raw brine volume</td><td>L</td><td colspan="2">15</td></tr>
<tr><td colspan="2">Temperature</td><td>˚C</td><td colspan="2">150</td></tr>
<tr><td colspan="2">Pressure</td><td>bar</td><td colspan="2">1 (atmospheric)</td></tr>
<tr><td colspan="2">Time for heating</td><td>min</td><td colspan="2">50</td></tr>
<tr><td colspan="2" rowspan="2">Mg in raw brine</td><td>mg L^{-1}</td><td colspan="2">2811</td></tr>
<tr><td>g</td><td colspan="2">42</td></tr>
<tr><td colspan="2" rowspan="2">Ca in raw brine</td><td>mg L^{-1}</td><td colspan="2">1694</td></tr>
<tr><td>g</td><td colspan="2">25</td></tr>
<tr><th colspan="5">EVAPORATION</th></tr>
<tr><th>Time
(h)</th><th colspan="2">Volume distillate each step (L)</th><th>Vol. distillate cum.
(L)</th><th>V. Distil. / V initial
(%)</th></tr>
<tr><td>0</td><td colspan="2">0</td><td>0</td><td>0</td></tr>
<tr><td>0.5</td><td colspan="2">1.83</td><td>1.8</td><td>12</td></tr>
<tr><td>1.0</td><td colspan="2">2.05</td><td>3.9</td><td>26</td></tr>
<tr><td>1.5</td><td colspan="2">1.42</td><td>5.3</td><td>35</td></tr>
<tr><td>2.0</td><td colspan="2">1.39</td><td>6.7</td><td>45</td></tr>
<tr><td>2.5</td><td colspan="2">1.73</td><td>8.4</td><td>56</td></tr>
<tr><td>3.0</td><td colspan="2">1.26</td><td>9.7</td><td>65</td></tr>
<tr><td>3.5</td><td colspan="2">1.09</td><td>10.8</td><td>72</td></tr>
<tr><td>4.0</td><td colspan="2">1.28</td><td>12.1</td><td>80</td></tr>
<tr><td>4.5</td><td colspan="2">0.76</td><td>12.8</td><td>85</td></tr>
<tr><td>5.0</td><td colspan="2">0.73</td><td>13.5</td><td>90</td></tr>
<tr><td>5.5</td><td colspan="2">0.03</td><td>13.6</td><td>90</td></tr>
<tr><td>Average 0 - 4 h</td><td colspan="2">1.5</td><td colspan="2">= evaporation rate (L /30 min)</td></tr>
<tr><td>Standard deviation 0 - 4 h</td><td colspan="2">0.3</td><td colspan="2"></td></tr>
<tr><td>Average 4 - 5.5 h</td><td colspan="2">0.5</td><td colspan="2">= evaporation rate (L /30 min)</td></tr>
<tr><td>Standard deviation 4 – 5.5 h</td><td colspan="2">0.4</td><td colspan="2"></td></tr>
<tr><th colspan="5">FINAL CONDITIONS</th></tr>
<tr><th colspan="2">Parameter</th><th>M.U.</th><th colspan="2">Value</th></tr>
</table>

Mg in distillate	mg L^{-1}	206
	g	3
Ca in distillate	mg L^{-1}	1839
	g	25
TS concentrated	mg L^{-1}	1569900
Mg in concentrated (solid)	%	8.5
	g	133
Ca in concentrated (solid)	%	1.3
	g	20

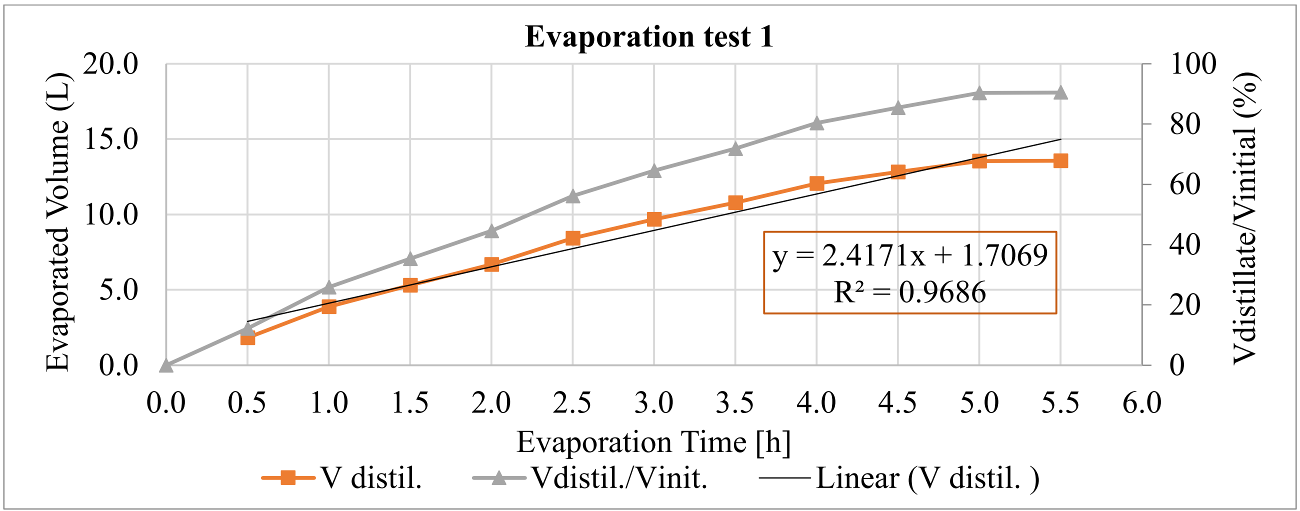


Figure 3.35: Evaporation curve of the test 1

By analysing the graph of the first experimental test, the evaporation rate is quite constant for the first four hours, with 3 L of distillate per hour. Whereas, in the last phase, the evaporation rate goes down to 1 L of distillate per hour due to the fact that the salinity of the brine has been increased significantly limiting the evaporation (L. F. Petrik et al., 2015).

Table 3.27: Results of the evaporation test 2

EVAPORATION TEST 2		
OPERATIONAL CONDITIONS		
Parameter	**M.U.**	**Value**
Raw brine volume	L	15
Temperature	˚C	150
Pressure	bar	-0.3
Time for heating	min	50
Mg in raw brine	mg L^{-1}	2811
	g	42
Ca in raw brine	mg L^{-1}	1694
	g	25
EVAPORATION		

Time (h)	Volume distillate each step (L)	Vol. distillate cum. (L)	V. Distil. / V initial (%)
0	0	0	0
0.5	2.1	2.1	14
1.0	2.1	4.3	28
1.5	2.1	6.4	43
2.0	1.5	7.9	53
2.5	1.5	9.4	63
3.0	1.5	10.9	73
3.5	1.6	12.7	85
4.0	0.9	13.6	91
Average 0 - 4 h	1.7	= evaporation rate (L /30 min)	
Standard deviation 0 - 4 h	0.4		

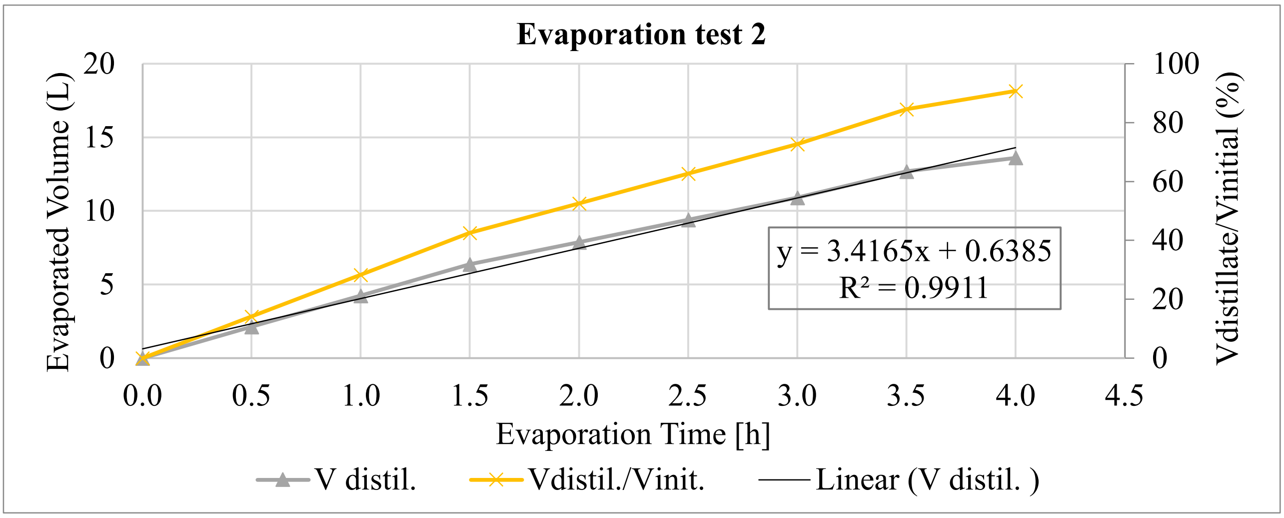


Figure 3.36: Evaporation curve of the test 2

Regarding the second test, the evaporation rate is quite constant at 3.4 L of distillate brine per hour for the whole duration of the test. Thus, the vacuum condition at -0.3 bar may have increase the overall evaporation rate; moreover, it may have hampered the reduction of the evaporation rate, which occurs as the salinity increases.

Table 3.28: Results of the evaporation test 3

EVAPORATION TEST 3		
OPERATIONAL CONDITIONS		
Parameter	**M.U.**	**Value**
Raw brine volume	L	15
Temperature	°C	150
Pressure	bar	-0.4
Time for heating	min	50
Mg in raw brine	mg L^{-1}	2811
	g	42
Ca in raw brine	mg L^{-1}	1694

		g	25
EVAPORATION			
Time (h)	**Volume distillate each step (L)**	**Vol. distillate cum. (L)**	**V. Distil. / V initial (%)**
0	0	0	0
0.5	2.0	2.4	16
1.0	2.0	4.5	30
1.5	2.0	6.5	43
2.0	2.0	8.5	57
2.5	2.0	10.6	70
3.0	2.0	12.6	84
3.5	1.0	13.6	91
4.0	0.5	14.1	94
Average 0 - 4 h	1.7	= evaporation rate (L /30 min)	
Standard deviation 0 - 4 h	0.6		
Average 0 - 3 h	2.0	= evaporation rate (L /30 min)	
Standard deviation 0 - 3 h	0.0		
Average 3 – 4 h	0.8	= evaporation rate (L /30 min)	
Standard deviation 3 - 4 h	0.3		

FINAL CONDITIONS		
Parameter	**M.U.**	**Value**
Mg in distillate	mg L^{-1}	137
	g	2
Ca in distillate	mg L^{-1}	1121
	g	16
TS concentrated	mg L^{-1}	2970800
Mg in concentrated (solid)	%	7.2
	g	193
Ca in concentrated (solid)	%	1.5
	g	40

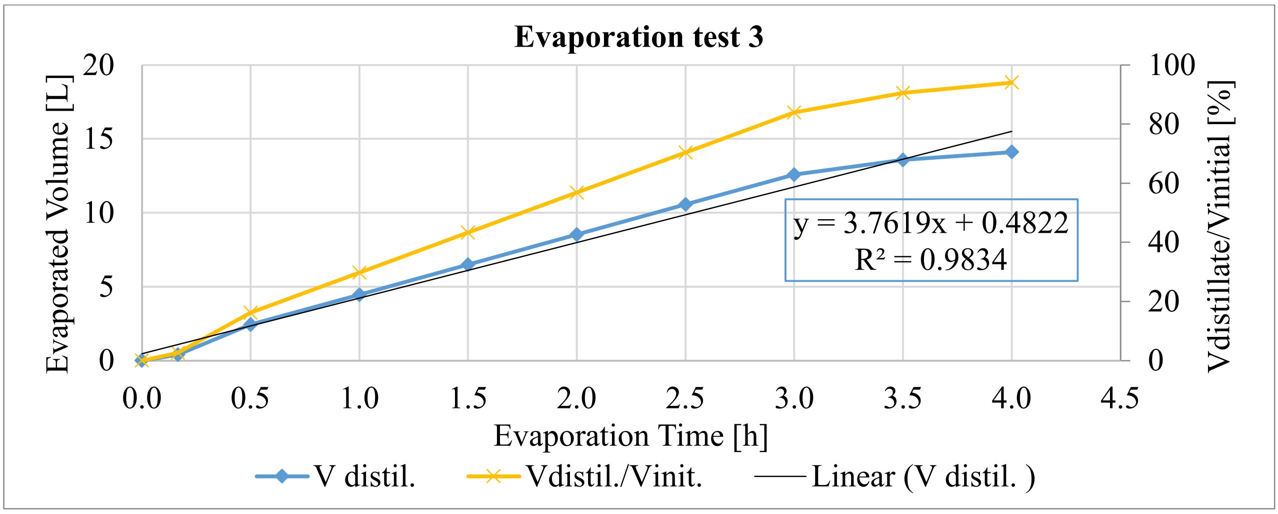


Figure 3.37: Evaporation curve of the test 3

By analysing the graph of the third test, the overall evaporation rate is about 3.4 L of distillate per hour as the evaporation test 2. However, in the first 3 hours, the rate is quite high at 4 L of distillate per hour reaching the 91% of volume distillate over the initial volume, as the final percentage of the second trial. Subsequently the last hour the evaporation rate drops to 1.6 L of distillate per hour, due likely to the increase of salinity.

