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Techno-economic model for desalination plant, supplied by renewable energy.

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Abstract

The problem of desalinized water production in a reverse osmosis plant using energy sourced from renewable sources is addressed in this work.

Using recent historic data for natural energy elements (sun, wind, temperature), different plant configurations are proposed to supply the RO facility and look at minimizing the average cost of a delivered water liter. The process used to calculate the best configurations is described as an iterative semi-optimization, using discrete input data.

Mitigating the investment costs and the needed supply constraint, some configurations emerge from the calculation process to produce desalinized water at costs comparable today's market values. They leverage the benefits of solar and wind production as well as battery and water storages.

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Acronyms

BoS Balance of Systems. 32

CAEC Capex Annual Equivalent Cost. 34

CAPEX Capital Expense. 30

CRF Capital Recovery Factor. 34

ERD Energy Recovery Device. 15

FF WT/PV ratio. 35

HPP High Pressure Pump. 12

kWhe Electrical Kilo Watt hour. 34

LCOE Levelized Cost of Electricity. 25

LCOW Levelized Cost of water. 34

MED Multi Effect Distillation. 9

MLD Millions of Liters per Day. 31

MSF Multistage Flash. 9

N reference case multiplication factor. 35

OPEX Operating Expense. 30

PV Photovoltaic. 16

r discount rate. 34

RO Reverse Osmosis. 9

SWRO Sea Water Reverse Osmosis. 9

TDS Total Dissolved Solids. 31

WGP Water Global Practice. 30

WT Wind Turbine. 16

Symbols

$\Delta P_{norm}[bar]$ Normalized variation of pressure through the membrane.

ΔP Variation of pressure through the membrane.

$T_{wat}[^{\circ}C]$ Water temperature.

$BG[\%]$ PV panels bifacial gain.

$E_{PV}[Wh]$ Electrical energy produced by PV panels.

$A_{PV}[m^2]$ Total area of PV panels.

$G[Wh/m^2]$ Global tilted irradiation.

$AreaPV_{ref}[m^2]$ PV panels area needed for the reference case.

$ConsoRO_{tot}[Wh/year]$ Total energy consumption of the RO plant over 1 year.

$G_{year}[Wh/(m^2 \cdot year)]$ Total irradiation received over 1 year.

$NumberWT_{ref}[-]$ Number of winds turbines needed for the reference case.

$Area_{PV}[m^2]$ Total area of PV panels (calculated in the algorithm).

$Number_{WT}[-]$ Number of winds turbines (calculated in the algorithm).

$ProdWT[Wh]$ Electrical production of one WT Enercon E-92.

$ProdWT_{tot}[Wh/year]$ Total electrical production of one WT Enercon E-92 over 1 year.

$E_{WT}[Wh]$ Electrical production by the wind turbines.

$E_{tot}[Wh]$ Electrical production by the mix PV/WT.

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0.1 Introduction

Water scarcity is currently a problem for part of the world and the number of affected people is likely to increase significantly in the future. Despite this, it is much less covered by the media than other environmental and social problems such as CO_2 emissions and famine. However, half the human population lives in countries that have already experienced severe water scarcity for at least one month during the year. In addition, some studies indicate that by 2030, up to 700 million people living in arid and semi-arid regions could be [1].
There are two different type of water scarcity :

- "Scarcity in availability due to physical shortage".[1]
- "Scarcity in access due to the failure of institutions to ensure a regular supply or due to a lack of adequate infrastructure."[1]

The first one generally occurs in arid or semi arid places, when there is no enough water to meet the needs. The demands come from human consumption, agriculture, industries, cities, etc.
The consumption growth is driven by the general economic development of a region or a country.
The question of sustainable resource management usually arises when it is too late. It has been put forward by studies, that the water use has been growing at more than twice the rate of the population increase in the last century. This phenomenon affects many countries in the world, even the most developed ones.

The second source of scarcity is generally due to a limited financial capital which induce a lack of water infrastructure or a poor management of the resources when the infrastructure is present and there is sufficient water to meet human and environmental needs. It is estimated that about 1.6 billion people face economic water scarcity.[2] [3]

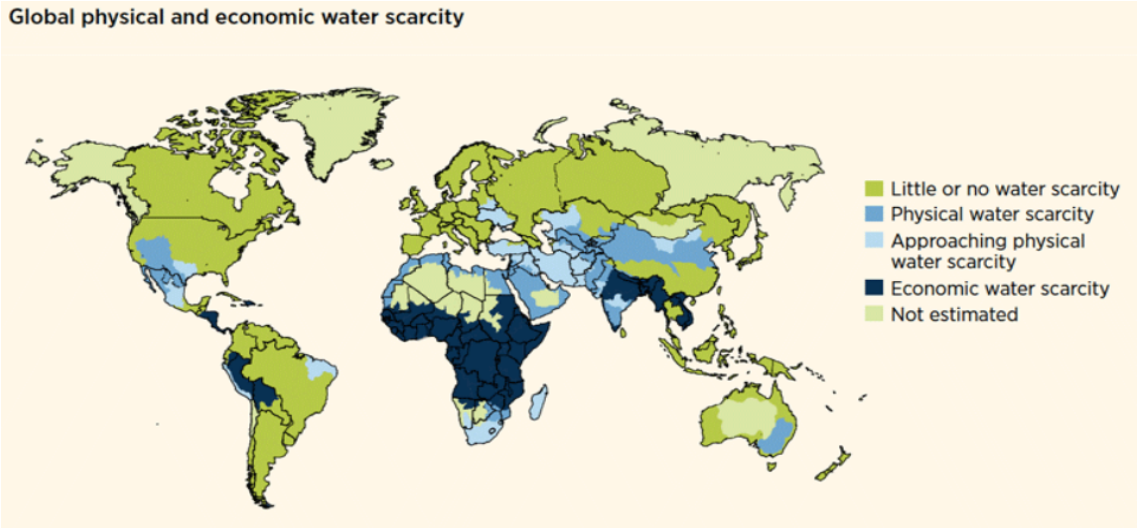


Figure 1: Physical and economical water scarcity in the world[4]

Solutions exists and must be based on three axis : environmental, economic and social, and engineering.

- Adopt an environmental policy to restore or preserve the ecosystems such as wetlands and forests.
- Avoid waste of fresh water from heavy users such as industries and agriculture.
- Making good use of technologies provided by technical advances.

This last point will attract our attention in this report. Different techniques exist to produce drinking water from raw water such as Multi Effect Distillation (MED), Multistage Flash (MSF) and Sea Water Reverse Osmosis (SWRO). In this report, we will focus on the sea water desalination by Reverse Osmosis (RO) technique. This solution has seen its price as well as its energy needs fall sharply in recent years and its use grow, as shown in figure 2. This makes it a process worth investigating.

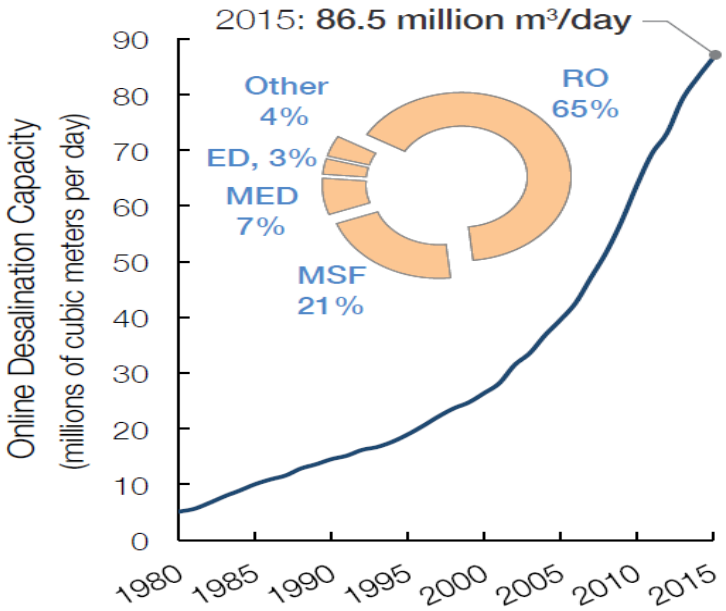


Figure 2: Desalination methods market shares[5]

We note that the growth of this market has been very high for almost 30 years and the reverse osmosis desalination method has done very well because it does not use thermal energy and has a much lower global energy consumption than other methods. A conservative consumption estimate of a large scale (production of water higher than $60000 m^3/day$) SWRO plant can be made at $3.5[kWh_e/m^3]$. This remains significant.
As greenhouse gas emissions are making the problem worse, the next logical step is to identify solutions to make this production of fresh water as environmentally friendly as possible.

Coal	Oil	Natural Gas	Biomass	Solar-PV	Geothermal	Wind	Hydro-electric	Nuclear
Average lifecycle GHG emissions for electricity production[19] (g CO_{2e}/kWh_e)								
1023 **g/kWh_e**	780	606	86	71	67	31	25	14
× 3.5 kWh_e/m^3								
Carbon footprint associated with powering a modern RO plant (g CO_{2e}/m^3)								
3580 **g/m^3**	2729	2121	300	248	233	109	89	49

Figure 3: Average lifecycle GHG emissions for electricity production[5]

As per figure[3], CO2 emissions are largely related to the way the electricity is produced. Knowing that about 66% of the electricity produced in the world come from fossil fuels[5], the question of making the desalination plant cleaner in terms of greenhouse gas emissions becomes interesting to investigate.

Chapter 1

Problem statement

The aim of this thesis is to simulate via different models the stakes and the viability of a reverse osmosis desalination project powered exclusively by renewable energies. The goal is to estimate the final production cost of fresh water. Then, compare these results with the values obtained for plants operating in a more conventional way with a connection to the electricity grid. Different cases will be simulated starting with a constant operation of the plant. Then flexible operation will be introduced to allow a smoother adaptation to renewable energies. In order to obtain the most accurate estimate possible, it was decided to focus on a specific desalination plant project in Dakhla, Morocco. Dakhla is located on the Atlantic coast of Western Sahara and it was possible to use real data for the weather conditions or the mineral composition of the seawater as well as its temperature.

1.1 Process Operation

1.1.1 Osmosis versus Reverse Osmosis

To understand the process of sea water desalination by reverse osmosis, let's look at the naturally occurring phenomenon of osmosis. It is represented on figure 1.1 on the left : when a strong saline solution is in contact with a weaker solution separated by a semi-permeable membrane, the less concentrated solution will have a natural tendency to migrate to a solution with a higher concentration in an attempt to equalize concentrations. The semi-permeable membrane will allow water molecules to pass through but will block other larger molecules such as dissolved salt. We will see a difference in height between the two compartments, in fact, the one initially more concentrated will have received water from the other. This difference is called the osmotic pressure, and depends on the molecule concentration of the initial solution. For example, this phenomenon occurs when kidneys absorb water from blood.[6]
Reverse osmosis is the reverse process, we will apply an external pressure (higher than the osmotic pressure) on the most concentrated compartment and extract the water molecules through the semi-permeable membrane. The highly concentrated compartment on the left is called concentrate or brine, and the one on the right is called permeate.[6]

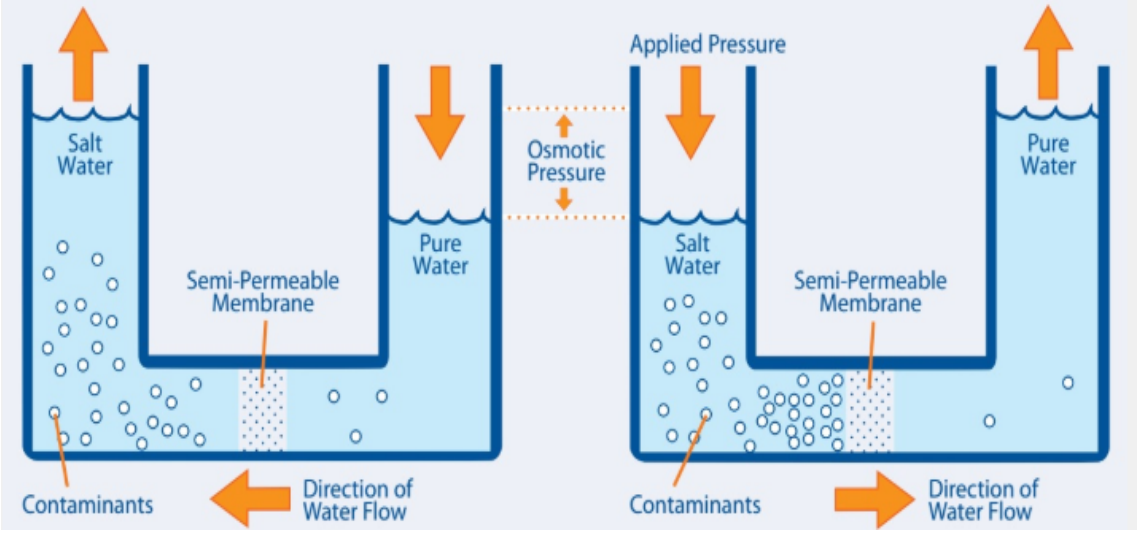


Figure 1.1: Osmosis vs Reverse Osmosis[7]

1.1.2 Complete plant installation

Basic principle

The basic principle of reverse osmosis is illustrated on figure 1.2, a High Pressure Pump (HPP) drives the feed water into the membranes which are cylindrical so the permeate arrive inside the membrane by the cylindrical surface. The brine stays outside and is evacuated.

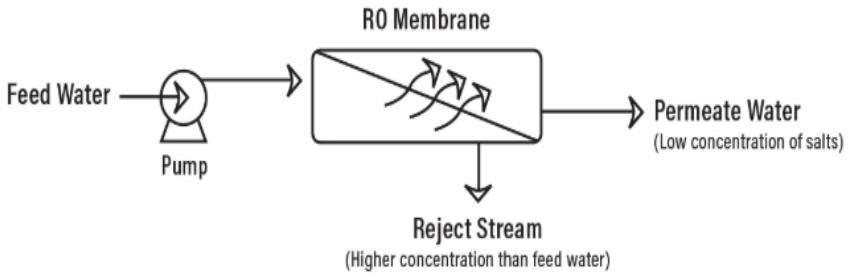


Figure 1.2: Simple diagram of reverse osmosis

Stage and pass

The configuration presented above is relatively simple and in most cases, especially for the production of drink water, the installations are more complex. The terms stage and pass are often confused. The first is represented on the figure 1.3, two stages represent the case where the concentrate from the first pass is recovered and injected into a second membrane to be filtered a second time. This increases the recovery ratio, which is the ratio of permeate to feed water.[6]

$$Recovery = \frac{PermeateFlowRate}{FeedFlowRate}[\%] \tag{1.1}$$

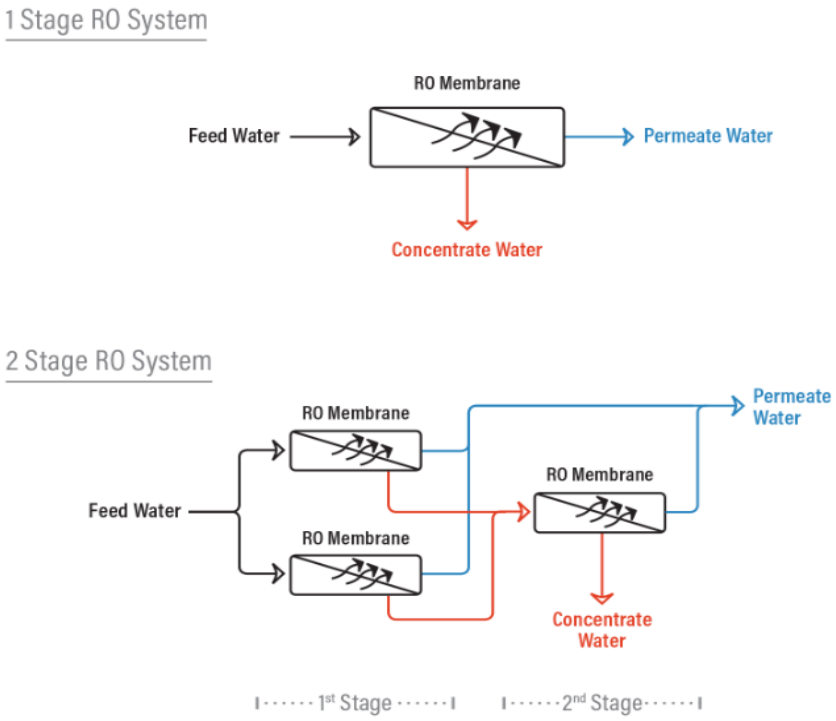


Figure 1.3: 1 stage vs 2 stage

Another case is a system composed of two passes, the difference compared to the two stages is that it is the permeate that will become the feed water for the second pass. This can be seen in figure 1.4, which in reality is an installation with two passes and two stages since the concentrate is also reprocessed before arriving in the second pass. [6]

