Trabajo fin de Máster
Máster Sistémas de Energía Térmica

Diagnosis tool for seawater desalination plants

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Proyecto Fin de Carrera: Diagnosis tool for seawater desalination plants

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El tribunal nombrado para juzgar el Proyecto arriba indicado, compuesto por los siguientes miembros:

Presidente:

Vocales:

Secretario:

Acuerdan otorgarle la calificación de:

Sevilla, 2022

El Secretario del Tribunal

Gratitude

A mi familia animarme siempre y no dejar que me rinda y a mis amigos que me hacen bonita la vida, muchas gracias a todos por hacer que esto sea posible.

Summary

El objetivo principal de este proyecto consiste en crear una herramienta capaz de realizar un análisis termoeconómico de plantas de desalación configurable manualmente considerando los siguientes aspectos:

- Estado actual de la tecnología de desalación.
- Actualización de costes económicos de cada uno de los componentes que entran en funcionamiento en una planta de desalación
- Obtención de graficas que ayuden a analizar el funcionamiento de la planta

Una vez generada esta herramienta se revisarán las distintas gráficas y teniendo estas graficas es posible realizar un análisis más exhaustivo de procesos de desalación, como ver como afecta la localización al funcionamiento de la planta, ver como afecta cambio de presión de funcionamiento y ver como influye el porcentaje de recuperación que se desea obtener.

Finalmente, también se va a realizar un análisis basado en la literatura de la situación actual que hay tanto para las distintas configuraciones de plantas que se pueden utilizar. Del mismo modo se va realizar un repaso del concentrado y de los distintos métodos de extracción de concentrado que existen.

Abstract

The main objective of this project is to create a tool capable of performing a manually configurable thermoeconomic analysis of desalination plants considering the following aspects:

- Current state of desalination technology.
- Updating of the economic costs of each of the components that go into operation in a desalination plant.
- Obtaining graphs to help analyze plant operation.

Once this tool is generated, the different graphs will be reviewed and having these graphs it is possible to perform a more exhaustive analysis of desalination processes, such as seeing how the location affects the operation of the plant, see how it affects the change in operating pressure and see how it influences the percentage of recovery to be obtained.

Finally, a literature-based analysis of the current situation for the different plant configurations that can be used will also be carried out. In the same way, a review of the concentrate and the different methods of concentrate extraction that exist will be carried out.

TABLE INDEX

FIGURE INDEX

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1 INTRODUCTION

Knowledge of the technologies gives the possibility of trying to improve them and thus achieve greater performance.

In the specific case of desalination technologies, which are very important for obtaining drinking water with maximum concentration requirements. A tool that allows interactions to selected configuration of desalination process is developed to allow energy diagnosis as well as thermo-economic analysis. Besides, this tool enables analyses of plant retrofitting.

1.1 Objective

The objectives to be achieved in this project are:

- Creation of a tool that allows the design and assessment of a desalination process independently of the location of the plant.
- Implementation of the thermoeconomic analysis of a desalination plant retrofitting.

1.2 Scope

To achieve those objectives, it would be necessary the knowledge of thermodynamics properties of the energy and material flows existing in a desalination plan. In addition to this, it would be necessary to know the economic characteristics of the plant components and flows which take part in the operation of the plant.

1.3 Starting point

The starting point of this project is an excel tool that has implemented a specific configuration of the desalination process of a saline water flow with specific properties of temperature and salt concentration. This tool has an inside desalination process configurated with an ERI pressure exchanger as a recovery system. The tool generates different charts that give information about exergy and cost of the energy and material flows and equipment.

The main goal of this project is to expand the tool mentioned and adapt these tools as flexible as possible allowing the users to configure by themselves the desalination configuration that is analyzed.

1.4 Desalination History

Commercial desalination plants began to operate in the early 20th century and were immediately established in the Middle East, where it is reported that the first desalination plant in the Gulf region was built in 1907 in Jeddah, Kingdom of Saudi Arabia (KSA)

During the XX century, the contribution of the desalination plants increased due to the necessity of desalted water in addition to the evolution of equipment over the years. Moreover, the XXI century exhibits significant growth of the number of power plants and installed capacity of desalination, as described in the following chart.

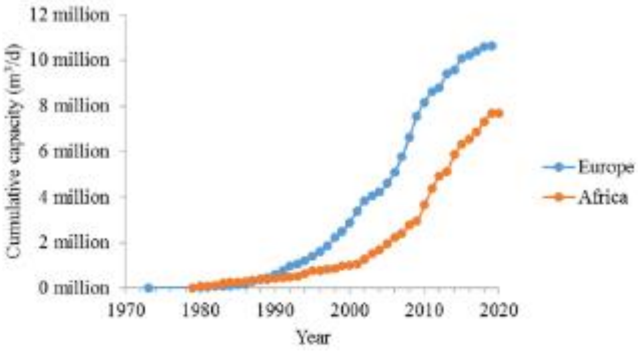

Figure 1.Evolution of the salinity capacity [1]

Desalination has become a conventional method for water treatment globally. As Figure 2 describes, the cumulative capacity in Europe has increased from 604272 m^3/d in 1990 to 10.6 million m^3/d in 2020, thus the quantity has increase over 1600%.

This pattern of growth, as reflected in the graph, is not only occurring in Europe, but also in other locations that use desalination as the necessary source of drinking water.

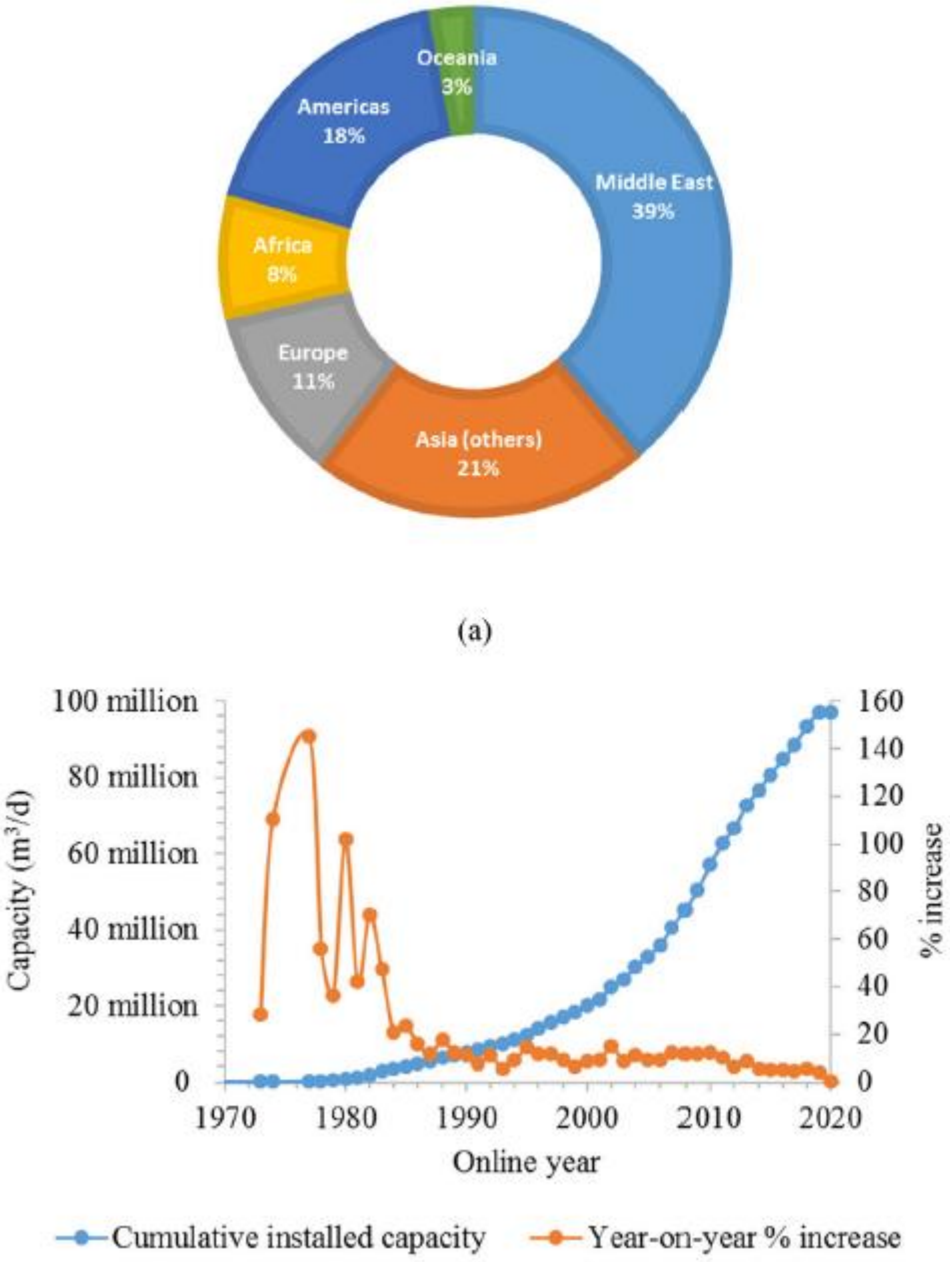

Figure 2. Increase desalination water capacity [1]

The current use of desalination is not only focus on seawater, despite being the pioneering use of this technology. Indeed, seawater desalination has opened the door to numerous investigations in which the feasibility and reliability of desalting not only seawater but also water from different sources has been proved. As the following graph shows, the use of these sources has also increased over the years, and this means that the accumulated capacity is growing in general terms.

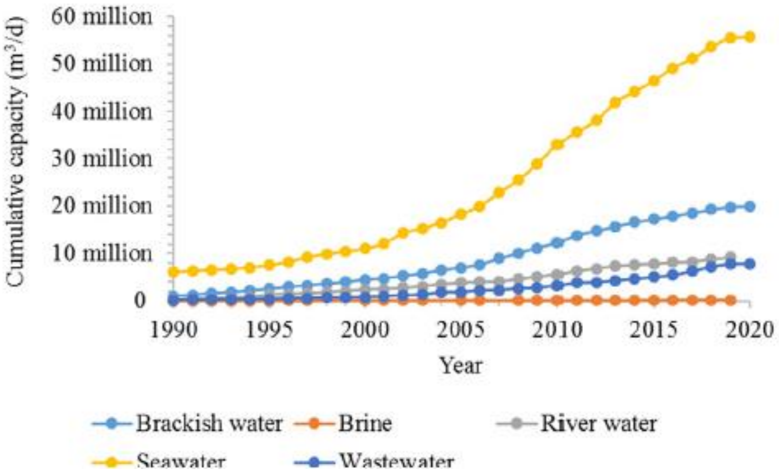

Figure 3. Different origins of desalinated water [1]

Modernizations have been made over the years to improve the efficiency of desalination systems.

One of the most common studies are based on optimizing the method of desalination due to there are numerous methods and all have pro and contras [1][2].

- ***Thermal desalination***

  Thermal desalination was the most common and reliable technology, but one of the negative points is that the energy requirements are high both, main (thermal) and auxiliary (electricity) energies. In these days thermal desalination driven by conventional or renewable energies make no sense in comparison to current standards of reverse osmosis desalination plants, even at small capacity.

- ***Membrane-based desalination***

  Seawater desalination through thermal technologies dominated the market for many decades, but due to the substantial energy requirements, a larger technological shift has occurred during the last two.

  Over 70 % of desalination plants globally are based on membranes, and over 90 % of the desalination capacity contracted since 2010 uses membrane technologies, mainly Reverse osmosis (RO).

  The feedwater is desalted by the pressure applied at the feed side of a semipermeable membrane, which is a cross-flow configuration considering circulation of feed and permeate. The concentrate (brine) outlet has similar pressure than that of feedwater. Working pressures should be high enough to achieve final concentration, and for that reason a number of tools are used to cover or reuse as much energy as possible. For example in the past – see fig. 4 - Pelton turbines, which use the energy produced in the turbine thanks to the pressure of the brine at the membrane modules outlet. Nowadays energy recovery systems based on pressure exchangers are the most common systems. They are used to elevate the pressure of part of the feed water flow using the remaining energy of the brine.

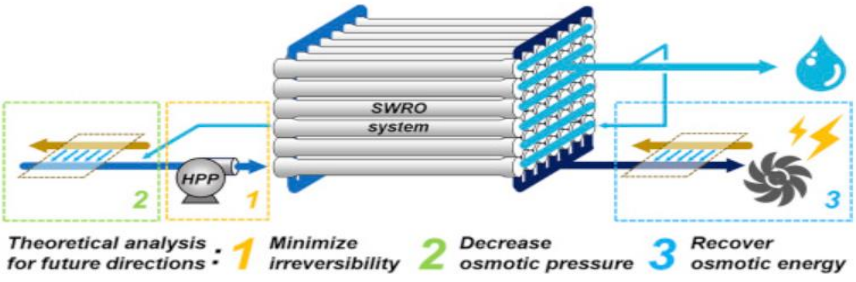

Figure 4.SWRO Desalination process [3]

- ***Hybrid thermal and membrane-based desalination***

  Forward Osmosis (FO) is a developing technology that combines membranes and thermal-driven separation. It is a process based on the osmotic pressure gradient between a highly concentrated solution (draw solution) and a more dilute solution (feed solution). In the case of desalination, feedwater is used as the flow with a lower concentration of the FO process, and water passes from seawater through membranes to the draw solution side, thus diluting the highly concentrated flow. Finally, the draw solution is partially evaporated to obtain fresh water and the remaining draw solution recovers its initial high concentration. Desalination by FO does not compete with reverse osmosis technology.

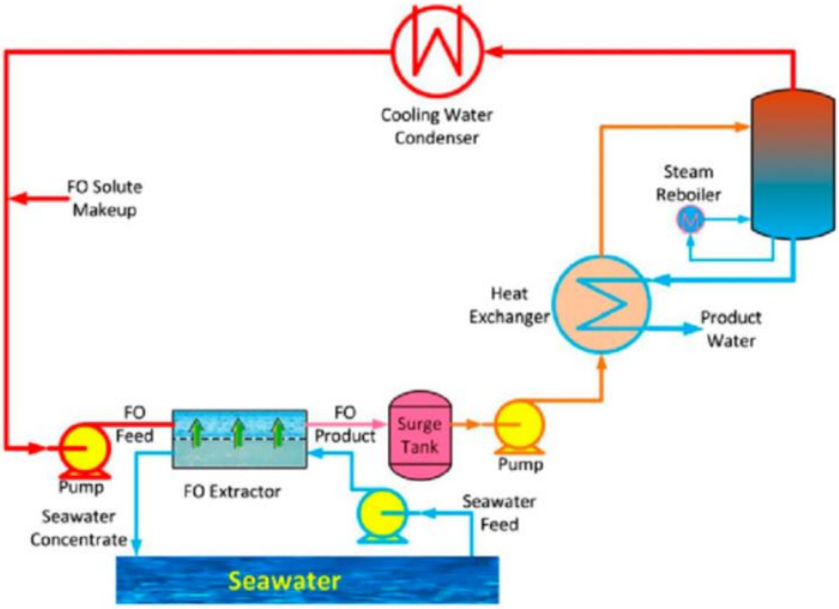

Figure 5.FO Desalination process [4]

- ***Energy requirements of commercial desalination technologies***

Energy is one of the most critical components of any desalination method, despite all the advances made over the last years, the consumption of desalination continues so high (at least 2-2.5 kWh/m^3 excluding auxiliaries) and this has a direct impact on the cost of the process.

For that reason, during the last years, some new desalination plants try to have a renewable support generator, with this solution coupling the desalination technology with the sustainability of the renewables[3]

1.5 Methodology

To economically assess the impact of modernization of a desalination plant configuration, a thermo-economic analysis will be carried out.

The main objective of a thermoeconomic[4] analysis is to determine and minimize the time costs of the output flows of the machine to be studied, for this purpose the results obtained from the thermodynamic and economic analysis are treated together. It is desired to know the real cost of each of the generated utilities, the costs are evaluated according to the use given to each energy or material flow.

According to the above, the objective of analysis[5] must be[6]:

1. To assign costs to the system's products.

2. To study and understand the formation of process costs.

3. To optimize energy variables.
4. To optimize the complete system.
5. To economically value the external costs.

It is necessary to know the procedures through which the thermoeconomic[7] analysis is calculated. To this end, some concepts are defined to characterize the different energetic flows, these will be used in the same way for the energetic studies, although with some nuances, these concepts are the following ones: fuels, products, lost exergy and destroyed exergy.

The product of equipment is what you want to achieve by investing time, money, and work to put a component into the system. The fuel is the set of inputs required to obtain that product. The exergy lost from a component is the exergy associated with the exergy flows, which leave the component without being used by other equipment in the installation and which are not a product or by-product of the plant. The exergy destroyed is the exergy losses due to irreversibility of the process that occurs at that equipment. It corresponds to the product of the variation of the entropy of the universe by the ambient temperature, expressed in K.

For example, it is not the same to analyse thermodynamically a simple heat exchanger as to analyse completely a thermal power plant, since the simple heat exchanger is a single element in which it is possible to study the output and input flows as they leave the apparatus, However, when analysing a thermal power plant, numerous machines produce changes in the flows so that it can be studied equipment by equipment, which would be the most valuable method since it allows to see the creation of costs or study the plant as a black box in which only the characteristics of the incoming and outgoing flows are known at the end of the process, thus losing information on how the costs have been created [8].

For the economic analysis, it is necessary to have the price of the equipment that takes part in the desalination process, having the prices [9] of the equipment referring to the year 2007 for instance, it is necessary to update those costs referred to the current year. For the actualization of the prices index, CEPCI are use the following formula.

$$Cost\ reference\ year\ = Original\ cost\ \cdot (\frac{Index\ CEPCI\ reference\ year}{Index\ CEPCI\ orginal\ year})$$

The index for the years is present in Table1 .

Table 1. Index CEPCI [10][11]

Year	Index CEPCI
2002	395.6
2005	568.2
2010	532.9
2019	627.7
2022	806.9

2 PROJECT COLLABORATION

This excel tool will be used in collaboration with the EERES4WATER project [12]. Figure 6 depicts the list of project partners sorted by countries, all of them belonging to the Atlantic Area. This project is funded by thye Programme INTERREG-Atlantic.

2.1 Objective

Main objective of the EERES4WATER project is to provide Atlantic Area stakeholders with the tools and instruments needed to overcome the Energy-Water nexus challenges and increase its utilization.

2.2 Specific objectives

- Providing recommendations and legal frameworks for policymakers and public administration
- Developing innovative technological solutions.
- Developing an ICT tool for decision-making and support services.
- Establishing cooperation agreements between academia and the private sector.
- Providing information and awareness about resource efficiency.

Figure 6.Plants of the projects.

2.3Integration with the project

The excel tool will be integrated with this project because in the tool that we have developed, the specific consumption is an input, depending on the plant analyzed as a function of the configuration and characteristics of the plants, identified in the EERES4WATER project.

This point is where the two projects are going to confluence. Specifically, this work is framed in one of the objective addressed by the University of Seville concerning energy diagnosis of seawater desalination plants and recommendations on plant retrofitting.

3 TOOL DEVELOPMENT

This chapter aims to describe the evolution of the tool which will be created to calculate and visualize the desalination process configuration.

First of all the initial status of the tool will be described and followed by the improvement made in the tool point-to-point.