Therefore, it seems that as the vacuum increases, the evaporation rate increases, and it remains almost constant until the 91% of the initial volume is evaporated. If the percentage increases, the rate drops dramatically. However, the vacuum cannot be increased above -0.4 bar since the current system is not able to hold such condition. A cooling system should be needed to cool down the vacuum equipment and decrease the pressure though it might represent a significant increase of energy consumption.

The following test has been carried out at -0.4 bar and at 110 ˚C in order to evaluate the effects of the temperature on the evaporation rate.

Table 3.29: Results of the evaporation test 4

EVAPORATION TEST 4			
OPERATIONAL CONDITIONS			
Parameter	**M.U.**	**Value**	
Raw brine volume	L	15	
Temperature	˚C	110	
Pressure	bar	-0.4	
Time for heating	min	35	
Mg in raw brine	mg L^{-1}	2811	
	g	42	
Ca in raw brine	mg L^{-1}	1694	
	g	25	
EVAPORATION			
Time (h)	**Volume distillate each step (L)**	**Vol. distillate cum. (L)**	**V. Distil. / V initial (%)**
0	0	0	0
0.5	0.8	0.8	5
1.0	0.8	1.6	11
1.5	0.8	2.5	16
2.0	0.7	3.2	21
2.5	0.7	3.9	26
3.0	0.7	4.6	31
3.5	0.7	5.3	35
4.0	0.7	6.0	40
4.5	0.7	6.6	44
5.0	0.6	7.3	48
5.5	0.6	7.9	53
6.0	0.6	8.5	57
Average 0 - 6 h	0.7	= evaporation rate (L /30 min)	

Standard deviation 0 - 6 h	0.1	
FINAL CONDITIONS		
Parameter	**M.U.**	**Value**
Mg in distillate	mg L^{-1}	131
	g	1
Ca in distillate	mg L^{-1}	892
	g	8
TS concentrated	mg L^{-1}	162400
Mg in concentrated (in liquid and solid phase)	%	7.6
	g	12
Ca in concentrated (in liquid and solid phase)	%	1.4
	g	2

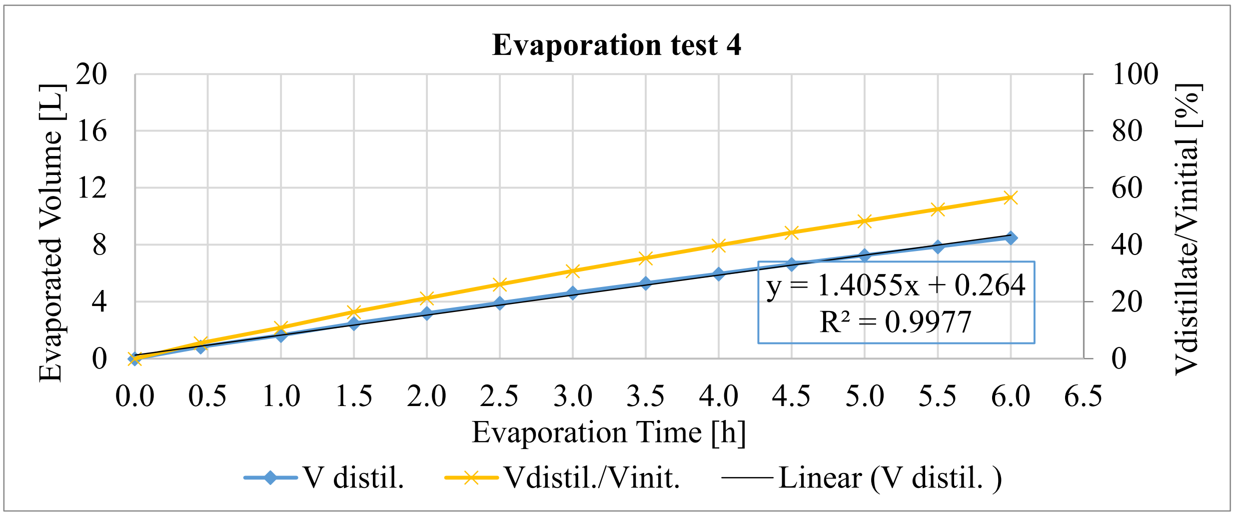


Figure 3.38: Evaporation curve of the test 4

In the fourth test, the evaporation rate has gone down to 1.4 L of distillate per hour and, after 6 hours the remaining volume is still the 43% of the initial volume. Therefore, as the literature review reports (L. F. Petrik et al., 2015), the evaporation temperature is the main driven parameter of the process kinetic.

Furthermore, the dissolved concentration of Mg^{2+} and Ca^{2+} in the distillate and precipitated amount in the concentrated flow are unaffected by the operational conditions of the evaporation. The concentration of Mg^{2+} in the distillate is about 120-200 mg L^{-1}, while the Ca^{2+} is around 800-1800 mg L^{-1}. The high concentrations of calcium in the distillate may be mainly due to the present fouling in the cooling and vacuum system.

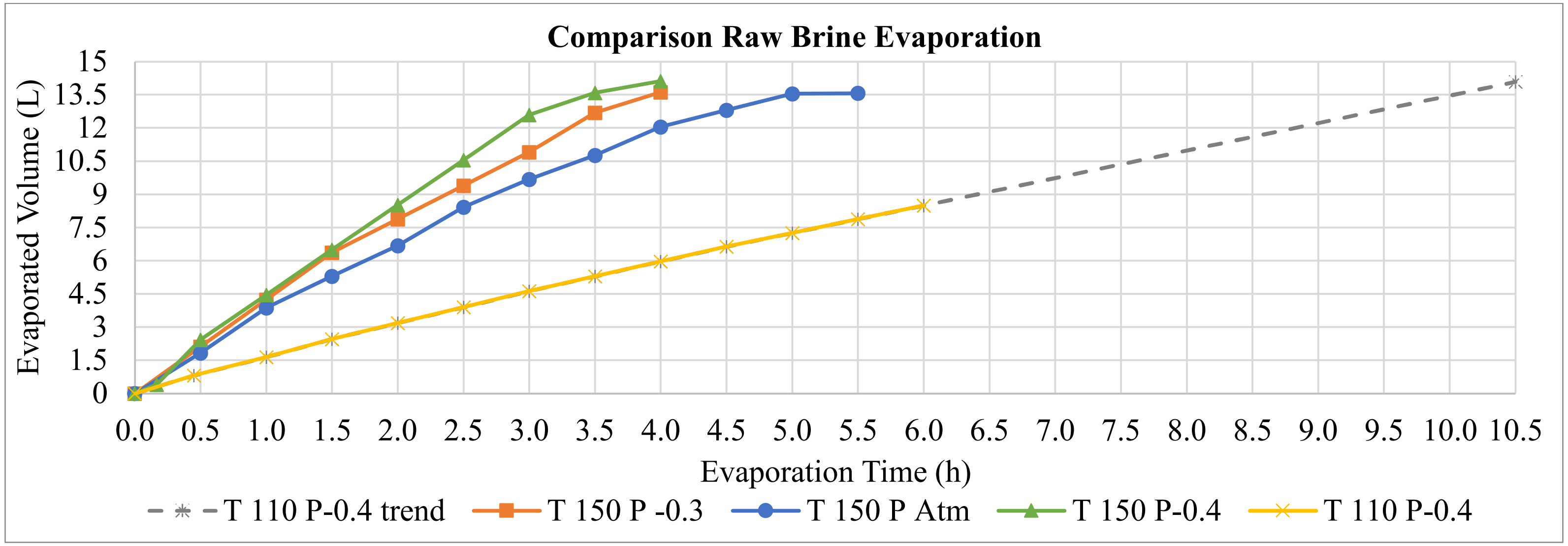


Figure 3.39: Comparison of the evaporation curves

Table 3.30: Comparison of the evaporation tests

COMPARISON RAW BRINE EVAPORATION				
OPTIMIZATION OF EVAPORATION TIME				
V distillate (%)	**EVAP 1 vs EVAP 2**	**EVAP 1 vs EVAP 3**	**EVAP 2 vs EVAP 3**	**EVAP 4 vs EVAP 3**
70	15%	24%	12%	68%
80	18%	30%	13%	67%
90	20%	30%	13%	65%

When comparing the four evaporation tests, the evaporation temperature results as the main driven parameter as explained before. In particular, if the evaporation trial 3 and 4 are compared, an increase of 40 ˚C leads to the optimization of the operational time around 65%. For instance, the 70% of the volume is evaporated at 2.5 h for the evaporation temperature of 150 ˚C and at 7.5 h for 110 ˚C. Moreover, the vacuum condition improves significantly the reduction of evaporation time, especially if higher percentage of distillate volume over the initial volume (i.e. 80, 90%) are reached. For example, if the 90% of distillate volume over the initial volume aims to be achieved, a vacuum of -0.3 bar and -0.4 bar cut the evaporation time, respectively, of a 20% and a 30% respect the evaporation at atmospheric conditions.

Furthermore, when the vacuum is increased of 0.1 bar, from -0.3 to -0.4 bar, the optimization of the evaporation time is about 12-13%.

Finally, the energy performance of the four tests have been compared in order to choose the most cost-effective operational parameters. The energy is consumed by evaporator mainly for the heating, stirring and the cooling. The heating is carried out by the oil, which is heated by the electrical resistance. When the oil reaches the set temperature, the heating is automatically switched off reducing the energy absorbed. So, when the heating is on, the real energy absorbed is about 1.8 kW while if it is off, the real energy absorbed drops to 0.2 kW. Therefore, the heating cycle ON and OFF has been monitored and reported below in order to evaluate the real electrical consumption of the trials.

Table 3.31: Comparison of the energy performances

COMPARISON RAW BRINE EVAPORATION					
OPTIMIZATION OF ENERGY PERFORMANCE					
Parameter	**M.U.**	**EVAP 1**	**EVAP 2**	**EVAP 3**	**EVAP 4**
Heating time	h	0.83	0.83	0.83	0.58
Evaporation time	h	5	4	3.5	10.5
V distillate /V initial	%	91	91	91	91
Heating ON	%	100	100	100	53
Heating OFF	%	0	0	0	47
Real energy absorbed ON	kW	1.8			
Real energy absorbed OFF	kW	0.2			
Consumption ON	kWh	10.7	8.9	7.9	13.3
Consumption OFF	kWh	0	0	0	1.1
Total consumption	kWh	10.7	8.9	7.9	14.5

Analysing the evaporation test 4, although the heating is not always on, it has the highest total consumption since it lasts 10.5 hours in order to reach 91% of distillate volume. While as the vacuum increases, the energy consumption decreases thanks to the reduction of the evaporation time.

It results that the best investigated operational conditions are temperature at 150 ˚C and pressure at -0.4 bar. However, the vacuum of -0.4 bar may not be easily implemented at real scale. Since a cooling system for the vacuum equipment was needed during the evaporation test 3 in order to hold constant the negative pression, otherwise the vacuum stabilized at -0.3 bar. Therefore, the most-coeffective operational conditions may be the ones of the evaporation test 2: temperature at 150 ˚C and pressure at -0.3 bar.

3.2.2.2. Integrated systems

The following mass balances and energy performances of the three scenarios have been obtained from the pilot plant tests. In the scenario 1, the chemical precipitation has been carried out dosing 13.5 mL L^{-1} of NaOH, 24 hours of settling before the supernatant goes to the FO/RO membrane.

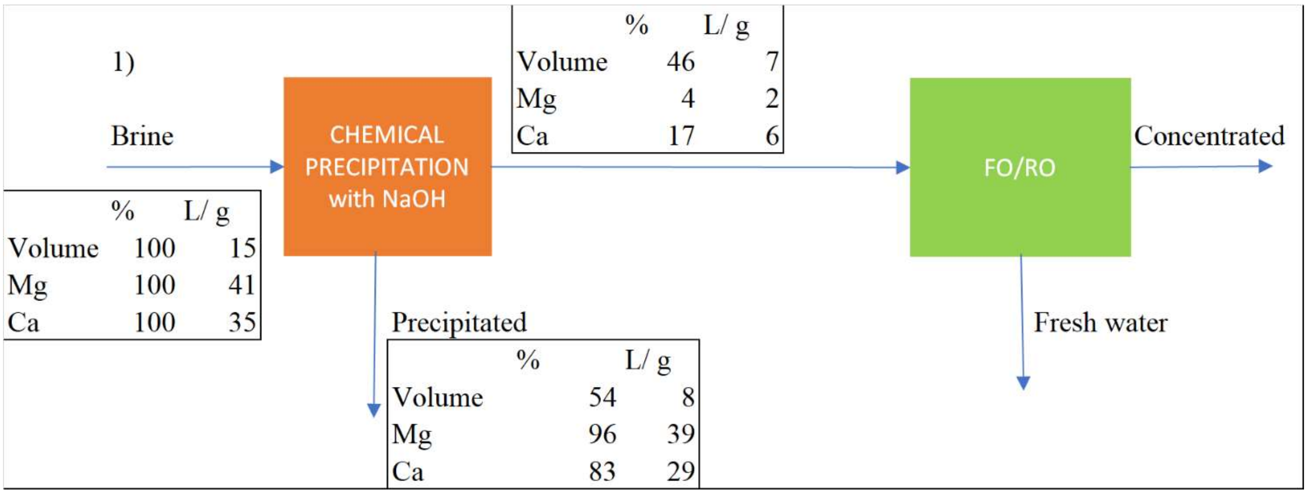


Figure 3.40: Mass balance of the scenario 1

Table 3.32: Energy consumption of the scenario 1

ENERGY PERFORMANCES SCENARIO 1		
Parameter	**M.U.**	**Mixer Chemical Precipitation**
Working time	h d^{-1}	1
Real absorbed power	kWh	0.4
Real Consumption	kWh d^{-1}	0.4

In the scenario 2, the evaporation has been performed at 150 ˚C and -0.3 bar until the 91% of the initial has been evaporated, with the distillate going to the FO/RO.