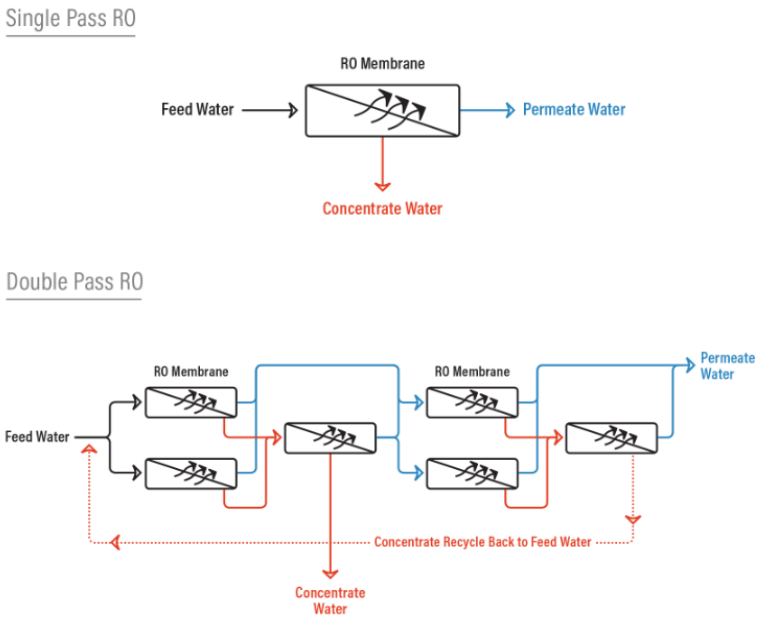


Figure 1.4: 1 pass vs 2 pass

One of the main advantages of this configuration is to remove boric acid(H_3BO_3) from the permeate

between the two passes by injecting caustic to increase the pH. As we can see on figure 1.5, Boron is present in sea water in two different forms : Boric acid (H_3BO_3) in blue and Borate (H_3BO_2-) in pink, the second is less problematic because the membranes are better able to remove it. The pH is therefore increased to around 9.2 to decrease the boric acid fraction and increase the removal of boron from the water.[8]

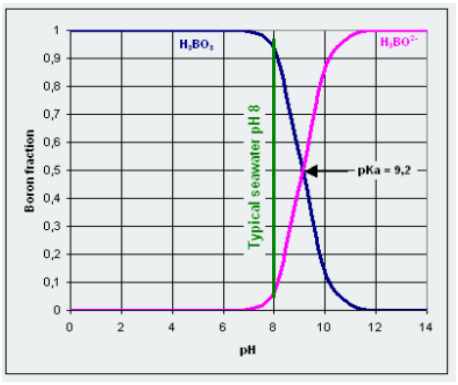


Figure 1.5: Ratio Boric acid/borate in sea water

The maximum level of boron must be less than 1mg/L from UE standards, otherwise it can cause headaches, vomiting and diahrrea on human. It is also very harmful to the plants good development.[8]

Typical plant configuration

The main elements of a reverse osmosis desalination plant can be seen in figure 1.6.

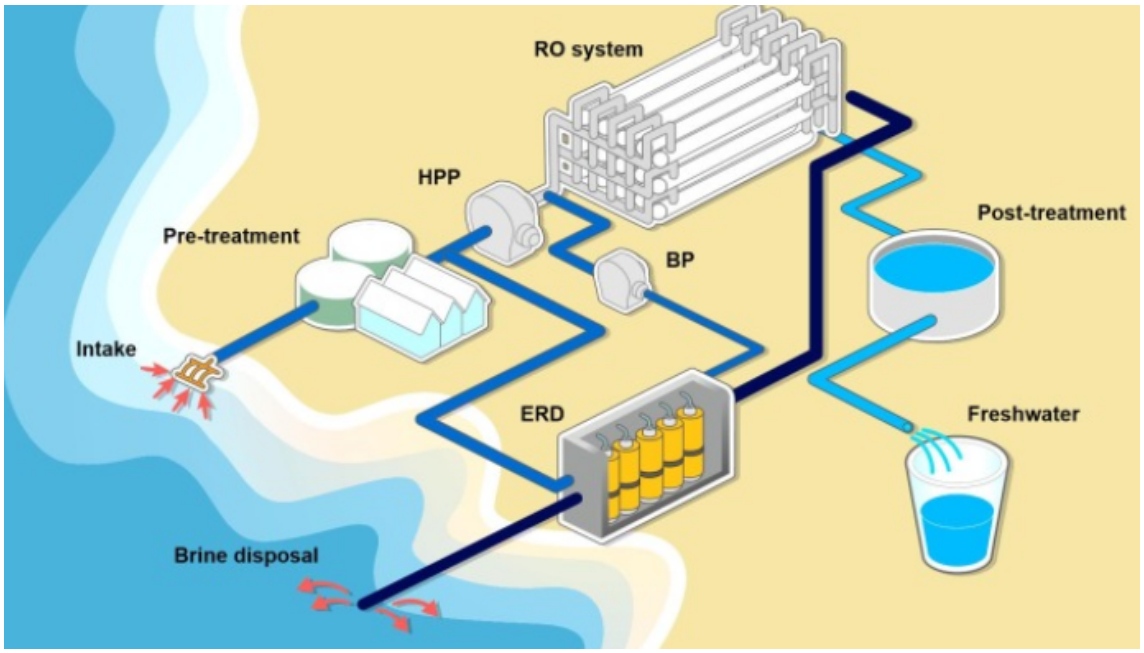


Figure 1.6: SWRO plant configuration

- **Water intake** : There are two types of water intake, the first one is **beach wells intake** which is usually located on the seashore. The water is ducted below the beach. The main advantages of this facility are the relatively low complexity to build, the quality of the water which is pretreated

via slow filtration through the subsurface sand. The main disadvantage is the limited water flow (about 20 000 m^3/day) but there are exceptions such as the Pembroke plant in Malta with a production of 54 000 m^3/day.
The second one is **open surface intakes**, which is a more complex facilities with intake piping of hundreds or even thousands meters into the sea. The quality of the raw water pumped is lower and a pretreatment is required. The pumping capacity is not limited and this facility is therefore generally used for large scale plants.[9]

- **Pre-treatment** : RO membranes are highly sensitive to variations in water quality, temperatures or the presence of algae. Usually both mechanical and chimical pre-treatment is used to prevent fouling, scaling and costly premature RO membrane failure leading to frequent cleaning requirements. Fouling can be caused by particulate matter like dirt, clay or by microorganism such as bacteria. Scaling occurs when certain inorganic dissolved compounds exceed their solubility limits and precipitate on the membrane surface. The main pre-treatment solutions are multimedia filtration, micro or ultra filtration, anti-scalant or sodium bisulfite injection and many more.[10]

- **High pressure pump** : High pressure pumps provide the necessary pressure to push the feed water through the membranes and thus recover the filtered water at the end of the process. Typical values for brackish water are about 16 to 26 bar and 55 to 80 bar for sea water.

- **Reverse osmosis** : As explained before, the type of RO installation depends on the final water use cases. For drinkable water generally two pass RO is used. The recovery ratio varies also with the water salinity and the plant size. For a large scale desalination unit a typical ratio is 40-50% for sea water and 80-90% for brackish water.[11]

- **Energy Recovery Device (ERD)** : In the most modern desalination plants, an energy recovery device is present. The purpose of this device is to minimize electricity consumption by recovering the energy contained in the concentrate. Indeed, the concentrate does not pass through the membrane and therefore undergoes only a slight pressure drop (around 3 bar) compared to what the high-pressure pump supplied.
  One particularly efficient type of pressure exchanger is a rotary pressure exchanger, "the pressure energy is transferred directly from the high pressure stream to the low pressure stream in the ducts of the rotor".[12]

- **Post-treatment** : Sodium chloride and boron presence can be reduced by adding a second pass with brackish or sea water membranes but the concentration of calcium and magnesium is then reduced and close to zero. The water needs to be re-mineralized to be drinkable. For food use it is also necessary to disinfect it, which is not necessarily necessary for irrigation or process water. Finally, liming material is used to adjust pH between 6.8 and 8.1 to meet the potable water specifications.[13]

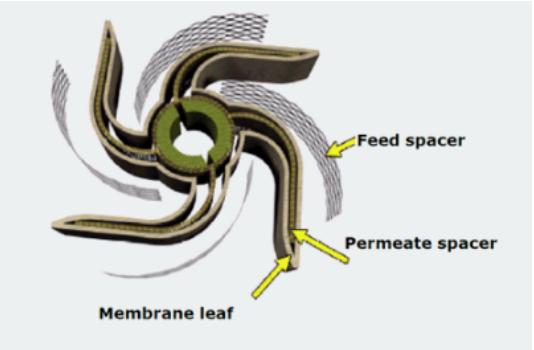
- **Brine disposal** : Brine disposal is an environmental problem that needs to be taken into account to avoid problems on the flora and marine life near the brine outfall pipe. As the disposal has a much higher concentration than the sea water, the salt falls down on the seafloor.
  Three solutions to avoid this problem :

First, **mixing**, it consists of placing the outfall pipe in a zone with strong sea current.
The second one, **diffusion**, consists of having several outlets on the outfall pipe and add on each a nozzle diffuser. This requires a brine pump to have a sufficient pressure.
The last one, **dilution**, is needed when brine discharge limits are applied, the brine is diluted with less concentrated water(river, sea water...) to stay below this limits.[14]

1.1.3 Membranes technologies

The more frequently used membranes are composed of three different layers : a polyester support, a microporous polysulfone interlayer and an ultra thin polyamide barrier layer on the top surface. These form a thin film composite membranes which are packed in a spirally wound configuration.[15]

When the water is fed longitudinally into the pressure vessels in a pressurized condition, part of it will pass radially through the leaf membrane and will be evacuated by the perforated permeate pipe.

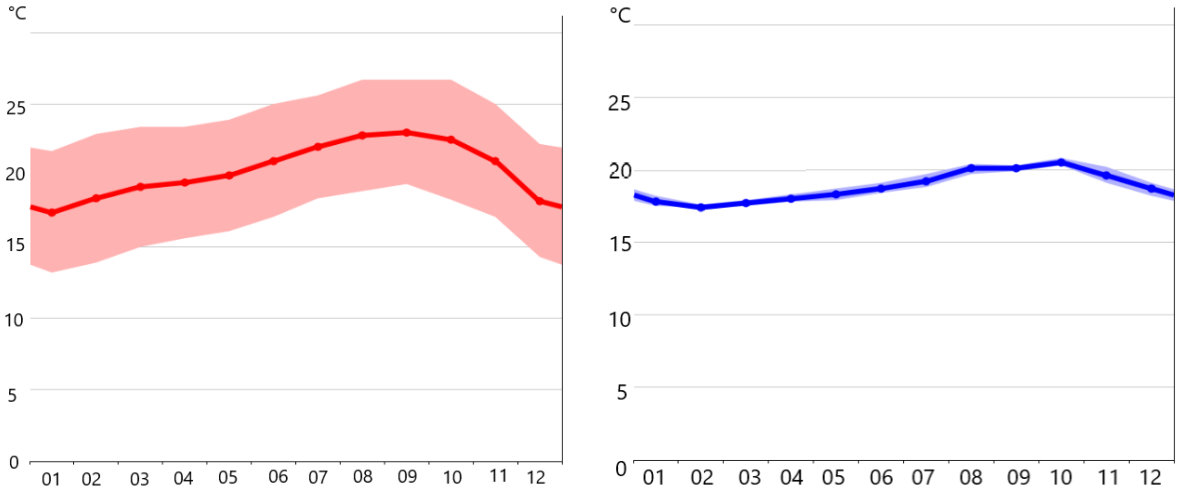


1.2 Case study in Dakhla

To find out the viability of a seawater desalination plant powered by renewable energies, we will look at a special case. The plant will be located in Dakhla in Morocco. Dakhla is a peninsular city, located on the Atlantic coast of the Western Sahara.

1.2.1 Renewable energy resources in Dakhla

As observed on figure 1.7, the average air temperature is relatively constant over the year and does not reach high values, which is good for installations like batteries and Photovoltaic (PV) panels. The average water temperature is quite constant too, it has an influence on the plant consumption because the osmotic pressure varies with temperature.
As we can see on figure 1.8, the wind speed is most of the time between 7-22 knots(13-41km/h) and coming from North. Furthermore, the area around Dakhla is clear of obstacle which is favorable for Wind Turbine (WT).



(a) Monthly average air temperature[16]

(b) Monthly average water temperature[16]

Figure 1.7: Monthly average temperatures

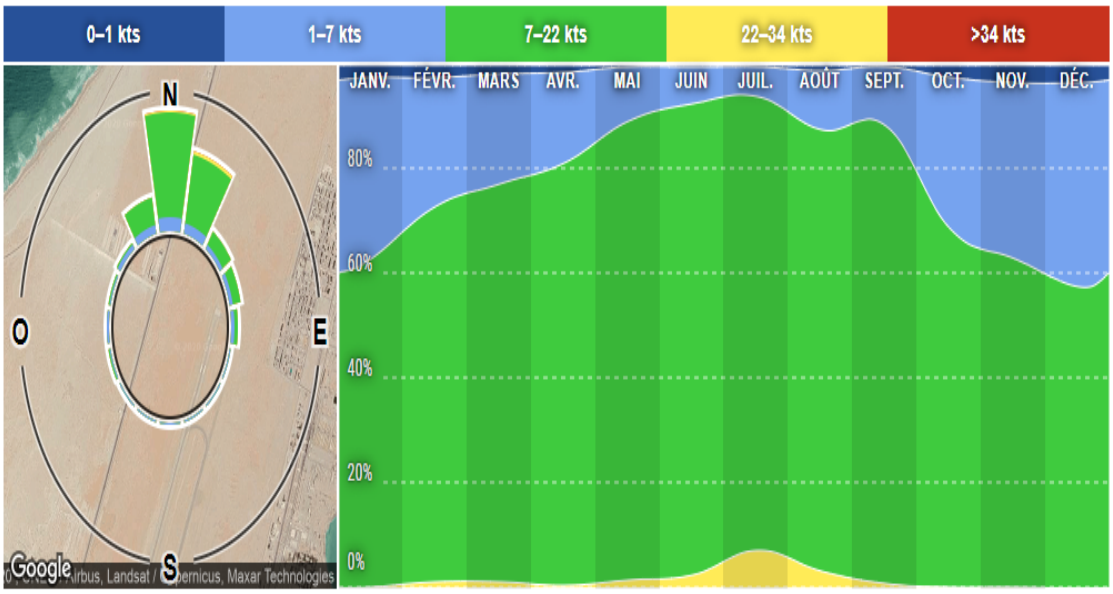


Figure 1.8: Wind speed and direction at Dakhla[17]

The average daily irradiation data on figure 1.9 are expressed in kWh/m^2: they are high, indicating a good potential for PV installation too.