3.1 Initial status

An initial status is a tool that allows the user to visualize the characteristics of a desalination configuration, knowing that the location of the plant is Canary Islands, and also knowing the input of the plant [13]. Figure 7 depicts said configuration. SWRO means Sea water Reverse Osmosis rack, consisting in membrane elements coupled in series within a pressure vessel and several pressure vessels interconnected in parallel. Besides, PEX means Pressure Exchanger, which corresponds to the more energy efficient energy recovery device. At the feed output of the PEX, a booster pump is required to achieve the working pressure of the plant, set by the main pump (high pressure pump). Before feed pretreatment, a pump symbol represents the seawater intake pumps. Distribution pumps are shown downstream the posrtreatment unit.

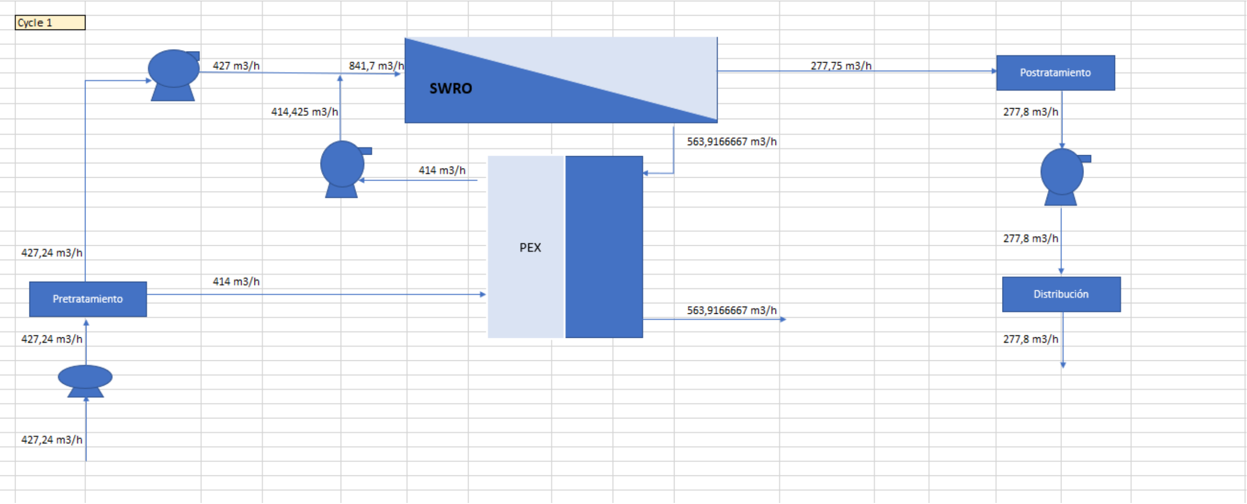

Figure 7. The only configuration of the desalination plants that can be analysed in the previous version of the tool.

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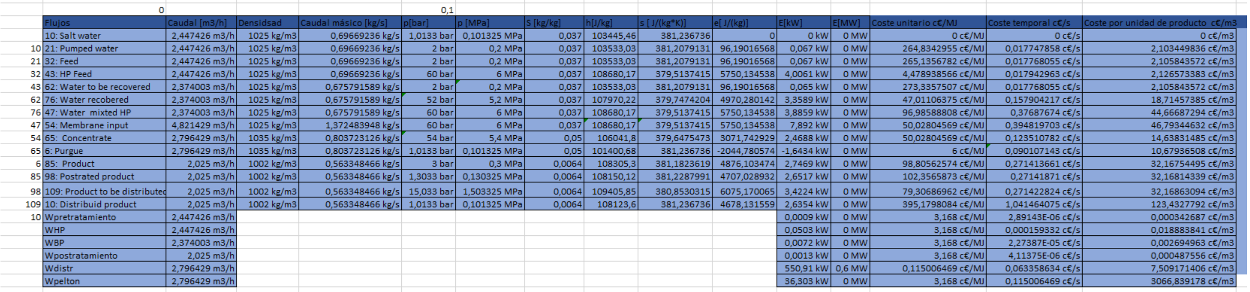
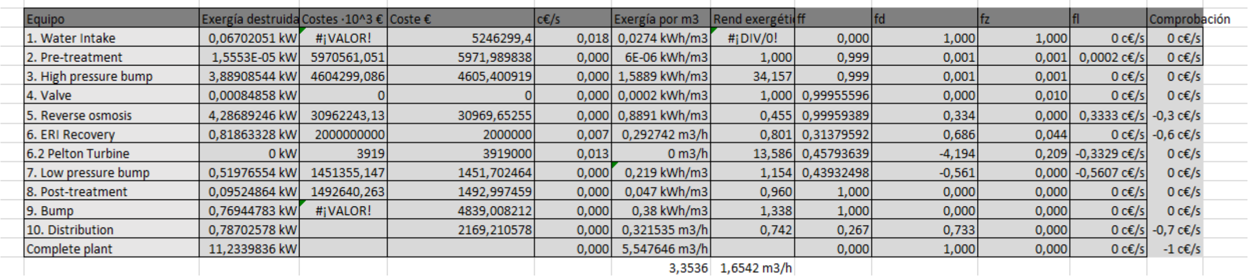
This excel tool has implemented equations of estate of seawater and its concentrated and dilutes as a function of temperature and salinity [14]. Therefore, density, enthalpy, entropy and exergy can be calculated



	0				0,1										
	Flujos	Caudal [m3/h]	Densidsad	Caudal másico [kg/s]	p[bar]	p [MPa]	S [kg/kg]	h[J/kg]	s [J/(kg*K)]	e[J/(kg)]	E[kW]	E[MW]	Coste unitario c€/MJ	Coste temporal c€/s	Coste por unidad de producto c€/m3
	10: Salt water	2,447426 m3/h	1025 kg/m3	0,69669236 kg/s	1,0133 bar	0,101325 MPa	0,037	103445,46	381,236736	0	0 kW	0 MW	0 c€/MJ	0 c€/s	0 c€/m3
10	21: Pumped water	2,447426 m3/h	1025 kg/m3	0,69669236 kg/s	2 bar	0,2 MPa	0,037	103533,03	381,2079131	96,19016568	0,067 kW	0 MW	264,8342955 c€/MJ	0,017747858 c€/s	2,103449836 c€/m3
21	32: Feed	2,447426 m3/h	1025 kg/m3	0,69669236 kg/s	2 bar	0,2 MPa	0,037	103533,03	381,2079131	96,19016568	0,067 kW	0 MW	265,1356782 c€/MJ	0,017768055 c€/s	2,105843572 c€/m3
32	43: HP Feed	2,447426 m3/h	1025 kg/m3	0,69669236 kg/s	60 bar	6 MPa	0,037	108680,17	379,5137415	5750,134538	4,0061 kW	0 MW	4,478938566 c€/MJ	0,017942963 c€/s	2,126573383 c€/m3
43	62: Water to be recovered	2,374003 m3/h	1025 kg/m3	0,675791589 kg/s	2 bar	0,2 MPa	0,037	103533,03	381,2079131	96,19016568	0,065 kW	0 MW	273,3357507 c€/MJ	0,017768055 c€/s	2,105843572 c€/m3
62	76: Water recobered	2,374003 m3/h	1025 kg/m3	0,675791589 kg/s	52 bar	5,2 MPa	0,037	107970,22	379,7474204	4970,280142	3,3589 kW	0 MW	47,01106375 c€/MJ	0,157904217 c€/s	18,71457385 c€/m3
76	47: Water mixted HP	2,374003 m3/h	1025 kg/m3	0,675791589 kg/s	60 bar	6 MPa	0,037	108680,17	379,5137415	5750,134538	3,8859 kW	0 MW	96,98588808 c€/MJ	0,37687674 c€/s	44,66687294 c€/m3
47	54: Membrane input	4,821429 m3/h	1025 kg/m3	1,372483948 kg/s	60 bar	6 MPa	0,037	108680,17	379,5137415	5750,134538	7,892 kW	0 MW	50,02804569 c€/MJ	0,394819703 c€/s	46,79344632 c€/m3
54	65: Concentrate	2,796429 m3/h	1035 kg/m3	0,803723126 kg/s	54 bar	5,4 MPa	0,05	106041,8	379,6475473	3071,742929	2,4688 kW	0 MW	50,02804569 c€/MJ	0,123510782 c€/s	14,63831485 c€/m3
65	6: Purgue	2,796429 m3/h	1035 kg/m3	0,803723126 kg/s	1,0133 bar	0,101325 MPa	0,05	101400,68	381,236736	-2044,780574	-1,6434 kW	0 MW	6 c€/MJ	0,090107143 c€/s	10,67936508 c€/m3
6	85: Product	2,025 m3/h	1002 kg/m3	0,563348466 kg/s	3 bar	0,3 MPa	0,0064	108305,3	381,1823619	4876,103474	2,7469 kW	0 MW	98,80562574 c€/MJ	0,271413661 c€/s	32,16754495 c€/m3
85	98: Postrated product	2,025 m3/h	1002 kg/m3	0,563348466 kg/s	1,3033 bar	0,130325 MPa	0,0064	108150,12	381,2287991	4707,028932	2,6517 kW	0 MW	102,3565873 c€/MJ	0,27141871 c€/s	32,16814339 c€/m3
98	109: Product to be distributed	2,025 m3/h	1002 kg/m3	0,563348466 kg/s	15,033 bar	1,503325 MPa	0,0064	109405,85	380,8530315	6075,170065	3,4224 kW	0 MW	79,30686962 c€/MJ	0,271422824 c€/s	32,16863094 c€/m3
109	10: Distribuid product	2,025 m3/h	1002 kg/m3	0,563348466 kg/s	1,0133 bar	0,101325 MPa	0,0064	108123,6	381,236736	4678,131559	2,6354 kW	0 MW	395,1798084 c€/MJ	1,041464075 c€/s	123,4327792 c€/m3
10	Wpretratamiento	2,447426 m3/h									0,0009 kW	0 MW	3,168 c€/MJ	2,89143E-06 c€/s	0,000342687 c€/m3
	WHP	2,447426 m3/h									0,0503 kW	0 MW	3,168 c€/MJ	0,000159332 c€/s	0,018883841 c€/m3
	WBP	2,374003 m3/h									0,0072 kW	0 MW	3,168 c€/MJ	2,27387E-05 c€/s	0,002694963 c€/m3
	Wpostratamiento	2,025 m3/h									0,0013 kW	0 MW	3,168 c€/MJ	4,11375E-06 c€/s	0,000487556 c€/m3
	Wdistr	2,796429 m3/h									550,91 kW	0,6 MW	0,115006469 c€/MJ	0,063358634 c€/s	7,509171406 c€/m3
	Wpelton	2,796429 m3/h									36,303 kW	0 MW	3,168 c€/MJ	0,115006469 c€/s	3066,839178 c€/m3

Figure 8.Thermodynamic properties of the mass flows.

Economic characteristics are also known, as can be seen in the following Figure 9



Equipo	Exergía destruida	Costes ·10^3 €	Coste €	c€/s	Exergía por m3	Rend exergéti	ff	fd	fz	fl	Comprobación
1. Water Intake	0,06702051 kW	#¡VALOR!	5246299,4	0,018	0,0274 kWh/m3	#¡DIV/0!	0,000	1,000	1,000	0 c€/s	0 c€/s
2. Pre-treatment	1,5553E-05 kW	5970561,051	5971,989838	0,000	6E-06 kWh/m3	1,000	0,999	0,001	0,001	0,0002 c€/s	0 c€/s
3. High pressure bump	3,88908544 kW	4604299,086	4605,400919	0,000	1,5889 kWh/m3	34,157	0,999	0,001	0,001	0 c€/s	0 c€/s
4. Valve	0,00084858 kW	0	0	0,000	0,0002 kWh/m3	1,000	0,99955596	0,000	0,010	0 c€/s	0 c€/s
5. Reverse osmosis	4,28689246 kW	30962243,13	30969,65255	0,000	0,8891 kWh/m3	0,455	0,99959389	0,334	0,000	0,3333 c€/s	-0,3 c€/s
6. ERI Recovery	0,81863328 kW	2000000000	2000000	0,007	0,292742 m3/h	0,801	0,31379592	0,686	0,044	0 c€/s	-0,6 c€/s
6.2 Pelton Turbine	0 kW	3919	3919000	0,013	0 m3/h	13,586	0,45793639	-4,194	0,209	-0,3329 c€/s	0 c€/s
7. Low pressure bump	0,51976554 kW	1451355,147	1451,702464	0,000	0,219 kWh/m3	1,154	0,43932498	-0,561	0,000	-0,5607 c€/s	0 c€/s
8. Post-treatment	0,09524864 kW	1492640,263	1492,997459	0,000	0,047 kWh/m3	0,960	1,000	0,000	0,000	0 c€/s	0 c€/s
9. Bump	0,76944783 kW	#¡VALOR!	4839,008212	0,000	0,38 kWh/m3	1,338	1,000	0,000	0,000	0 c€/s	0 c€/s
10. Distribution	0,78702578 kW		2169,210578	0,000	0,321535 m3/h	0,742	0,267	0,733	0,000	0 c€/s	-0,7 c€/s
Complete plant	11,2339836 kW			0,000	5,547646 m3/h		0,000	1,000	0,000	0 c€/s	-1 c€/s
					3,3536	1,6542 m3/h					

Figure 9.Economic characteristic

As output of the tool, some charts with the principal characteristic of the desalination process are created, as is depicted in the following Figure 10 that will be explained one by one in following followings chapters.

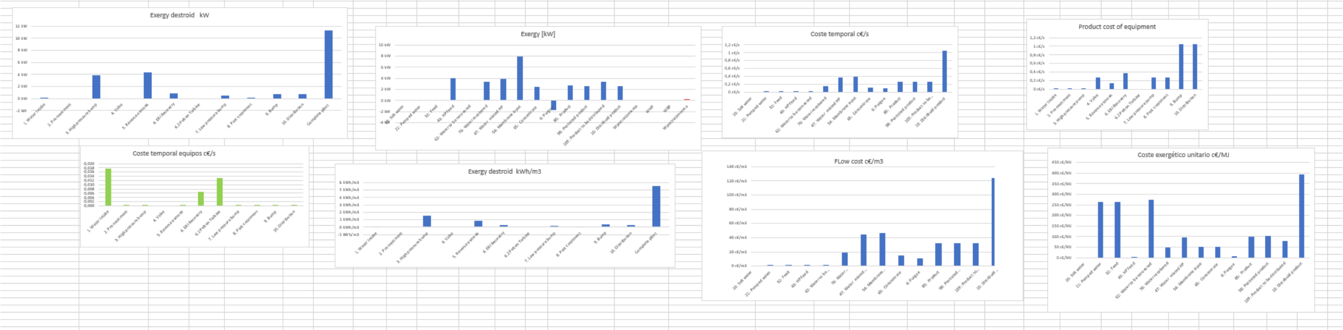


Figure 10. The output of the tool in its initial version.

3.2 Diagram updated

Another point in which the excel tool has evolved from the previous one corresponds to the figure of the plant configuration. The figure was just an image so the values of the flows could not be updated when these flows changed after performing corresponding calculations.

Now it is possible to visualize the values of flows in the diagram of the system configuration, and these flows are automatically updated whenever the flows change, as is visualized in Figure 11.

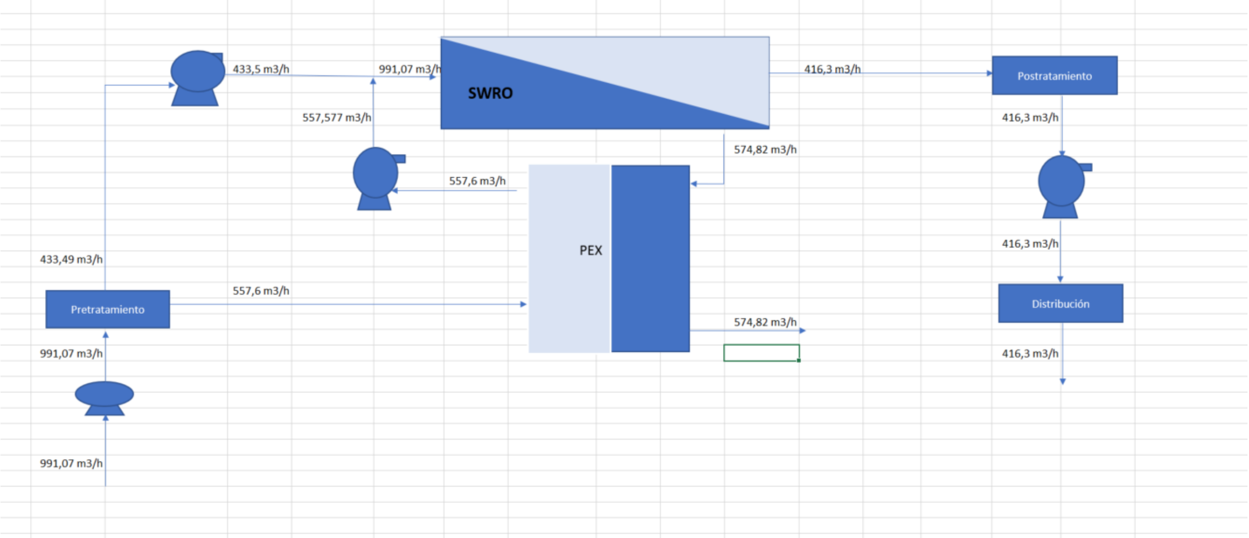


Figure 11. Diagram automatically updated

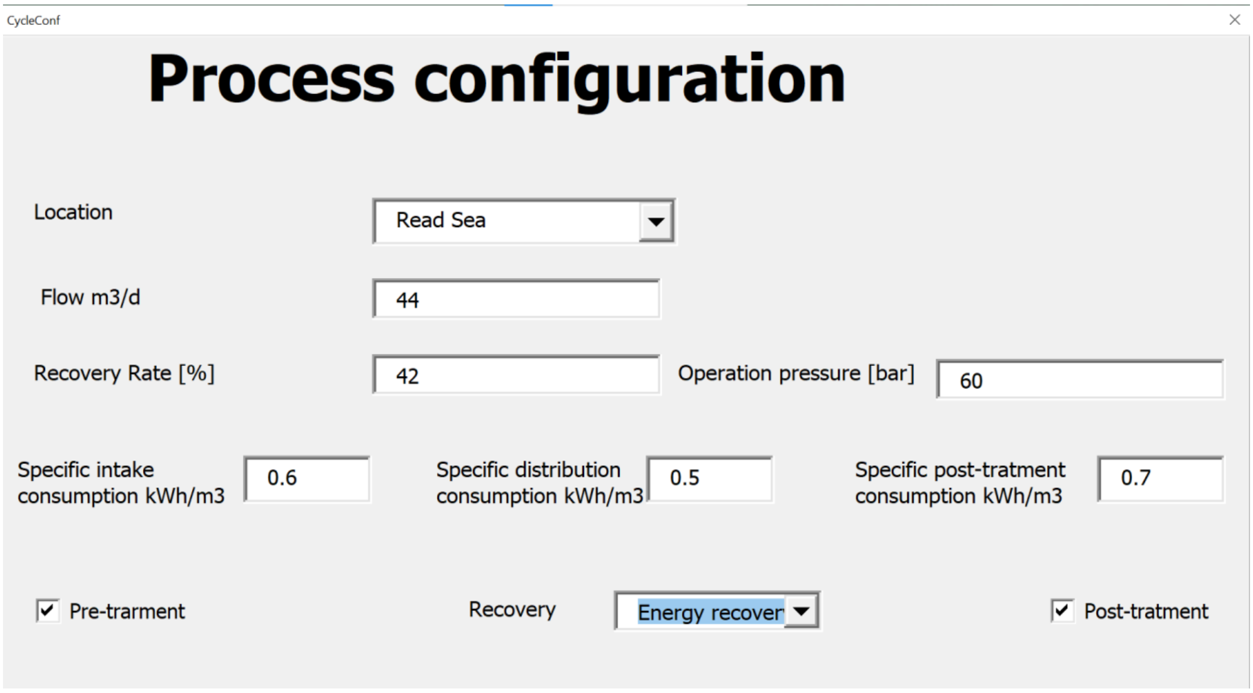
4 USER CONFIGURATION

It is very important to give the user the possibility to configure manually (depending on the necessities) the main characteristic of the desalination system configuration. This is addressed in the development of the new version of the excel tool produced.