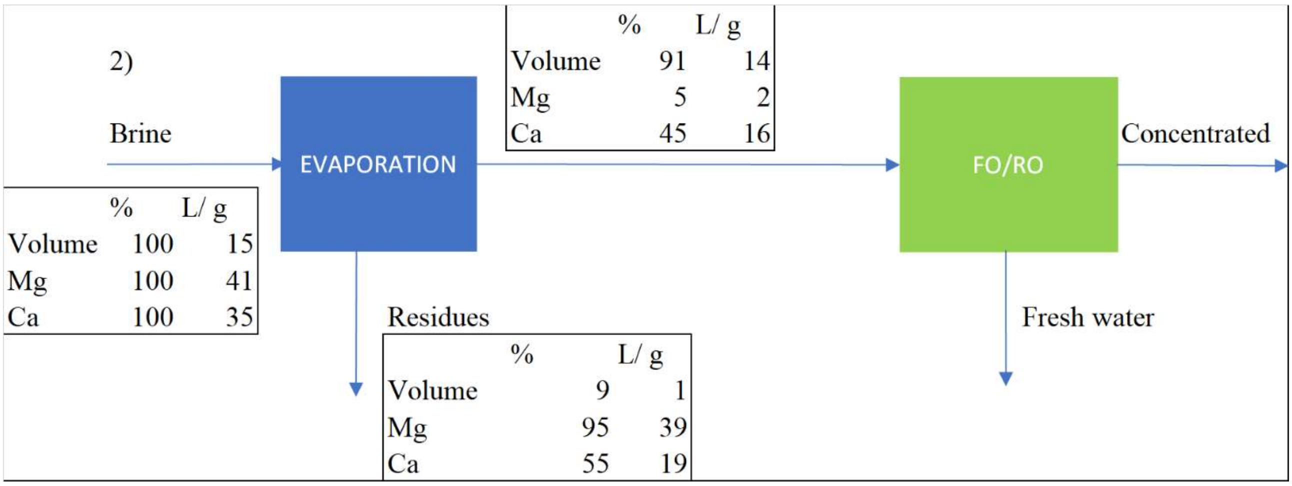


Figure 3.41: Mass balance of the scenario 2

Table 3.33: Energy consumption of the scenario 2

ENERGY PERFORMANCES SCENARIO 2			
Parameter	**M.U.**	**Mixer Evaporation**	**Thermal resistance**
Working time	h d^{-1}	4	4
Real absorbed power	kW	0.2	1.8
Real Consumption	kWh d^{-1}	1.0	7.4
Total consumption	kWh d^{-1}	8.3	

In the scenario 3, the evaporation has been performed at 150 ˚C and -0.3 bar until the 91% of the initial has been evaporated. Moreover, 13.5 mL L^{-1} of NaOH has been dosed on the distillate flow in order to precipitate the high dissolved residues of calcium. Finally, the supernatant is conveyed to the FO/RO membrane.

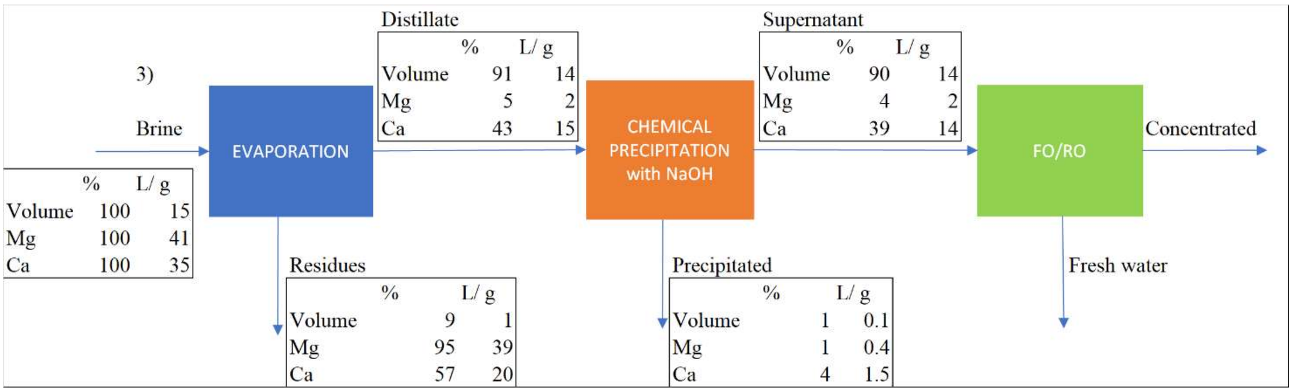


Figure 3.42: Mass balance of the scenario 3

Table 3.34: Energy consumption of the scenario 3

ENERGY PERFORMANCES SCENARIO 3				
Parameter	**M.U.**	**Mixer Evapor.**	**Thermal resistance**	**Mixer Precipit.**
Working time	h d^{-1}	4	4	2
Real absorbed power	kW	0.2	1.8	0.4
Real Consumption	kWh d^{-1}	1.0	7.4	0.7
Total consumption	kWh d^{-1}	9.1		

In the following graphs, the performance of the three scenarios are compared. The Mg and Ca recoveries are, respectively, expressed in percentage of magnesium and calcium in the precipitate/residues over the total Mg and Ca in the raw brine. While the flow going to the FO/RO is expressed in percentage respect to the initial volume of the raw brine.

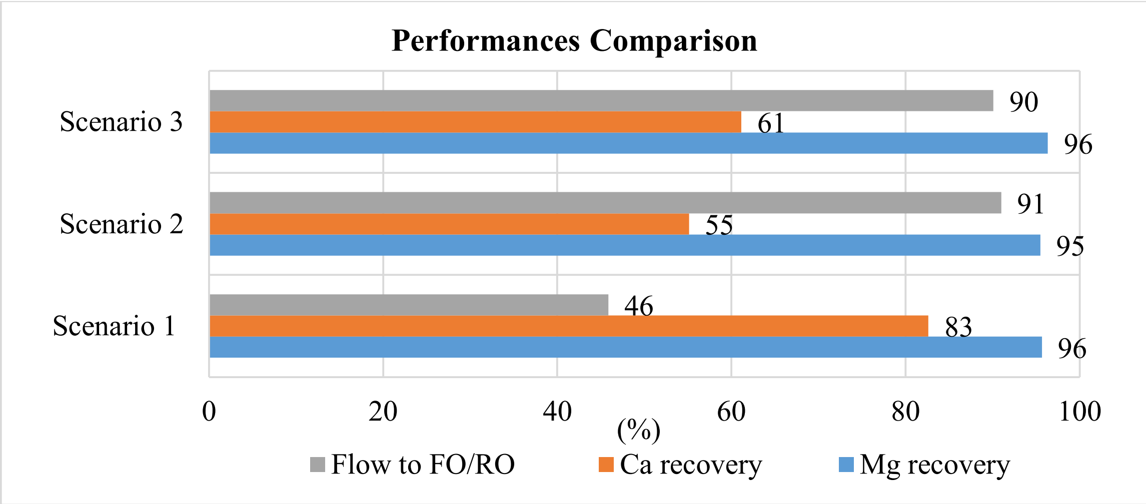


Figure 3.43: Performances comparison of the three scenarios

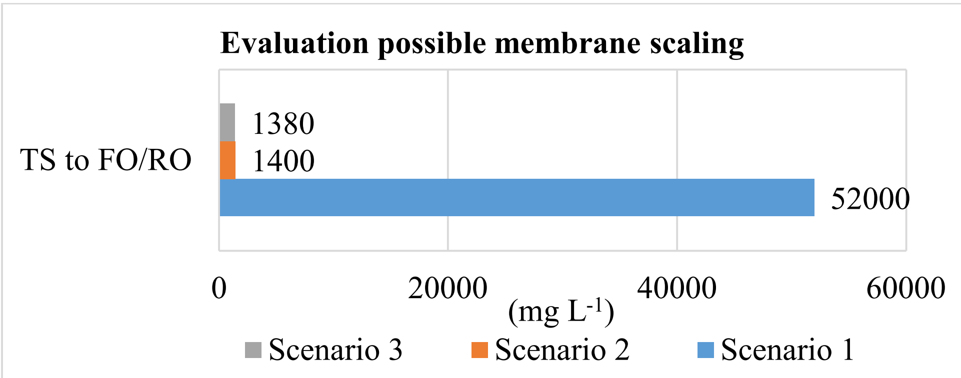


Figure 3.44: Concentrations of solids going to the FO/RO membrane

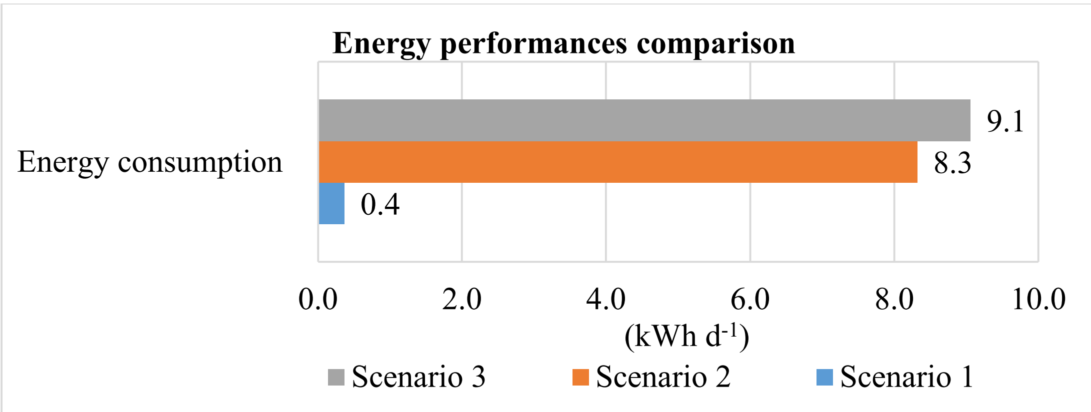


Figure 3.45: Comparison of the energy consumptions

Analysing the results from pilot tests, in the scenario 1 a high recovery of Mg and Ca occurs even though the volume of supernatant going to the FO/RO membrane is quite scarce, by recovering less freshwater from RO membrane. In addition, the high TS concentration of the supernatant may lead to the scaling of the membrane.

Considering the scenario 2 and 3, the recoveries of Mg and Ca are high and medium respectively. Moreover, the distillate flows are significant and with low concentrations of TS avoiding membrane-related issues. However, if the energy performances are taken into account, the scenario 1 is the most energy saving solution.

Comparing the scenario 2 and 3, the performances in figure 3.39 and the TS concentrations going to the FO/RO membrane are quite alike. However, in the scenario 3 the energy consumption is the highest and the slightly increase of Mg and Ca recovery may not justify the addition of 13.5 mL L^{-1} of NaOH to the distillate flow.

To sum up, the most cost-effective pre-treatment trains are the scenario 1 and 2, their respective advantages and disadvantages are reported below.

Table 3.35: Advantages and disadvantages of the scenario 1 and 2

SUMMARY		
SCENARIO	**ADVANTAGES**	**DISADVANTAGES**
1	High recovery of Mg; high recovery of Ca, low energy consumption	Possible membrane scaling (24 hours of operation have been estimated for FO/RO); low water recovery by RO; reagent dosage
2	High recovery of Mg; middle recovery of Ca; Poor membrane scaling (44 hours of operation have been estimated for FO/RO); high water recovery by RO	Very high energy consumption

CONCLUSIONS

Regarding the HYDROUSA project, the methodology of the feasibility study for HYDROUSA solutions has been provided. It is based on the multi-criteria decision analysis (MCDA) method, the assessed criteria for the feasibility evaluation are social, policy, technical and economic feasibility. This methodology has been used to evaluate the feasibility of HYDRO1&2 on Gorgona island, Italy. From the replicability study, the realization of the proposed HYDROs in the replication site of the island results feasible from a social, legislative, technical and economical point of view.

The social feasibility of the HYDROs results to be 91/100, since the involvement of the stakeholders in the project is large leading to the increase of the others social sub-criteria. However, the monitoring and the assessment of the green infrastructures at national and regional level are currently quite poor; these instruments should be more valorised as they might help to rise social awareness of the advantages of the nature-based solution for water-stressed community.

The legislative feasibility is estimated to be 80/100, no general barriers that completely prevent the application of HYDRO 1&2 and of its final products have been found in the Italian and regional regulatory framework. Besides, the main detected issue is the lack of ad-hoc legislative instruments in the Italian policy framework for the realization of NBS and for an economic viable reuse of the HYDROs by-products.

The technical feasibility is about 90/100 due to the fact that, in addition to the proper treatment of the domestic wastewater, the HYDRO 1 is able to provide reclaimed water for HYDRO 2 and energy for the UASB reactor.