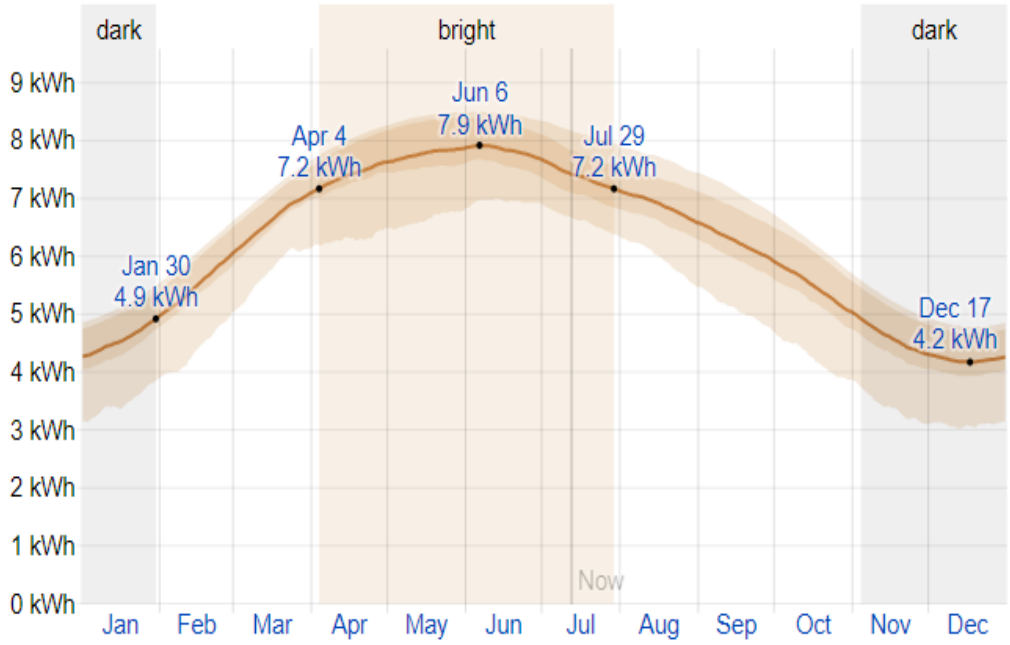


Figure 1.9: Daily average irradiance[18]

The site therefore has a good potential for the installation of wind turbines and PV. On top, there is a lot of free space in the surroundings for the installations, which will reduce space constraints when dimensioning the WT-PV-RO hybrid model.

1.3 Wave model

To model the desalination plant, the Wave software has been used to size the membrane plants and to estimate the energy consumption. It takes as input the configuration plant configuration type, the water parameters to be treated and the size of the installation.
The plant is sized for a constant operation with a water production of 96 000 m^3/day, running on 4 trains in parallel each producing 1000 m^3/h. It will be equipped with ultra-filtration pre-treatment and a single pass for the RO. The recovery ratio is 45%. We considered a flow factor of 0.85 which represents the fouling state of the membrane. A flow factor of 0.6 represents a heavily soiled membrane and 1 represents a clean membrane.
The water ions concentration is presented in table 1.1 :

Ions	K	Na	Mg	Ca	CO_3	HCO_3	Cl	SO_4
Concentration[mg/L]	415.36	12045.45	1453.76	698.84	1.83	135	21860.54	3370.57

Table 1.1: Ions concentrations

In Wave, only one train of the factory has been modeled. The software allows you to obtain several pieces of information such as power consumption, number of modules, etc.

Ultra filtration(pre-treatment)

The installation of ultra filtration is shown on figure 1.10,

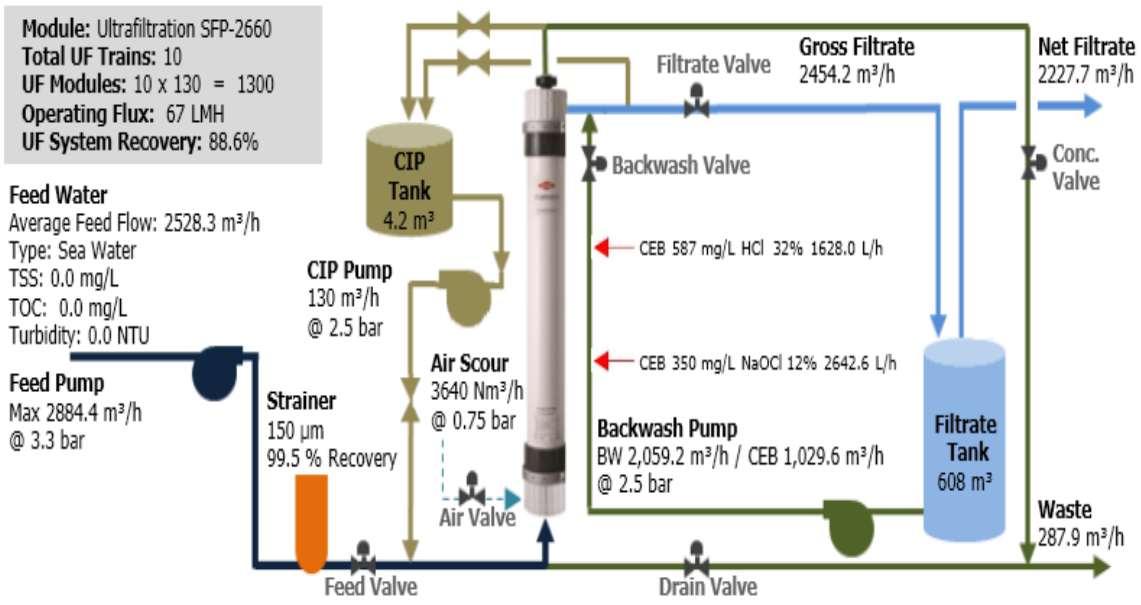


Figure 1.10: Pre treatment installation

It is composed of 10 trains each containing 130 filtration modules, i.e. 1300 modules in total. Its pump is capable of delivering 2884 m^3/h at 3.3 bar. The system operates in intervals of 20 minutes, after which a 2.8 minute backwash is carried out. At nominal operation, the system has a recovery of 88.56% with a feed water flow rate of 2528.3 m^3/h and a net product of 2227.7 m^3/h.

Reverse osmosis

The installation of reverse osmosis is shown on figure 1.11,

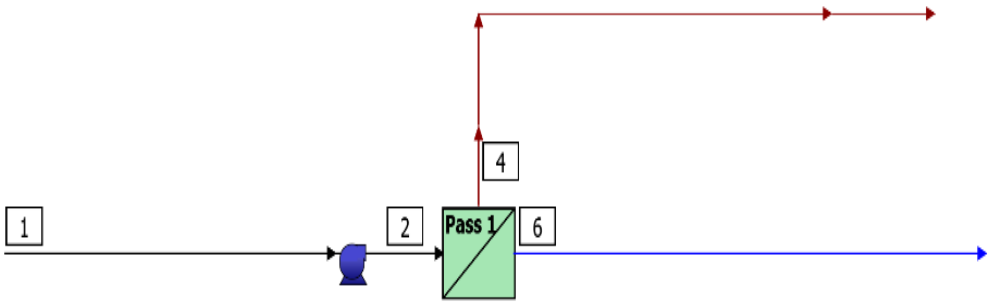


Figure 1.11: reverse osmosis installation

The membrane used is the Dow SEAMAXX-440[19][20][21] which is a spiral-wound element with polyamide thin-film composite membrane. The installation has 1600 elements. With a recovery ratio of 45%, $2222m^3/h$ of feed flow rate are pressurized at 55.1 bar to obtain at the end $1000m^3/h$ of permeate.
As explained before, the temperature of the feed water has an effect on the plant energy consumption. On table 1.2, the consumption of one train for the whole desalination process(i.e. intake, pre-treatment, RO, post-treatment and disposal) are provided depending on the water temperature.

T$[°C]$	14	15	16	17	18	19	20	21	22	23
Cons$[kWh/m^3]$	4.47	4.46	4.46	4.45	4.45	4.45	4.44	4.44	4.44	4.44

Table 1.2: One train whole process energy consumption as function of feed water temperature

The consumption varies a little with the feed water temperature but considering figure 1.7, the average water temperature stays globally between 17 and 21 $°C$. To simplify the models, we will consider a constant consumption of $4.45kWh/m^3$ per train.

1.4 Amercoeur plant data

It is established that the yield of the RO facility is impacted by different phenomenon's like membrane fouling, leading to higher pressure drop and cleanings. Since the Dakhla desalination plant has not yet been built, we elected to consider the data coming from the Amercoeur plant which operates intermittently to quantify these effects.
It is a combined cycle gas turbine plant which uses a RO plant to demineralize river brackish water for the vapor cycle. The fouling evolution is obtained via the pressure variations in the membranes. In fact, the more the fouling increases, the greater the pressure variations across the membranes will be. The values provided in the databases are measured values. In order to obtain usable values it is necessary to normalize these pressure variations in relation to the water temperature. This is done via the equations below.
For a water temperature greater than $25°C$:[22]

$$\Delta P_{norm}[bar] = \Delta P[bar] \cdot e^{2640(\frac{1}{298} - \frac{1}{T_{wat}+273})} \tag{1.2}$$

For a water temperature lower than $25°C$:[22]

$$\Delta P_{norm}[bar] = \Delta P[bar] \cdot e^{3020(\frac{1}{298} - \frac{1}{T_{wat}+273})} \tag{1.3}$$

Where T_{wat} is given in $°C$.

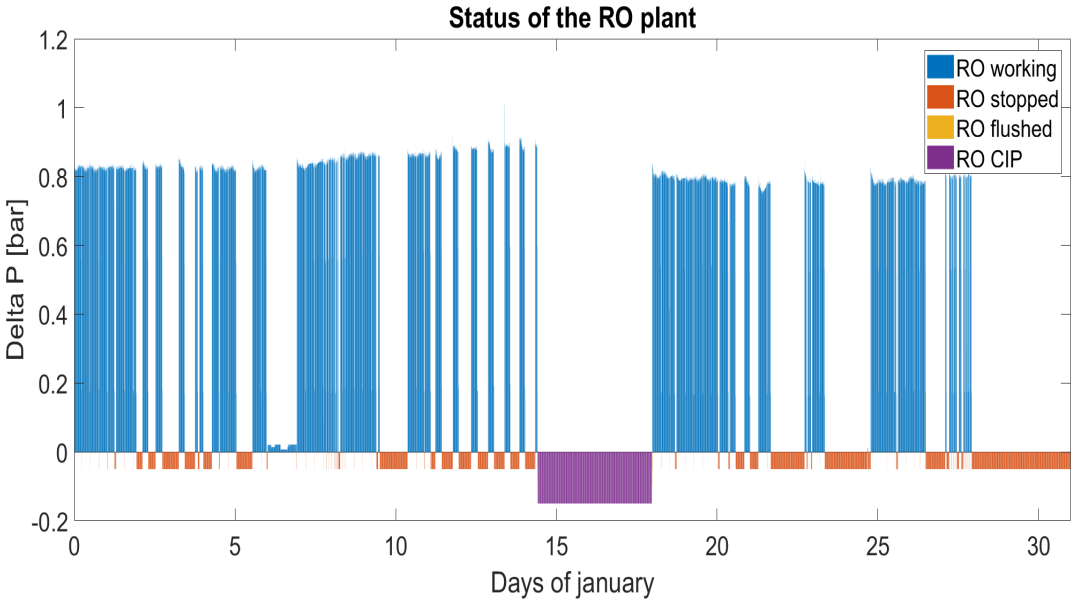


Figure 1.12: Second stage ΔP evolution during January

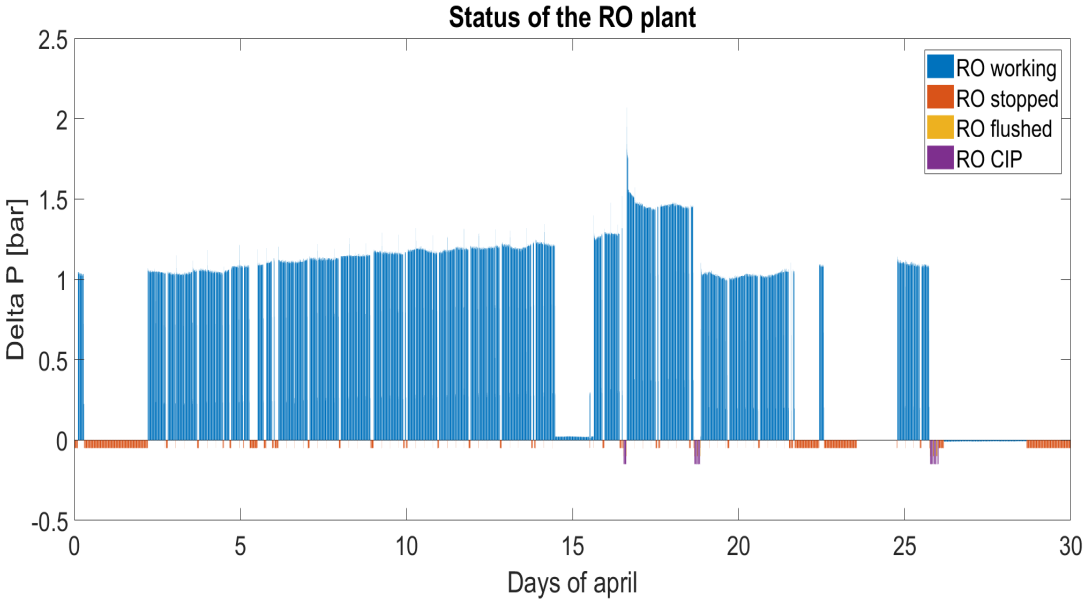


Figure 1.13: Second stage ΔP evolution during April

The aim is to derive the impact of fouling on the energy consumption of the desalination plant. As can be seen in the figures 1.12,1.13, RO fouling increases as the days go by and is then strongly decreased after a cleaning(y-axis is only for the blue curve which is the delta P of the second stage, the three others colours are showing which procedure of cleaning was applied or if the train was stopped).
This fickle fouling rate would be too complicated too model, and it would be to imprecise to estimate the pressure (and so the energy consumption) increase at a constant flowrate since it depends on many parameters and its profile varies a lot during the different months of the year. This is why in this model, we decided to ignore the progressive fouling effect over time to keep the algorithm simple. Instead, we have applied a constant yield ratio. Considering a well-managed plant in terms of membrane cleaning, we can assume that our membranes are in a state of wear, and the fouling factor at 0.85

throughout the year.[22]

With regard to the start and stop time of the installation, the data allowed us to calculate an average value of **12 minutes for the start** and **4 minutes for the stop**. Start-up time will be taken into account in flexible multi-train models. Each time a train will be start-up, the water production during the first hour will be reduced by nearly 20%. It is not necessary to take the stop time into account because it is considered that no more desalinated water is produced and only backwash procedures are applied to maintain the membranes properly. Moreover, since the stopping time is less than one hour, the train will be usable again at the next time step.

Chapter 2

System components models

Once the energy consumption of the desalination plant has been estimated, it is necessary to establish the relationships between the production of electricity by the renewable installations and the storage systems used to meet the constraints of the models presented below.
In our case it will be a PV/WT hybrid system. Considering the wind speed and irradiance data in Dakhla over a year, in hour per hour, we will identify criteria to be used for the selection of the plant model. Then we will establish the mathematical relationships leading to the electricity hourly production for each of the renewable installations.

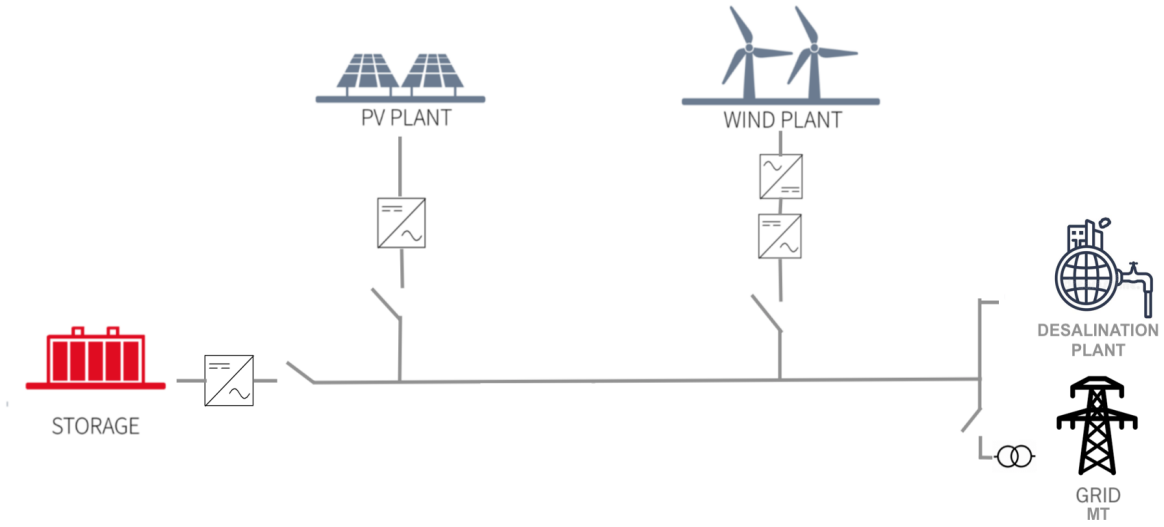


Figure 2.1: Electrical installation diagram

2.1 PV generator model

Computing the production of PV panels is quite complicated because a lot of elements have to be taken into account in the actual operating conditions, such as the temperature effect, inverters efficiency, losses in the cables, etc. In this work, we will consider efficiency factors for all these elements. The goal is to be as realistic as possible.
The selected solar panel is the LG NEON 2 Bifacial LG385N2T-A5 [23], a monocrystalline photovoltaic module. This technology has been preferred to polycrystalline photovoltaic modules for its advantage in power per square meter. However, it has the disadvantage of being sold at a higher price.
In addition, we have chosen bifacial panels. This technology is developing more and more, because it allows to increase the energy production while keeping a reasonable extra cost compared to the monofacial panels. The characteristics listed in the table 2.1, characterizes only the front side of the panel.