4.1 User form

To make easier for the user to enter data manually, a tool has been programmed using VBA that allows to enter data manually as well as to select the configuration that you want to consider in the analysis of the desalination system to be carried out.

The user form has numerous inputs which can be configured manually by the user, as the following figure depicts. In this chapter, all the inputs will be explained one by one.



Process configuration

Location: Read Sea

Flow m3/d: 44

Recovery Rate [%]: 42

Operation pressure [bar]: 60

Specific intake consumption kWh/m3: 0.6

Specific distribution consumption kWh/m3: 0.5

Specific post-tratment consumption kWh/m3: 0.7

☑ Pre-trarment

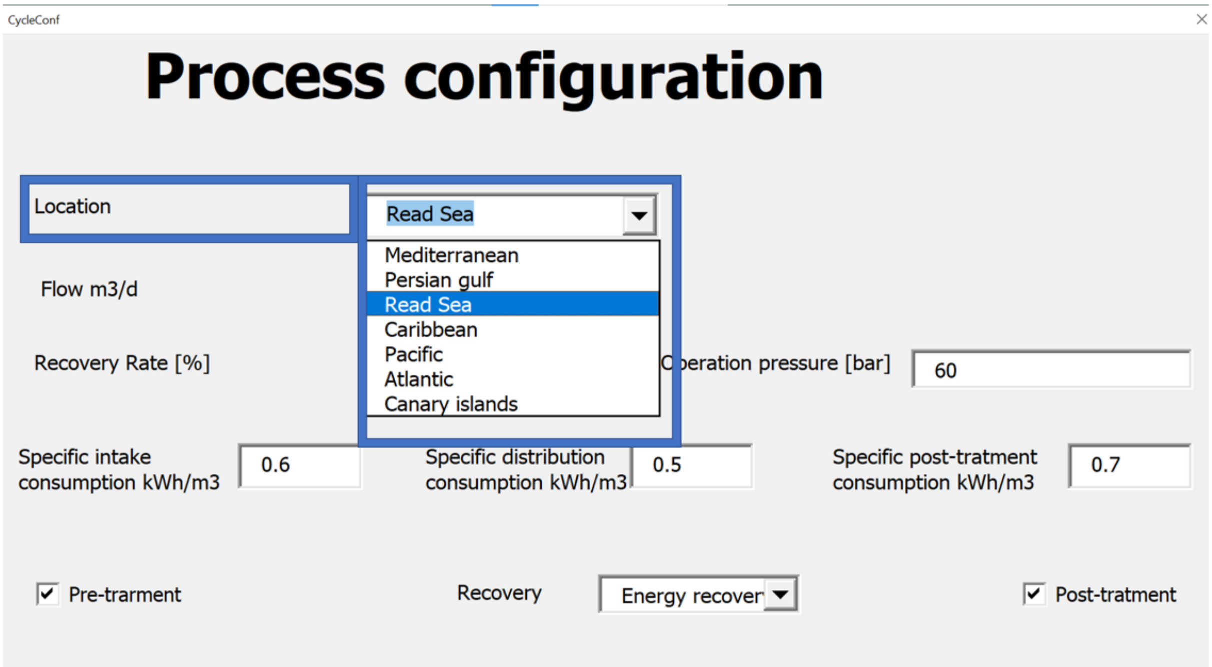
Recovery: Energy recover

☑ Post-tratment

Figure 12. User form Interface

4.1.1 Location selector

It is possible to select the location where the plant is going to be installed. The tool has inside the main features of the seawater [15]. In Figure 13 by clicking on the arrow in location a list is displayed, and the location can be selected.



Process configuration

Location: Read Sea

Operation pressure [bar]: 60

Specific intake consumption kWh/m3: 0.6

Specific distribution consumption kWh/m3: 0.5

Specific post-tratment consumption kWh/m3: 0.7

☑ Pre-trarment

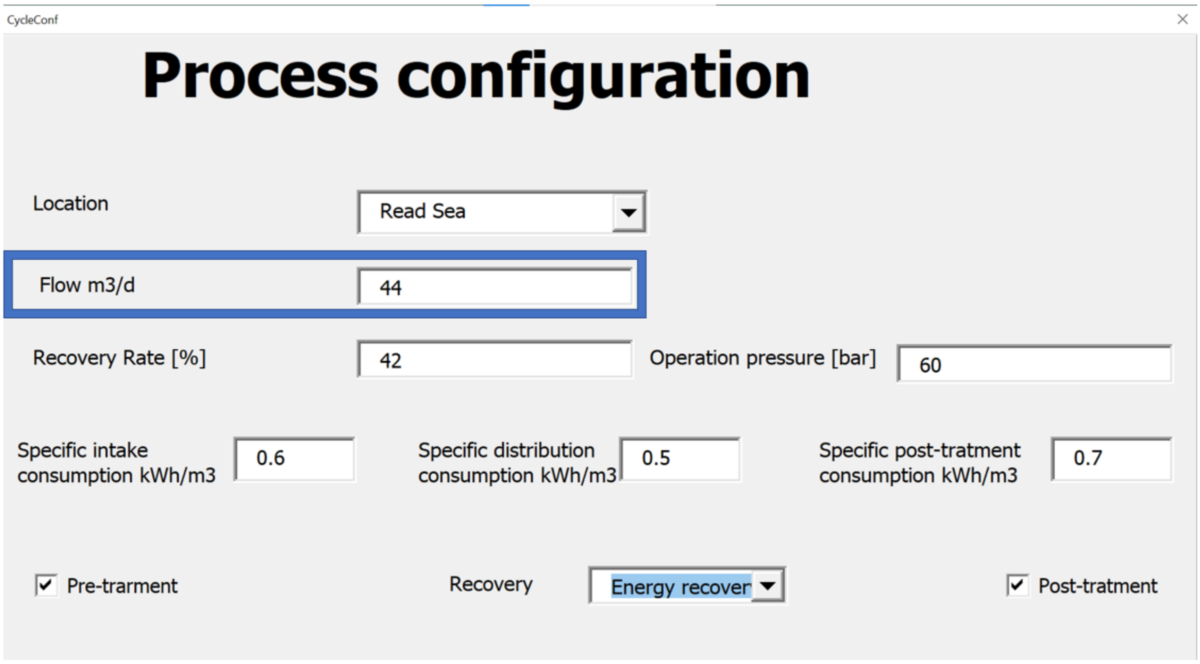
Recovery: Energy recover

☑ Post-tratment

Figure 13. User form Location selector

4.1.2 Flow selector

Following the same objective of having a tool as much flexible as possible. It is possible to insert the mass flow of water desalted. The mass flow that is going to be manually introduced corresponds to the nominal plant capacity see Figure 14



CycleConf

Process configuration

Location: Read Sea

Flow m3/d: 44

Recovery Rate [%]: 42

Operation pressure [bar]: 60

Specific intake consumption kWh/m3: 0.6

Specific distribution consumption kWh/m3: 0.5

Specific post-tratment consumption kWh/m3: 0.7

☑ Pre-trarment

Recovery: Energy recover

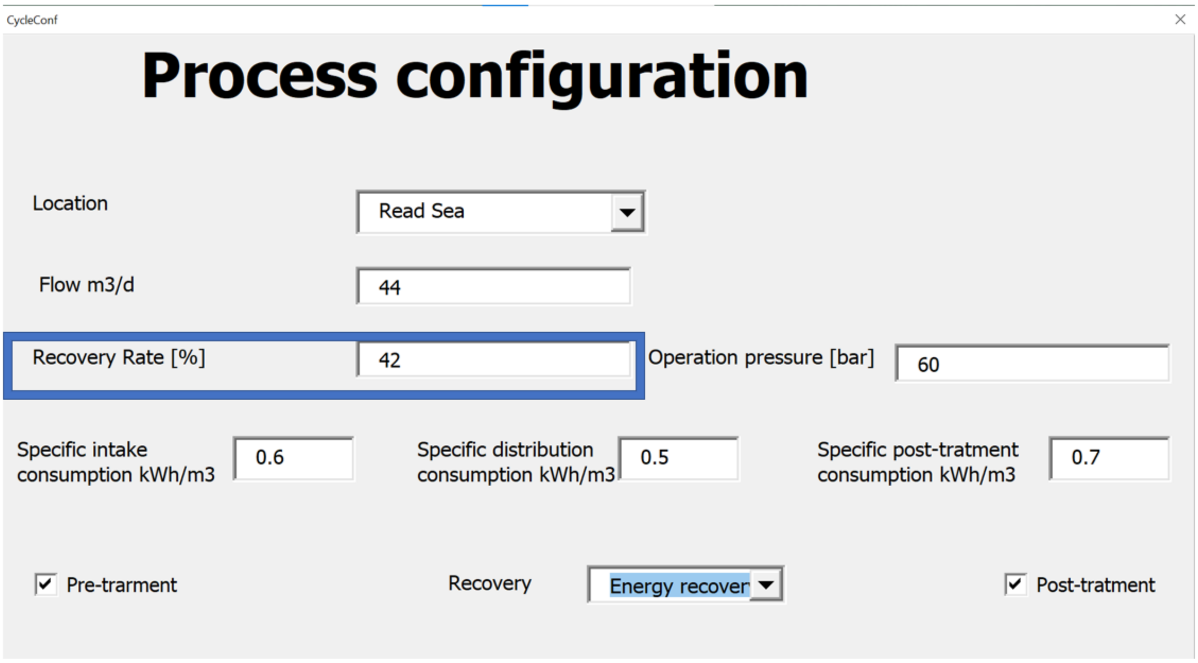
☑ Post-tratment

Figure 14. User form flow manual introduction

4.1.3 Recovery rate

Another input that is manually introduced is the percentage of recovery rate see Figure 15. This percentage follows the following formula.

$$Recovery\ rate = \frac{m_{product}}{m_{feed}} \cdot 100$$



CycleConf

Process configuration

Location: Read Sea

Flow m3/d: 44

Recovery Rate [%]: 42

Operation pressure [bar]: 60

Specific intake consumption kWh/m3: 0.6

Specific distribution consumption kWh/m3: 0.5

Specific post-tratment consumption kWh/m3: 0.7

☑ Pre-trarment

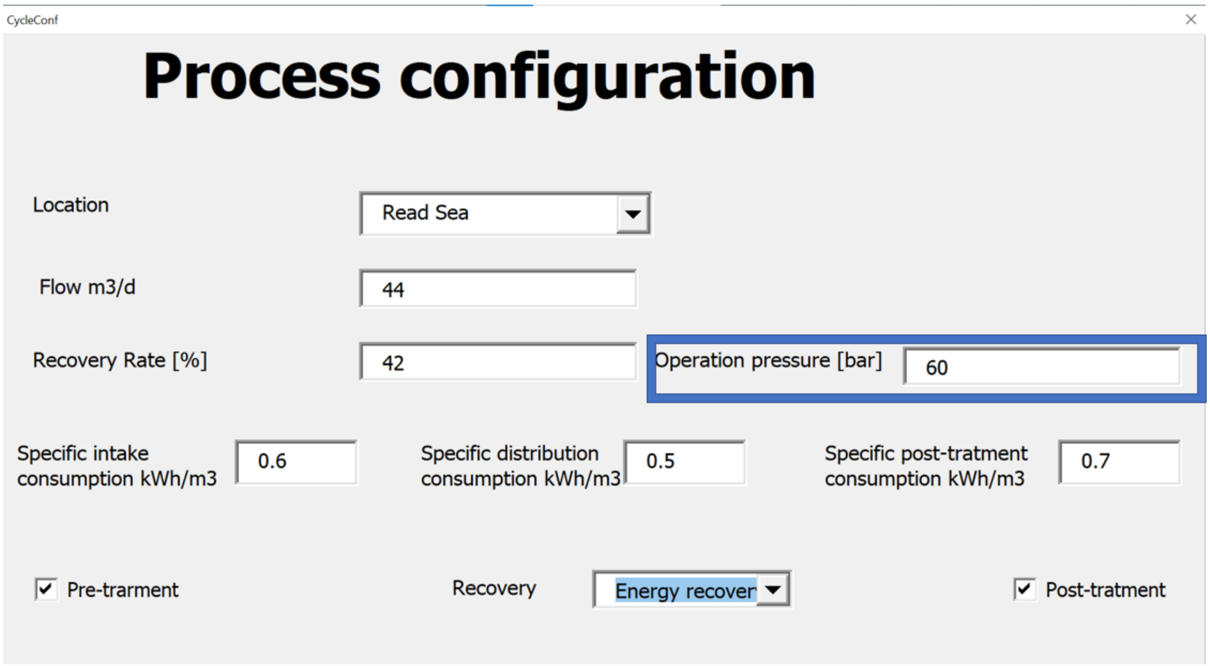
Recovery: Energy recover

☑ Post-tratment

Figure 15. Recovery rate manual introduction

4.1.4 Operation pressure

It is possible to insert manually the operating pressure of the plant see Figure 16.



CycleConf

Process configuration

Location: Read Sea

Flow m3/d: 44

Recovery Rate [%]: 42

Operation pressure [bar]: 60

Specific intake consumption kWh/m3: 0.6

Specific distribution consumption kWh/m3: 0.5

Specific post-tratment consumption kWh/m3: 0.7

☑ Pre-trarment

Recovery: Energy recover

☑ Post-tratment

Figure 16. Operating pressure

If the working pressure is not known, this could be estimated by means of the following formula, applicable to modern desalination plants.

$$P_{Feed} = \Pi_{brine} + 5\ bar$$

Previous equation guarantees a minimal Net Driving Pressure (NDP) at the tail of the series of RO membrane elements. NDP at a given point of the series of membrane modules is the difference between the gradients of pressure Δp and osmotic pressure ΔΠ across the membrane. The RO process occurs at a given point only if the corresponding NDP is positive, thus resulting in a permeate flow through the membrane from the feed side to the permeate side.

$$NDP = \Delta p - \Delta\Pi$$

The osmotic pressure can be obtained from the following formula:

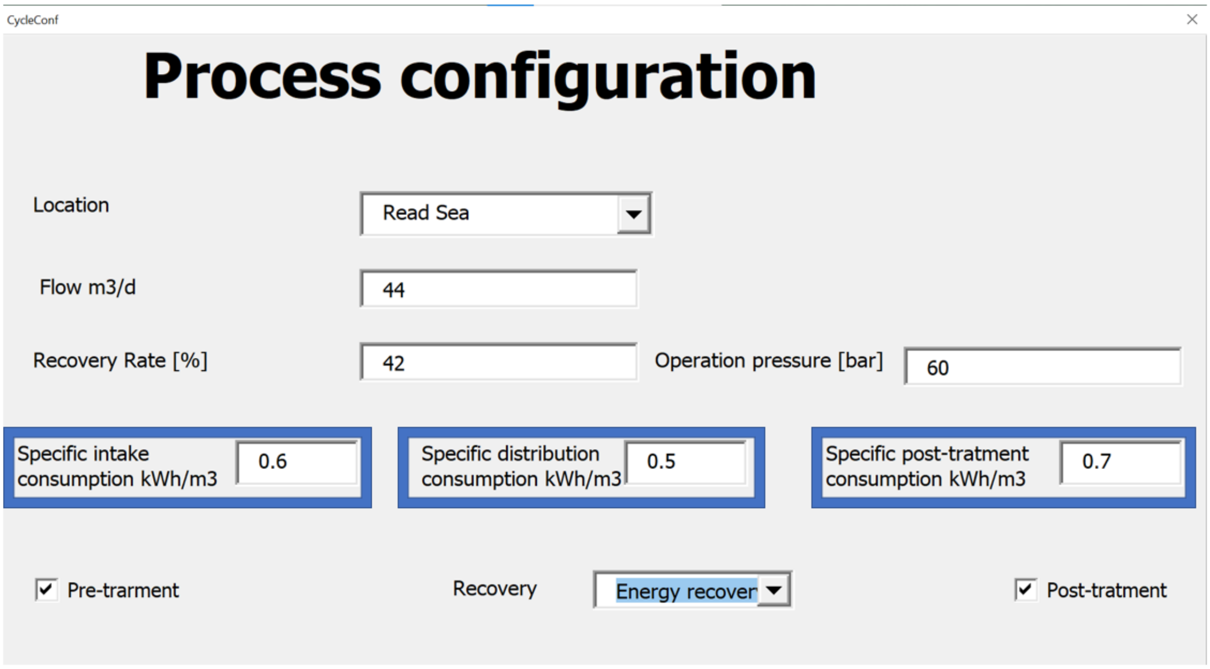
$$\Pi(\mathrm{S,T,P}) \cong \Pi(\mathrm{S,T}) \cong \varphi \cdot \rho_w \cdot R \cdot T \cdot 2 \cdot \frac{S}{M_s \cdot (1-S)}$$

Where S means salinity; Ms, the molar mass of salts; R, the universal gas constant, φ, the solvent osmotic coefficient, and ρ_w, the density of pure water.