Finally, the economic feasibility is estimated to be 65/100 with a payback period of 5.5 years, which may seem modest. Nevertheless, the result is lowered by the assumption that the revenues from HYDRO 2 are supposed to be completely given to the inmates in order to enhance the local economic and the social inclusion of the local penitentiary.

Considering all the previous aspects, the interest of the possible involved stakeholders about the HYDROUSA solutions results quite relevant and it might be the key factor for the concrete realization of the project. Indeed, the HYDROs values are largely recognized by the water utility and authorities, due to the fact that these nature-based solutions might at once:

- tackle the water criticalities of the island,
- close the water loops,
- implement a circular and self-sustaining natural resource management,
- preserve the landscape and the naturalistic value of Gorgona.

Considering the FIT4REUSE project, the final pilot tests in real environment have proven the chemical precipitation (i.e. scenario 1) and the total evaporation of the raw brine (i.e. scenario 2) are the most cost-effective pre-treatments for the FO/RO membrane. The chemical precipitation of the raw brine dosing 9-13 mL L^{-1} of NaOH results in a high Mg and Ca recovery (96% and 83% respectively) though the supernatant to be send to FO/RO is modest and with a relevant total solids concentration. Thus, further evaluations are needed regarding the membrane scaling. Although, the total evaporation of the raw brine at 150 ˚C and -0.3 bar results in high Mg recovery (95%), middle Ca recovery (55%), high distillate flow with low TS is obtained for FO feeding. Moreover, the energy consumption assessment highlighted that electricity needed to run evaporation process is the highest compared to chemical processes.

Therefore, the assessment of the scenario 1 and scenario 2 in real scale is recommended in order to determine the best pre-treatment solution before FO/RO.

ANNEX

I. REPLICABILITY STUDY OF THE ITALIAN CASE STUDY

I.I. Project Strategic Context

The involved project consists in the replication of the nature-based technologies HYDRO 1 and HYDRO 2, which have been developed within the HYDROUSA project, on the Gorgona Island, located in the Tuscan Archipelago (Italy).

HYDRO 1 consists of a sewage treatment system usually applied in decentralized areas with high seasonal loads. HYDRO 1 combines an anaerobic process (Upflow Anaerobic Sludge Blanket (UASB) reactor) with constructed wetlands and tertiary processes in order to treat municipal wastewater as a completely circular solution. Its final effluent, rich of nutrients, can be reused for irrigation purposes; the produced sludge is stabilized by drying reed beds and reused in agriculture. Moreover, the biogas from the UASB could be reused for self-heating through a CHP generator. Finally, in HYDRO 2 the reclaimed water from HYDRO 1 is used to cultivate the local crops and plants of Gorgona.

The project's scopes are to close the water loops and the establishment of a sustainable resource management, in order to overcome the water-related challenges of the island. This report is analysing the feasibility of the project and possible scenarios for the implementation of the HYDRO 1 and HYDRO 2 taking into account social, legislative, technical and economic aspects. For the realization of the HYDRO 1, the proposed scenario is the upgrading and revamping of the existing wastewater treatment plant (WWTP) of Gorgona Island, which currently treats domestic wastewaters from the local penitentiary, the harbour houses and the guesthouse. The reclaimed by-products from HYDRO 1 could be reused on the neighbouring lands for crops cultivation.

Scenario analysis and related benefits

The main water related issues of Gorgona Island are:

- Water scarcity
- Preservation of the natural resources from pollution
- Sludge management.
- Lack of a circular natural resources (e.g. water, sludge, crops, plants, etc.) management

The nature-based solution HYDRO 1 treats the wastewater and provides reclaimed water and compost for fertigation and biogas. Benefits strictly related to HYDRO1+HYDRO2 implementation on Gorgona Island are:

- Reduce the water scarcity
- Reclaim of nutrient-rich effluent wastewater for agricultural purposes
- Optimization of sludge management and reuse on-site
- Reduce the environmental impact in terms of pollution and use of resources
- Promote alternative scenarios of bio-economy to support the local social cohesion and business

Moreover, as Gorgona Island hosts a penitentiary, HYDROs may be directly managed by the inmates, representing an interesting opportunity for the prisoners' rehabilitation and reintegration into the society. The others HYDROs have been considered and excluded since they do not simultaneously tackle all water related issues of Gorgona. Instead, HYDRO 1 and HYDRO 2 could face at once all the challenges preserving the historical and environmental worth of the island.

I.II. Characterization of the replication site

The replication site is located on Gorgona island, which is the smallest island of the Tuscan Archipelago with a surface of 2.2 km^2. It is part of the Livorno Municipality, Tuscan region (Italy), which is 36 km far away.

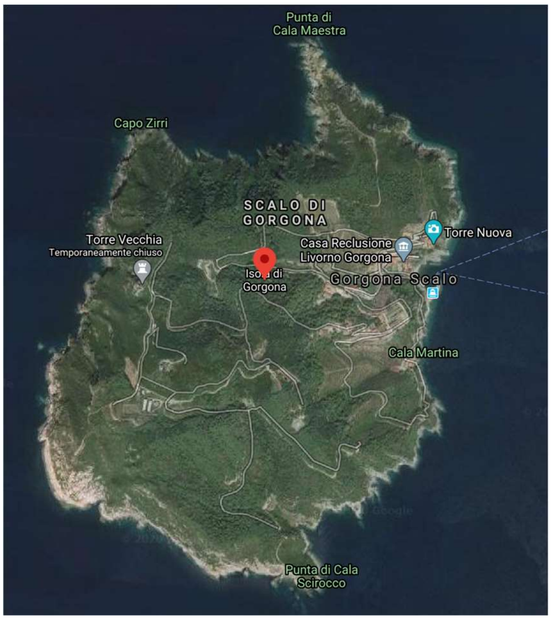


Figure 0.1: Gorgona Island

The mountainous island is characterized by a typical rural landscape and Mediterranean vegetation. It hosts an agricultural penal colony, so its population is composed of the local citizens and the correctional facility inmates, which take care of the cattle farm and agriculture areas on the Island. The island is characterized by a Mediterranean climate with moderate daily temperature oscillations. The precipitations are usually scarce and prevalent throughout the autumn.

Description of the area

The proposed replication site for the implementation of the HYDRO 1 might be the area where the existing WWTP is actually situated (see Figure 0.2, coordinate GPS: 43°25'50.94"N; 9°54'11.80"E).

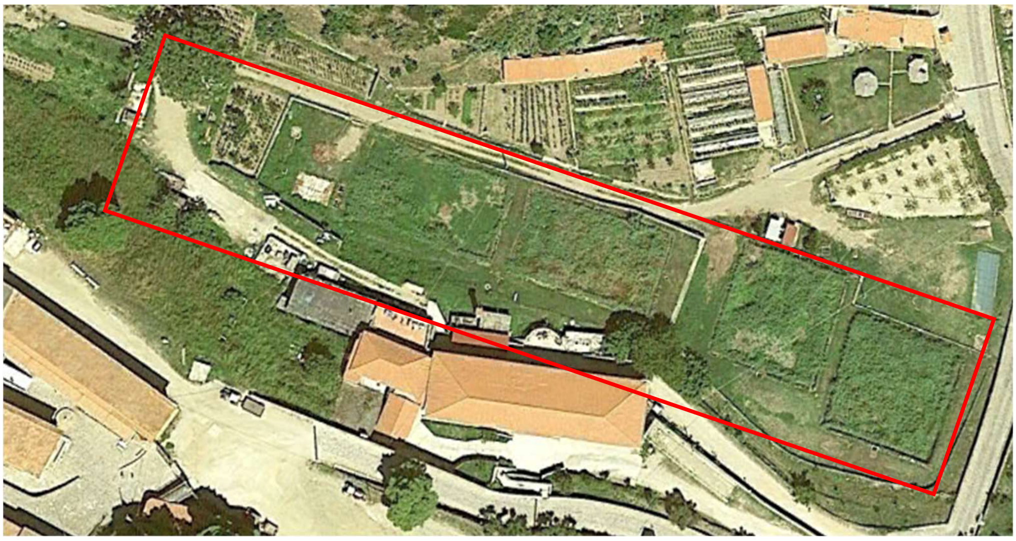


Figure 0.2: Replication site (existing WWTP)

The extension of the area is about 5.5 ha on a slope which is gently dipping towards the sea; the nearby zone is characterized by artificial terraces.

The existing WWTP is composed of an inlet canal, equipped with a grit for the inert material removal, an Imhoff tank for the removal of coarse/fine materials and horizontal flow (HF) constructed wetlands (2 lines in parallel, each line 2 beds in series) for domestic wastewater treatment; the flow is completely driven by gravity. The plant is currently treating the wastewater coming from the correctional facility, the harbour houses and the guesthouse. The inlet load is about 195 population equivalent (PE) with a daily average flow rate of 13 m^3d^{-1} during the winter and is about 270 PE with a daily average flow rate of 18 m^3d^{-1} during the summer. The above existing agriculture lands could be used for HYDRO 2 replication.

Environmental constraints

Gorgona is subjected to different environmental constraints at different levels (national and regional), due to its historical and environmental value. It is part of the National Park of the Tuscany archipelago; whose plan distinguishes the island into two protection zones. The proposed replication site is situated in zone C of “extensive protection”.

The whole island is submitted to landscape constraint (D.M. 31/03/1971; G.U. n. 150 del 1971); the island and the nearby sea areas are included into the network Natura 2000, they are classified as special area of conservation (SAC) under the Birds directive and as special protection area (SPA) under the Habitats directive.

From an acoustic point of view, the replication site is located in area II (area with residential use) and subjects to acoustic emission limits.
Moreover, the proposed replication site is close to an area which has a high probability of flooding (return time between 20 and 50 years) according to the hydraulic hazard map. Therefore, the project might carefully develop outside this zone for safety reasons.
These constraints might hinder the implementation of HYDRO 1 and HYDRO 2, thereby each of them is going to be addressed in the chapter 4 “Policy analysis and institutional framework” according to their level (national, regional and local).
Although environmental constrains are detected, the project might be likely feasible: the interested technologies may be easily integrated into the island landscape and environment thanks to their nature-based feature.

I.III. Social analysis and final end-users’ identification

In this section, the feasibility of the project HYDRO 1 and HYDRO 2 is assessed from a social point of view. According to the sub-criteria of the table 2.1, a score is assigned to each sub-criterion. Thus, the overall Social Feasibility Score of the HYDROs has been obtained and reported in the table 3.1.

I.IV. Policy analysis and institutional framework

The policy analysis for the implementation of the HYDRO 1 and HYDRO 2 on the replication site is carried out considering regulatory instruments at different institutional levels.
According to the table 2.2, a score for each sub-criterion is provided and reported, as table 3.6 highlights, for an overall assessment of the policy framework.
Considering the circular approach of the HYDROs and the degree of innovation in terms of reuse, the local and national legislation are below analysed in order to identify the regulatory instruments to implement the HYDROs and the reuse of the by-products.

Regulatory instruments for decentralized community systems

In the following chapters, the Italian and Tuscany regulatory instruments are going to be assessed. No general barriers that completely prevent the application of HYDRO 1 and HYDRO 2 have been found in the regulatory framework. However, the achievement of the high-quality standards for reclaimed water and sludge, enforced by national and regional legislation, may be a challenge to the economic sustainability of the project.

There is not a clear legislation to support small, decentralized water-related services as well as for the implementation of regenerated close loops. Therefore, a collaborative debate is needed between the water utility and the water authority/local governance in order to address the possible legislative constrains and implement a technical, social and economic viability of the project.
Besides, the European commission has been lately moving forward legislations to support regenerative water loops. On the 25 May 2020, the EU approved the regulation on the water reuse for fertigation: "REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on minimum requirements for water reuse". The deal summarizes the minimum requirements for water reuse depending on the vegetative species and their final use on the market. The introduction of these quality standards results in a more economically feasible reuse of reclaimed wastewater for irrigation purposes, even for small and decentralized water systems.

National/regional strategies and action plans

The following national/regional strategies and actions plans have been analysed for the regulatory framework since they can affect the realization of the HYDRO 1 and HYDRO 2 on Gorgona Island:

- Structural plan (in Italian "Piano Strutturale") of Livorno Municipality (municipality level)
- Acoustic classification plan (in Italian "Piano di Classificazione Acustica") of Livorno Municipality (municipality level)
- Water protection plan (in Italian "Piano Tutela delle Acque") of "Tuscany coast" basin (basin level)
- Territorial direction plan (in Italian "Piano di indirizzo territoriale") of Tuscany Region (regional level)
- Plan of the national park (in Italian "Piano parco nazionale") of Tuscany Archipelago (archipelago level)
- Network Natura 2000 (in Italian "Rete natura 2000) (regional level)
- Plan of Management Flooding Risk (in Italian "Piano di gestione rischio alluvioni") of "Tuscany Coast" basin (basin level)
- Territorial Plan of Provincial Coordination (in Italian "Piano territoriale di coordinamento provinciale") of Livorno Province (province level)

In the table 3.2, these national/regional strategies are summarized and evaluated.

National/regional legislations and quality standards/targets

The main products from the HYDRO 1 could be the reclaimed water and the stabilized sludge. Their reuse so far may be subjected to different national/regional legislations, which require different quality standards, and may either hinder or promote the implementation of HYDRO 1 and HYDRO 2 on Gorgona Island. Therefore, the regulatory framework is assessed below, taking into account both the reclaimed water and the stabilized sludge.