Name	**LG385N2T-A5**
Nominal Power P_N	385W
Module Area A_{mod}	$2.113m^2$
Module efficiency η_{mod}	18.2 %
Nominal Voltage V_{MP}	41V
Nominal Current I_{MP}	9.4A
Open Circuit Voltage V_{oc}	49.1V
Short circuit current I_{sc}	10.11A
Maximum system voltage	1000V
Performance Guarantee	25 years

Table 2.1: Characteristics of the PV module [23]

As we can see in table 2.1, the efficiency of monocrystalline photovoltaic module is high (around 5% better than polycristalline). At this point, we need to list all the efficiency losses due to external factors. [24] [25]

- $\eta_{inverter} = 0.95$: Inverter losses.
- $\eta_{heating} = 0.88$: Losses related to module heat up. These losses are difficult to estimate precisely because the relation between the temperature of the cell and the electricity production is non-linear. In this report, it will be estimated around 12%.
- $\eta_{wire} = 0.98$: Losses in electrical wiring.
- $\eta_{df} = 0.98$: The de-rate factor of the installation take into account all remaining losses, for example the dust that settles on the panels, or an exterior element that could cast a shadow over some of the panels. These disturbances remain quite low considering the installation location will be clear of obstacles and that a regular maintenance is carried out.
- $\eta_{overall} = \eta_{mod} \cdot \eta_{Inverter} \cdot \eta_{Heating} \cdot \eta_{Wire} \cdot \eta_{DF}$

2.1.1 PV installation pre-sizing

Photovoltaic installations are in continuous improvement with new technologies that are becoming more and more accessible and better the efficiency of these installations. The oldest and simplest solution is fixed tilt monofacial panels. Tracking systems have developed a lot, whether on 1 or 2 tracking axis. In addition, there are now bi-facial panels, with PV cells on both sides, that can also capture the solar rays reflected from the ground. This is the most promising solution currently available to achieve a minimum Levelized Cost of Electricity (LCOE). In this work, we decided to model bi-facial panels and compare the results obtained between a conventional installation with fixed panels and panels mounted on a dual axis tracking installation to illustrate the gains provided by the latter technology.
The bifacial coefficient gain(BG[%]), depends on several parameters such as : the ground reflectivity(albedo), the height of the module above the ground, the module row spacing. Based on the experience of laborelec, the bifacial gains is around 15% for fixed tilt panels, 10% for 1-axis tracking panels. There is little information about dual axis tracking panels so we will consider slightly lower bifacial gain : $BG_{2axis} = 8\%$.
We will therefore consider the following panel characteristics:

Name	**LG385N2T-A5**
Nominal Power P_N	442.8W
Module Area A_{mod}	$2.113m^2$
Module efficiency η_{mod}	20.93 %
Nominal Voltage V_{MP}	41V
Nominal Current I_{MP}	10.81A
Open Circuit Voltage V_{oc}	49.1V
Short circuit current I_{sc}	11.63A
Maximum system voltage	1000V
Performance Guarantee	25 years

Table 2.2: fixed tilt bi-facial panel

Name	**LG385N2T-A5**
Nominal Power P_N	415.8W
Module Area A_{mod}	$2.113m^2$
Module efficiency η_{mod}	19.66 %
Nominal Voltage V_{MP}	41V
Nominal Current I_{MP}	10.152A
Open Circuit Voltage V_{oc}	49.1V
Short circuit current I_{sc}	10.92A
Maximum system voltage	1000V
Performance Guarantee	25 years

Table 2.3: 2-axis tracking bi-facial panel

From this, it is possible to estimate the amount of electricity produced by the relation :

$$E_{PV}[Wh] = \eta_{Overall} \cdot A_{PV}[m^2] \cdot G(i)[Wh/m^2] \tag{2.1}$$

Where :

- $\eta_{Overall}$ is the overall efficiency of the PV module.[-]
- A_{PV} is the total area of PV panels.$[m^2]$
- G(i) is the global tilted irradiation$[Wh/m^2]$ hour by hour, which is the total irradiance$[W/m^2]$ received by a surface. This is the sum of the scattered radiation, direct and reflected. The data we used contained the irradiance given hour by hour. Considering the irradiance on a one-hour time step it gives us the irradiation used in the formula above.
  We will compare two cases, first with a fixed tilt and azimuth(resp. 24° and 4 °) and second by

considering a dual axis sun tracking installation. We will thus be able to compare whether these tracking technologies, which will be developed in the future, allow a real interesting gain on the final levelized cost of the water.[26] [27]

2.2 Wind turbine system model

In order to determine the electricity produced hour by hour by wind turbines several elements are considered :
First, we need the speed of wind hour by hour, this is usually provided at a height of 10 metres. It is therefore necessary to correct this speed for a height corresponding to the height of our wind turbine. This can be done with the logarithmic wind profile law :[28]

$$v = v_0 \cdot \frac{ln(H/z_0)}{ln(H_0/z_0)} \tag{2.2}$$

Where :

- v is the corrected speed of wind [m/s].
- v_0 is the speed at 10 meters [m/s].
- H is the height of the wind turbine [m].
- H_0 is equal to 10 meters [m].

Second, the coefficient z_0 is the roughness coefficient length and is expressed in metres, it depends on the landscape type.

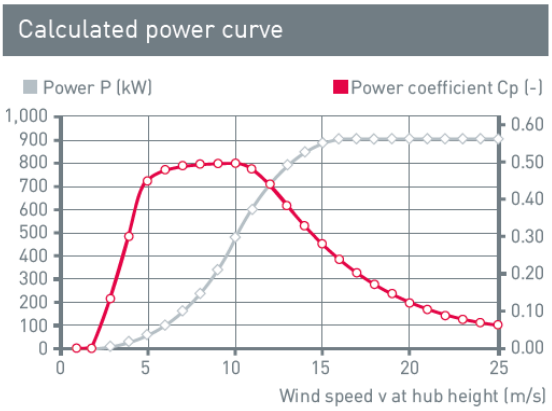
Roughness class	Roughness length[m]	Landscape type
0	0.0002	Water surface
0.2	0.0005	Inlet water
0.5	0.0024	Completely open terrain with a smooth surface
1	0.03	Open agricultural area without fences and hedgerows and very scattered buildings
1.5	0.055	Agricultural land with some houses separated by approximately 1250 metres
2	0.1	Agricultural land with some houses separated by approximately 500 metres
2.5	0.2	Agricultural land with many houses separated by approximately 250 metres
3	0.4	Villages, small towns.
3.5	0.8	Larger cities with tall buildings
4	1.6	Very large cities with tall buildings and skyscrapers

Table 2.4: Roughness length coefficient[28]

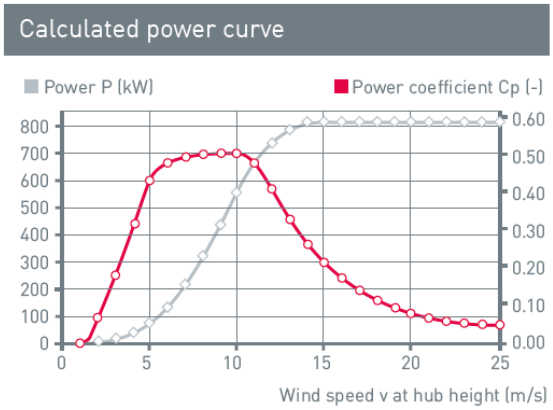
In our case, the Roughness class 0.5 will be used.
Once the wind speed has been corrected, it is possible to find the electrical energy that a wind turbine can produce throughout the year by taking its power curve generally provided by the manufacturer. In this report, we're going to choose from Enercon's wind turbines. They have a wide choice for the power range we are interested in.

2.2.1 Electricity production and choice of the better model

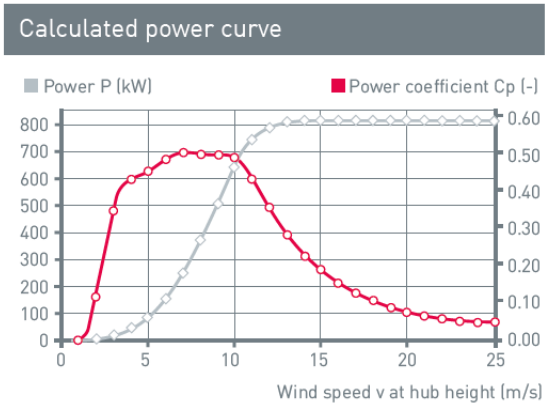
To find out which WT model is the best choice with our wind data, an algorithm has been developed on Matlab. It models all the power curves via polynomial fit and then calculates the electrical production of each wind turbine over one year. The result is then divided by the nominal power of the wind turbine to obtain the WT power factor, which is the equivalent number of hours operating at



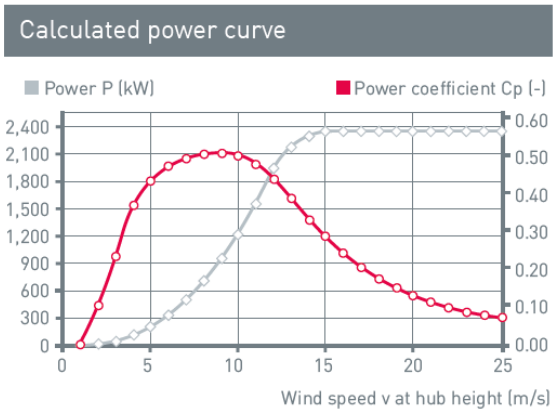
(a) Power curve E44 900kW



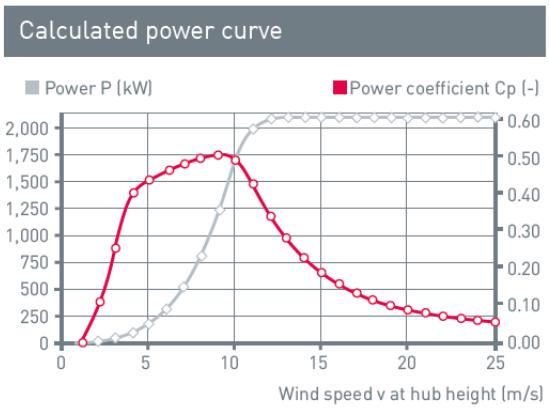
(b) Power curve E48 800kW



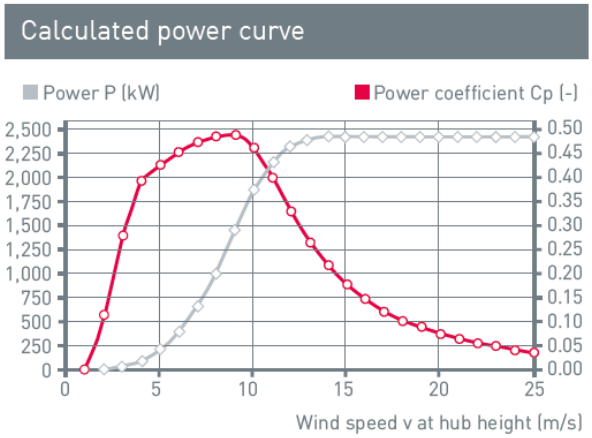
(c) Power curve E53 800kW



(d) Power curve E70 2300kW



(e) Power curve E82 2000kW



(f) Power curve E92 2350kW

Figure 2.2: Power curves of the manufacturer Enercon[29]

nominal power. The results are in the table 2.5.

As we can see, in our wind conditions, the best are the E-53, the E-82 and E-92 which respectively have a nominal power of 800kW, 2000kW and 2350kW. As the ground clearance between wind turbines is proportional to the size of the rotor diameter and the ground area should not be too large, the choice is to use the Enercon E-92 which makes a good compromise between energy produced and ground

Name	E-44	E-48	E-53	E-70	E-82	E-92
Equivalent hours	3493	4391	4986	3601	4893	4833
Rotor diameter [m]	44	48	52.9	71	82	92

Table 2.5: Equivalent number of operating hours at nominal power

area.[29]

2.3 Storage system model

In any installation based on renewable energy supply, storage plays a key role. It acts as a buffer to allow the plant to operate when renewable energy is not available. In the different models that will be explained later in this report, different types of storage will be used.

2.3.1 Electricity storage

The first is a lithium-ion battery system. As we can see in table 2.6, 2.7, this type of battery is widely used since it has the advantages of having a very fast response time as well as a better energy density and power density in comparison to the NaS and lead-acid battery. Furthermore, the manufacturing costs have dropped significantly in recent years. The choice that has been made is to use the RSU-4000 energy storage unit from General Electric[30] [31]. The technology used in this installation is the Lithium Nickel Manganese Cobalt(NMC) Oxide ($LiNiMnCoO_2$).[32] Table 2.8 provides the datasheet of this storage unit. As we can see the efficiency of this storage unit is not provided so we will take[33] :

- $\eta_{capacity} = 0.95$: takes into account the fact that we can not discharge the battery until 0.
- $\eta_{temp} = 0.95$: takes into account the effect of the temperature on the battery.
- $\eta_{discharge} = 0.997$: takes into account the self discharge of the battery.
- $\eta_{inverter} = 0.985$: takes into account the efficiency of the inverter RIU-2500 recommended by GE.[34]
- $\eta_{overall} = 0.886$

Technologies	Power rating (MW)	cycling	self discharge(%)	Energy density(Wh/l)
Lead-acid	0.001-100	6-40 years	0.1-0.3	50-80
NaS	10-100	2500-4400	0.05-20	130-300
Li-ion	0.1-100	1000-10000	0.1-0.3	200-400

Table 2.6: Different battery technologies comparison[33]

Technologies	Power density(W/l)	Efficiency(%)	Time response
Lead-acid	90-700	80-90	<sec
NaS	120-160	70-90	10-20ms
Li-ion	1300-10000	85-98	10-20ms

Table 2.7: Different battery technologies comparison[33]

Name	ENERGY STORAGE UNIT RSU-4000
Battery Chemistry	Lithium-Ion / NMC
Nameplate Energy Capacity	4184 $[kWh_{DC}]$
Maximum Power	1300$[kW_{DC}]$
Maximum DC Current	1760[A]
Nominal DC Voltage	1300[V]
Design Life	20 years
Operating Temperature Range	-20 to +50 $[°C]$
Dimensions (L x W x H)	6058 X 2438 X 2890[mm]

Table 2.8: Datasheet of the storage unit[31]

2.3.2 Fresh water storage

In some model variants that will be explained later in this report, fresh water storage will be used instead or in combination with batteries. For drinking water storage, a galvanized or vitrified steel tank is recommended, the company Eufor Inter offers tanks of 25.000 m^3.[35]

2.4 Costs analysis

This section will detail all the costs of the installations either to produce the energy or the infrastructures of the desalination plant. As the ultimate goal of this report is to give a precise estimate for the price of water, it is important to consider realistic cost values for the constitutive elements. Nevertheless, it is difficult in this kind of model to find the exact prices since they depend on many external factors. We will therefore rely on price estimates for each of the plant's facilities. These prices will be separated into two parts, the Capital Expense (CAPEX) which is the initial fixed cost of the facility and then the Operating Expense (OPEX) which will contain the operating costs per year.

2.4.1 Desalination plant

The cost estimate for the desalination plant is provided by a report from the organization Water Global Practice (WGP) which brings together financing, knowledge and implementation in one plateform. It is important to specify that the capital recovery cost will be considered by taking into account all the installations at once.