4.1.5 Specific consumption

It is also possible to configure the specific consumption for the followings subsystems see Figure 17

- Intake
- Distribution
- Post-treatment



Process configuration

Location: Read Sea

Flow m3/d: 44

Recovery Rate [%]: 42

Operation pressure [bar]: 60

Specific intake consumption kWh/m3: 0.6

Specific distribution consumption kWh/m3: 0.5

Specific post-tratment consumption kWh/m3: 0.7

☑ Pre-trarment

Recovery: Energy recover

☑ Post-tratment

Figure 17. Specific consumption

The Specific Energy Consumption (SEC) is going to take part in the calculation of the consumption of the pumps as it is possible to see in the following formula.

$$SEC = \frac{P_{Pump\ HP} + P_{Pump\ LP}}{m_{Vol}}$$

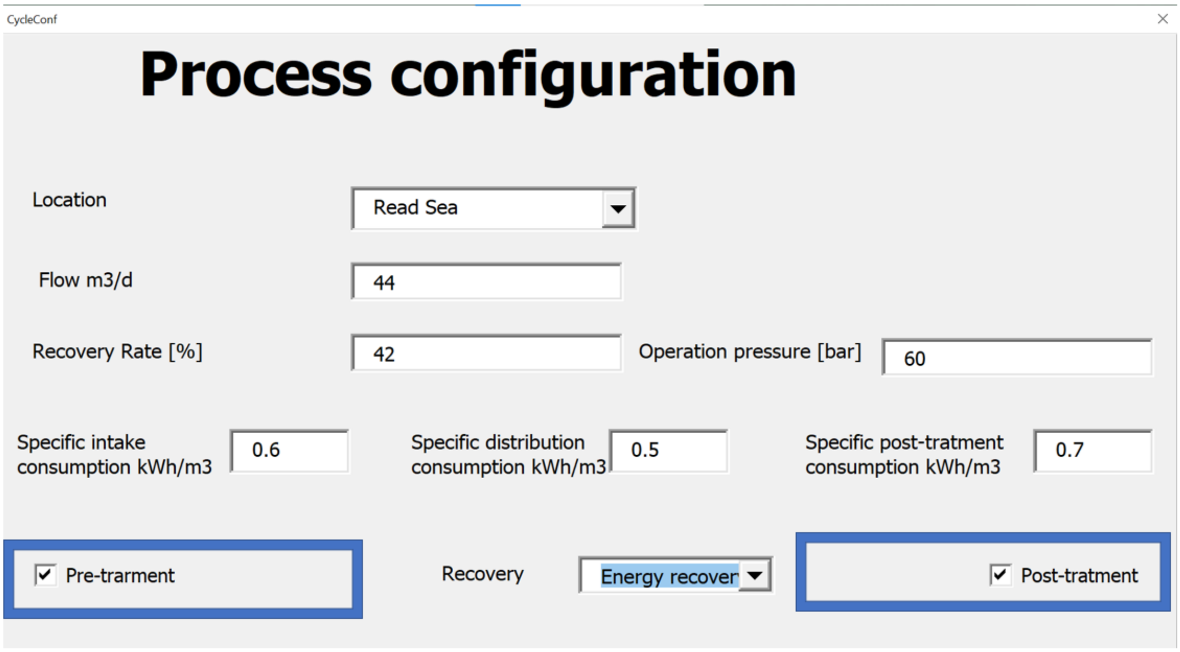
Where Mvol is the volume desalinated

4.1.6 Treatment selector

It is possible to select if the desalination plant analysis will include just the separation process or if the desalination process includes pre-process or post-process. To this end, it is possible to activate and deactivate them.

The possible preprocess and post-process are see Figure 18:

- Preprocess- Pretreatment
- Postprocess- Posttreatment



CycleConf

Process configuration

Location: Read Sea

Flow m3/d: 44

Recovery Rate [%]: 42

Operation pressure [bar]: 60

Specific intake consumption kWh/m3: 0.6

Specific distribution consumption kWh/m3: 0.5

Specific post-tratment consumption kWh/m3: 0.7

☑ Pre-trarment

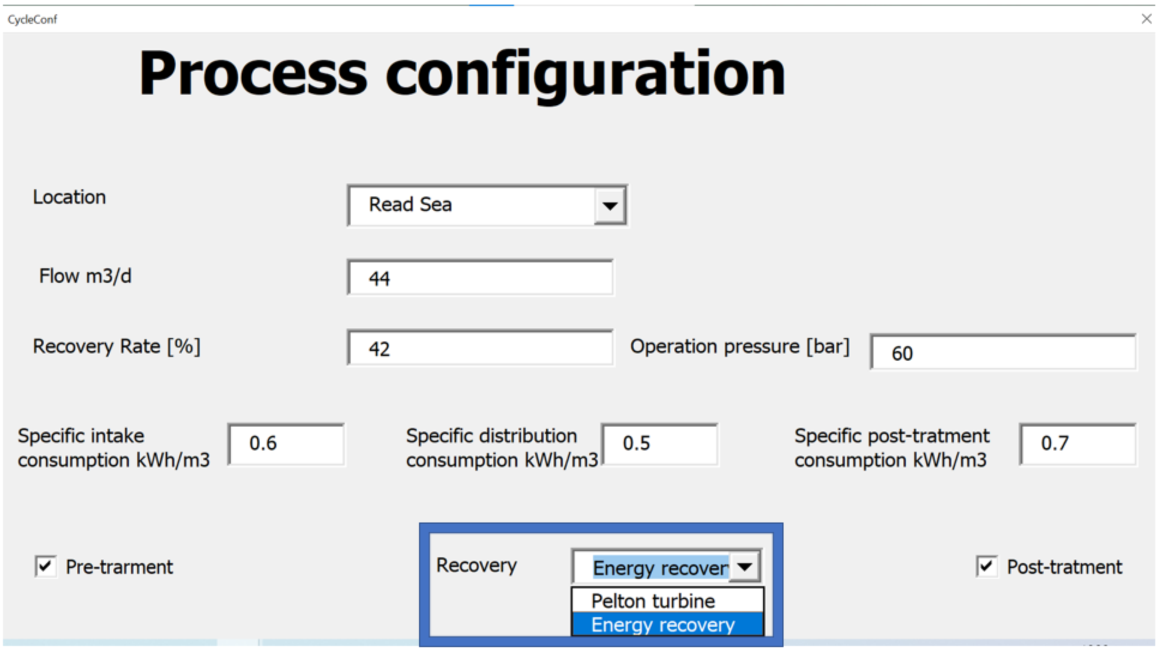
Recovery: Energy recover

☑ Post-tratment

Figure 18. Post and pre-treatment selector

4.1.7 Energy recovery configuration

The user also will be able to select if the energy is going to be recovered with a Pelton turbine or by an energy recovery. It is possible to select the equipment for energy recovery by clicking on the recovery selector as Figure 19 describes.



Process configuration

Location: Read Sea

Flow m3/d: 44

Recovery Rate [%]: 42

Operation pressure [bar]: 60

Specific intake consumption kWh/m3: 0.6

Specific distribution consumption kWh/m3: 0.5

Specific post-tratment consumption kWh/m3: 0.7

☑ Pre-trarment

Recovery: Energy recover

☑ Post-tratment

Figure 19. Selection of the energy recovery system.

5 OUTPUT CHART GENERATED

The tool is able to generate different charts that are going to be used in the analysis, the charts that are generated by the tool are the followings:

5.1 Exergy destroyed

The exergy destroyed is a thermo-economic factor that is calculated after obtaining the exergy values of both the product and the fuel.

Considering the product and fuel value, the losses are calculated according to the equipment studied, e.g. the thermal losses for the pumps are as follows $E_{Q\,S\dot{W}RO\to E}$, being $E_{Q\,S\dot{W}RO\to E}$, the heat losses with the environment.

The value of the destroyed exergy is calculated with the following formula

$$\dot{E_D} = \dot{E_F} - \dot{E_P} - \dot{E_L}$$

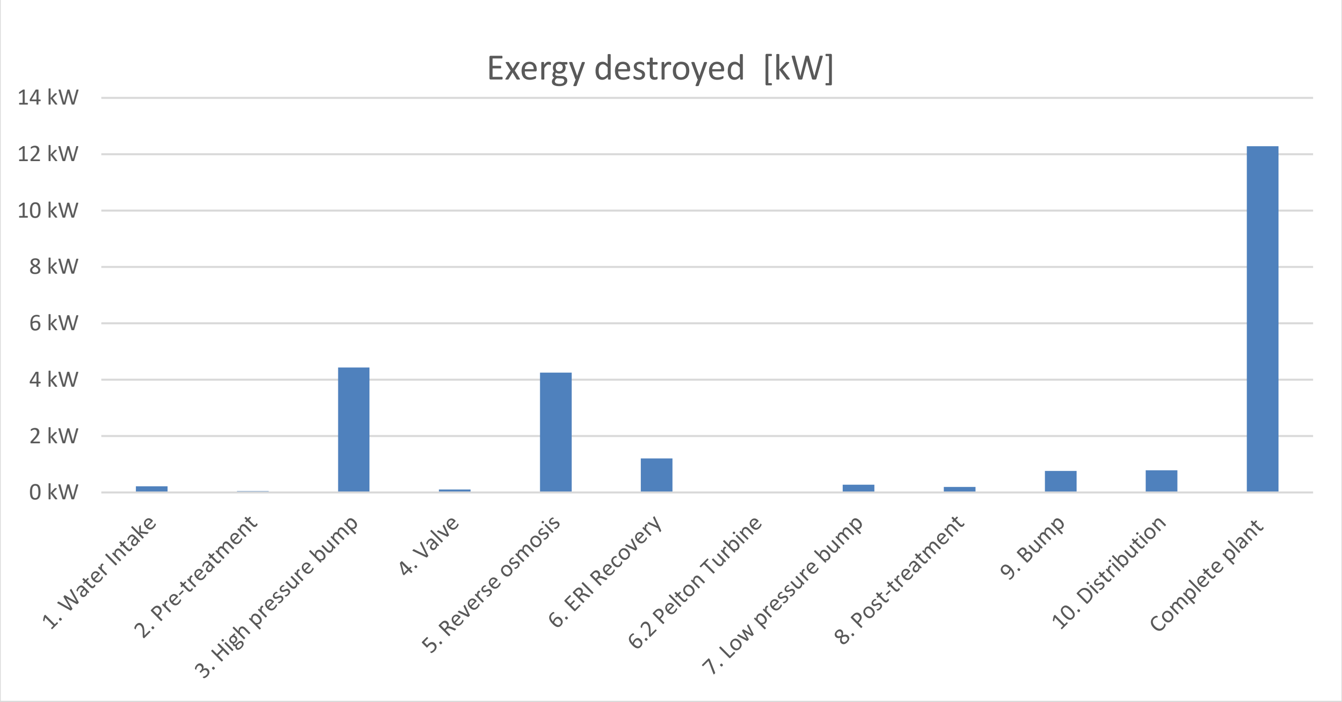


Figure 20. Exergy destroyed in each equipment

5.2 Exergy

The exergy of each flow is displayed in the following chart. The exergy of the purge is negative due to the purge has a high value of salinity.

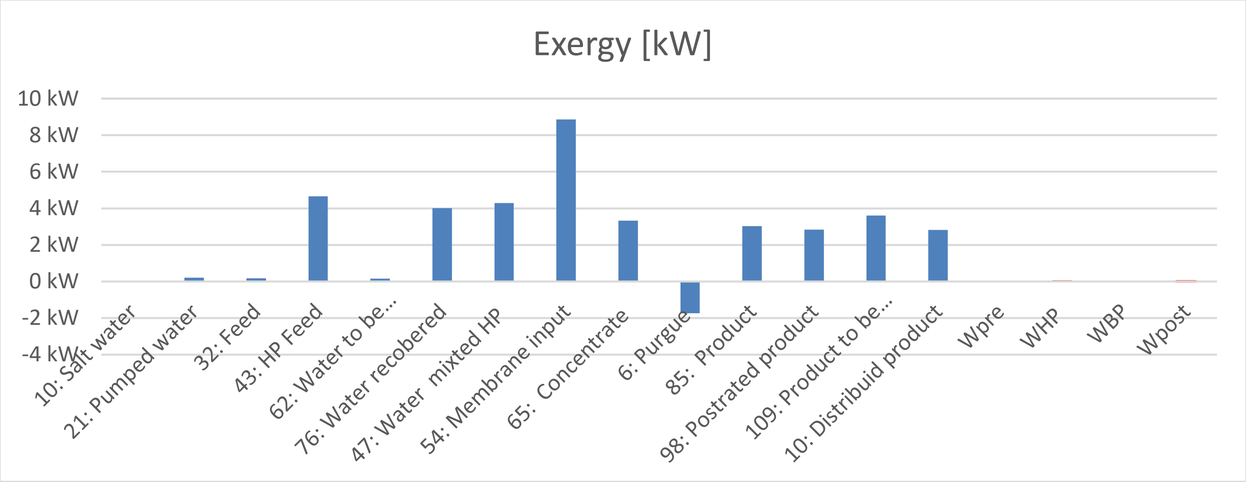


Figure 21.Exergy chart

5.3 Temporal cost of the equipments

Knowing the costs of the equipment working in the desalination process at a past date, it is possible to update the costs of this equipment.

There is an equation that allows calculating the acquisition cost of any equipment with known capacity or size (X_y), knowing the cost of the same equipment ($C_{PE,W}$) of different capacity or size (X_w).

$$C_{PE,Y} = C_{PE,W} \cdot (\frac{X_Y}{X_W})^{\alpha}$$

The exponent α for the same equipment may change with the reference year or with the size of the equipment.

All cost data used in an economic analysis must be taken in the same reference year, the year used as the basis for the cost calculation, to bring the cost of a known piece of equipment to the reference year it is necessary to apply the following formula, this is called the cost index.

The cost index is an inflation indicator that is used to correct the cost of equipment for different aspects such as material, labor and supply.

In this way, the equipment costs for 2019 will be updated, since the equipment costs for 2005 are known, with the so-called CEPCI indices, whose main function is to approximate the costs [10].

To perform this price update it will be necessary to use CEPCI values , which by definition are chemical plant cost indices, which are dimensionless numbers used to update the capital cost needed to build a chemical plant from a past date to a later date, following changes in the value of money due to inflation and deflation.

$$Cost\ reference\ year\ = Original\ cost\ \cdot (\frac{Index\ CEPCI\ reference\ year}{Index\ CEPCI\ orginal\ year})$$

Table 2. Index CEPCI [10], [11]

Year	Index CEPCI
2002	395.6
2005	568.2
2010	532.9
2019	627.7
2022	806.9

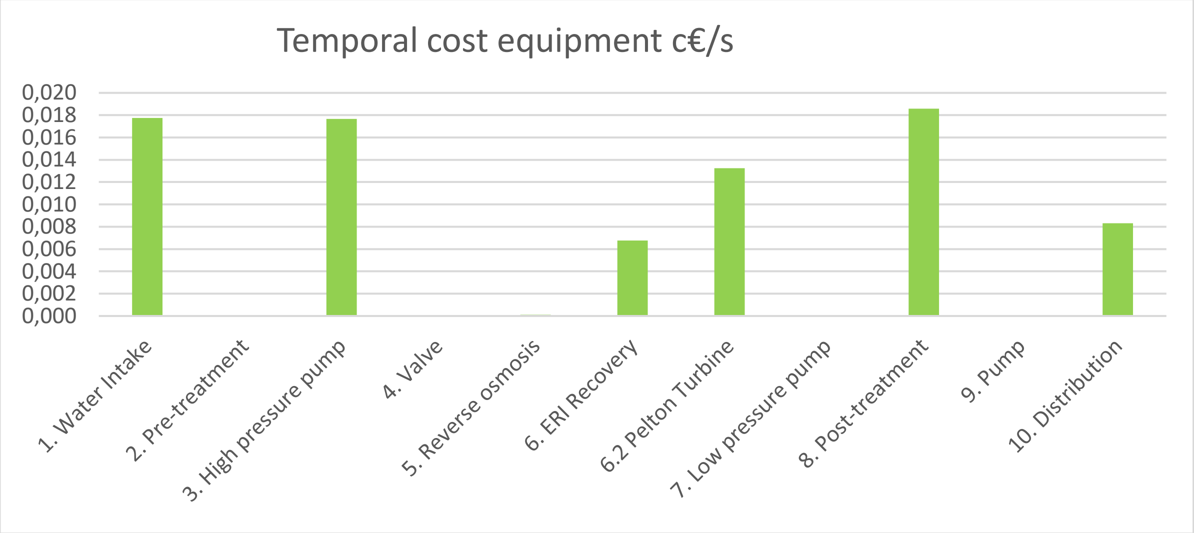


Figure 22.Temporal cost equipment

5.4 Temporal cost of each flow

By observing the time cost of each of the equipment, it is possible to know how the costs of each of the flows that enter the desalination system are formed. As can be seen in the Figure 23 these costs are cumulative and this is the reason why the cost of the product once distributed is the highest. Because it accumulates the temporary costs of the downstream flows in the process and of the equipment involved in the process.

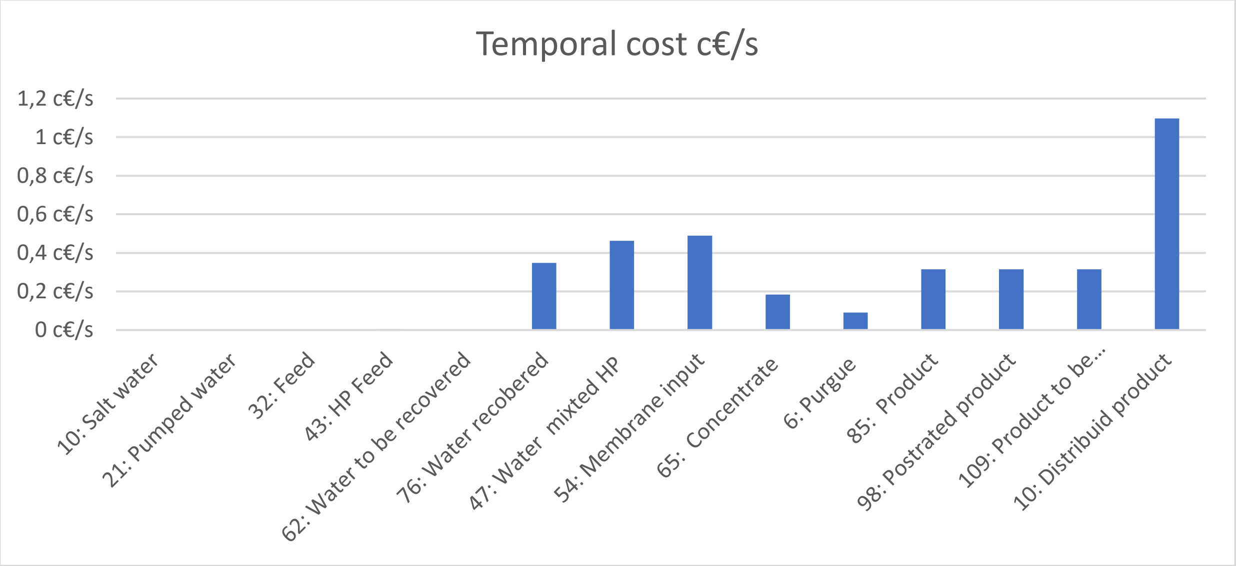


Figure 23. Temporal cost

5.5 Exergy destroyed per product volume

In the same way that the exergy of the flows is known, and the thermodynamic interaction that these flows have in each equipment working in the desalination process is known, it is possible to calculate the exergy destroyed in each of the equipment, referred to the unitary product volume.