Regulatory framework of reclaimed water

At national and regional level, four different legislative instruments may govern the reuse of reclaimed water from HYDRO 1 to HYDRO 2:

1. Ministerial Decree n. 185/2003, the reclaimed water has to fulfil the technical rules of the Decree for its reuse in agriculture.
2. Legislative Decree n. 152/2006, the reuse of reclaimed water is set as discharge on soil and it has to fulfil the relative limits.
3. Decree of the President of Regional Government n. 46/R 2008, the reclaimed water is set as "agri-food wastewater" for fertigation purposes and it has to fulfil the relative limits.
4. Regulation (EU) n. 741/2020, which paves the way to a European regulation for a more feasible reuse of the reclaimed water in agriculture.

Firstly, the Ministerial Decree n. 185/2003 establishes the technical rules for the reuse of domestic, urban and industrial wastewaters in order to preserve the water resource. In the following table, taking into account the reuse of the reclaimed water for irrigation purposes, the main quality standards enforced by the Decree are listed.

Table 0.1: Reclaimed water quality standards of Ministerial Decree n. 185/2003

Parameters	Measurement Unit	Limit Value
pH		6-9.5
TSS	mgL^{-1}	10
BOD_5	mgL^{-1}	20
COD	mgL^{-1}	100
TP	mgL^{-1}	10
TN	mgL^{-1}	35
$N\text{-}NH_4$	mgL^{-1}	2
Electrical Conductibility	$\mu S\ cm^{-1}$	3000
E. coli	UFC $100mL^{-1}$	10 (for 80% of samples) 100 (max value)

The reuse for irrigation purposes should fulfil the "Code of good agricultural practice" (D.M. n. 86/1999) according to the article 10 of the D.M. n. 185/2003. The quality monitoring by the regional agencies is usually quite demanding particularly for a small solution as "HYDRO 1".

Secondly, the reuse of the effluent from "HYDRO 1" may be set as discharge on soil, which is ruled by the Legislative Decree n. 152/2006, since the effluent load is quite modest. In the following table, the main quality standards enforced by the Decree for discharge on soil are listed.

Table 0.2: Reclaimed water quality standards of Legislative Decree n.152/2006

Parameters	Measurement Unit	Limit Value
pH		6-8
TSS	mgL^{-1}	25
BOD_5	mgL^{-1}	20
COD	mgL^{-1}	100
TP	mgL^{-1}	2
TN	mgL^{-1}	15
E. coli	UFC $100mL^{-1}$	5000 (max value)

Although the Decree identifies parameters and monitoring frequency for discharge on soil, the fertigation purpose is not specifically mentioned.

The third scenario could allow the identification of the reclaimed water as "agri-food wastewater" for fertigation purposes (Decree of the President of Regional Government n. 46/R 2008), since the main goal is the recovery of nutrients for crops and plants. Concerning the quality standards, the article 28 of D.P.G.R n. 46/R 2008 reports: "*the agri-food use of agri-food wastewater is allowed if the following points are fulfilled: a) preservation of water bodies and achievement of the quality standards, b) water resource and nutrients are recovered according to the needs of the crops, c) observance of the hygienic sanitation norms*." However, different effluent limits are mentioned based on the crop variety (attachment 4 of the D.P.G.R.).

While the fourth scenario considers the application of the new European regulation, which sets reclaimed water quality in function of the allowed agricultural use and irrigation methods, as follow.

Table 0.3: Classes of reclaimed water quality and allowed agricultural use and irrigation method (Regulation (EU) n. 741/2020)

<table>
<tr><th>Minimum reclaimed water quality class</th><th>Crop category</th><th>Irrigation method</th></tr>
<tr><td>A</td><td>All food crops, including root crops consumed raw and food crops where the edible part is in direct contact with reclaimed water</td><td>All irrigation methods</td></tr>
<tr><td>B</td><td rowspan="2">Food crops consumed raw where the edible part is produced above ground and is not in direct contact with reclaimed water, processed food crops and non-food crops including crops to feed milk- or meat-producing animals</td><td>All irrigation methods</td></tr>
<tr><td>C</td><td>Drip irrigation only</td></tr>
<tr><td>D</td><td>Industrial, energy, and seeded crops</td><td>All irrigation methods</td></tr>
</table>

Table 0.4: Reclaimed water quality requirements for agricultural irrigation (Regulation (EU) n. 741/2020)

<table>
<tr><th rowspan="2">Quality class</th><th rowspan="2">Indicative technology target</th><th colspan="5">Quality standards</th></tr>
<tr><th>E. coli (cfu $100 mL^{-1}$)</th><th>BOD_5 (mg L^{-1})</th><th>TSS (mg L^{-1})</th><th>Turbidity (NTU)</th><th>Altri</th></tr>
<tr><td>A</td><td>Secondary treatment, filtration, and disinfection</td><td>≤ 10 or below detection limit</td><td>≤ 10</td><td>≤ 10</td><td>≤ 5</td><td rowspan="4">Legionella spp.: <1,000 cfu/L where there is risk of aerosolization in greenhouses Intestinal nematodes (helminth eggs): ≤1 egg/l for irrigation of pastures or forage</td></tr>
<tr><td>B</td><td>Secondary treatment, and disinfection</td><td>≤ 100</td><td rowspan="3">≤ 25 with 70-90% of reduction (Directive 91/271/EEC1, Annex I, Table 1)</td><td rowspan="3">≤ 60 with 70% of reduction in case PE = 2000-10000 (Directive 91/271/EEC1, Annex I, Table 1)</td><td>-</td></tr>
<tr><td>C</td><td>Secondary treatment, and disinfection</td><td>≤ 1000</td><td>-</td></tr>
<tr><td>D</td><td>Secondary treatment, and disinfection</td><td>≤ 10000</td><td>-</td></tr>
</table>

Furthermore, clear monitoring frequencies are reported in the table 3 and 4, annex I.

The European regulation n.741/2020 represents an ad-hoc legislative instrument for a cost-effective reuse of the reclaimed water in agriculture. The quality standards are differentiated based on the irrigated crops thereby even simple and decentralized systems may meet the limits without further expensive treatments.

In the following table, the main advantages and disadvantages of the above regulatory instruments concerning reuse of the reclaimed water are listed.

Table 0.5: Summary regulatory instruments for reclaimed water reuse

Regulatory instruments	Advantages	Disadvantages
D.M. n. 185/2003	The irrigation use is ruled by the “Code of good agricultural practice”	Restrictive limits and demanding quality monitoring
D.lgs. n. 152/2006	Low sampling frequency	Restrictive limits, the irrigation use is not mentioned
D.P.G.R. n. 46/R 2008	Moderate limits, irrigation use is mentioned	Not clear information about quality monitoring
Regulation (EU) n. 741/2020	Ad-hoc legislative instrument for a feasible reuse of reclaimed water in agriculture	It will be applied by 2023.

Analysing the previous legislative instruments, the European regulation results as the most appropriate legislative instrument for an economic advantageous reuse of the reclaimed water in agriculture. However, it shall apply from three years after the date of entry into force (i.e. 2023).

Regulatory framework of treated sludge

The excess sludge from the UASB could be stabilized by drying reed beds and then reused on the HYDRO 2 area. So far, the absence of a clear national regulatory instruments makes the sludge reuse on soils difficult. Some Regions adopt their own legislation adapting the content of the Legislative Decree n. 75/2010, which defines the criteria to classify different treated matrixes (i.e. dehydrated sludge after aerobic/anaerobic stabilisation) as fertilizers.

Actually, Tuscany Region is not provided with a specific regional Decree, therefore the stabilized sludge should comply the national standards before its reuse in agriculture.

At national level, three different legislative instruments may govern the reuse of reclaimed water from HYDRO 1 to HYDRO 2:

1. Legislative Decree n. 99/1992 governs the reuse of the sludge on soil.
2. Legislative Decree n. 75/2010 and the following update by the Legislative Decree n. 218/2013 defines the parameters to produce fertilizers from treated sludge.
3. Ministerial Decree n. 266/2016 for the implementation of a composting community system.

According to the Legislative Decree n. 99/1992, the stabilized sludge should meet the quality standards in the attachment IA and IB (table 0.7).

Table 0.6: Soil and sludge quality standards of Legislative Decree n. 99/1992

Quality standards for the agricultural land		
Parameters	**Measurement Unit**	**Limit Value**
Cadmium	mg kg SS^{-1}	1.5
Mercury	mg kg SS^{-1}	1
Nickel	mg kg SS^{-1}	75
Lead	mg kg SS^{-1}	100
Cooper	mg kg SS^{-1}	100
Zinc	mg kg SS^{-1}	300
Quality standards for the stabilized sludge		
Parameters	**Measurement Unit**	**Limit Value**
Cadmium	mg kg SS^{-1}	20
Mercury	mg kg SS^{-1}	10
Nickel	mg kg SS^{-1}	300
Lead	mg kg SS^{-1}	750
Cooper	mg kg SS^{-1}	1000
Zinc	mg kg SS^{-1}	2500
Organic carbon	% SS	20
TP	% SS	0.4
TN	% SS	1.5
Salmonella	MPN gSS^{-1}	10

According to Article 11, the analytical characterisation of the stabilized sludge has to be performed twice or once per year according to the size of the plant (in this case, once per year), while the analysis of the agriculture land must be carry out once every three years. Moreover, at the national level, the decree law n. 109/2018 (“Genova decree”) in the art. 41 establishes a more restrictive quality standard for the hydrocarbons in the sludge (i.e. 1000 mg/kg as-is) respect the table IB of the D. lgs. n. 99/1992. The second scenario, defined by the Decrees 75/2010 and 218/2013, allows the utilization of the sludge to produce fertilizer through composting systems. The main quality standards, which must be fulfilled by the fertilizer, are listed in table 0.8Table 0.7.

Table 0.7: Sludge quality standards of Legislative Decree n. 218/2013

Quality standards for fertilizer from composted sludge		
Parameters	**Measurement Unit**	**Limit Value**
Water content	0%	50
pH		6-8.8
Organic Carbon/ solid fraction	%	20 (minimum)
Organic Nitrogen/ solid fraction	%	80 (minimum)
C/N		25
Zinc	mg $kgSS^{-1}$	2500
Organic carbon	% SS	20

Moreover, if a composting system is going to be implemented in the HYDRO 1 for fertilizer production in small communities, the national legislation provided a legislative framework for composting system managed by small communities (Ministerial Decree n. 266/2016). This third scenario could be appropriate for HYDRO 1, where the inmates of the local penitentiary could manage the composting system. Although, the Ministerial Decree n. 266/2016 does not include the sludge for the compost production, it represents a possible pathway for the reuse of the sludge from HYDRO 1 to HYDRO 2 and it might be discussed with the involved legislators.
Therefore, these three legislative instruments are present at national level for the direct reuse of the sludge in agriculture or for its use as compost. However, the Tuscany region has been hindering the direct reuse of the sludge in agriculture since 2016, especially for organic farming, imposing further restrictive limits. Indeed, the Tuscany region is stalling for the rearrangement of the relative legislation at the national level. Thus, the more feasible legislative instrument for the application of the treated sludge in agriculture is the D. lgs. n. 75/2010 (and following updates by the D. lgs. n. 218/2013). The treated sludge of the HYDRO 1 has to be labelled as “compost”, before its reuse in the HYDRO 2.

Identification of the permitting pathway

The permitting pathways for the construction and management of the HYDROs, are assessed in the following subchapter. The realization and authorization phases of the HYDROs could be carried out by the water utility of the integrated water service, “ASA Livorno S.p.A.”; which might also identify the proper authorization pathways for the reuse of by-products with the involved stakeholders.

Permitting pathways for HYDROs construction and management

According to the Regional Law 65/2014, the HYDRO 1 may be considered as primary urbanization work thereby its realization is subjected to the building permission, which has to be submitted to the office for the productive activities (SUAP) of Livorno Municipality.

The permission comprehends three regional standard paperwork: parties involved attachment (in Italian “Allegato soggetti coinvolti”), form for building permission (in Italian “Richiesta di permesso a costruire”) and asseveration report (in Italian “relazione tecnica di asseverazione”). Within the asseveration report, the attachments in table 3.5 are needed.

Although the art. 158 bis of the D. lgs n. 152/2006 imposes a simpler procedure for the construction of wastewater treatment plant with the presentation of the authorisation to the water authority. The replication site is out of the integrated water service perimeter, so the building permission is needed for HYDRO 1 construction.

Moreover, a combined heat and power (HCP) generator unit could be installed in order to reuse the biogas from the UASB for the heating of the reactor itself. According to the Legislative Decree n. 387/2003, the realization and the management is not subjected to authorization since the nominal power of the generator is below 3 MW thermal.

The realization of the “HYDRO 2” is not subjected to authorisations.

Permitting pathways for use of HYDROs by-products

The use of reclaimed water and the stabilized sludge from HYDRO 1 need usually specific authorization which varies according to the applied legislative instruments.

If the technical rules for the reuse of the reclaimed water are applied (D.M. n. 185/2003), the reuse is authorized by the presentation of the single environmental authorisation to the SUAP of Livorno municipality.

In the same way if the reuse of the effluent from “HYDRO 1” is set as discharge on soil (D. Lgs. n. 152/2006), the discharge on soil is authorized by the presentation of the environmental authorisation (AUA Autorizzazione Unica Ambientale) to the SUAP of Livorno municipality.

However, if the reclaimed water from “HYDRO 1” is set as agri-food wastewater for the agri-food reuse (D.P.G.R. 46/R), its reuse is authorized by submission of the simplified communication to the SUAP of Livorno municipality.