Capex

You can see in table 2.9 the distribution of the capital expenses(expressed in Millions of Liters per Day (MLD)) for the construction of the SWRO desalination plant.[36]

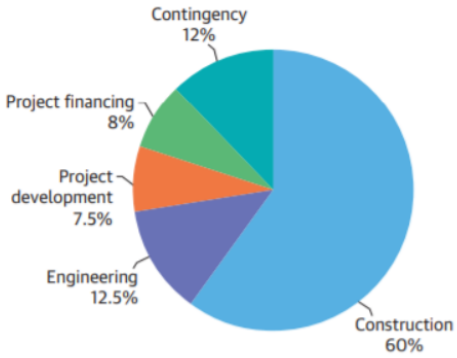


Figure 2.3: Typical Capex[37]

Component	Costs [M$/MLD]
Construction costs	0.68-1.1
Engineering services	0.13-0.19
Project development	0.07-0.12
Contingency	0.13-0.19
Total capital Costs	1.01-1.6

Table 2.9: Capex distribution[37]

In our case, as the technologies implemented in the plant are not the most complex (single pass, relatively low Total Dissolved Solids (TDS) of water, water temperature remaining within an acceptable range, no energy recovery system). We will consider that the cost of the installations corresponds to 125% of minimum cost provided i.e **1.2625 [M$/MLD]**. This value of 125% is chosen arbitrarily but seems reasonable to account for inflation since WGP report was issued. Since the plant is designed to produce 96,000 m^3 of water a day, that gives us :

$$CAPEX_{plant} = 121.200.000[\$] \tag{2.3}$$

Opex

You can see in table 2.10 the distribution of the operational expenses for the construction of the SWRO desalination plant.

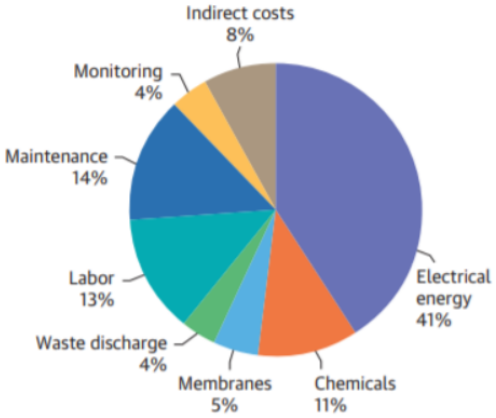


Figure 2.4: Typical Opex[37]

Component	Costs [M$/MLD]
Labor	0.02
Maintenance	0.02
Treatment	0.03
Other variable costs	0.04
Total operational Costs	1.1

Table 2.10: Opex distribution[37]

Since the plant is designed to produce 96,000 m^3 of water a day over 20 years, that gives us :

$$OPEX_{plant} = 105.600.000/20years[\$] = 5.280.000[\$/year] \tag{2.4}$$

2.4.2 PV installation

Capex

For the installation of solar panels there are two distinct elements to consider, first of all the costs of the module itself as well as the costs of the balance system of components which includes the inverter, the mounting structure, the installation work, the DC cables, the infrastructure, the planning and documentation, the transformer and finally the switch gear. It is important to take this into account since the price of modules tends to decrease significantly over the years, which is not the case for the Balance of Systems (BoS). Prices for a large scale infrastructure in 2020 range between 790 and 888 $/kWp. We will consider **840$/kWp** for an industrial large scale installation.[38]
For the voltaic installation with dual axis tracking system, we will consider an additional cost of 280$/kWp for the tracking system, for a total of **1120$/kWp**.[39]

Opex

For the operational expenses, we will consider it is 2% of the CAPEX so **16.8$/kWp/year** for the fixed installation and **22.4$/kWp/year** for the dual axis tracking.[38]

2.4.3 Wind Turbines

Capex

The capital expense of a land based wind turbine can is divided into two parts, the turbine capital cost and the balance of system and is equal respectively to 1094 and 360 $/kW. So for the Enercon E-92 of 2300kW we will estimate a CAPEX of **3.34 M$**.[40] [41] [42] [43]

Opex

The operational expense for the operating and maintenance of this same wind turbine is estimated to 44$/kW/year so **101 k$/year** per wind turbine. [40] [41] [42] [43]

2.4.4 Battery storage

Capex

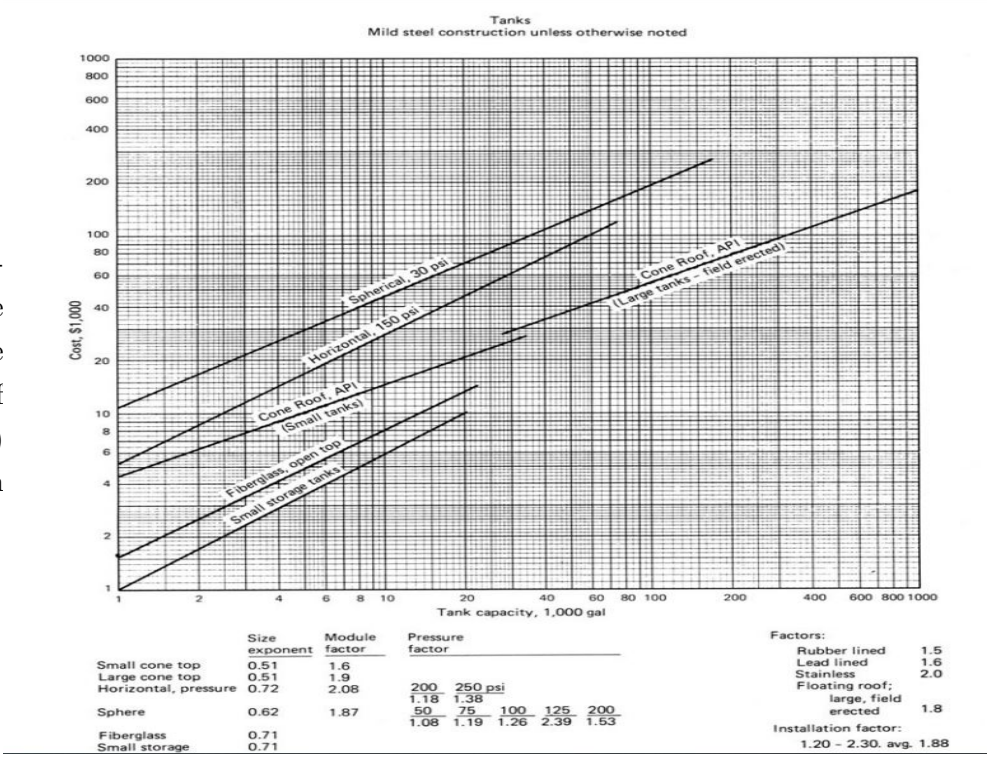
The capital expense of the battery installation is between 200 and 840 $/kWh for NMC Li-ion batteries depending on the use. For this project, we will consider a CAPEX of **420$/kWh**. This value was estimated by Laborelec for a battery in a large scale plant.[44]

Opex

The operational expense for the operating and maintenance of the battery installation, as well as the replacement of worn-out battery cells, to allow a 20-year service life with a reduced drop in performance. The OPEX is estimated to **12$/kWh/year**.[44]

2.4.5 Fresh water storage

For the price of drinking water storage, based on the price shown in the figure on the right, for a field erected tank of 1,000,000 gallons($4546.09 m^3$) the price is 180,000$, so we can estimate a price of **40** [$\$/m^3$].



2.4.6 Project financing costs

The project financing costs are an important part to take into account when we want to estimate the total cost of an installation. This is due to the fact there are risks inherent to the development of large desalination infrastructure. Indeed, the investor or organization that will advance the money to the plant owner, will consider all of these risks and will value them in the form of interest in the amount that will be reimbursed as annuity.
There are different sorts of risks specific to the development of large SWRO desalination infrastructure :[37]

- **Site-related risk** : Suitability of the selected site (raw water quality, raw water availability).
- **Construction risk** : Potential construction delays and costs overruns.
- **Performance risk** : Ability of the plant to operate at its originally planned conditions. In terms of fresh water production, consumption, chemical consumption and membrane replacement frequency.
- **Operational risk** : Concerns mainly energy costs in our case based on renewable energy there should not be a significant price increase compared to those initially planned.
- **Demand risk** : Possible lower than expected fresh water demand.

- **Force majeure risk** : Events beyond the control of the parties involved in the development of the project.
- **Political and regulatory risk** : political decision to cancel of change the terms of the contract.
- **Environmental risk** : Linked to climate-friendly legislation that could endanger certain installations, in the case of this report this should not be considered.
- **Social risk** : In the event of a social movement that could block the progress of the construction or the well running of the plant.
- **Currency exchange risk** : A project is financed through loans denominated in a foreign currencies, whereas project revenues are denominated in local currency. If the value of the local currency falls significantly it can increase the size of the debt.

Considering all this, a 6-8% discount rate (r) can be negotiated. In this report, a rate $\mathbf{r = 7\%}$ will be used. It is then necessary to calculate the Capital Recovery Factor (CRF) that will allow to find the Levelized Cost of water (LCOW). [45]

$$CRF = \frac{r(1+r)^n}{[(1+r)^n] - 1}[-] = 0.0944[-] \tag{2.5}$$

Where n = 20 is the useful life in years.
The Capex Annual Equivalent Cost (CAEC) which represents the annuity to be paid back to the investor. It is obtain by the equation:

$$CAEC[\$/year] = CAPEX[\$] \cdot CRF[-] \tag{2.6}$$

We can then obtain the LCOW :

$$LCOW = \frac{CAEC[\$/year] + OPEX[\$/year]}{Water_{prod}[m^3/year]}[\$/m^3] \tag{2.7}$$

The Levelized Cost Of Electricity is also calculated, however only the electricity useful for the operation of the RO plant is taken into account to obtain values comparable to the cost per Electrical Kilo Watt hour (kWhe) of the grid. This is done via the formula :

$$LCOE = \frac{CAEC[\$/year] + OPEX[\$/year]}{Elec_{prod}[kWh/year]}[\$/kWh] \tag{2.8}$$

Only PV, WT and battery costs are considered in Capex and Opex for the LCOE.

Chapter 3

Simulation algorithm explanation

3.1 Cases study

This part of the report will focus on explaining the algorithms that have been implemented for different power supply situations in the plant. The final goal of each will be to minimize the Levelized cost of water and thus see which configuration will be the best. The inputs of models will use the methods described in chapter 2 to calculate the renewable production as well as the estimated efficiencies and costs. [46] [47] [48]

3.2 100% renewable with battery

The first model consists of supplying the desalination plant with a renewable installation consisting of wind turbines and solar panels. This is supported by Li-ion batteries to compensate for production troughs. As far as the desalination plant is concerned, it operates in a constant way, which means a constant electrical power throughout the year equal to 17.8 MW.
This algorithm is not, strictly speaking, an optimization since the problem has not been posed mathematically with constraints also expressed in a mathematical form. The approach here is to calculate the solution for a large number of configurations in an iterative way and finally take the solution with the lowest LCOW. To do so, two iterative variables will be used as a multiplying factor. The first one the reference case multiplication factor (N) and the second the WT/PV ratio (FF). You can see on the figure 3.1 a diagram which represents the code in a simplified way.

1. **Inputs** : The inputs are entered in the form of a 7-column excel table, each column representing respectively the date, time of measurement, irradiance with optimal tilt and azimuth $[W/m^2]$, air temperature $[°C]$, wind speed at 10m [m/s], water production$[m^3/h]$, and system consumption [MW]. All these quantities are given hour per hour, over 1 year. In this first model the water production is constant and equal to 96,000$[m^3/day]$, which implies (for the moment) a constant consumption. This would be different if the influence of the temperature can be considered. As hourly data of this temperature are not available, we considered values averaged over a month with minimum influence of temperature. The model operates with constant electrical consumption.

2. **Pre-sizing** : Is meant to calculate the two boxes of the diagram[3.1] "Area PV ref", "Number WT ref", which will be reference values that we will vary via the variables N and FF to iterate and simulate all possible configurations.

   - Area PV ref : This value corresponds to the surface area of panels needed to produce as much electricity as the plant's consumption over 1 year. It is therefore a gross value that does not take into account the hourly variations.

   $$AreaPVref[m^2] = \frac{ConsoRO_{tot}[Wh/year]}{\eta_{PV} \cdot G_{year}[Wh/m^2/year]} \tag{3.1}$$

   Where, $ConsoRO_{tot}$ is the total consumption of the RO over 1 year, η_{PV} is the efficiency of the PV installation, G_{year} is the total irradiation over 1 year.

   - Number WT ref : In the same idea as for the solar panels, we will calculate the number of wind turbines necessary in the case of a static model.

   $$NumberWTref[-] = \frac{ConsoRO_{tot}[Wh/year]}{ProdWT_{tot}[Wh/WT/year]} \tag{3.2}$$

   Where, $ProdWT_{tot}$ is the total electricity production over one year of one Wind turbine Enercon E-92.

3. **Iterative variables** : It is at this point that the iterative variables are introduced, indeed FF will be the ratio WT/PV so FF=0 corresponds to 100% photovoltaic panels and FF = 1 the production is 100% from Wind turbines. This coefficient varies in steps of 0.1. The second one N is a multiplicative factor of the reference case found above because it is obvious that from a more dynamic point of view (hour by hour) the reference panel surface and wind turbine number values will no longer be sufficient or else at the price of a gigantic storage. This coefficient N varies from 1 to 5 in steps of 0.1. The choice of $N_{max} = 5$ is arbitrary but the algorithms confirmed that it was not necessary to choose a higher value since no optimal configuration (presented below in the report) has N=5.

   $$Area_{PV}[m^2] = N \cdot (1 - FF) \cdot AreaPVref \tag{3.3}$$

   $$Number_{WT}[-] = N \cdot (FF) \cdot NumberWTref \tag{3.4}$$

   So each are matrix of 2 dimensions (11x41).

4. **Electrity production** : For each configuration, for each element of the two matrices[3.3, 3.4], we will calculate the energy produced by the panels, by the wind turbines via the equations below and then add them together to obtain the total energy produced hour by hour[3.7] (box "Total energy"), which will be stored in a 3-dimensional matrix (11x41x8670).

   $$E_{PV}(N, FF, h)[Wh] = \eta_{PV} \cdot Area_{PV}(N, FF)[m^2] \cdot G(h)[Wh/m^2] \tag{3.5}$$

   Where, E_{PV} is the PV electricity produced in every configuration hour by hour, G(h) is the

irradiation vector hour by hour.

$$E_{WT}(N, FF, h)[Wh] = Number_{WT}(N, FF)[-] \cdot ProdWT(h)[Wh] \tag{3.6}$$

Where, E_{WT} is the wind turbine elctricity produced in every configuration hour by hour, ProdWT(h) is the electrcity porduced by one wind turbine hour by hour.

$$E_{tot}(N, FF, h)[Wh] = E_{PV}(N, FF, h)[Wh] + E_{WT}(N, FF, h)[Wh] \tag{3.7}$$

5. **Battery capacity** : Now that we know the energy production capacity of our system in each of the configurations as well as the energy consumption of the desalination plant, it is possible to determine the battery energy capacity required for the proper operation of the plant.
   A sub-function in the algorithm is in charge of calculating this capacity for each case, starting from a minimum reference capacity, the function runs the production and consumption vector over the year. Each time the production is insufficient, the battery discharges and conversely recharges when the production is greater than the consumption. When the capacity of the battery is less than 0, the initial capacity of the battery is increased by a factor of 1.05 and the loop starts again until it reaches the end of the vector corresponding to the last hour of the year. The battery capacity is then the last initial value of the battery to which the losses must still be factored in($\eta battery = 0.886$).
   This process is applied for all configurations PV/WT.

6. **Costs** : For each of the configurations, the costs of the installations are calculated, then the LCOW of each configuration is calculated and put in a matrix (11x41). The minimum of this matrix will correspond to the optimal configuration that will be chosen.

7. **Outputs** : The outputs are:

   - The panel area to be installed.
   - The number of wind turbines.
   - The battery capacity.
   - The FF, R (WT/PV ratio).
   - The LCOW, LCOE.
   - And finally, the graphs provided in the next section.