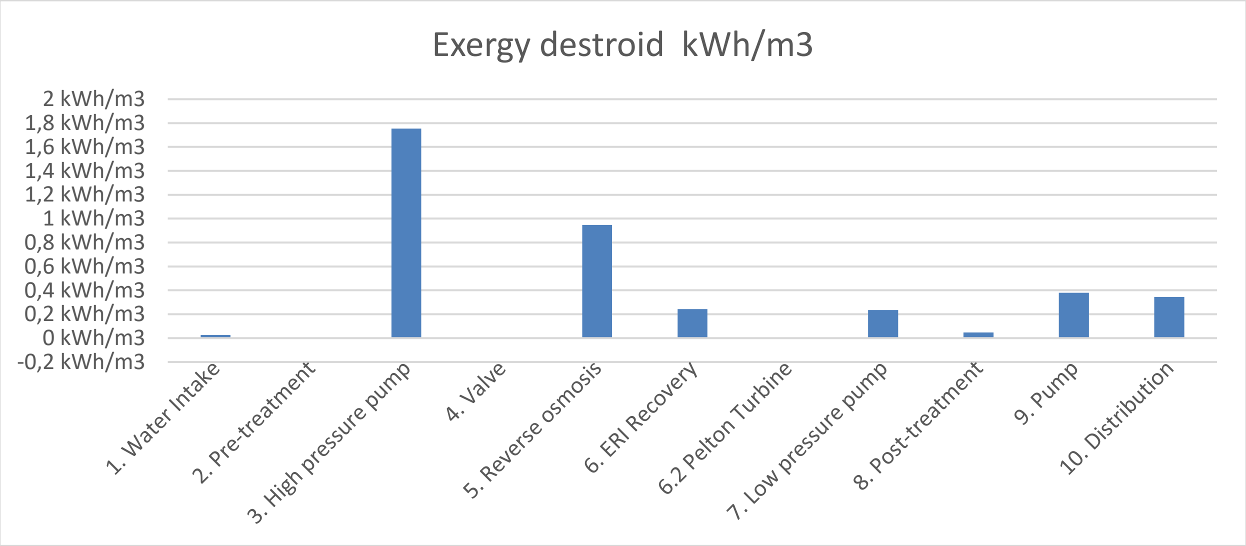


Figure 24. Exergy destroyed

5.6 Cost flow per product volume

The cost of these flows is cumulative, so the cost of the last flow is higher.

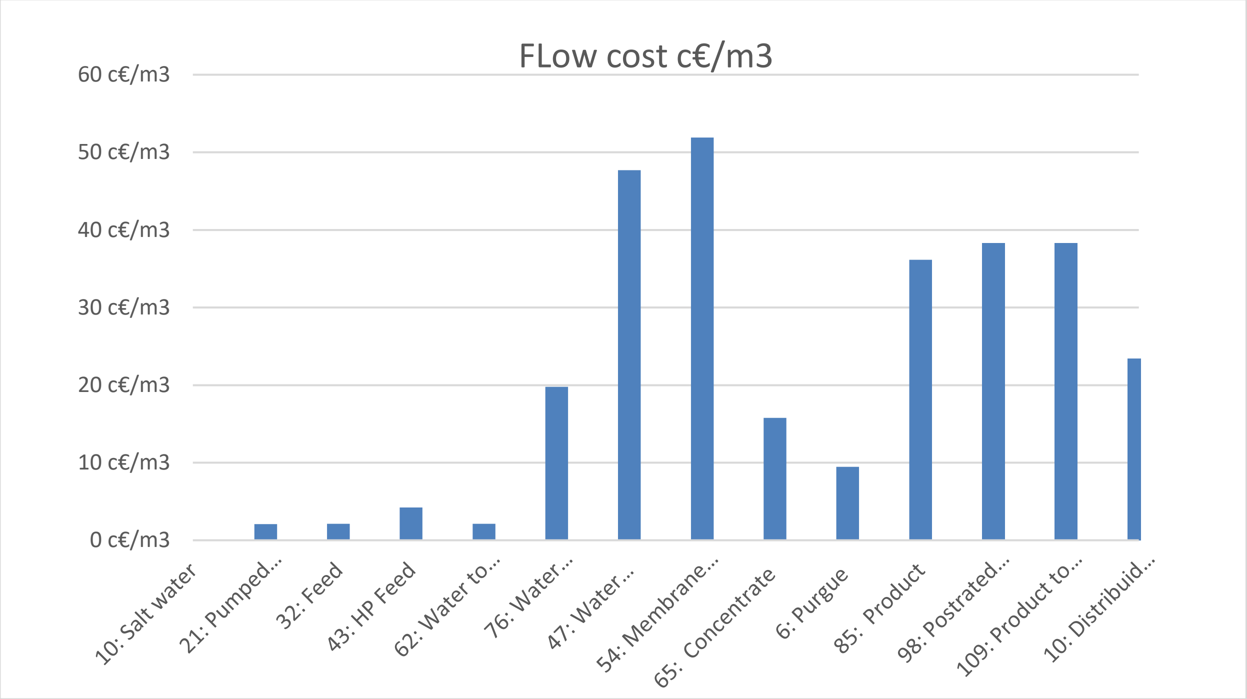


Figure 25.Flows cost per volume generated

5.7 Product cost of equipment

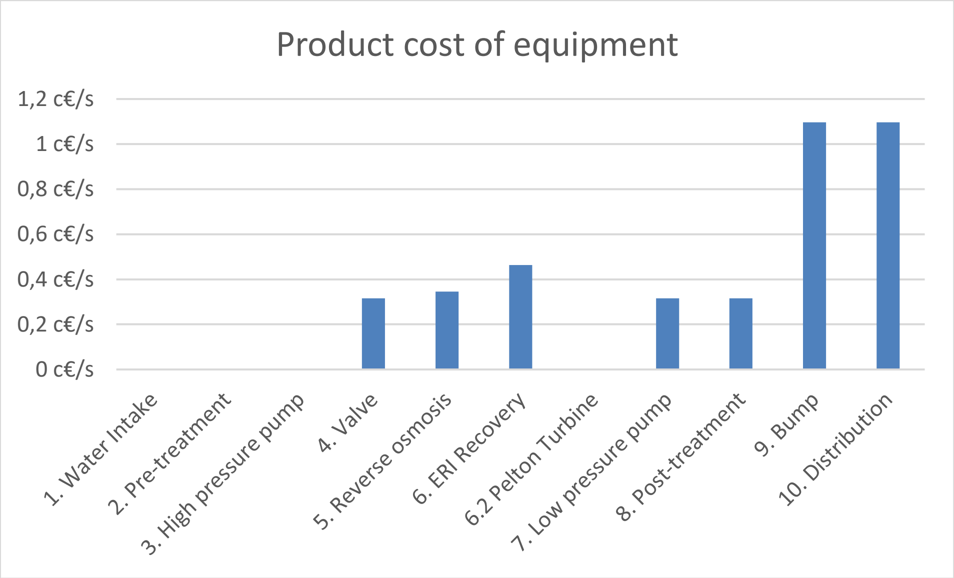


Figure 26. Product cost of equipment

6 ANALYSIS OF A GIVEN CONFIGURATION AT DIFFERENT PLANT LOCATION

The purpose of this chapter is to analyse how can affect the location where the cycle is placed.

6.1 General configuration

The analysis of the plant is going to have a base configuration, this configuration will be used for each location that the tool has available, in addition, the result of the general plant configuration will give the user the result of consumption and cost depending on the location.

The configuration that the base plant will have the following parameters:

- Flow desalinated 48,6 m^3/d
- Pre-treatment consumption: 0,2 kWh/m^3
- Intake consumption: 0,6 kWh/m^3
- Distribution consumption: 0,6 kWh/m^3

6.2 Exergy recovery

The diagram of the conventional configuration is automatically updated is the following one

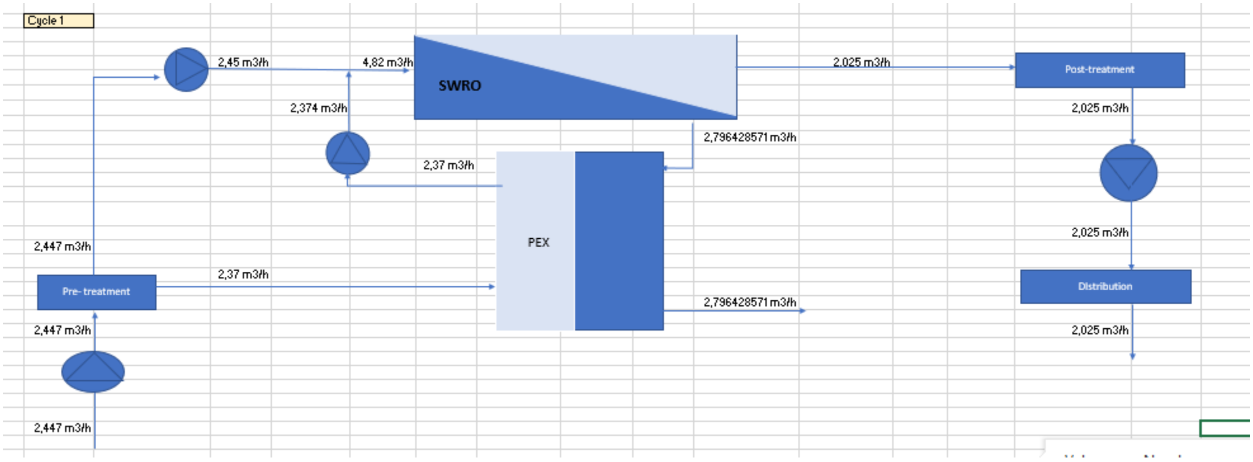


Figure 27. Configuration automatically updates with the base configuration

The developed tool enables the global assessment of a given configuration depending on the plant location.

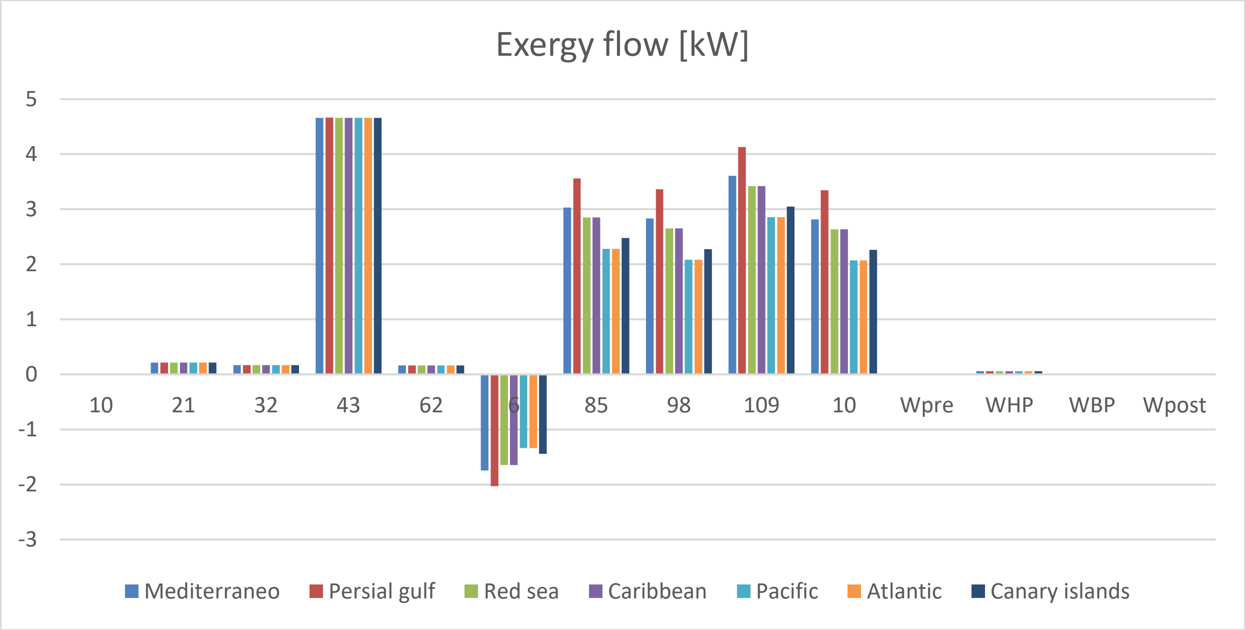


Figure 28. Exergy flow for a different location considering the same working pressure (but different recovery rate).

As it is possible to see in the Figure 28 depending on the location of the pant it can see the exergy of the flows is different. The exergy of the inputs is practically the same, as a consequence of the exergy of the input flow is related to the salinity in the case of the Persian Gulf that was in where the exergy is superior due to the salinity being higher than in the other. Note that the exergy of feedwater (seawater input), flow number 10 is null since it corresponds to ambient conditions of the seawater input of the seawater intake. Then, flow 21, which is the outlet seawater of the seawater intake, and flow 32, corresponding to pretreated seawater exhibits the same value of flow exergy. This is attributable to the initial hypotheses of equal auxiliary pumping consumption of both, the seawater intake and the seawater pretreatment system. Besides, by hypothesis, feed pressure is the same for all plant locations, thus resulting in similar flow exergy, since the change of flow exergy is only attributable to the pressure change at constant temperature and salinity.

The concentration of salt has a direct impact on the exergy in the flows, in addition to that, it is possible to see that for the location in which the concentration is lower for example the Pacific and the Atlantic where the energy is lower due to the direct relation between salinity and exergy.

Moreover, it is remarkable the significant difference of brine exergy, which negative values are attributable to the possible work generation by a process of controlled missing with seawater. This is possible by means of the pressure retarded osmosis process.

Analyzing in the same way how the cost of the flows depends on the same way of location, it is worth noting that for the locations which have higher salinity the cost of the flow is higher.

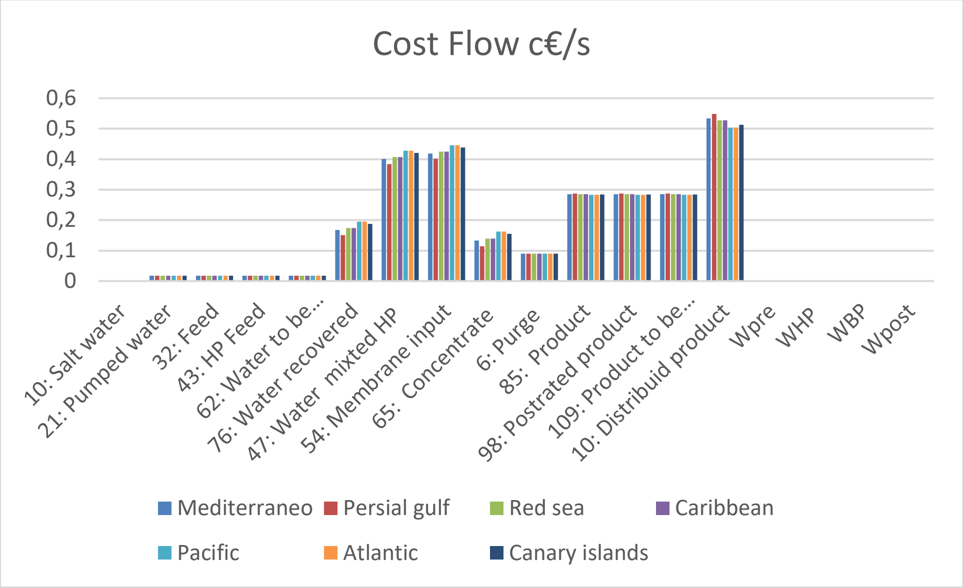


Figure 29. Cost flows

If instead of studying the temporally cost, the cost corresponding to 1 m^3 of product is studied it is possible to see that the behaviour is the same as it is possible to see in Figure 30.

The cost flow per volume produced comes in the following formula:

$$Cost\ \left(\frac{c€}{m3}\right) = Temporal\ cost\ \left(\frac{c€}{s}\right) \cdot 3600 \left(\frac{s}{h}\right) \cdot Product\ Flow\ (\frac{h}{m3})$$

The temporal cost come from the following formula:

$$\dot{C\imath} = ci \cdot Ei.$$

$\dot{C\imath}$ Is the time exergy cost of current i [€/time].

ci Is the unit exergy cost of current i [€/exergy unit].

Ei Exergetic power of current i [exergy/time], obtained by thermodynamic analysis.

All the logic of cost creation is explain in the annex II

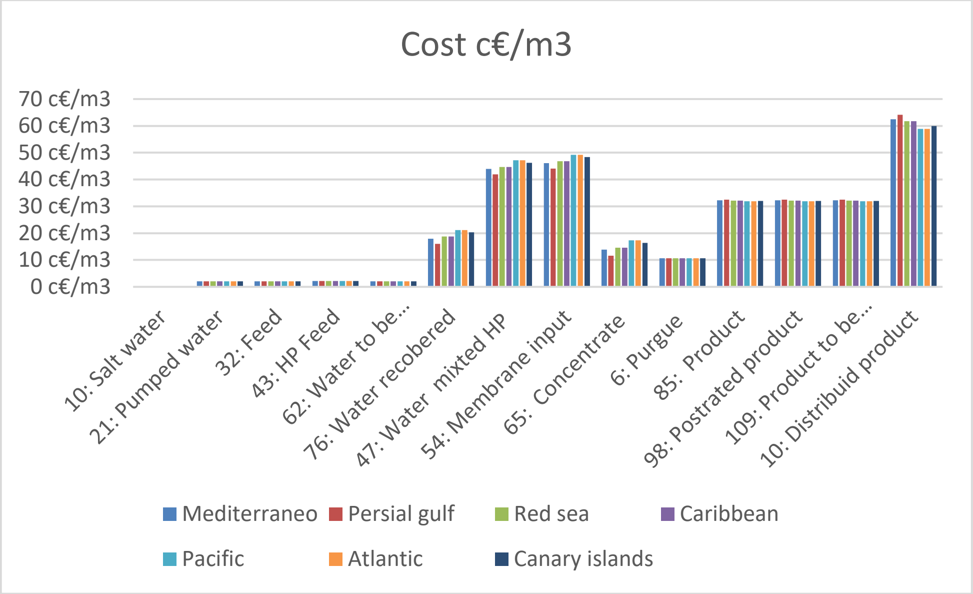


Figure 30. Flow cost

In the same way that the flow cost was analysed is also important to analyse how the salination and temperature of the location can affect the exergy destroyed for each component of the cycle.

As it is possible to see in Table 3 exergy destroyed in each component has the same correlation with the salinity of the sea. The location with more salinity has a higher absolute value of exergy destroyed.

It is possible that in the chart the values seem the same but they have some differences

Table 3. Exergy destroyed depending on the location

	Mediterranean	Persian gulf	Red sea	Caribbean	Pacific	Atlantic	Canary Islands
1:Water Intake	0,213	0,213	0,213	0,213	0,213	0,213	0,213
2:Pretratament	0,046	0,046	0,046	0,0469	0,0468	0,0468	0,0468
3:High pressure pump	4,439	4,4389	4,438	4,4386	4,438	4,438	4,438
4:Valve	0,1025	0,102	0,102	0,103	0,102	0,102	0,1025
5: Reverse osmosis	4,248	4,297	4,2318	4,2318	4,182	4,1825	4,1991
6: Booster pump	1,204	1,204	1,2046	1,2047	1,204	1,204	1,2045
6.2 Pressure exchange	39,616	39,61	39,61	39,616	39,61	39,6165	39,6163
7: Low-pressure pump	0,2744	0,27	0,274	0,274	0,274	0,2744	0,274
8: Postrattamient	0,198	0,198	0,198	0,1981	0,198	0,1981	0,1981
9: Pumping	0,768	0,768	0,768	0,7680	0,768	0,768	0,768
10: Distribution	0,787	0,787	0,787	0,787	0,787	0,787	0,7870
Complete plant	12,281	12,331	12,2	12,26	12,22	12,2	12,23

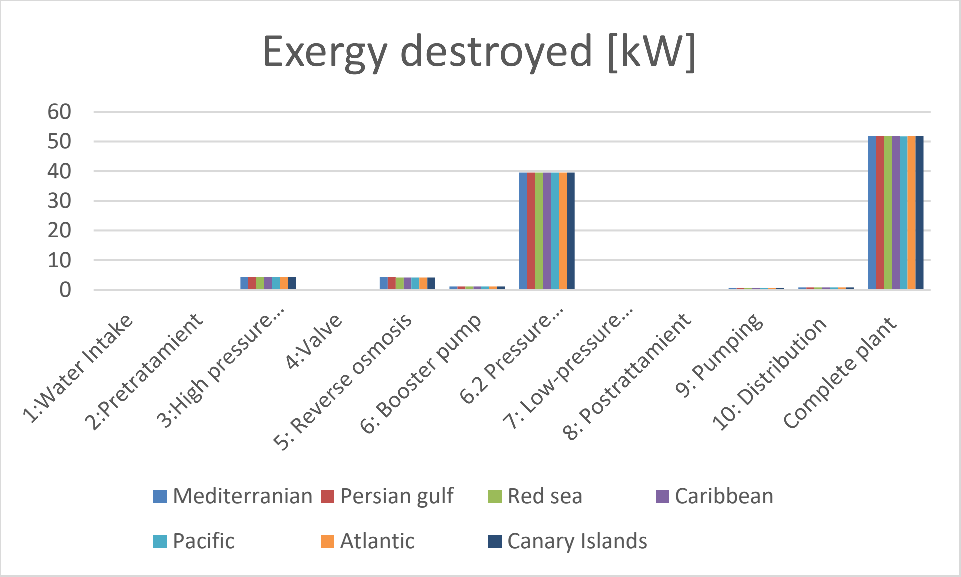


Figure 31. Exergy destroyed

6.3 Turbine Pelton

If the same analysis is made for a given desalination configuration but instead using a pressure exchanger as recovery system, a Pelton turbine is considered, it is possible to carry out the same analysis depending on the location.