Finally, if the stabilized sludge is going to be reused in agriculture as soil improver according to the D. Lgs. N.99/1992, the utilization is allowed by means of presentation of the environmental authorisation (AUA Autorizzazione Unica Ambientale) to the SUAP of Livorno municipality.

Results of policy analysis

Finally, the score for each sub-criterion are assigned in order to provide an overall policy evaluation. Results are summarized in table 3.6.

I.V. Stakeholders and policymaker's identification

The stakeholders and policymakers which could be involved in the project were preliminary identified and classified. Their likely expectations and needs are reported in the table below.

Table 0.8: Relevant stakeholders identification

RELEVANT STAKEHOLDERS		CATEGORY	NEEDS AND EXPECTATIONS
Stakeholders' group	**Example**	**P/S/E**	
At National authorities	Italian government: Ministry of Economic Development, of Environment and Justice. State property agency.	External	Supplying the policy framework, with specific reference to the integrated water service and public goods.
At Regional/Local authorities	Tuscany region. Livorno province. National park authority. Archaeology, fine arts, and landscape superintendence. Livorno municipality.	External	Supplying the policy framework, with specific reference to the integrated water service, decentralised systems and Gorgona territory.
Decentralized government services (Health, Education, Water, Environment etc.)	Local penitentiary.	Primary	Operative management of the HYDROs technologies and related by-products
Education (e.g. universities, training centre, schools)	Research Groups: UNIVPM. UNIFI.	Secondary	Evaluation of the replicability of the HYDRO solutions in an Italian decentralized territory as Gorgona.
Communication (e.g. Media)	Website of Livorno municipality.	Secondary	Providing information about the project, promoting social acceptability
Water authority	Tuscany water authority.	External	Supplying the policy framework at local level, with specific reference to the integrated water service.
Civil society (e.g. users, private citizens etc.)	Correctional facility inmates, local citizens.	Primary	Final users of the HYDROs by-products
Water utility	ASA Livorno.	Secondary	Administrative and technical management of the HYDROs

I.VI. Technical analysis

Hydro scheme implementation

The original configurations of HYDRO 1 and HYDRO 2, developed within HYDROUSA project, could be modified in order to meet the needs and expectations of the final end-users (correctional facility inmates, local citizens, etc.) of Gorgona Island.

Hence, in the following pages the preliminary project of the HYDRO 1 and HYDRO 2 is going to be showed, discussed and analysed.

According to the preliminary proposal, HYDRO 1 could be composed of:

- N. 1 Existing screening for the removal of inert materials and a pumping station
- N. 1 Upflow Anaerobic Sludge Blanket (UASB) reactor
- N. 1 Existing Imhoff tank, which would be used as pumping station for vertical flow (VF) constructed wetland
- N. 2 VF constructed wetlands (two lines in parallel)
- N. 2 Existing horizontal flow (HF) constructed wetlands (two lines in parallel)
- N. 1 Sand Filtration (tertiary treatment)
- N. 1 UV disinfection (tertiary treatment)
- N. 1 Combine heat and power (CHP) unit in order to generate heat
- N. 1 Sludge Drying Reed Bed (SDRB) for the treatment of the excess sludge

The screening and the Imhoff tank are present on the replication site as part of the actual existing WWTP thereby they might be integrated into the HYDRO 1. Although the flow would be mainly driven by gravity, a pump might be needed to carry the wastewater from the influent canal, after the screening, to the UASB reactor. Furthermore, a pump could be installed inside the Imhoff tank in order to convey the wastewater to the two VF constructed wetlands.

The local community does not need biomethane; in addition the involved UASB reactor could have small dimensions and the production of biomethane for human consumption is not technically feasible. Therefore, the produced biogas might be reused by the CHP unit for UASB heating.

The constructed wetlands are supposed to be developed on 2 lines in parallel, each line could be made of a new VF constructed wetland (by revamping the existing wetland) and the existing HF constructed wetland. The first one is under aerobic condition while the last one is in anoxic condition, so both nitrification and denitrification are carried out. The tertiary treatment could be composed of sand rapid filtration and UV disinfection, in order to meet the quality standards for the reuse of the reclaimed water in HYDRO 2. Since the plant is supposed to be managed by the correctional facility inmates, a sand filtration is preferred to the ultrafiltration for its simplicity.

Finally, the sludge drying reed beds might be chosen for simplicity, flexibility and possibility to reuse the dried sludge in agriculture as well as it may be easily integrated within the local landscape. Unfortunately, treated sludge from SDRB might not have the quality characteristics to be labelled as “compost from sludge”. Therefore, a composting system will be proposed in order to meet the quality standard of the D. lgs. n. 75/2010 and to treat also the organic waste of the whole island.
Regarding HYDRO 2, the original system is composed of an agroforestry, which is divided in three main groups: (1) forestry trees for fruit and timber production; (2) orchards/bushes; and (3) herbs and annual crops. The agroforestry fertigation system combines traditional irrigation methods with precision irrigation and is carried out by applying both drip and channel irrigation. Besides, HYDRO 2 on Gorgona island could be represented by the existing surrounding agricultural areas for vegetables and fruits cultivation, managed by the correctional facility inmates.

Design data and sizing criteria for hydro replicability

HYDRO 1 could be designed for a global capacity of 220 PE during the summer and 150 PE during the winter and the influent wastewater flow rate is calculated assuming a water supply equivalent to 350 L $d^{-1}PE^{-1}$ and applying a coefficient equal to 0.8. The table below summarised the characterisation of the influent wastewater used to carry out preliminary designs, mass and energy balances.

Table 0.9: Influent wastewater characterization to the UASB reactor

Influent Wastewater Characteristics:					
Parameters	**Units**	**Typical**	**Summer**	**Winter**	**Notes**
Population equivalent	PE		220	150	
Flowrate	$m^3\ d^{-1}$	-	61.6	36	
COD concentration	mg L^{-1}	500	464	542	
BOD5 concentration	mg L^{-1}	300	214	250	
TSS concentration	mg L^{-1}	320	145	145	
Organic Load	kg COD d^{-1}	-	28.6	19.5	
pH	-	-	7.6	7.6	
Conductivity	µS cm^{-1}	-	1164	1164	
TKN	mgN L^{-1}	40	42.9	50.0	
Ammonia Concentration	mgN L^{-1}	25	42.9	50.0	
Temperature of WW	°C	-	20	12	

Regarding the design of the UASB reactor, the following operating parameters are determined considering the previous influent characterization.

Table 0.10: Design data UASB reactor

Design data UASB reactor					
Parameters	**Units**	**Typical**	**Summer**	**Winter**	**Notes**
HRT design	h	5 ÷ 10	7	7	Set as hypothesis
Volume tot	m^3	-	18.0	18.0	
n° of operative lines	n°	-	1	1	
Volume of each line	m^3	-	18.0	18.0	
OLR	kgCOD $m^{-3}d^{-1}$	0.8-2	1.59	1.08	
HRT operative	h	-	7	12	
Area (reactor sectional area)	m^2	-	3.67	3.67	
Diameter	m	-	2.16	2.16	
Reactor height	m	-	4.9	4.9	
COD removal	%	70 – 80	0.35	0.35	Set as hypothesis
COD removed	kgCODd^{-1}	-	70	70	
Daily methane production	$m^3CH_4d^{-1}$	-	20.0	13.7	Set as hypothesis
Daily Biogas production	m^3biogas d^{-1}	-	60	60	
Sludge production	kg sludge d^{-1}	-	1.24	0.85	
TS% of sludge	mgTSS L^{-1}	-	20000	20000	Set as hypothesis
Q excess sludge	m^3d^{-1}	-	0.062	0.042	

Subsequently, the mass balance of the UASB reactor is reported.

Table 0.11: Mass balance UASB reactor

Mass balance UASB reactor					
Parameters	**Units**	**Typical**	**Summer**	**Winter**	**Notes**
Qout	m^3 d^{-1}	-	61.54	35.96	
CODin	kgCODin d^{-1}	-	28.6	19.5	
CODout	kgCODout d^{-1}	-	8.6	5.9	
	Mg L^{-1}	-	139	163	
TSS in	kgTSS d^{-1}	-	8.9	5.2	
TSS removal	%	60 – 70	67	67	
TSS removed	kgTSS d^{-1}	-	6.0	3.5	
TSSout	kgTSSout d^{-1}	-	2.9	1.7	
	mg L^{-1}	-	48	48	
Energy production	kWh m^{-3}	-	1.13	1.32	
	kWh d^{-1}	-	69.8	47.6	

The liquid effluent from the UASB is supposed to go to the Imhoff tank and then might be divided into 2 equal lines in parallel, each of them could be composed of a new VF constructed wetland and the existing HF constructed wetland. The following wastewater characterization is taking account for the VF constructed wetlands design.

Table 0.12: Wastewater characterization to the VF constructed wetlands

Wastewater Characteristics:					
Parameters	**Units**	**Typical**	**Summer**	**Winter**	**Notes**
Flowrate	$m^3\ d^{-1}$	-	61.6	36.0	
COD concentration	$mg\ L^{-1}$	-	139.4	162.7	
BOD5 concentration	$mg\ L^{-1}$	-	69.7	81.3	assumed 50% of COD
TSS concentration	$mg\ L^{-1}$	-	47.9	47.9	
TSS loading	$kg\ TSS\ d^{-1}$	-	3.0	1.7	
Ammonia Concentration	$mgN\ L^{-1}$	-	42.9	50.0	

Regarding the design of the constructed wetlands (VF plus HF), the following operating parameters and performance of the VF constructed wetlands are determined, considering the previous influent characterization.

Table 0.13: Design data of the VF constructed wetlands

Design data of VF constructed wetlands					
Parameters	**Units**	**Typical**	**Summer**	**Winter**	**Notes**
Total Depth of filter media	m	0,8 ÷ 1,5	1	1	Set as Hypothesis
Total Depth	m		1.3	1.3	
Lenght of VF sector	m	-	15.00	15.00	
Width of VF sector	m	-	12.7	12.7	
n° of sector	n°	-	2	2.00	
n° of bed per sector	n°	-	2	2.00	
Area of VF per sector	m^2	-	190	190	existing in site
Area of VF total	m^2	-	380	380	
TKN removal	%	60 - 70	67	98	Set as design value
TN removal	%	-	5	5	Set as design value
BOD5 removal	%	-	90	95	Set as design value
COD removal	%	-	90	95	Set as design value
Solids loading rate	$gTSS\ m^{-2}d^{-1}$	-	7.76	4.54	
Tss concentration out	$mg\ L^{-1}$		20.0	10.0	

TSS removal	%		58	79	Set as design value
Specific surface of total CW	m^2 PE^{-1}	3-5 m^2/PE	1.7	2.5	
Organic Loading Rate	$gBOD_5$ $m^{-2}d^{-1}$	touristic fluctuation < 20; constant flow rate < 10	11.30	7.71	Verify
OTR	g O_2 $m^{-2}d^{-1}$	23-64	32	32	
HRT	h	from 3 to 6	0.26	0.44	
HLR	m^3 $m^{-2}d^{-1}$	touristic fluctuation < 160; constant flow rate < 80	0.16	0.09	Verify

Table 0.14: Performance of the VF constructed wetlands

Performance of VF constructed wetlands					
Parameters	**Units**	**Typical**	**Summer**	**Winter**	**Notes**
COD_5 removed	kg d^{-1}	-	7.7	5.6	
COD_5 out from CW	mg L^{-1}	-	13.9	8.1	
	kg d^{-1}	-	0.9	0.3	
BOD5 removed	kg d^{-1}	-	3.9	2.8	
BOD5 out from CW	mg L^{-1}	-	7.0	4.1	
	kg d^{-1}	-	0.4	0.1	
TKN removed	kg d^{-1}	-	1.8	1.8	
TKN out from CW	mg L^{-1}	-	14.1	1.0	
	kg d^{-1}	-	0.9	0.04	
TSS removed	kg d^{-1}	-	1.7	1.4	
TSSout	kg d^{-1}	-	1.2	0.4	
	mg L^{-1}	-	20	10	

Subsequently, the design data of existing HF constructed wetlands are drawn up.

Table 0.15: Design data of the existing HF constructed wetlands

Design data of existing HF constructed wetlands					
Parameters	**Units**	**Typical**	**Summer**	**Winter**	**Notes**
n° of sector	n°	-	2	2	existing in site
Area of VF per sector	m^2	-	500	500	
Area of VF total	m^2	-	1000	1000	

The effluent from the HF constructed wetlands might be carried to the tertiary treatments, which could be composed of a sand filter for the removal of solids and UV disinfection for the abatement of the pathogenic. The table 0.14 highlights the influent wastewater characteristics to the tertiary treatments.

Table 0.16: Characterization of wastewater to tertiary treatments

Wastewater Characteristics					
Parameters	**Units**	**Typical**	**Summer**	**Winter**	**Notes**
Flowrate	$m^3\ d^{-1}$	-	62	36	
COD concentration	$mg\ L^{-1}$	-	13.9	8.1	
BOD5 concentration	$mg\ L^{-1}$	-	7.0	4.1	
TSS concentration	$mg\ L^{-1}$	-	20	10	
Organic Load	$kg\ COD\ d^{-1}$	-	0.86	0.29	

The design and operating parameters of sand filter and UV disinfection are stated in the following tables.