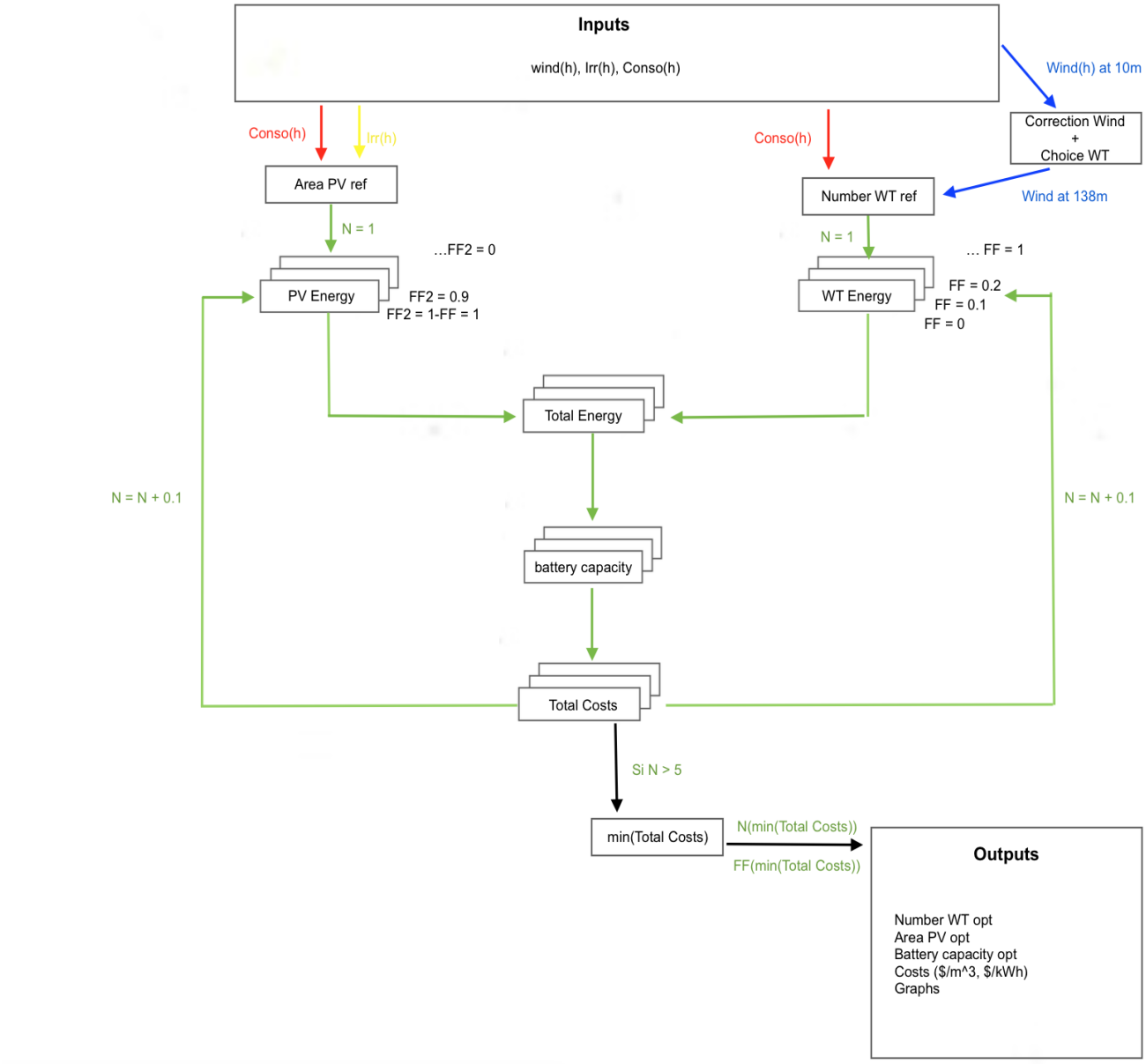


Figure 3.1: Model 1 algorithm diagram

3.3 Renewable with battery and grid

The second model consists of also using wind turbines and photovoltaic panels to supply the desalination plant, but in order to lighten the storage facility, the grid would be used before the batteries to supply the plant in the event of a shortfall in electricity production. There is nevertheless a constraint on the use of the network, in order to limit the costs of connection between the plant and the network we will consider a connection on the medium voltage level.

We considered that the maximum power the MT level can supply is $S = 5MVA$. By considering a asynchronous machine to drive the high pressure pump of the RO plant. We consider a power factor of $cos\phi = 0.85$ when the asynchronous machine is working at nominal speed. This gives us the maximum active power supplied by the grid : $P = 4.25MW$. As reminder the RO plant absorbs a constant power of 17.8MW. This is why, a maximum of 23.9% of the nominal power of the plant, has been considered for the grid supply.

The basis of the algorithm of the second model is the same as the first one up to point 5. The difference comes when the storage must be calculated.

- **Grid supply** : As in the previous model, for each configuration (N,FF) the total renewable electrical production is run hour by hour and each time the production is in deficit in relation to the consumption, the grid is used up to its maximum value of 23.9% of the consumption of the desalination plant. For all configuration, the values of the grid supply(hour by hour) are stored in a vector.
- **Battery capacity** : When the grid supply is not sufficient, the batteries take over. In the same way as in the first model, the capacity of the batteries is incremented by running through the entire production/consumption vector.
- **Output** : The outputs are the panel area to be installed, the number of wind turbines, the battery capacity, grid supply, the FF WT/PV ratio, the LCOW, the LCOE and finally the graphs provided in the next section.

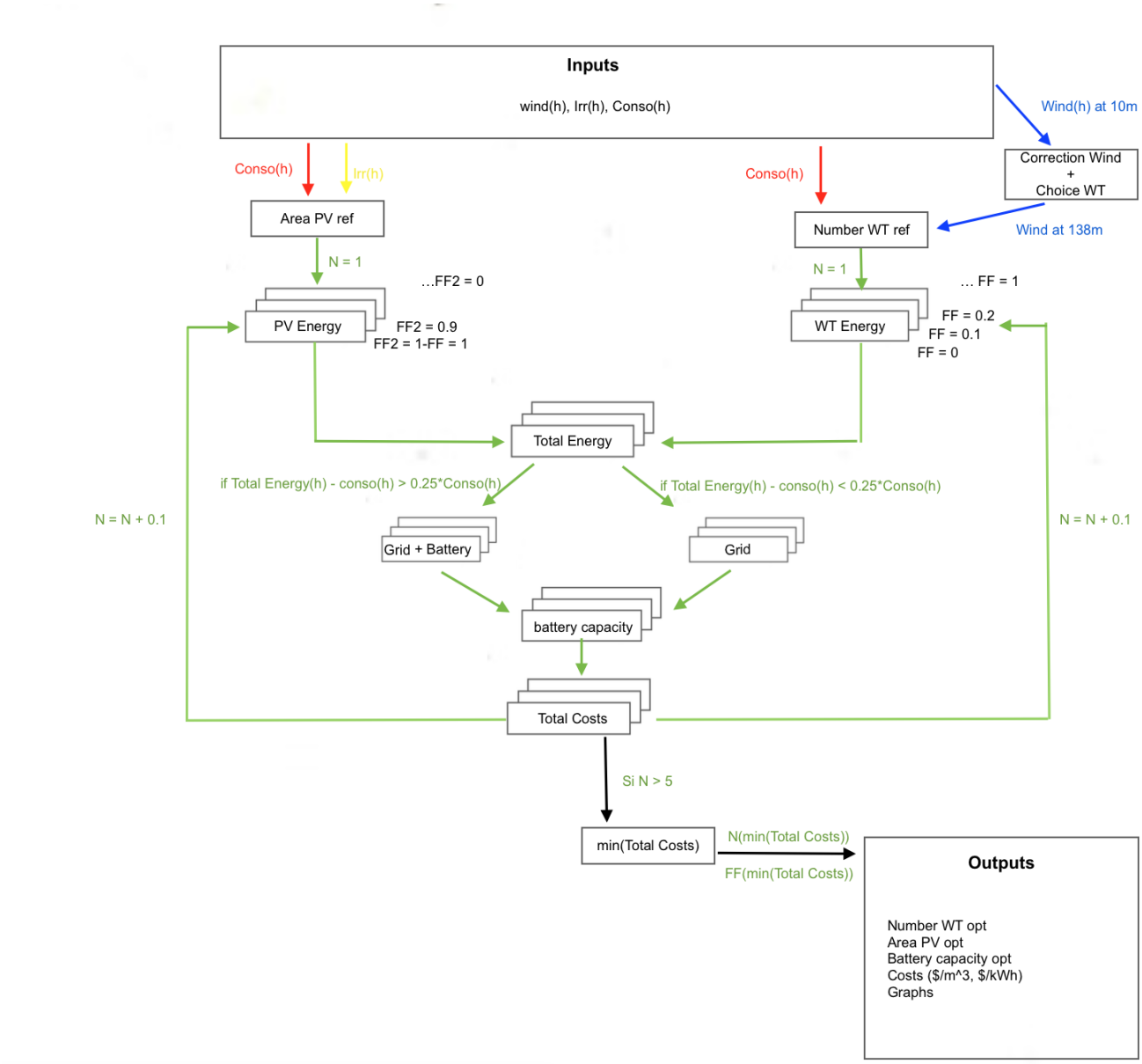


Figure 3.2: Model 2 algorithm diagram

3.4 Flexible working with renewable and fresh water storage

Model 3 is based on a renewable PV/WT power supply with fresh water storage and flexible desalination plant operation.[49] [50] This means that our plant can switch on its trains successively up to its nominal operation according to the amount of renewable electricity produced to have a consumption adapted to each time step. We can see on the figure 3.3 the consumption steps of the RO plant. We considered the case of a RO plant with 6 identical trains of 1000$[m^3/h]$. We have also made the hypothesis that the plant must supply a minimum of 2000$[m^3/h]$. So when the water production of the desalination plant is lower, the water from the water tank storage is supplied. This value of 2000$[m^3/h]$ is an arbitrary choice, but it seems reasonable to ensure a minimum of water for the end consumer. When the production of the plant runs at its maximum i.e. 6000$[m^3/h]$, we make the hypothesis here that the excess of water will have the same value. Indeed, as a reminder, the real project in Dakhla is to make a desalination plant that provides 4000$[m^3/h]$, so this value is based

on the real water demand of the region. Switching to a flexible model, the water production will be variable and will therefore have an influence on the consumer and the demand. Indeed, during long periods when the desalination plant is operating at $6000[m^3/h]$, it is possible that without consumer demand this excess water will lose its market value. However, we will consider that consumers have personal storage and therefore will be able to store water during peak production periods and reuse this water when the desalination plant can only provide $2000[m^3/h]$.
In this model, the train start-up time has also been taken into account and is equal to 12 minutes as explained earlier in the report. To model it, at every time step a train is started-up, the water production of this particular train is reduced by 20%.

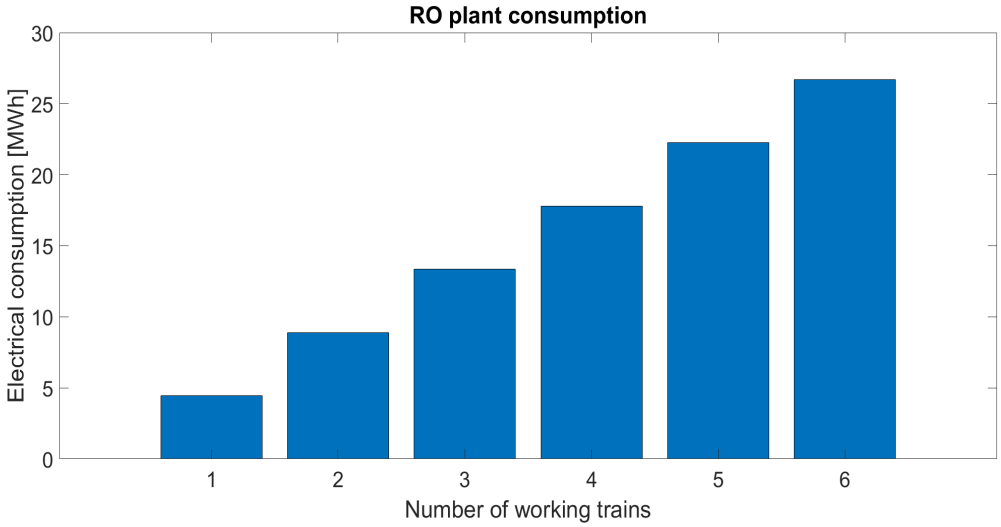


Figure 3.3: Consumption steps of the RO plant

The basis of the algorithm of the third model is the same as the first one up to point 5.

- **RO plant consumption** : For each of the configurations (N, FF), from the renewable production it is determined how many trains of the desalination plant will be turned on. When the renewable production is between the consumption of i-1 and i trains, there will be i-1 trains turned on. There is therefore some loss of production in this model since no electrical storage is installed and electricity production is constantly higher than the plant's real-time consumption.
- **Water tank capacity** : A constraint has been imposed in this model: the quantity of water produced hour by hour must be at least equal to half the nominal plant production of the two previous models i.e. $2000m^3/h$. In the algorithm, the fresh water tank capacity has been implemented in a similar way to the batteries capacity in the previous models, i.e. iteratively hour by hour for each configuration (N, FF). Knowing the desired amount of fresh water and the number of active trains every hour, it is possible to determine the compensation that the water tank must be able to provide.
- **Output** : The outputs are the panel area to be installed, the number of wind turbines, the water tank capacity, the FF WT/PV ratio, the LCOW, the LCOE and finally the graphs provided in the next section.

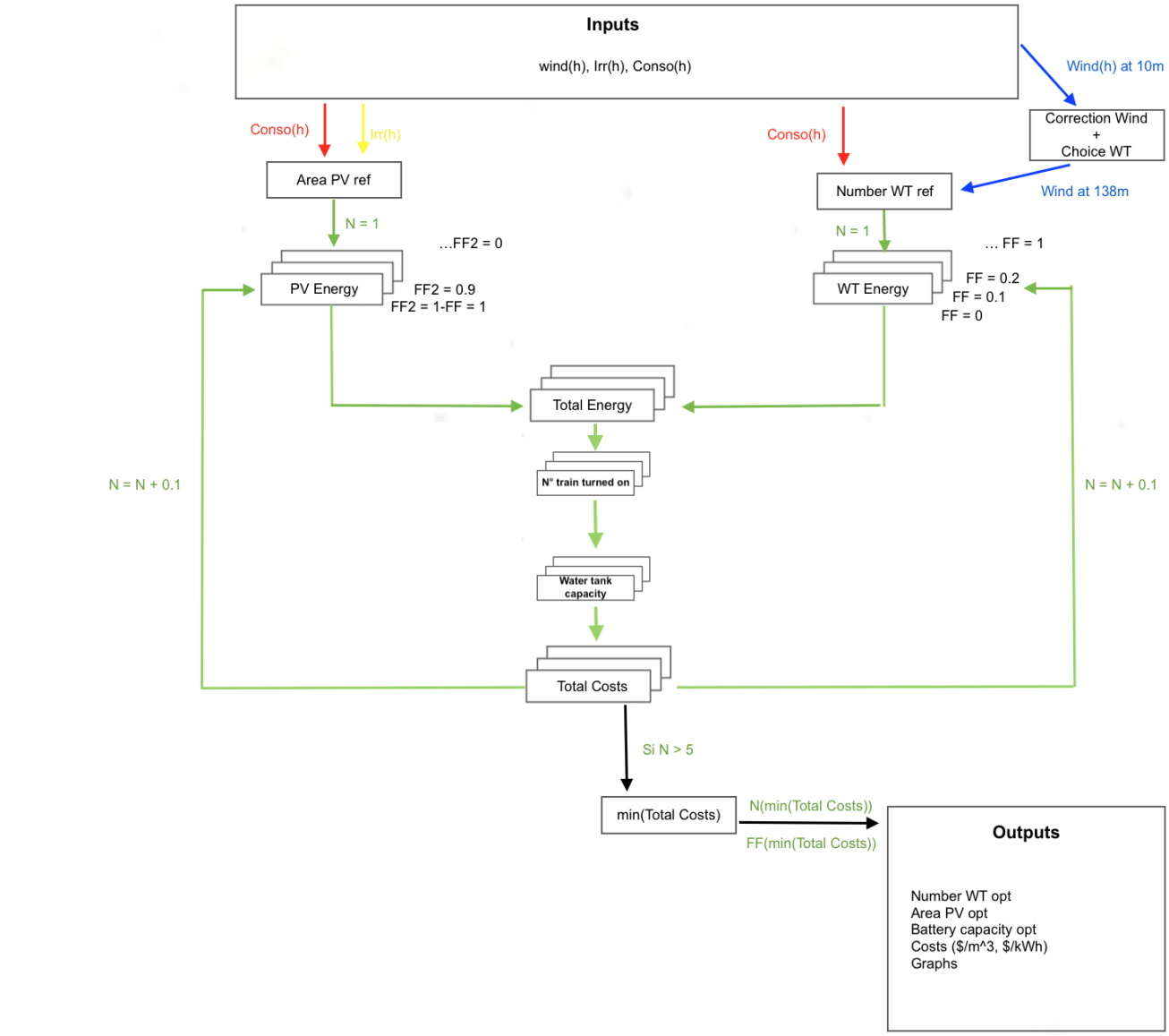


Figure 3.4: Model 3 algorithm diagram

3.5 Flexible working with renewable and fresh water storage and battery

As indicated, the previous model has a big flaw : it loses a large amount of the produced energy. The idea in this 4th model is to add a battery storage in addition to the fresh water tank. When the produced electrical energy is sufficiently close to the upper consumption level, the batteries provide the supplement energy needed to reach this level. This is shown in figure 3.5, 3.6 with 65% as the threshold. When the threshold is not reached then the plant remains on the lower number of trains and the batteries are recharged.