The configuration with the Pelton turbine automatically updated in the tool is the following

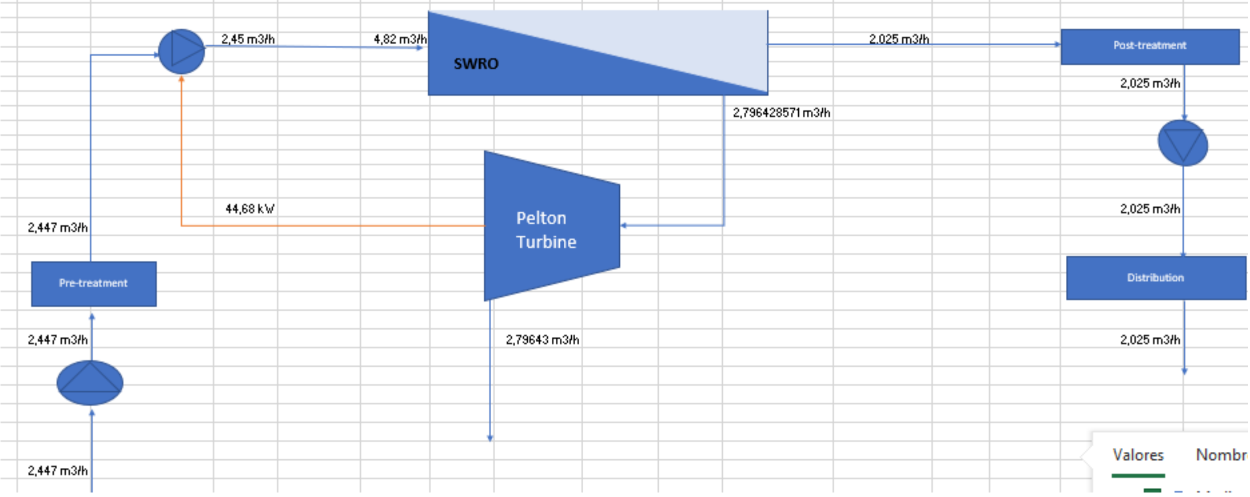


Figure 32. Diagram automatically updated Pelton turbine with the base configuration

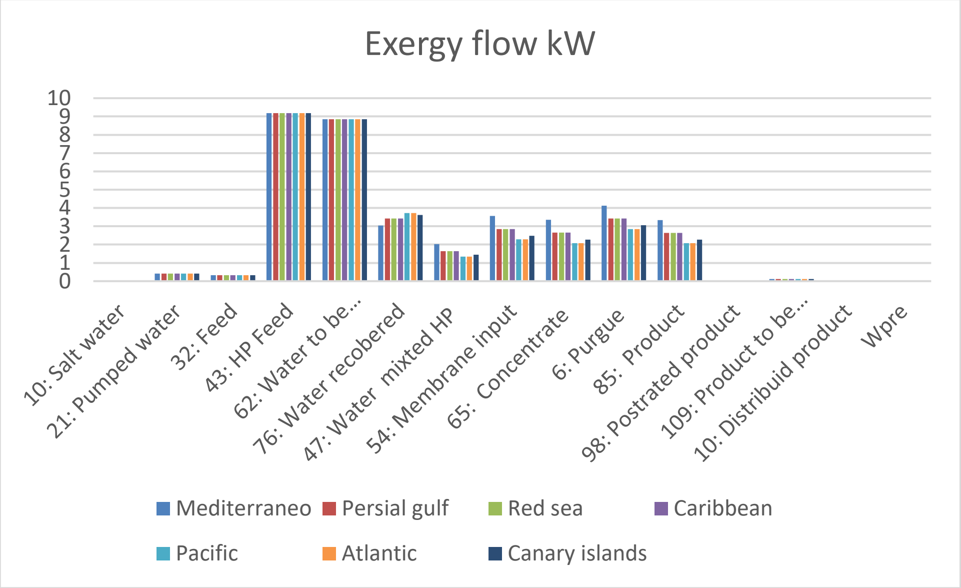


Figure 33. Exergy flow

As it is possible to see in the [16] if instead of analysis the exergy the cost are analysed, with Pelton Turbine it is possible to see that the cost follows the same approach, in which it is possible to see that the location with more salination has a ha higher cost.

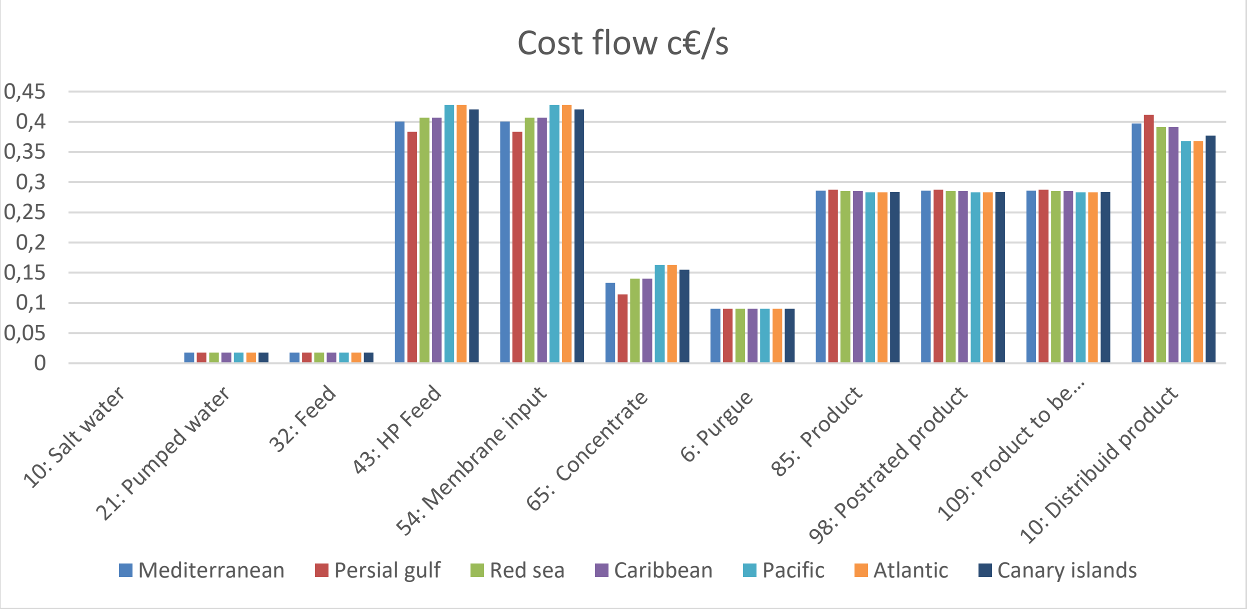


Figure 34. Cost Flow

6.4 Modernization

Instead of analysing the two configurations by separated (energy recovery and Pelton turbine), it is possible to analyse the difference between both configuration due to this is the most common modernization that is made in desalination plants.

In the same way that the user cases were analysed it is possible to analyse the modernization, with different locations and with a base configuration.

If, as mentioned above, an analysis of modernisation is carried out, the time cost per cubic metre of product treated can be studied Figure 35.

Having a similar recovery rate and converting the same volume.

The difference in costs can be seen using a Pelton turbine and an energy recovery unit.

The analysis has been carried out at 4 points of the plant:

1.After leaving the pre-treatment, as can be seen in the table this cost is practically the same, what makes it different is the salinity of the location.

2. Entrance to the membrane, here you can see the difference in costs between the Pelton turbine and the energy recovery system, as the investment cost is higher for the energy recovery system.

3. Product, the cost of the product once it leaves the membrane frame is higher for the energy recovery unit.

4. The cost of the post treated and distributed product, here it can be seen that the cost value increases, this is due to the fact that the reference plant has a high consumption for distribution, and this makes the cost increase.

c€/m3	Mediterranean	Persial gulf	Red sea	Caribbean	Pacific	Atlantic	Canary islands
Pelton turbine Pre-tratment	2,1037	2,10	2,103	2,103	2,103	2,1034	2,1037
Recovery Pre-tratment	2,10344	2,103	2,103	2,1034	2,1034	2,1034	2,1034
Pelton turbine Membrane feed	2,1493	2,149	2,149	2,149	2,1493	2,1493	2,14933
Recovery Membrane feed	2,12657	2,126	2,126	2,128	2,1265	2,1265	2,12657
Pelton turbine Product	1,5283	1,606	1,501	1,50144	1,41755	1,41755	1,4460
Recovery Product	32,238	32,443	32,167	32,167	31,947	31,9476	32,021
Pelton turbine Postrated-product	1,5300	1,608	1,503	1,5030	1,4192	1,41922	1,44770
Recovery Postrated-product	62,439	64,19	61,71	61,716	58,899	58,8996	59,970

Table 4. Moderniazation

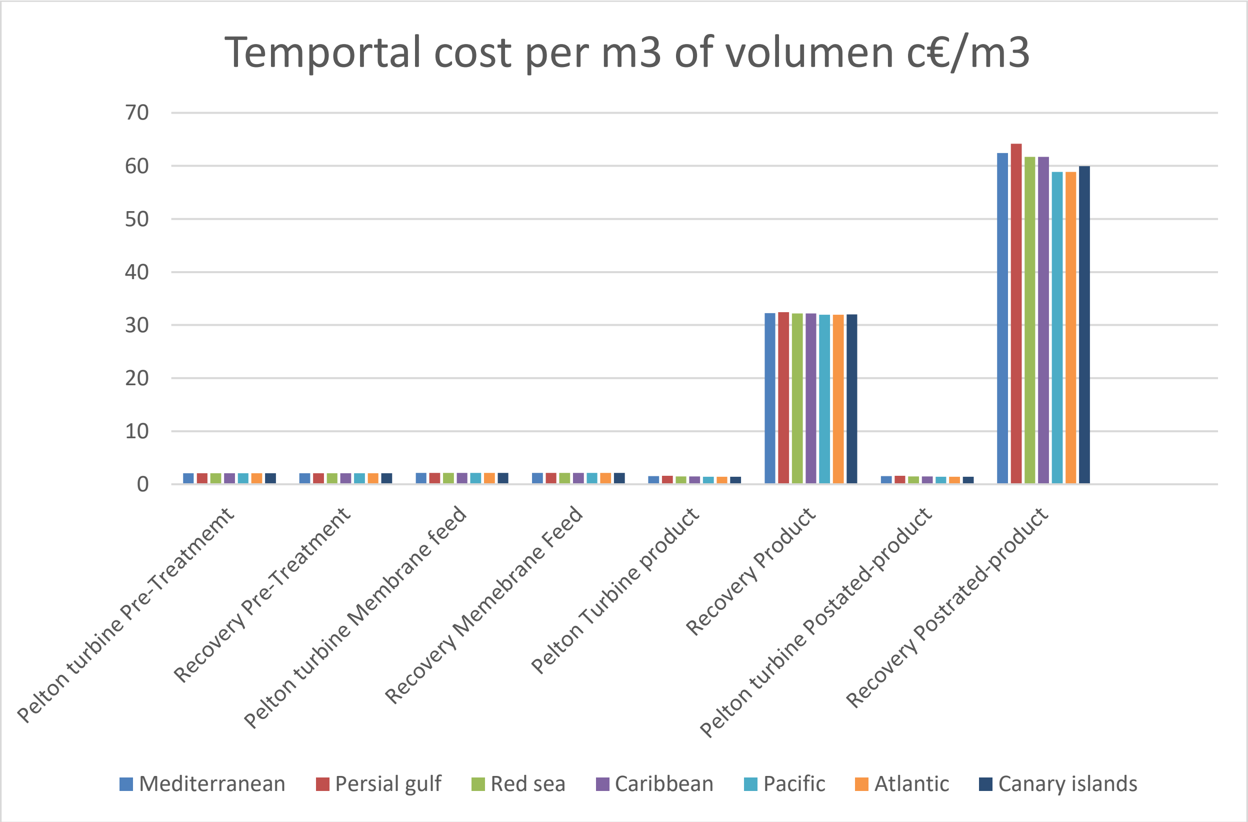


Figure 35. Modernization analysis

6.5 Operating pressure

An analysis of how operating pressure would affect plant energy and plant costs will be carried out.

Taking as reference a base desalination process with the following characteristics:

- Flow 48.6 m3/h

-Specific intake consumption 0.6

- Specific distribution consumption 0.5

-Specific post-treatment specific consumption 0.7

The operating pressure at which the analysis is to be carried out varies from 50 to 70 bar, and the results are as follows

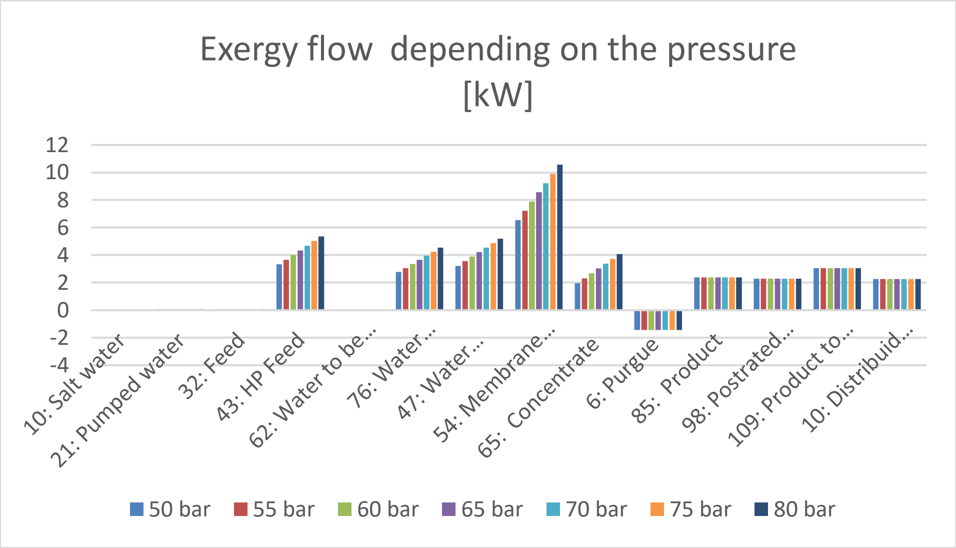


Figure 36. Exergy flows

As can be seen in the Figure 36 the exergy values are directly proportional to the operating pressure, at the membrane outlet the values remain constant because these values have been kept fixed for both the concentration and the pressure at the membrane outlet.

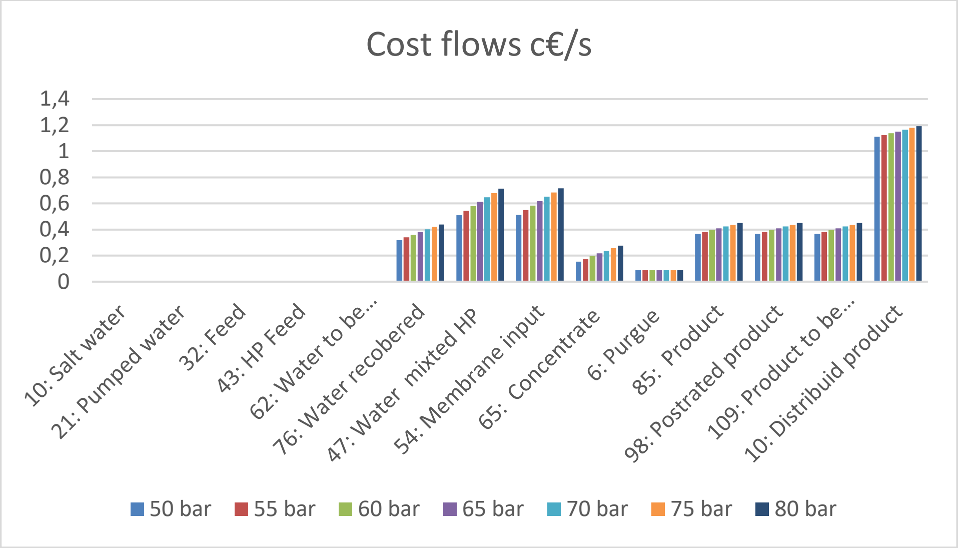


Figure 37.Cost flows

As can be seen in the Figure 37, the cost is directly proportional to the pressure, this is because the economic analysis takes into account the consumption of the pumps and as the operating pressure rises, the consumption of the pumps increases.

It can also be seen that the cost of the distributed product is higher since the costs are analyzed cumulatively and the generation of these costs makes the cost of the distributed product higher.

6.6 Energy recovery

It is also possible to perform an analysis of how the desired plant recovery affects the process operation, and an analysis will be performed with the following reference configuration:

- Flow 48.6 m^3/h

-Pressure 60 bar

-Specific intake consumption 0.6

- Specific distribution consumption 0.5

Specific post-treatment specific consumption 0.7

Recovery values range from 30% to 50% recovery.