Table 0.17: Sand filter design parameters

Design data of sand filter					
Parameters	**Units**	**Typical**	**Summer**	**Winter**	**Notes**
Filtering Layer	m	-	2	2	
Filtering Area	m^2	-	0.43	0.25	
Filtering Diameter	m	-	0.74	0.56	
Filter volume	m^3	-	0.86	0.50	
HLR	$m^3\ m^{-2}\ h^{-1}$	Max 15	6	6	
TSS removal efficiency	%	60 - 80	70	70	
TSS out	$mg\ L^{-1}$	-	6.0	3.0	
BOD5 removal efficiency	%	50	50	50	
BOD5 out	$mg\ L^{-1}$	-	3.3	0.4	
Water for filter washing	$m^3\ h^{-1}$	Each 24 h for 20 min	6.4	3.8	
	$m^3\ d^{-1}$	-	2.1	1.3	
Effluent flow rate	$m^3\ d^{-1}$	-	59.5	34.8	

Table 0.18: UV disinfection design parameters

Design data of UV disinfection					
Parameters	**Units**	**Typical**	**Summer**	**Winter**	**Notes**
Influent TSS concentration	$mg\ L^{-1}$	< 1 – 5	59	35	
Water trasmittance (UVT)	%	50 – 85	75	75	
Minimum Dose to ensure for discharge limit	$mWxs\ cm^{-2}$	50 - 60 for < 2.2 MPN/100mL for Intermittent sand filter effluent	50	50	
Treatable flowrate/each lamp	$m^3\ d^{-1}$	-	115	115	
n°lamps	n°	-	1	1	

Finally, the effluent from UV disinfection might be pumped to the HYDRO 2 and reused for irrigation purposes as reclaimed water. The produced biogas from UASB reactor could be conveyed to the combine heat and power (CHP) unit where it will be transformed into heat by means of an internal combustion engine and then reused for the heating of the UASB reactor.

The heat recovery efficiency of an internal combustion engine is typically about 40% thereby, from the 69.8 kWh d^{-1} of energy produced by the UASB reactor, 28 kWh d^{-1} of energy could be internally recovered. Generally, small compacted CHP unit has a footprint about 10 m^2.

The produced sludge from the UASB reactor is supposed be carried to the sludge drying reed bed (SDRB) for the stabilization treatment. In the context of small and decentralized WWTPs, the SDRB technology is able to fully substitute conventional sludge line, leading to economic advantages in terms of sludge treatment and allowing a safe reuse in agriculture of dried sludge. The design of the HYDRO 2 is not carried out since the existing agricultural areas nearby HYDRO 1 might be used.

Finally, according to the preliminary project, the technical requirements for HYDROs replicability are summarized.

Table 0.19: HYDROs expected technical requirements

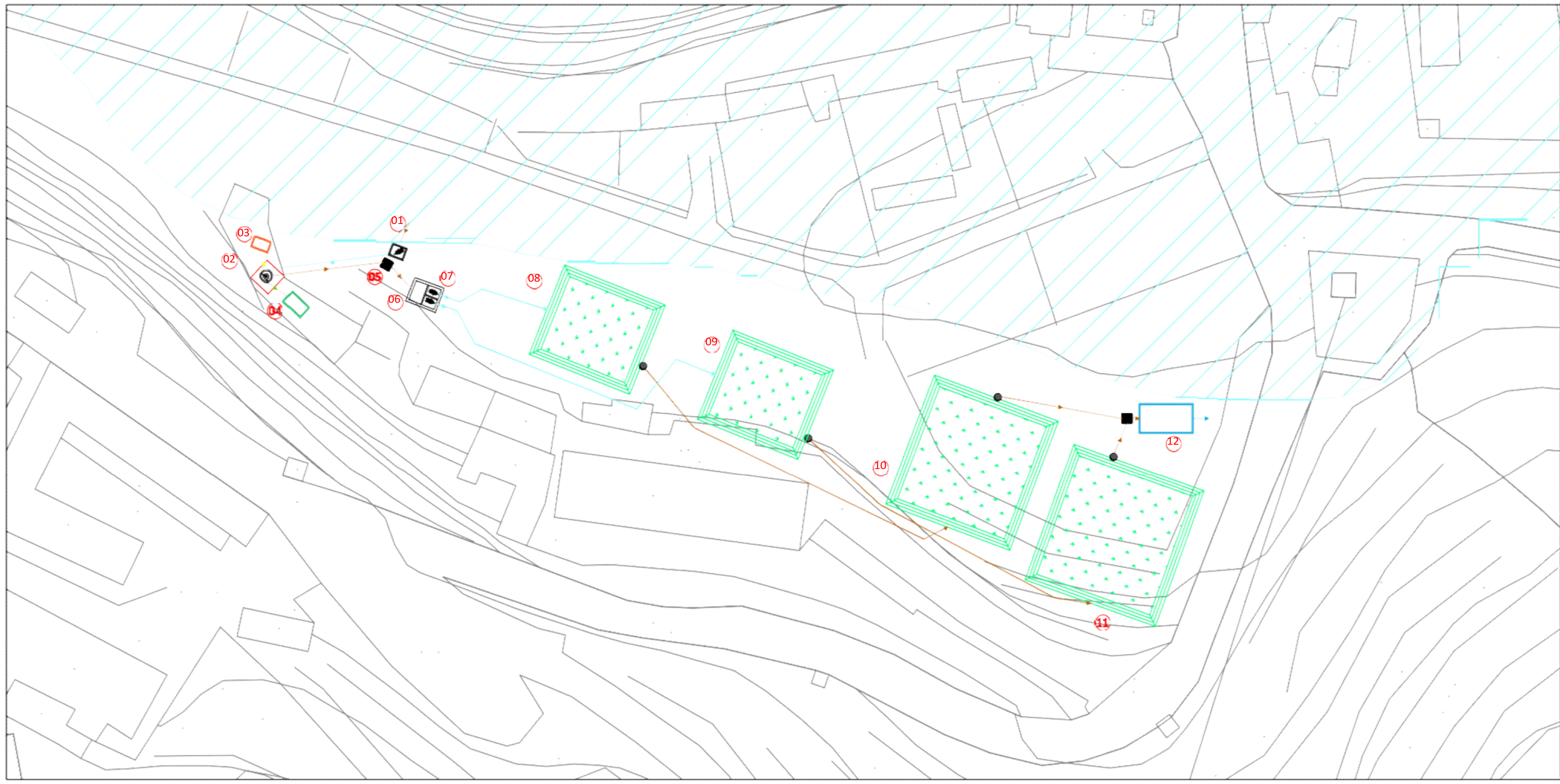
Technical requirements for HYDROs replicability				
FOOTPRINT				
Parameter	**Unit**	**System**	**Value**	**Remarks**
System area requirement	*m^2*	System 1: UASB reactor	27.4	
		System 2: constructed wetlands (2 lines)	1780	
		System 3: sand filtration and UV disinfection	8	
		System 4: CHP unit	10	
		System 5: sludge drying reed beds	n.a.	
		System 6: HYDRO 2	10000	
Total area requirement	*m^2*	**Considering all the equipment**	**22000**	
ENERGY				
Parameter	Unit	Specifications	**Value**	**Remarks**
Maximum Energy Consumption	*kWh d^{-1}*	System 1: UASB reactor	2.1	Electricity
		System 2: constructed wetlands (2 lines)	2.3	Electricity
		System 3: sand filtration and UV disinfection	3	Electricity
		System 4: CHP unit	-28	Recovered as heat
		System 5: sludge drying reed beds	n.a.	
		System 6: HYDRO 2	n.a.	
Total energy consumption	*kWh d^{-1}*	**Considering all the equipment**	**7.4**	Electricity

Graphic design (e.g. planimetry, block flow diagram)

The proposed preliminary block flow diagram and planimetry of the HYDRO 1 are, respectively, reported in the figure 3.3 and below.

Geographical location - Island of Gorgona, Livorno, Italy

Geographical location - Isle of Gorgona, Livorno, Italy



LEGEND

Operation Units

01 Inflow with Screening and Pumping Station
02 UASB Reactor
03 Combined Heat and Power Unit
04 Sludge Drying Reed Beds
05 Existing Flow Partition
06 Existing Imhoff Tank
07 Pumping Station
08 VF Constructed Wetland 1
09 VF Constructed Wetland 2
10 Existing HF Constructed Wetland 1
11 Existing HF Constructed Wetland 2
12 Sand filtration and UV disinfection

Liquid and Solid Flows

Influent wastewater by gravity
Influent wastewater by pressure
Treated water for reuse
Composted sludge
Biogas

Areas

Involved area
Flooding probability frequently, hazard level P3

Hydro Solution	*HYDRO 1 + HYDRO 2*			
Location	Island of Gorgona, Livorno - Italy			
Partner *UNIVPM* *ASA Livorno*		**Graphical elaborate** *Planimetric Layout*	**Scale** *1:1000*	**Date** *09/2020*

Results of technical analysis

The efficiencies of the proposed HYDRO 1+2 are evaluated taking into account the table 2.3. Therefore, the overall technical feasibility score of the HYDROs is obtained by averaging the sub-criteria scores as table 3.7 shows. Unfortunately, as explained before, the amount of the compost from the composting systems was not considered in the technical feasibility.

I.VII. Economic analysis

Identification of the financing pathway

The following economic instruments are identified to cover the capital expenditure (CAPEX) and operating expenditure (OPEX) of the preliminary project.

Table 0.20: Economic instruments

Economic instrument	Type of instrument	Example
Pricing	**Taxes and charges/fees**: Compulsory payment to the fiscal authority for a service from a regulatory authority: e.g., charge for new development sites as a means of recovering costs for e.g. urban regeneration or green and blue infrastructure investments such as recreation programs ("fee in lieu")	Aspects to be evaluated by water utility (ASA Livorno), water authority (Autorità Idrica Toscana), municipality (Livorno) and the local penitentiary.
	Reduced taxes/charges e.g. if a landowner provides a certain (green/unsealed) area of its property for water to infiltrate and therewith reduced run-off of rainwater or stormwater drainage	HYDROS are supposed to be realized on a site, which is property of the state.
	Trading of permits for using a resource or trading (Building or development permits, etc.) of permits for pollution / emission levels	The investments may be funding through green/white certificates (certificate Bianchi/Verdi)
	Tariffs: A price paid by users to a service provider for a given quantity of service or a schedule of rates or charges of a business or a public utility that provides a product or service which may affect the quality of green and blue areas	Aspects to be evaluated by water utility (ASA Livorno), water authority (Autorità Idrica Toscana), municipality (Livorno) and the local penitentiary.
Payments/ Subsidies	**Payments to landowners** or private actors for practices (e.g. installing green roofs of natural water retention areas)	HYDROS are supposed to be realized on a site, which is property of the state.
	Financing targeted research projects (e.g. developing more efficient urban sustainable solutions)	HYDROs could be funding by regional investments for the support of minor islands of the Tuscany archipelago, national funds for economic development.
	Payments for insurances which can cover the risk associated with the performance of newer green technologies	N/A (criticality: absence of risk management)
Voluntary agreements/ Cooperation	**Individual voluntary agreements**: negotiated voluntary arrangement between parties to adopt agreed practices by governmental bodies in order to	A Declaration of intent (collaboration agreement) has been signed between entities for

	influence the development of products or the adoption of production processes that benefit the Gl/reduce environmental degradation. These are not linked to payments. Voluntary agreements linked to subsidies are included under payments category.	the development of territorial systems on the island: Park, UNIFI, ASA, penitentiary, Municipality of Livorno, etc.
	Public-Private Partnerships: Contractual instruments between public and private actors that enhance the ability of the public sector to provide public services thanks to the involvement of the private sector. These are a sub-form of voluntary agreements and can include multiple public and private actors. E.g. flood protection projects, coastal defences. These can be structured in many different ways:	An agreement between water utility, water authority, province, municipality, archipelago park and local penitentiary is present for the development of the island territorial system.
	• private sector has control over all assets, including investment, maintenance, and operations decisions, although some specific, strategic decisions remain subject to regulatory oversight;	
	• concessions in the form of long-term contracts...[where] the private sector has full responsibility for the operation of the asset, usually recouping investment costs with service provision revenues (i.e. tariff collections); In this case also solutions for taking into consideration the fragmented nature of land ownership and how this could be tackled through incentives such as the sharing of benefits (e.g. agroforestry cultivations) should be reported.	
	• management and lease agreements, the private sector takes control on operations for shorter time, but also bears less financial risks, and initial capital investment is assured by the public.	
Private sector	**Loans** (from Investment and commercial banks) (especially low interest loans) to invest in green and blue infrastructure projects, such as green stormwater technologies or restoration projects or urban regeneration projects	The HYDROs project may be funding through specific public/private investments.
	Bonds (from Capital market) e.g. Financing of adaptation measures via an investment instrument with returns, green Bonds for investing in sustainable and nature-based adaptation solutions	The HYDROs project may be funding through specific public/private investments.
	Crowdfunding e.g. Crowdfunding platform established by the city council that allows citizens to propose and finance their ideas for the city such as urban farming for residents of a social housing quarter, edible streets etc.	Possible implementation of a crowdfunding initiative (and development of the Island brand) aimed at raising funds for the energy transition process (biodiversity development and environmental sustainability).
Liability schemes	Offsetting schemes where liability for environmental degradation leads to payments of compensation for environmental damage. E.g. Eco-	N/A (criticality: absence of risk management)

	accounts, wetland destruction, brownfields funds, habitat banking.	