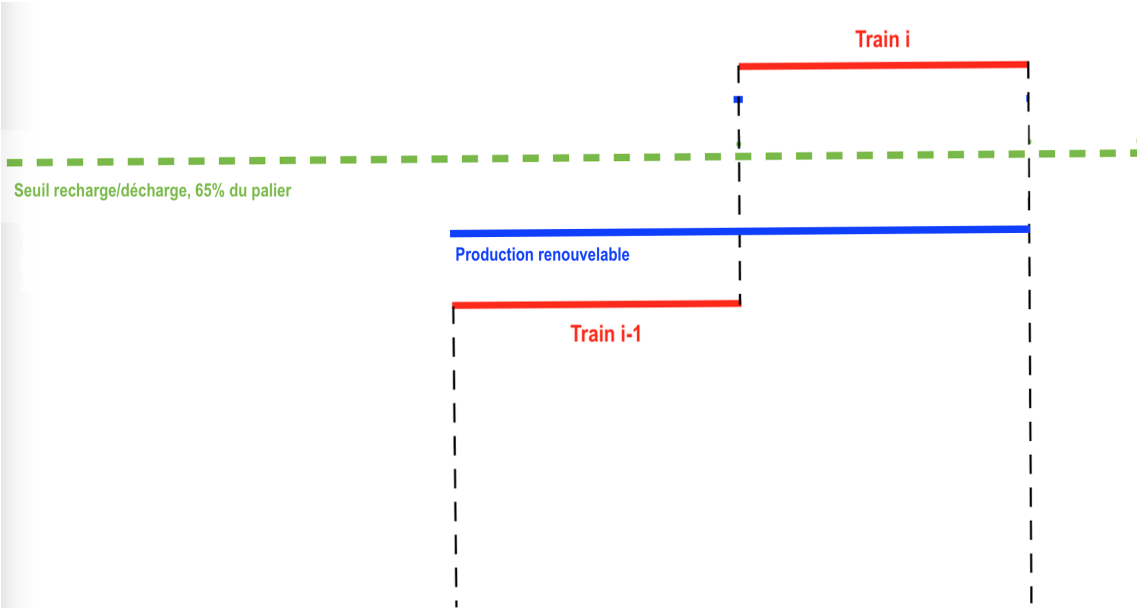


Figure 3.5: Battery recharging and train i-1 working

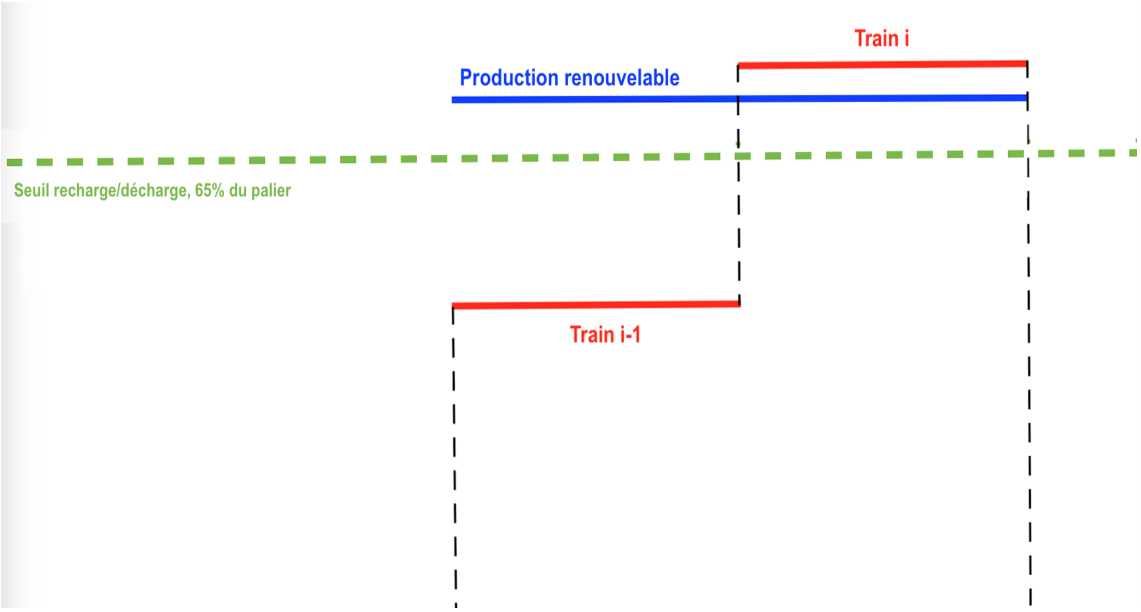


Figure 3.6: Battery discharging and train i turned on

Chapter 4

Results

As the models are dependent on diffuse energy (irradiation, wind speed), the results can be very different year on year. In this type of installation, it is sometimes necessary to stop the plant for several hours in a row to avoid unnecessary oversizing of the installations, especially for storage. We opted for the following analysis scheme:

- We will first indicate the best configuration for each year separately.
- Compare the worst year with the best to determine the parameters that differentiate these two years.
- Finally, we will try some of these configurations over the eleven years to determine which one could be a viable solution for a real plant and discuss the possibilities for an efficient plant management.

In the tables below, by year, we report the results obtained for a fixed photovoltaic installation and then, on the line below, the results for a dual axis tracking installation.

2019 Market situation for desalinized water

Launched in 2014, the World Bank Group's Water Global Practice brings together financing, knowledge, and implementation in one platform. The organization provided relevant cost numbers for desalinization facilities.[37]

A survey of 50 recent desalinization plants

"Recent typical costs of water production show considerable reductions for both thermal technologies (MSF and MED), but particularly for SWRO, which is now registering costs as low as US$ 0.64 per cubic meter in favorable physical and business environments. For the purposes of this study, a database was built containing over 50 desalination projects from around the world constructed over the last two decades. Table ES.1, which draws on this database, shows the actual costs of desalination by technology and feedwater source for SWRO plants."[37]

TABLE ES.1. Summary of Worldwide Seawater Desalination Costs

Desalination method		Capital costs (million US$/MLD)		O&M costs (US$/m³)		Cost of water production (US$m³)	
		Range	Average	Range	Average	Range	Average
MSF		1.7–3.1	2.1	0.22–0.30	0.26	1.02–1.74	1.44
MED-TVC		1.2–2.3	1.4	0.11–0.25	0.14	1.12–1.50	1.39
SWRO Mediterranean Sea		0.8–2.2	1.2	0.25–0.74	0.35	0.64–1.62	0.98
SWRO Arabian Gulf		1.2–1.8	1.5	0.36–1.01	0.64	0.96–1.92	1.35
SWRO Red Sea		1.2–2.3	1.5	0.41–0.96	0.51	1.14–1.70	1.38
SWRO Atlantic and Pacific oceans		1.3–7.6	4.1	0.17–0.41	0.21	0.88–2.86	1.82
Hybrid	MSF/MED	1.5–2.2	1.8	0.14–0.25	0.23	0.95–1.37	1.15
	SWRO	1.2–2.4	1.3	0.29–0.44	0.35	0.85–1.12	1.03

Note: Costs are at 2016 values. MED-TVC = multiple effect distillation with thermal vapor compression; MLD = million liters per day; MSF = multistage flash distillation; O&M = operation and maintenance; SWRO = seawater reverse osmosis.

The world Bank Group also predicts further cost reduction in next 20 years with values down to $0.3[\$/m^3]$ in favorable conditions:

TABLE ES.7. Forecast of Desalination Costs for Medium- and Large-Size Seawater Reverse Osmosis Projects

Parameters	Year 2016	Within 5 years	Within 20 years
Cost of water (US$/m³)	0.8-1.2	0.6-1.0	0.3-0.5
Construction cost (US$/MLD)	1.2-2.2	1.0-1.8	0.5-0.9
Electrical energy use (kWh/m³)	3.5-4.0	2.8-3.2	2.1-2.4
Membrane productivity (m³/membrane)	28-47	35-55	95-120

Sources: Voutchkov 2016; World Bank 2017a.
Note: The figures are estimated for best-in-class desalination plants.

These above numbers might be conservative as a recent project has been approved in Saudi Arabia with a promise of a levelized cost of water of $0.46[\$/m^3]$.[51]

4.1 Model 1

Here are the results of model 1, which, as a reminder, is the simplest case with a energy supply to the desalination plant (with a constant electricity consumption) via a PV/WT mix with a battery energy storage system.

4.1.1 Results

Year	FF[-]	PV[ha]	WT[-]	Bat[MWh]	Tank[m^3]	N[-]	LCOW[$/$m^3$]	LCOE[$/$kWh$]
2006	0.6	53.061	32.5	343.19	/	3.6	**1.675**	0.288
	0.5	63.584	33.14	311.29	/	4.4	**1.787**	0.315
2007	0.1	108.17	4.83	460	/	3.3	**1.834**	0.326
	0	91.175	0	559.03	/	3.2	**1.957**	0.356
2008	0.2	103.4	10.16	507.05	/	3.4	**1.939**	0.352
	0.7	31.69	36.6	616.33	/	3.5	**2.048**	0.378
2009	0.6	47.197	30.37	296.46	/	3.2	**1.546**	0.257
	0.7	29.646	37.65	296.46	/	3.4	**1.575**	0.264
2010	0.3	67.606	12.88	532.41	/	2.6	**1.803**	0.319
	0.3	59.741	14.362	559.03	/	2.9	**1.902**	0.343
2011	0.3	66.895	11.12	296.46	/	2.6	**1.431**	0.229
	0.5	34.796	17.09	417.16	/	2.4	**1.545**	0.257
2012	0.4	37.857	9.81	647.14	/	1.7	**1.765**	0.31
	0.3	28.93	8.22	647.14	/	1.9	**1.811**	0.321
2013	0	94.469	0	459.91	/	2.5	**1.698**	0.294
	0	93.134	0	482.91	/	3.1	**1.859**	0.332
2014	0.5	34.954	13.04	296.46	/	1.9	**1.27**	0.191
	0.4	36.61	11.53	282.35	/	2.1	**1.294**	0.196
2015	0.3	68.236	10.23	296.46	/	2.6	**1.428**	0.229
	0.3	60.458	11.41	311.29	/	2.9	**1.507**	0.248
2016	0.2	65.817	5.32	616.33	/	2	**1.827**	0.325
	0.1	51.001	2.39	616.33	/	1.8	**1.781**	0.314

Table 4.1: Best configuration year by year.

4.1.2 Graphs worst vs best year

The graphs below, compares the worst year with the best year in terms of LCOW. The graphs 4.1,4.2, represents the energy consumption of the desalination plant versus renewable production. The red line represents the energy consumption in hours per hour and is therefore equal to 17.8MWh. Then the graphs 4.3,4.4 compare the battery charge status over the year 2008 and 2014, so more precisely the charge/discharge of the battery during the year.