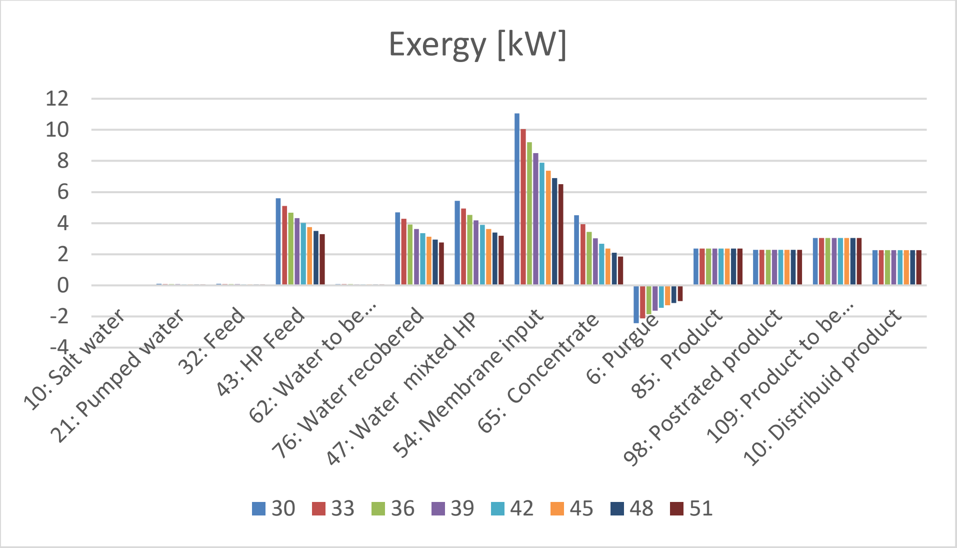


Figure 38.Exergy

As can be seen, the value of the recovery percentage is inversely proportional to the flow exergy, this is due to the fact that the lower the recovery percentage, the higher the salt concentration at the outlet and the lower the recovery. Since the characteristics of the water at the outlet of the membrane are fixed, this does not change at the outlet of the plant.

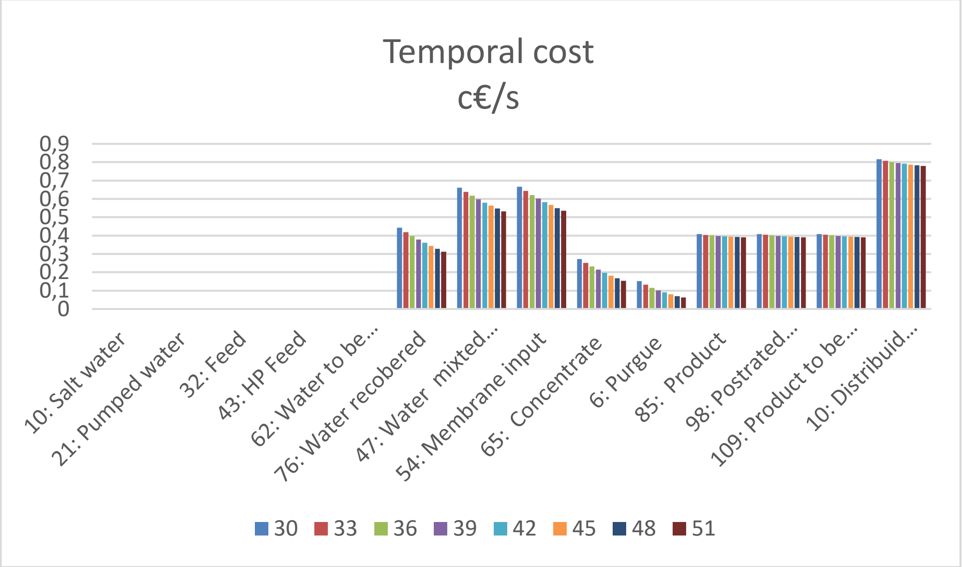


Figure 39. Temporal cost

In the same way that has been done to analyze how this affects the exergy, we will analyze how this affects the time cost of each of the flows in which it can be seen that the behavior is similar and that the lower the recovery percentage, the higher the costs, since these costs are directly proportional to the exergy of each of the flows.

7 OTHER DESALINATION CONFIGURATIONS

Once the tool created to carry out numerous studies has been analysed in general terms, changing the location and characteristics necessary to study a desalination process.

Moreover, as future work other configuration of desalination systems could be implemented in future versions of this tool. With this objective, the literature was reviewed in order to find potential configurations [17][18].

7.1 Multi-Stage RO

Multi-Stage configuration use the output concentrated from the previous step as an input for the other stages.

The pressure of the inputs for the second and successive steps needs to be increased using a low-pressure pump. It is commune also to have different kind of membranes in order to improve the quantity of concentrated [5]. One of the disadvantages of the multiple stages is the number of membranes and pumps needed, so the invesment cost are high[19].

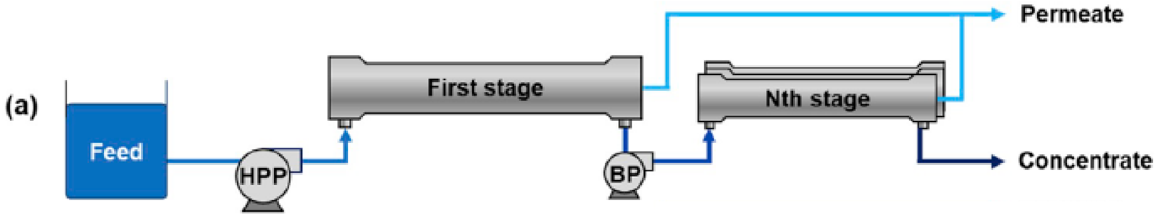


Figure 40. Multi-Stage RO [5]

7.2 Doble-Stage RO

As a solution of the inversion cost that the multi-stage implies, an intermediated solution is taken in order to provide similar values of percentage recovered and also reducing the inversion cost, the solution is double stage instead of using numerous stages, only a second step is used. Also is it possible to include an energy recovery system located at the exit of the second step. The percentage of recovery achieve can be higher than 50%.

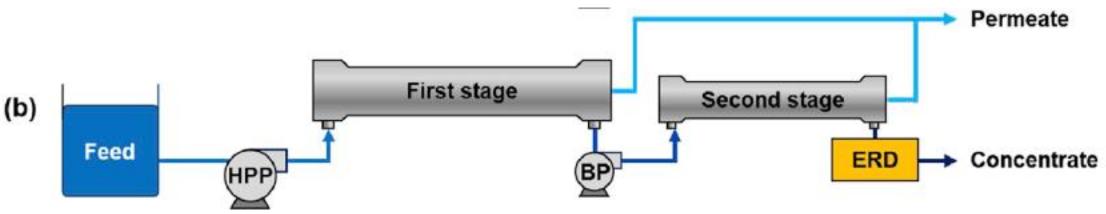


Figure 41. Doble step RO [5]

7.3 Second Stage LMS

Adding the second step produces more permeated by treating the concentrate from the first stage. As a solution to this problem a LMS (Low-Pressure Multi-staged System) system has been invented, the main difference between an LMS system and a conventional one, is that the LMS system is composed by a first stage with two to four elements of RO membranes and the second stage contain more than four elements. Is estimated that the LMS will reduce the specific consumption on a specific ant around a 20 % the consumption due to his high recovery.

One of the main disadvantages of the LMS is that this kind of membrane increase the capital cost, an the output is in high pressure too, in order to solve this problems recovery systems are installed at the exit of the LMS turbine in order to recuperate as much as possible the high pressure and with this recovery system also save the consumption that three high pressure pumps need to consume.

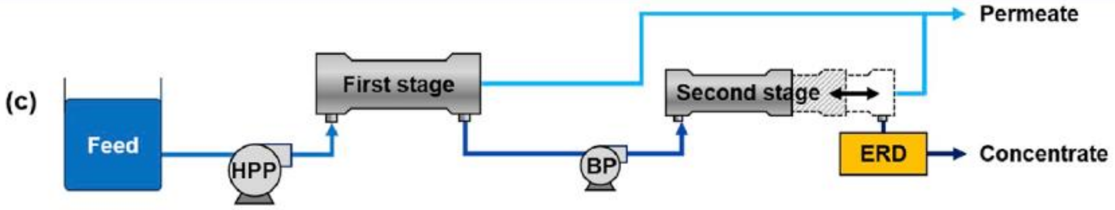


Figure 42. LMS Second step

7.4 Semi-bach load RO

In order to solve the installation problems with the multi-stage RO-RO (Reverse Osmosis), a new desalination configuration is proposed, the closed-circuit desalination, this closed-circuit desalination recircles the concentrate and mix it with the feed and the concentrated is continuously being recirculated. This configuration has several advantages over the conventional RO system, as for example reduce the energy consumption, high product is recovered and have high resistance to fouling.

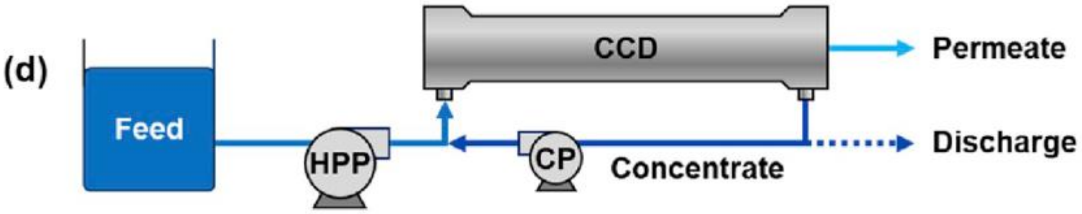


Figure 43. Closed circuit desalination (CCD) Configuration

7.5 Bach RO

The batch RO concept relies on the full batch proposed but instead of having a feed tank with a constant volume, it has one with variable volume that allows minimising the irreversible work due to the hydraulic pressure is increased.

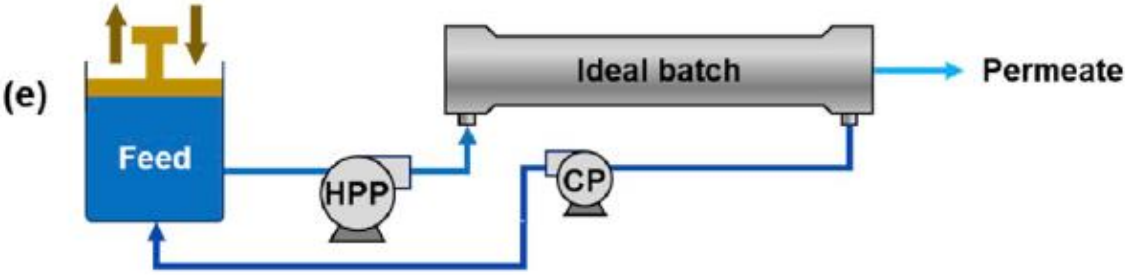


Figure 44. Ideal bach load

7.6 Bach with recuperation

In order to improve the ideal batch, an energy recovery is located at the exit of the membrane rack, with that a lot of energy is recovered and the consumption of the plant is lower .

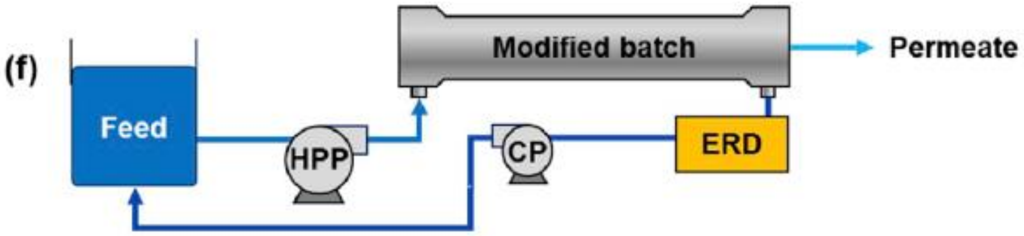


Figure 45. Modified batch

8 BRINE

One of the disadvantage of desalination process is the generation of brine, due to this flow has a high concentration and its discharge to the sea could generate significant environmental problems, for that reason there are numerous projects which study what is the best way to manage the brine and also how this can have the less side effect in the environment as possible[20].

8.1 Current status

Current global brine production stands at 141.5 million m3/day, totalling 51.7 billion m3/year. This value is approximately 50% greater than the total volume of desalinated water produced globally.
Global brine production is concentrated in the Middle East and North Africa, which produces almost 100 million m3/day of brine, accounting for 70.3% of global brine production. This value is approximately double the volume of desalinated water produced, indicating that desalination plants in this region operate at an (very low) average water recovery.

The countries that produce a large volume of concentrated are in the middle East and North Africa, and South-East Asia as it is possible to see in the Figure 46.

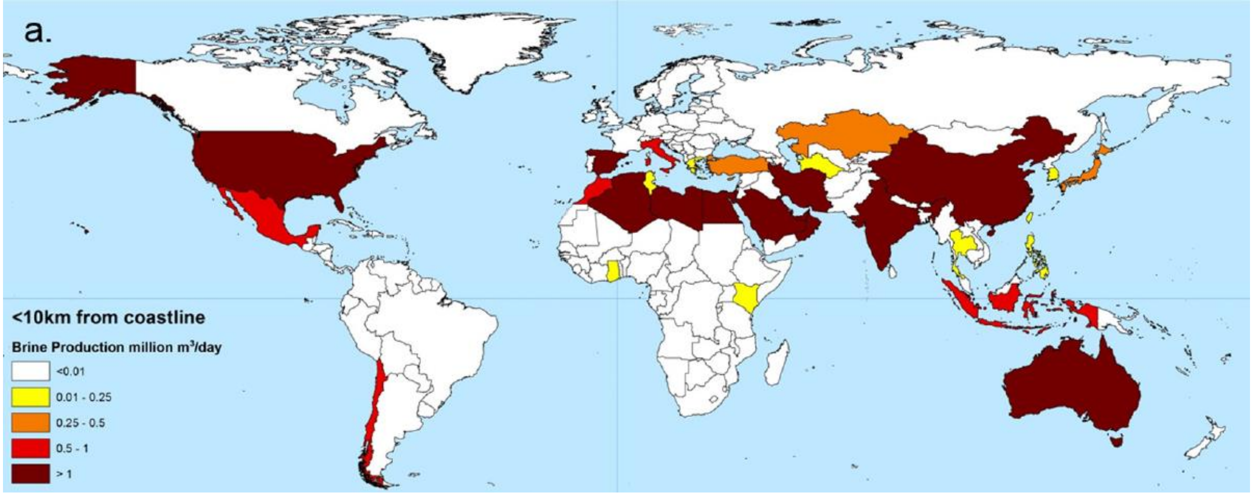


Figure 46. Brine production map in the distance lower than 10 km

Due to the high production of brine, the disposal of this brine could create some environmental problems, and despite the high production of brine there are very few economically viable and environmentally sound brine management option exist.

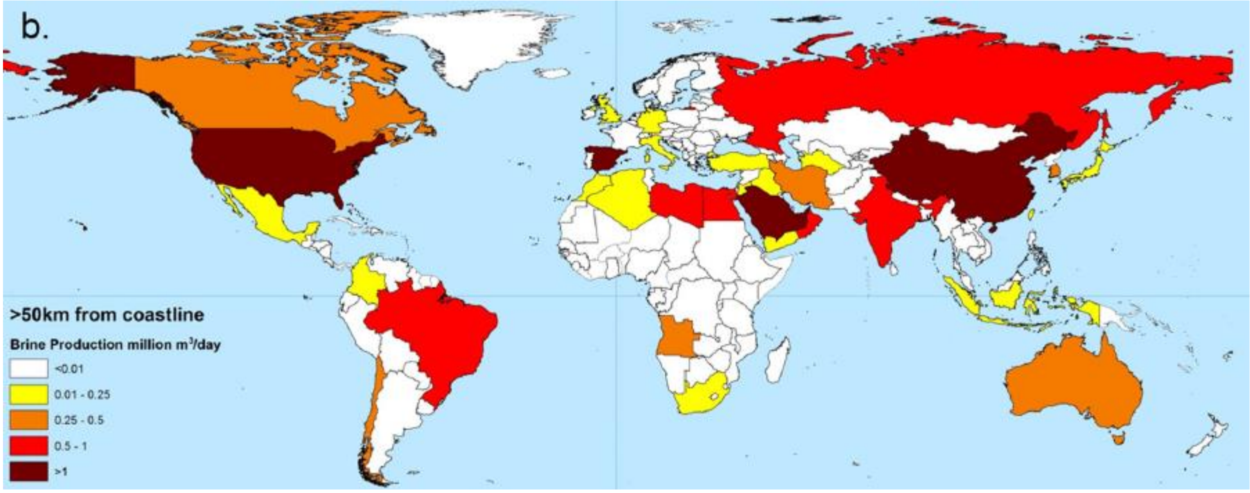


Figure 47. Brine production map in the distance lower than 50 km

8.2. Brine separation methods

In order to avoid the adverse effects of brine rejection, engineers and scientists are frequently focusing on brine concentration and zero liquid discharge (ZLD) processes. The main process are [21]:

8.2.1 Electrochemical processes

Membrane electrolysis uses an ion-exchange membrane to separate the cathode and anode in order to extract mineral from brine.

In electrolysis, the precipitation process covers the active area of electrodes, resulting in an increase in resistance. It decreases electrolysis performance and increases energy consumption.

8.2.2 Physiochemical driven processes

Adsorption/desorption and precipitation are the most common physiochemical techniques used for mineral mining from brine. The precipitation technique utilizes the degree of supersaturation to precipitate and separate/recover the minerals selectively. Also, the precipitation can be achieved chemically (chemical precipitation), in which the soluble metal component in a solution is reacted with a precipitating agent and converted into an insoluble solid.

As an example, obtaining sufficiently pure products is the main limiting factor in the carbonation process to recover the ions in the carbonates and bicarbonates.

8.2.3 Thermal driven techniques

The most common thermal-driven techniques reported in the literature are multi-effect distillation (MED), multi-stage flash (MSF) distillation, membrane distillation (MD) and adsorption desalination (AD)

In industrial applications, relatively low permeate flux, polarization-induced flux reductions, pore wetting and fouling of the membrane, and high operational and maintenance costs are the main obstacles preventing the widespread use of MDC.

8.2.4 Pressure driven techniques

In pressure-driven techniques, nanofiltration (NF) exhibited good potential for resource recovery from brine.

NF process is affected by the Donnan and Steric effects, making NF less economical for ion recovery due to its high resistance to mass transfer. In addition, membrane fouling, low selectivity, and low permeability are factors that impede the achievement of high ion recovery performance.[22]

Seawater and seawater desalination brine can be naturally evaporated using the sun's energy, resulting in a concentrated salt solution. As a result, salt crystallization occurs when the salts reach their saturation points. For thousands of years, many parts of the world have used this method to extract salt from seawater.

8.3. Brine concentrated future

The global desalination demand by 2050 is estimated to be in the range of (1700–4400)·106 m3/ day, compared to the 40·106 m3/day installed capacity in 2015[23], [24]

The brine volumes on a regional level for the future scenario in 2050 are presented Figure 48. The largest amounts of brine are found at the coasts of Pakistan, China, the United States, Iran, India, Ukraine and Moldova, Saudi Arabia, and Russia. The 2050 theoretical potential of Li and Mg in desalination brines for the IEP scenario. [23]

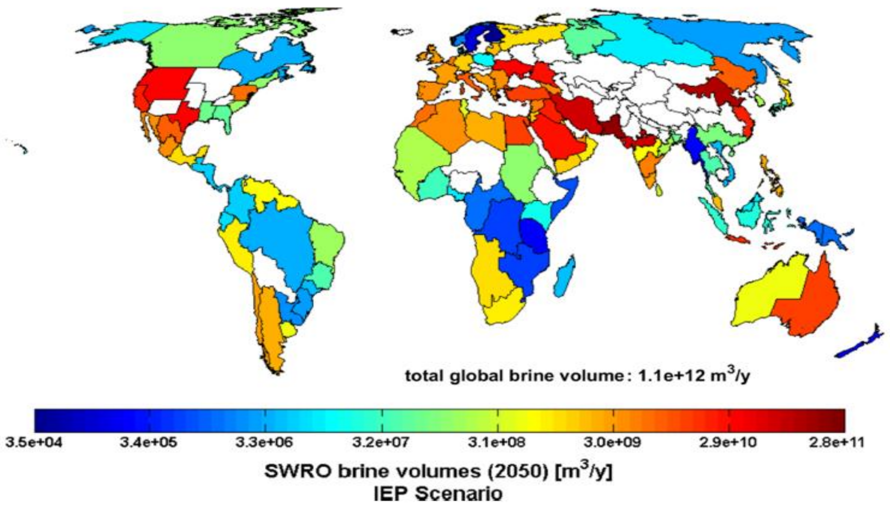
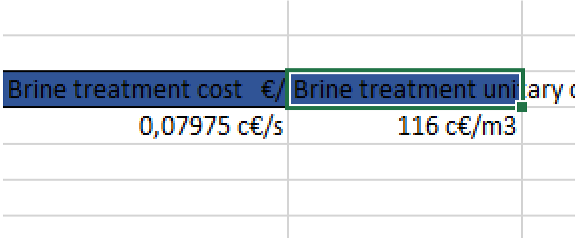


Figure 48. Global seawater reverse osmosis (SWRO) brine production for the irrigation efficiency push (IEP) scenario in 2050.