A grant representing 40% of the costs related to systems purchase and installation (CAPEX) could be funded by Livorno municipality, which might solve the water-related issues on Gorgona island (e.g. water pollution, water scarcity, etc.), thanks to the implementation of HYDRO 1 and HYDRO 2.

Cost estimation for hydro implementation (Capex)

The Capital Expenditures (CAPEX) of the preliminary project are estimated by comparing the project with the original HYDRO 1 and HYDRO 2 from the Greek case study and assuming specific costs from literature. The typical loan interest rate for water-related infrastructures is estimated about 5% and a loan duration of 25 years has been assumed.

Table 0.21: CAPEX summary table

CAPEX				
Parameter	Unit	Specifications	**Value**	**Remarks**
Cost of HYDRO implementation	€	Preparation of site (Earth works, excavation, etc.)	Included into other costs	
	€	Legal affairs/permit purchase /product certification/staff training, etc.	20,000.00	From Greek case study
	€	Land purchase	0	
	€	Unit supply and installation of UASB reactor	121,800.00	From Greek case study
	€	Unit supply and installation of two VF constructed wetlands	69,707.00	From literature
	€	Unit supply and installation of sand filtration and UV disinfection	21,098.00	From Greek case study
	€	Unit supply and installation of CHP unit	2,800.00	From literature
	€	Unit supply and installation of sludge drying reed beds	1,752.00	From literature
	€	Unit supply and installation of HYDRO 2	0.00	
	€	Other costs (if present)	0.00	
Funding	%	Investment grant	-40	
Total CAPEX	€		**142,294.00**	
Loan interest rate	%		5	
Loan duration	y		25	
Yearly CAPEX	€/y		**5,976.00**	

Cost estimation for hydro maintenance (Opex)

The Operating Expenditures (OPEX) of the preliminary project are estimated by comparing the project with the original HYDRO 1 and HYDRO 2 from the Greek case study. For energy costs, the total electricity consumption is 1,274 kWh y^{-1} and a specific energy cost of 0.15 € kWh^{-1} has been assumed; while 112 working days per year with a remuneration of 72 € per day have been estimated for staff costs.

Table 0.22: OPEX summary table

OPEX				
Parameter	Unit	Specifications	**Value**	**Remarks**
Reagents	€ y^{-1}	Considering reagents both for operation and maintenance (cleaning)	0	
Energy costs	€ y^{-1}	Considering cost of electricity [average between day and night, during week and weekend]	191.00	From Greek case study
Staff	€ y^{-1}	Considering personnel both for operation and maintenance	8,064.00	From Greek case study
Maintenance	€ y^{-1}	Considering substitution of pieces etc…	4,969.00	From Greek case study
Insurance	€ y^{-1}		Included into other costs	
TOTAL ANNUAL OPEX	€ y^{-1}		**13,224.00**	

Revenue & costs saving streams

The revenues from HYDRO 1 and HYDRO 2 in Gorgona are calculated by assuming the typical market value for each parameter. The biogas produced is supposed to be utterly reused for the UASB reactor heating and the composted sludge could be completely reused into HYDRO 2. The revenues from the sale of vegetable and fruits produced into HYDRO 2 are supposed to be completely provided to the inmates of the local penitentiary. While the incomes from treated wastewater for irrigation are reduced by a 50%, since half of the reclaimed water from HYDRO 1 could be likely reused into the HYDRO 2.

The water tariff is assumed to be 1.5 € per cubic meter of consumed water (national average price according to the national regulator ARERA). The selling price for reclaimed water have been estimated based on external information sources with average prices for EU and considering that 30% increase on the prices can be applied as the targeted market is on an island.

Table 0.23: Business model for HYDRO replicability

Revenue & costs saving streams						
Parameter	Unit	Quantity	Unit	Market value	Unit	**Value**
Treated wastewater for irrigation	m^3 $year^{-1}$	10,852.00	€ m^{-3}	0.5	€ y^{-1}	5,426.00
Biogas	MWh $year^{-1}$	25.48.00	€ MWh^{-1}	-	€ y^{-1}	It is completely reused in site
Fertilizers	kg $year^{-1}$	453.00	€ kg^{-1}	-	€ y^{-1}	It is completely reused in site
Wastewater treatment tax	m^3 $year^{-1}$	22,484.00	€ m^{-3}	1.5	€ y^{-1}	33,726.00

Vegetables and fruits	kg year^{-1}	5,000.00	€ kg^{-1}	-	*€ y^{-1}*	The inmates are the final beneficiaries
Yearly revenues					*€ y^{-1}*	**39,152.00**
Payback period	CAPEX/ (yearly revenues - OPEX)				*y*	**5.5**

Results of economic analysis

The economic feasibility of the project is evaluated considering the payback period sub-criteria according to the table 2.4 thereby the score is about 65/100 as table 3.8 shows.

The implementation of HYDRO 1 and HYDRO 2 on Gorgona Island has a medium payback period since the reclaimed water and the fertilizer from HYDRO 1 reused into HYDRO 2 is supposed to be completely granted on voluntary basis. Moreover, the revenues from the sale of vegetable and fruits produced into HYDRO 2 are supposed to be completely given to the inmates of the local penitentiary, which manages the HYDROs. Therefore, the economic feasibility score is not elevating, because the social inclusion and well-being of the inmates are assumed to be preferred rather than economic profits. Despite the payback period, the CAPEX of the project results quite low thanks to the assumption that the existing WWTP and the nearby agriculture areas will be, respectively, exploited as HYDRO 1 and HYDRO 2, which lead to cutting costs for land purchase and installation of new equipment.

I.VIII. Conclusion

In conclusion, the overall feasibility of the project on the replication site is evaluated through the weighted average of the main feasibility sub-criteria scores according to the table 2.5.

The results are reported in the table 3.9.

Therefore, the replicability of HYDRO 1 and HYDRO 2 on Gorgona island results feasible from a social, legal, technical and economic point of view. However, there are still paths for improvement.

The legal feasibility for the construction of HYDROs and the reuse of the by-products might be improved by implementing a discussion, within the policy stakeholders up to national level, about nature-based solutions and their advantages for small and decentralized communities, which are often “left behind” by economic policies.The social and economic feasibility could be enhanced by implementing touristic visits e.g. where the HYDROs, the local penitentiary and the surrounding landscape can be presented as an integrated system which aims to promote the well-being of inmates, local residents and present ecosystems.

Finally, the main issues detected for the feasibility of the HYDROs in the replication site of Gorgona are reported together with the possible solutions for improving the replicability, in table 3.10.

II. LABORATORY ANALYSIS

pH

The pH (Potential of Hydrogen) is the measurement scale of the acidity or basicity of an aqueous solution, it indicates the concentration of hydrogen ions H^+ inside and is expressed by the equation:

$$pH = -log_{10}[H^+]$$

Acid and basic solutions are distinguished in function of the pH value. The first ones release free ions H^+ in water leading to pH values lower than 7, while the latter ones release ions OH^- in water resulting in pH values higher than 7. If the pH is 7, the solution is neutral (e.g. distilled water). The measurement is a fundamental parameter for the monitoring of chemical and biological processes. It occurs by means of a pH probe, which is composed of an electrode and an electronic device collecting the data from the probe and gives the pH value. The probe is a glass electrode which measures the difference of electric potential between the two sides of the thin membrane at the tip of the electrode. The potential difference depends on the difference of hydrogen ions concentrations between the inside and outside of the membrane. The measurement is carried out by simply dipping and stirring the pH probe into the liquid until the value appears on the screen device.

TSS

The suspended solids represent the solid fraction in the solution and it is recovered through filtration of the sample at 0.45 μm. Firstly, the filter with porosity 0.45 μm is dried in an oven at 105˚C for 2 hours and then it is cooled in a dryer with hygroscopic salt. When the filter reaches the ambient temperature, it is weighted obtain the real weight of it. Subsequently, the filter is placed above a porous stone, it is connected below to a device which carry the filtrated sample in a flask and above a metallic cylinder is placed in order to avoid the spilling of the sample. The flask is attached to a vacuum pump in order to speed the filtration process. After the filtration, the filter is dried on a slide for few seconds and then it introduced in the oven at 105˚C for 2 hours. At the end, the dried filter is cooled in the dryer and weighted. The obtained value is subtracted by the initial weight in order to obtain the mg of TSS in solution, which are divided by the sampling volume in mL and multiplied by 1000 for the calculation of mg TSS/L, as expressed in the following formula:

$$Suspended\ solids\ at\ 105°C\ (mg/L) = \frac{(P_{105} - T_{105})}{V} * 1000$$

Where:

- T_{105} = tare of the filter at 105˚C (mg)
- P_{105} = tare of the filter + dried sample at 105˚C (mg)
- V = volume of the filtered sample (mL)

The accuracy of the measurement increases with the volume of filtered sample, in this study a volume of 50 mL has been analysed.

TDS

The total dissolved solids represent the soluble fraction of solids in solution, they pass through a filter with porosity of 0.45 µm and are measured through weightings. Firstly, a ceramic crucible is dried in an oven at 105˚C for at least 2 hours and then it cooled in a dryer with hygroscopic salt. Once it reaches the ambient temperature, the crucible is weighted. Subsequently, a known amount of filtered sample at 0.45 µm is poured in the crucible and is placed in an oven at 105˚C for at least 8 hours so the water content is evaporated. At the end, the crucible with the remaining sample (solids) is cooled in the dryer and then weighted. The mg TDS/L is obtained by using the following equation:

$$Dissolved\ solids\ at\ 105°C(mg/L) = \frac{(P_{105} - T_{105})}{V} * 1000$$

Where:

- T_{105} = crucible weight at 105˚C (mg)
- P_{105} = crucible weight + remaining sample after evaporation at 105˚C (mg)
- V = volume of the sample (mL)

TS%

The total solids in percentage represents the total amount of solids, both soluble and dissolved, in solution and they are measured by means of weightings. Firstly, a ceramic crucible is dried in an oven at 105˚C for at least 2 hours and then it cooled in a dryer with hygroscopic salt. Once it reaches the ambient temperature, the crucible is weighted. Subsequently, the raw sample is poured in the crucible and they are weighted. Afterwards, the crucible with inside the sample is placed in an oven at 105˚C for at least 8 hours so the water content is evaporated. At the end, the crucible with the remaining sample (solids) is cooled in the dryer and then weighted. The TS% is obtained by using the following equation:

$$Total\ solids\ at\ 105°C\ (\%) = \frac{(P_{105} - T_{105})}{(P - T_{105})} * 100$$

Where:

- T_{105} = crucible weight at 105˚C (mg)
- P_{105} = crucible weight + remaining sample after evaporation at 105˚C (mg)
- P = crucible weight + sample (mg)

ANIONS AND CATIONS

The principal cations (sodium, potassium, magnesium, calcium) and anions (chloride, nitrite, nitrate, phosphate and sulphate) in solution are determined by a chromatographic technique with the respectively use of the ionic chromatographs Dionex DX-120 and ICS-1000. The analysis is carried out on the filtered sample at 0.45 μm; hence the suspended solid fraction is removed, since it may clog the chromatographic columns and it can be dissolved by the acid eluent in the columns falsifying the results. The samples are inserted in vials, which are placed in the automatic sampler for the chromatographic separation of the species in solution. The chromatographic separation is carried out by exploiting the features of a stationary solid phase, which is composed by a polymer resin in the column, and a mobile liquid phase made of calcium carbonate, which is pumped into the column and carries the sample through the stationary phase. In the column, the ions are retained by the stationary phase in function of their affinity with the resin, which depends on the ion valence and concentration. After a specific period of time function of the specie, the ions are released by the resin then together they come back in the eluent and exit the column. Therefore, the initial solution is subdivided in species and the retention time of each specie versus its concentration are plotted in the response graph (chromatograph). In the chromatograph, the peaks are detected for each species in the solution and the comparison with the peak standards allows the unique identification of the ions and their concentrations.

CONDUCTIVITY

The conductivity is the ability of a solution to conduct electricity. It is measured by means of a conductivity meter, which is composed of a conductivity cell, a temperature probe and an electronic device. The conductivity meter measures the electrical conductivity of the dissolved ions in a solution, so an electric field is applied between two electrodes and the electric resistance is measured. An alternate current is applied to avoid alteration of the solution and hood effects on the electrodes. The measurement is expressed as either μS/cm or mS/cm, moreover alternative forms allow to express the conductivity of the solution in terms of salinity and total dissolved solids. The temperature affects the measurement since it affects the solution and ionic mobility of the electrolytes. So as the temperature rises, the conductivity increases. The portable conductivity meter COND 70 has been used for the measurement of the sample conductivity, it provides a conductivity value and the temperature as soon as the probe is dipped into the sample.

Mg% and Ca% in TSS and in TS%

The SEM (Scanning Electron Microscope) has been used in order to determine the percentages of magnesium and calcium in the solids. It has resolution limits three to five orders of magnitude higher than the optical microscope and it allows the determination of elements (e.g. magnesium, calcium, etc.) by means of an electron beam. Therefore, a small representative portion of the sample is golden and subsequently is inserted on a metallic support inside the SEM. The sample is under vacuum conditions to allow the production of the electron beam, which hits the sample and, secondary and backscattered electrons are produced. The first ones are used by the SEM for the detection of the sample morphology, while the latter ones are useful for the determination of element percentages in the sample. The gilding is essential for the trial otherwise the sample will produce electrostatic charges, which will interfere with the detection of secondary and backscattered electrons by the detector.

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