8.4 Brine cost tool

The tool will include the possibility of analyzing the cost of the dumping , taking this value as an output, as shown in the Figure 49, numerous studies have been made in order to prove that is possible to treat the brine with a huge variety of technique, and in order to validate economically the [25]



Brine treatment cost €/	Brine treatment uni
0,07975 c€/s	116 c€/m3

Figure 49. Brine treatment cost calculator

Knowing the unit cost of the concentrate treatment, an analysis will be made of the cost of the concentrate treatment depending on the percentage of recovery of the concentrate see Figure 50, as this percentage of recovery will directly affect the flow of concentrate generated, as can be seen in the graph, the higher the percentage of recovery, the lower the cost of the concentrate treatment, this is due to the flow of concentrate generated.

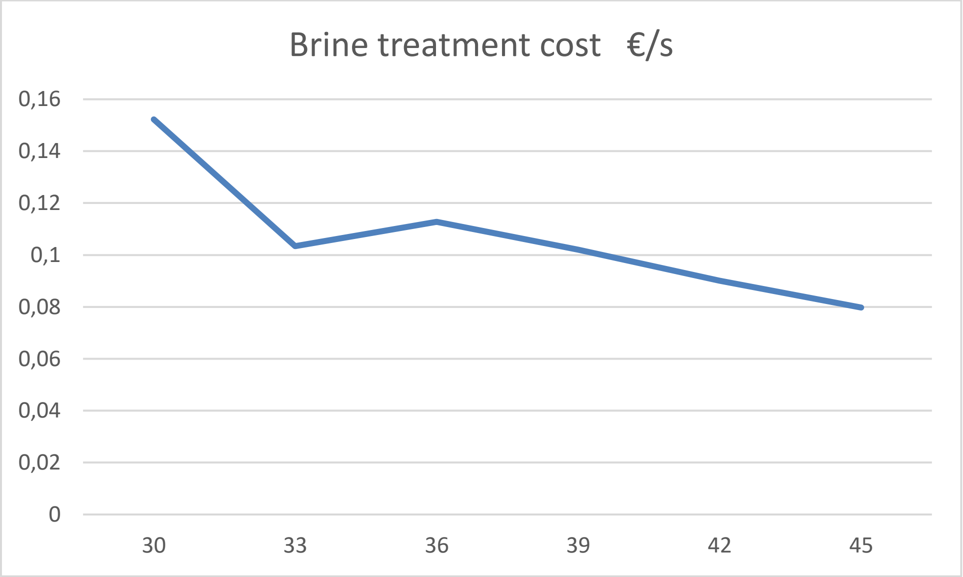


Figure 50. Brine treatment cost per recovery percentage

9 CONCLUSIONS

In conclusion, the objectives of this project have been achieved, since the thermos-economic tool created allows an analysis of a desalination plant in multiple locations, having in each of them the environmental characteristics of seawater that enable to carry out the thermodynamic analysis. In the same way, the tool also allows an economic analysis reverse osmosis plant as it has an economic analysis with updated costs for 2022.

Additionally, having the tool capable of performing exergy and economic analysis, a thermo-economic analysis is carried out on a typical plant to see how the environmental conditions of the location affect the operation and cost of the plant.

Additionally, a literature survey on desalination configurations and problems associated to brine discharge was conducted:

- An analysis has been performed on the different configurations of existing plants and future forecasts that could be included in the tool when they are commercially available.
- The current and future state of concentrate production and the different concentrate separation methods have been reviewed, so that in the future, thanks to the tool created, the characteristics of the concentrate can be analyzed in order to carry out feasibility analyses of its separation methods.

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ANNEX 1

```
Function hsw(t, Sg, P, hsw0, P0)

hsw = hsw0 + (P - P0) * (996.7767 - 3.2406 * t + 0.0127 * (t ^ 2) - (4.7723 * 10 ^ -5) * (t ^ 3) + Sg * (-1.1748 + 0.01169 * t - (2.6185 * 10 ^ -5) * (t ^ 2) + (7.0661 * 10 ^ -8) * (t ^ 3)))

End Function


Function hsw0(t, S, hw)

hsw0 = hw - S * ((-2.34825 * 10 ^ 4) + (3.15183 * 10 ^ 5) * S + (2.80269 * 10 ^ 6) * (S ^ 2) - (1.44606 * 10 ^ 7) * (S ^ 3) + (7.82607 * 10 ^ 3) * t - (4.41733 * 10) * (t ^ 2) + (2.1394 * 10 ^ -1) * (t ^ 3) - (1.99108 * 10 ^ 4) * S * t + (2.77846 * 10 ^ 4) * (S ^ 2) * t + 9.72801 * 10 * S * (t ^ 2))

End Function


Function hw(t)

hw = 141.355 + 4202.07 * t - 0.535 * (t ^ 2) + 0.004 * (t ^ 3)


End Function


Function ssw(ssw0, P, P0, t, Sg)

ssw = ssw0 + (P - P0) * ((-4.4787 * 10 ^ -3) - (1.1656 * 10 ^ -2) * t + (6.1154 * 10 ^ -5) * (t ^ 2) - (2.0696 * 10 ^ -7) * (t ^ 3) + Sg * ((-1.5531 * 10 ^ -3) + (4.0054 * 10 ^ -5) * t - (1.419 * 10 ^ -7) * (t ^ 2) + (3.3142 * 10 ^ -10) * (t ^ 3)))

End Function


Function ssw0(sw, S, t)

ssw0 = sw - S(-4.231 * 10 ^ 2 + (1.463 * 10 ^ 4) * S - (9.88 * 10 ^ 4) * (S ^ 2) + (3.095 * 10 ^ 5) * (S ^ 3) + 2.562 * 10 * t - (1.443 * 10 ^ -1) * (t ^ 2) + (5.879 * 10 ^ -4) * (t ^ 3) - (6.11 * 10) * S * t + 8.041 * 10 * (S ^ 2) * t + (3.035 * 10 ^ -1) * S * (t ^ 2))

End Function


Function sw(t)

sw = 0.1543 + 15.383 * t - (2.996 * 10 ^ -2) * (t ^ 2) + (8.193 * 10 ^ -5) * (t ^ 3) - (1.37 * 10 ^ -7) * (t ^ 4)

End Function
```

```
Function cpsw(cpsw0, P, P0, t, Sg)
cpsw = cpsw0 + (P - P0) * (-3.118 + 0.0157 * t + (5.1014 * 10 ^ -5) * (t ^ 2) - (1.0302 * 10 ^ -6) * (t ^ 3) + Sg
* (0.0107 - (3.9716 * 10 ^ -5) * t + (3.2088 * 10 ^ -8) * (t ^ 2) + (1.10119 * 10 ^ -9) * (t ^ 3)))
End Function

Function cpsw0(Sg, t)
cpsw0 = (5328 - 9.76 * 10 * Sg + (4.04 * 10 ^ -1) * (Sg ^ 2)) + (-6.913 + (7.351 * 10 ^ -1) * Sg + (3.15 * 10 ^ -
3) * (Sg ^ 2)) * (t + 273.15) + ((9.6 * 10 ^ -3) - (1.927 * 10 ^ -3) * Sg + (8.23 * 10 ^ -6) * (Sg ^ 2)) * ((t + 273.15)
^ 2) + ((2.5 * 10 ^ -6) + (1.666 * 10 ^ -6) * Sg - (7.125 * 10 ^ -9) * (Sg ^ 2) * ((t + 273.15) ^ 3))
End Function

Function wbomba(qv, pf, pamb, rendbom, rendmotor, cesp)
wbomba = ((qv / 3600) * ((pf - pamb) * cesp * 100) / (rendbom * rendmotor))
End Function

Function wturbina(qv, pe, ps, rentur, rendmotor)
wturbina = ((qv / 3600) * ((pe - ps) * 100)) * rentur * rendmotor
End Function

Function exergia(hw, hwo, t, sw, swo)
exergia = (hw - hwo) - (t + 273.15) * (sw - swo)
End Function

Function Hwpura(t)
Hwpura = 141.355 + 4202.07 * t - 0.535 * (t ^ 2) + 0.004 * (t ^ 3)


End Function

Function SWpura(t)
SWpura = 0.1543 + 15.383 * t - (2.996 * 10 ^ -2) * (t ^ 2) + (8.193 * 10 ^ -5) * (t ^ 3) - (1.37 * 10 ^ -7) * (t ^ 4)
End Function

Function densidadwpura(t)
densidadwpura = 9.999 * 10 ^ 2 + (2.034 * 10 ^ -2) * t - (6.162 * 10 ^ -3) * (t ^ 2) + (2.261 * 10 ^ -5) * (t ^ 3) -
(4.657 * 10 ^ -8) * (t ^ 4)
End Function
```

```
Function Hwsalada(hw, S, t)

Hwsalada = hw - S * ((-2.348 * 10 ^ 4) + (3.152 * 10 ^ 5) * S + (2.803 * 10 ^ 6) * (S ^ 2) - (1.446 * 10 ^ 7) * (S ^ 3) + (7.826 * 10 ^ 3) * t - (4.417 * 10 ^ 1) * (t ^ 2) + (2.139 * 10 ^ -1) * (t ^ 3) - (1.991 * 10 ^ 4) * S * t + (2.778 * 10 ^ 4) * (S ^ 2) * t + (9.728 * 10) * S * (t ^ 2))

End Function



Function Swsalada(sw, S, t)

Swsalada = sw - S * ((-4.231 * 10 ^ 2) + (1.463 * 10 ^ 3) * S - (9.88 * 10 ^ 4) * (S ^ 2) + (3.095 * 10 ^ 5) * (S ^ 3) + (2.562 * 10 ^ 1) * t - (1.443 * 10 ^ -1) * (t ^ 2) + (5.879 * 10 ^ -4) * (t ^ 3) - (6.111 * 10 ^ 1) * S * t + (8.041 * 10) * (S ^ 2) * t + (3.05 * 10 ^ -1) * (t ^ 2) * S)

End Function



Function densidadwsalada(t, S)

densidadwsalada = 9.999 * 10 ^ 2 + (2.034 * 10 ^ -2) * t - (6.162 * 10 ^ -3) * (t ^ 2) + (2.261 * 10 ^ -5) * (t ^ 3) - (4.657 * 10 ^ -8) * (t ^ 4) + (8.02 * 10 ^ 2) * S - (2.001) * S * t + (1.677 * 10 ^ -2) * S * (t ^ 2) - (3.06 * 10 ^ -5) * S * (t ^ 3) - (1.613 * 10 ^ -5) * (S ^ 2) * (t ^ 2)

End Function


Private Sub CheckBox1_Click()

If CheckBox1 = False Then

Worksheets("Modernización cambios TFM").Range("AC4") = 0

End If

End Sub


Private Sub CheckBox2_Click()

If CheckBox2 = False Then

Worksheets("Modernización cambios TFM").Range("C45") = 0

End If

End Sub


Private Sub CheckBox3_Click()

If CheckBox3 = False Then

Worksheets("Modernización cambios TFM").Range("AC7") = 0

End If

End Sub
```

```
Private Sub ComboBox1_Click()
Worksheets("Modernización cambios TFM").Range("B8").Value = ComboBox1.Value
End Sub

Private Sub ComboBox1_DropButtonClick()

End Sub

Private Sub ComboBox2_Change()

End Sub

Private Sub ComboBox2_Click()
Worksheets("Modernización cambios TFM").Range("B10").Value = ComboBox2.Value
End Sub

Private Sub Flow_Click()

End Sub

Private Sub Label2_Click()

End Sub

Private Sub Label3_Click()

End Sub

Private Sub Location_Click()

End Sub

Private Sub Posttratment_Click()
If Posttratment = True Then
Worksheets("Modernización cambios TFM").Range("V17") = 1
Else
Worksheets("Modernización cambios TFM").Range("V17") = 0
End If
```

```
End Sub

Private Sub Pretratment_Click()
If Pretratment = True Then
Worksheets("Modernización cambios TFM").Range("V16") = 1
Else
Worksheets("Modernización cambios TFM").Range("V16") = 0
End If
End Sub

Private Sub SPEdistrb_Click()

End Sub

Private Sub SPEintake_Click()

End Sub

Private Sub SPEposttreat_Click()

End Sub

Private Sub TextBox1_Change()
Worksheets("Modernización cambios TFM").Range("B9").Value = TextBox1.Value

End Sub

Private Sub TextBox2_Change()
Worksheets("Modernización cambios TFM").Range("V7").Value = TextBox2.Value / 100
End Sub

Private Sub TextBox4_Change()
Worksheets("Modernización cambios TFM").Range("V14").Value = TextBox4.Value
End Sub

Private Sub TextBox5_Change()
```

```
Worksheets("Modernización cambios TFM").Range("V15").Value = TextBox5.Value
End Sub

Private Sub TextBox6_Change()
Worksheets("Modernización cambios TFM").Range("V13").Value = TextBox6.Value
End Sub

Private Sub UserForm_Click()

End Sub

Private Sub UserForm_Initialize()
ComboBox1.AddItem "Mediterranean"
ComboBox1.AddItem "Persian gulf"
ComboBox1.AddItem "Read Sea"
ComboBox1.AddItem "Caribbean"
ComboBox1.AddItem "Pacific"
ComboBox1.AddItem "Atlantic"
ComboBox1.AddItem "Canary islands"
ComboBox2.AddItem "Pelton turbine"
ComboBox2.AddItem "Energy recovery"
End Sub
```

Anex II

Lo primero que hay que hacer al realizar un análisis termoeconómico es determinar cuáles son los productos, fueles, pérdidas y destrucción de exergía, para todos los equipos.

Suponiendo que el sistema funciona de forma estacionaria, y que se conocen las características termodinámicas de cada uno de los flujos. Es importante caracterizar los costes exergéticos temporales.

Los costes exergéticos temporales vienen dados por la siguiente fórmula:

$$\dot{C}\iota = ci \cdot Ei.$$

Siendo el significado de los términos los siguientes:

$\dot{C}\iota$ Es el coste exergético temporal de la corriente i [€/tiempo]

Ci Es el coste exergético unitario de la corriente i [€/unidad exergética]

$\dot{E}\iota$ Potencia exergética de la corriente i [exergía/tiempo], obtenida mediante análisis termodinámico

Balance exergético contable:

$$C\dot{s}, k = C\dot{e}, k + \dot{Z}k$$

$C\dot{s}, k$ Coste exergético temporal de las salidas

$C\dot{e}, k$ Coste exergético temporal de las entradas

$\dot{Z}k$ Coste temporal no exergético debido a los costes de operación

Para poder valorar qué porcentaje de coste tiene mayor peso sobre el coste total del funcionamiento del equipo es importante calcular los costes unitarios promedios de fueles y productos.

Los costes unitarios se calculan de la siguiente forma:

$$C^P = \frac{\dot{C}^P}{\dot{E}^P}$$

$$C^F = \frac{\dot{C}^F}{\dot{E}^F}$$

En las ecuaciones anteriores, los superíndices P y F corresponden respectivamente a Producto y Fuel.

Para poder valorar el impacto económico de las medidas a tomar en el ciclo del agua se va a realizar de este modo, calculando los costes unitarios de cada uno de los sistemas a estudiar durante el proyecto.

Del mismo modo se calcula el coste unitario de la exergía destruida (superíndice D):

$$C^D = \frac{\dot{C}^D}{\dot{E}^D}$$

Una vez que se tienen calculados todos los costes temporales unitarios resulta de gran utilidad calcular una serie de variables termoeconómicas para la evaluación del sistema.

Costes no exergético, estos son los costes de capital y los costes de operación y mantenimiento de los equipos, se calculan dividiendo la contribución anual total de estos costes por el número de horas al año que la planta se encuentra en funcionamiento.

$$\dot{Z} = Z^{\dot{C}L} + Z^{\dot{O}M}$$

El coste temporal $\dot{Z}$ se mide en [€/tiempo]

El factor exergoeconómico se define como el cociente de los costes temporales anualizados, es decir, la suma de los costes mantenidos más los costes de operación y mantenimiento y la suma de los de los costes temporales de las exergías destruidas y pérdidas, todo esto valorada al coste exergético unitario promedio de fuel y del producto. Concretamente es la fracción de costes de cada componente frente a los costes de los productos.

Los factores termoeconómicos informan sobre la influencia en el coste capital del producto de aquellos costes, directos u ocultos, imputables a la máquina analizada.

Siendo los factores exergéticos independientes los siguientes:

$$f^F = \frac{C_F}{C_P}$$

$$f^D = \frac{C_D}{C_P}$$

$$f^z = \frac{Z}{C_P}$$

El análisis termoeconómico se basa en estos tres factores exergoeconómicos independientes, también hay otro factor exergoeconómico que es dependiente de los anteriores

$$f^L = \frac{C_L}{C_P}$$

Esto proporciona una forma de comprobar que los cálculos realizados están correctos: $f^L = f^z + f^F - 1$, pudiendo ser alguno de ellos nulo.

El procedimiento está basado en la identificación de las causas de los costes del producto, según los valores de f^F, f^Z y f^D, seguido de la posibilidad de aprovechamiento de exergía pedida mediante su consideración de producto potencial.

2.1 Planteamiento de las ecuaciones y resultados termoeconómicos

Del análisis termoeconómico se obtienen las potencias exergéticas de todas las corrientes y las potencias exergéticas destruidas. Existen una serie de ecuaciones particulares para cada equipo[2], que dependen del equipo a analizar, pero primero es necesario realizar el cálculo de los costes temporales no exergéticos de cada uno de los equipos y posteriormente se analiza componente a componente.

2.1.1 Cálculo de los costes temporales no exergéticos

Los costes no exergéticos son los costes debido a la operación y mantenimiento y los costes mantenidos, se atribuyen a cada uno de los equipos de forma proporcional al coste de adquisición.

$$\dot{Z}_k = \frac{(OM_L + CC_L)}{PEC \cdot FC} \cdot PEC_k$$

Donde los términos que aparecen en la ecuación son los siguientes:

-Z_k Coste temporal no exergético asociado al equipo k

-OM Coste anualizado de operación y mantenimiento de la planta

-CC Coste mantenido

-PEC Coste de adquisición de los equipos

-PEC_K Coste de adquisición del equipo k

- FC Factor de capacidad