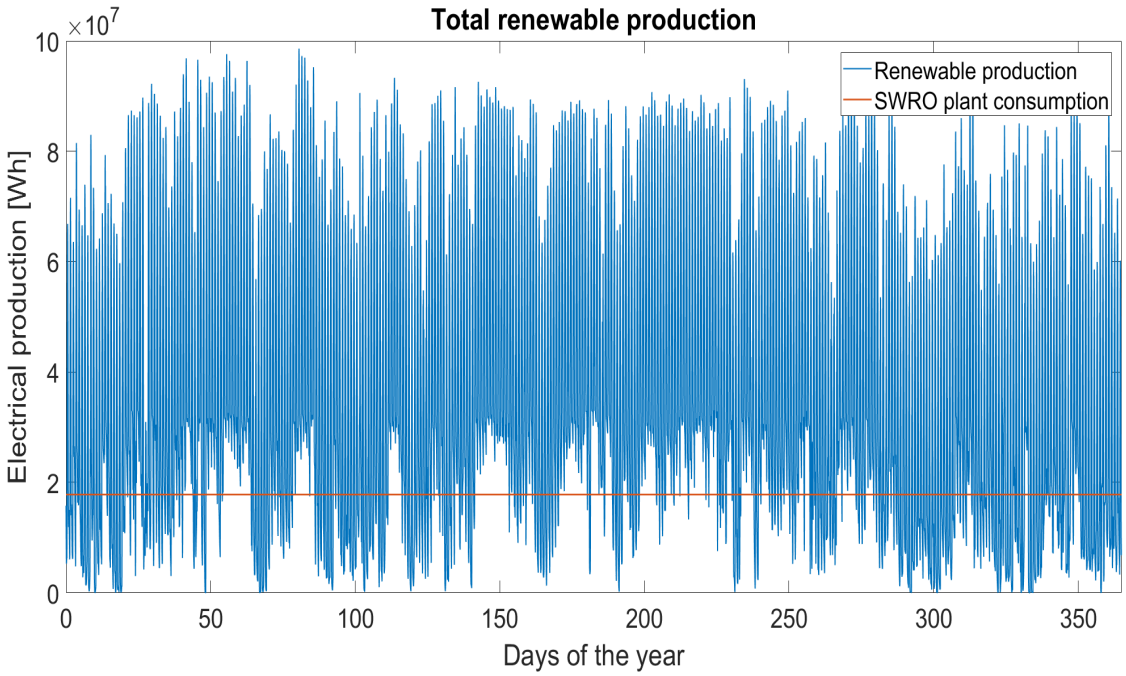


Figure 4.1: Electrical production and consumption 2014

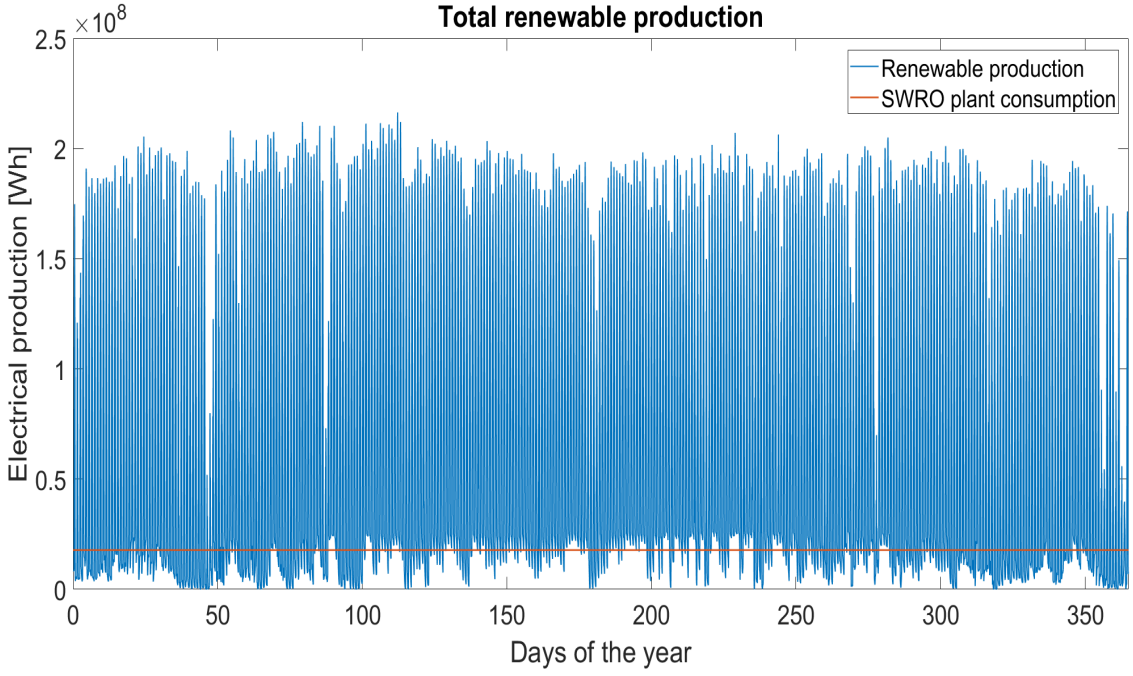


Figure 4.2: Electrical production and consumption 2008

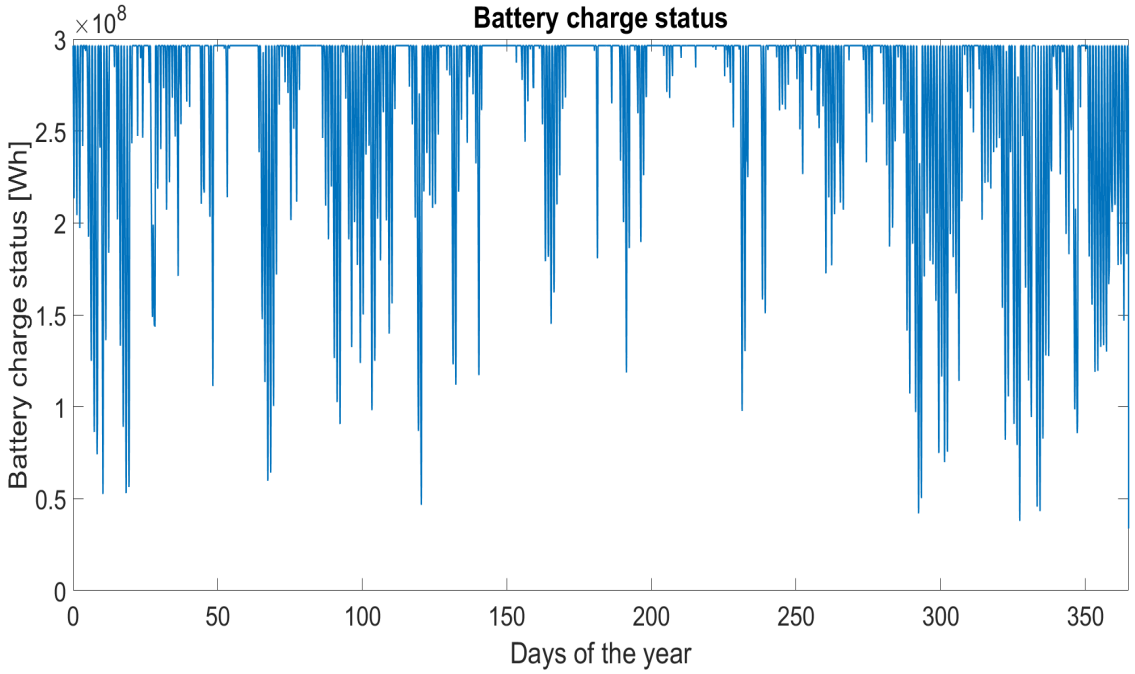


Figure 4.3: Battery charge status 2014

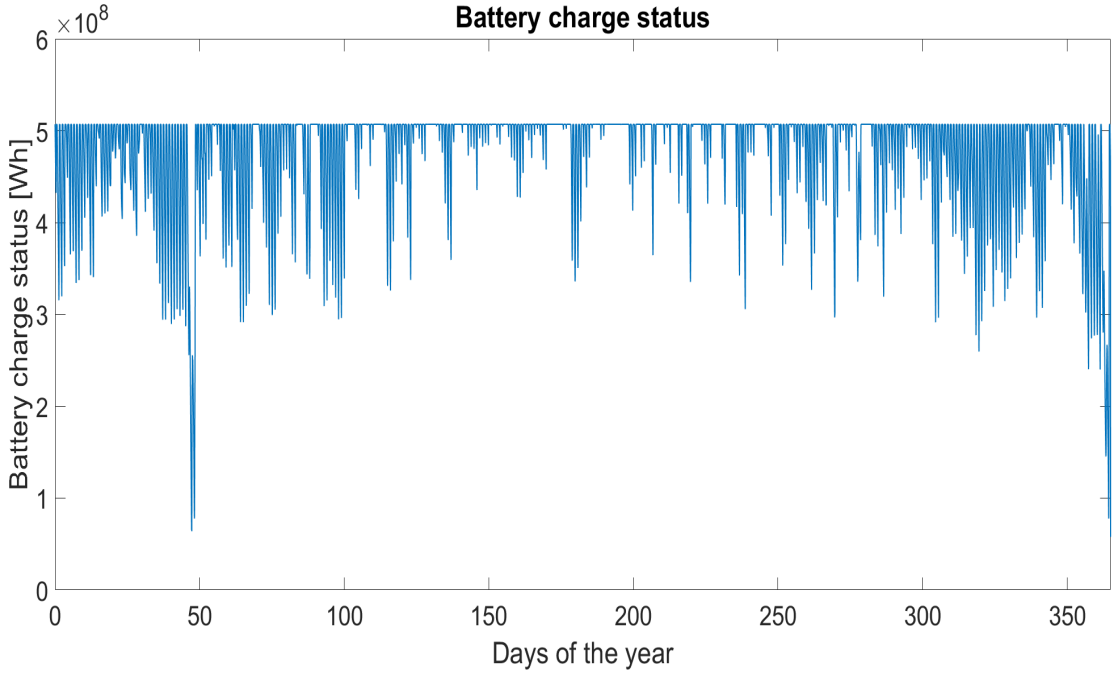


Figure 4.4: Battery charge status 2008

4.1.3 Interpretation

- From the table 4.1, we first observe that the configurations using fixed panels and dual axis tracking, are relatively similar. The years 2008 and 2011 are however different, combining tracking PV with a heavier use of wind turbines. This indicates that the production via tracking PV would be very low in these years compared to the additional cost of this installation.

- It can also be noticed that the LCOW with the use of dual axis tracking PV is each year higher than the classical case, except for the year 2016. The mobile PV solution at the current equipment costs assumptions is therefore not interesting according to this first model.

- For this model 1, we will therefore only focus on the case with a fixed PV installation. We can notice that the optimal configurations vary quite widely over the years, particularly for the plant sizing factor N (1.7-3.6). It can also be noted that for mosts years, there is a dominance in favour of PV panels, with 2013 even relying solely on PV energy. This is explained by the fact that for a constant operation of the desalination plant, the PV panels are more constant over the year even though they only produce part of the day. They do, however, require a large battery storage system

- Next, we note that the LCOW remains each year higher than market values. Indeed, a typical range of water production cost values for a conventional reverse osmosis desalination plant is between 0.6-1[$\$/m^3$].[37] Desalination plants generally should be able manage to produce water with a final cost of less than 1[$\$/m^3$].

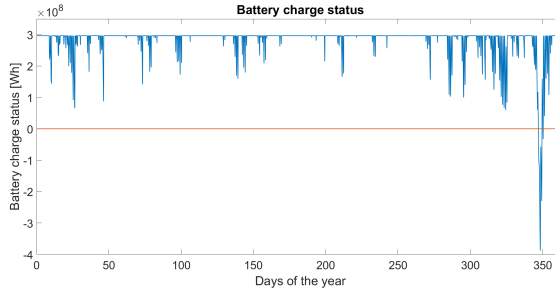
- A more detailed comparison of the results obtained for the best(2014) versus the worst year(2008) shows that the difference comes from the multiplying factor N (1.9 against 3.4), which implies that the total electricity production in 2008 will be strongly oversized and nevertheless the storage required is almost twice as much. This can be seen in the state of charge of the batteries, the total capacity of the battery is better used in 2014 than in 2008. In addition, it can be noted that storage is so important in 2008 for two periods (around the 50th day and the last ten days of the year). A countermeasure that would enable to divide the storage size by two would be to allow the plant to shutdown for these periods.

- Finally, it can be noted that the LCOE is also much higher than the electricity sales values on the market, which is around 0.09 [$\$$/kWh].

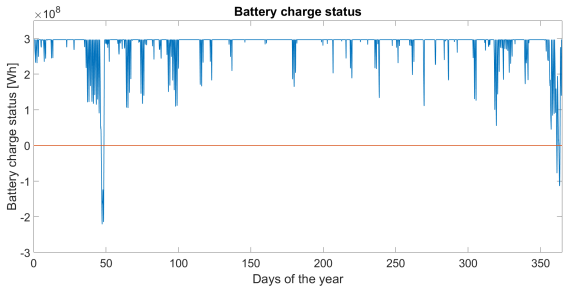
4.1.4 Final configuration choice

The optimal configurations for each year are useful information to get an idea of the quality of renewable energy year by year. However, it seems interesting to find a configuration that could be used for each year and that would provide good results. One could take the worst configuration to be sure to be operational all the time or one could take an intermediate configuration that would be functional for all the years by accepting plant shutdowns during the most critical periods, when renewable energy production is unsufficient. These plant shutdowns can be used for planned maintenance if they can be forecasted (preferably with a good estimate of the outage duration), otherwise it will require a specific "reactive" approach to maintenance. This could avoid revenue losses during favourable periods. Usually the cleaning of the membranes is done every 6 months and lasts between 6 and 9 hours, so it would be important to have these forced stops not too close to each other.
Still referring to table [4.1], the year 2009 with fixed PV panels offers a rather interesting configuration, indeed the ratio between PV in WT is well balanced (FF=0.6), the installations are moderately sized (N=3.2) and the storage is reasonably large (296.46MWh). Over the period of eleven years, there are five of them that are more critical (2007, 2008, 2010, 2013, 2016) as shown in the battery status

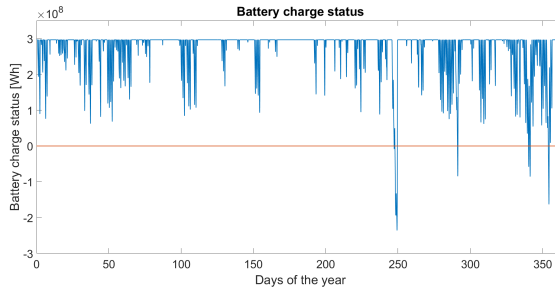
charts 4.5a, 4.5b, 4.6a, 4.6b, 4.7.



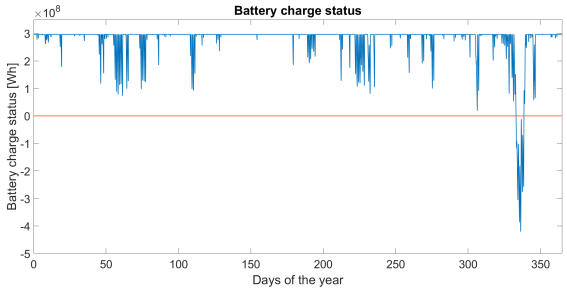
(a) 2007 battery charge state with 2009 configuration



(b) 2008 battery charge state with 2009 configuration



(a) 2010 battery charge state with 2009 configuration



(b) 2013 battery charge state with 2009 configuration

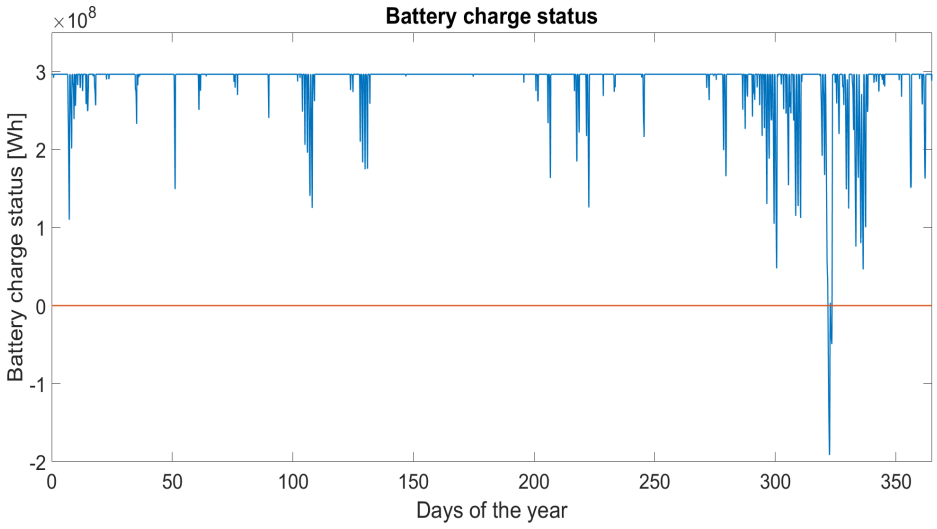


Figure 4.7: 2016 battery charge state with 2009 configuration

In 2007, there is only one shutdown period of the desalination plant(around 350th day) for approximately 5 days. This should therefore not be a problem in the management of the desalination plant. In 2008, we notice that there are two periods during the year when storage would not be sufficient (around the 50th and 360th day), these periods are relatively short (around 5 days) and spaced from each other. Considering that the plant can organize itself and that the water consumers could plan and have individual water storing capacity to go thru these production troughs. Possibly store water the days before and save water at those times. In addition, these plant shutdowns would occur during

the winter, which is positive because consumers generally use less water.
In 2010, we have four periods where storage is not enough (around the 250th, 290th, 340th and 360th day), their duration is not very long (less than 5 days) but these periods are closer together which can be more problematic for consumers. Here again an individual water storage would cope with the issue.
In 2013, we have a period where the storage is not sufficient (around the 335th day) and the duration is longer than 10 days. This is also very problematic and a solution outside the factory will have to be found for this period.
In 2016, there is one forced shutdown needed but it has a quite short duration (max 3 days). They therefore seem to be quite viable for both the consumers and the plant.
The 2009 factory size thus induces some rather hard constraints for some rather rare periods but allows to avoid oversizing the renewable electricity production installations and keeps a LCOW close to 1.546[$/$m^3$] over all the years as we can see in table 4.2. This value remains however higher than the market value, we conclude that this plant model does not seem able to compete with conventional SWRO desalination plants.
This seems logical, as for most off-grid systems, having a desalination plant running off-grid with only renewable power and batteries could only make sense in situations where a grid connection is not possible/affordable (hence where a conventional SWRO plant could not be implemented), a situation that may be encountered for locations with a lower water consumption, but rarer where large-scale desalination plants are necessary.

Year	**2006**	**2007**	**2008**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
LCOW [$/$m^3$]	1.545	1.558	1.555	1.561	1.546	1.548	1.57	1.546	1.546	1.549

Table 4.2: LCOW with the 2009 configuration, taking into account the shutdowns

4.2 Model 2

Combining renewable production with battery and grid electricity provided the following results :

4.2.1 Results

Year	FF[-]	PV[ha]	WT[-]	Bat[MWh]	Tank[m^3]	N[-]	LCOW[$/$m^3$]	LCOE[$/$kWh$]
2006	0.5	51.587	21.1	293.68	/	2.8	**1.475**	0.373
	0.6	39.306	30.732	279.69	/	3.4	**1.55**	0.386
2007	0.1	91.784	4.1	356.97	/	2.8	**1.632**	0.457
	0	79.929	0	433.89	/	2.7	**1.721**	0.479
2008	0.3	71.845	12.1	413.23	/	2.7	**1.673**	0.438
	0.7	26.257	30.32	478.37	/	2.9	**1.744**	0.435
2009	0.6	35.397	22.78	266.37	/	2.4	**1.364**	0.347
	0.6	29.146	23.73	266.37	/	2.5	**1.38**	0.349
2010	0.3	59.805	11.39	393.55	/	2.3	**1.572**	0.417
	0	58.858	0	478.37	/	2	**1.658**	0.463
2011	0.4	50.723	13.1	219.15	/	2.3	**1.275**	0.331
	0.6	20.878	15.38	339.97	/	1.8	**1.336**	0.344
2012	0.6	29.692	17.31	433.89	/	2	**1.517**	0.389
	0.6	25.962	19.04	433.89	/	2.2	**1.55**	0.395
2013	0	79.354	0	356.97	/	2.1	**1.514**	0.427
	0	84.121	0	356.97	/	2.8	**1.66**	0.463
2014	0.5	31.274	11.67	219.15	/	1.7	**1.151**	0.303
	0.4	29.638	9.337	219.15	/	1.7	**1.161**	0.31
2015	0.3	55.113	8.27	241.61	/	2.1	**1.29**	0.35
	0.4	48.247	14.17	230.1	/	2.7	**1.354**	0.347
2016	0.6	34.554	16.76	455.59	/	2.1	**1.566**	0.398
	0.4	32.112	9.04	478.37	/	1.7	**1.554**	0.41

Table 4.3: Best configuration year per year.

4.2.2 Graphs worst vs best year

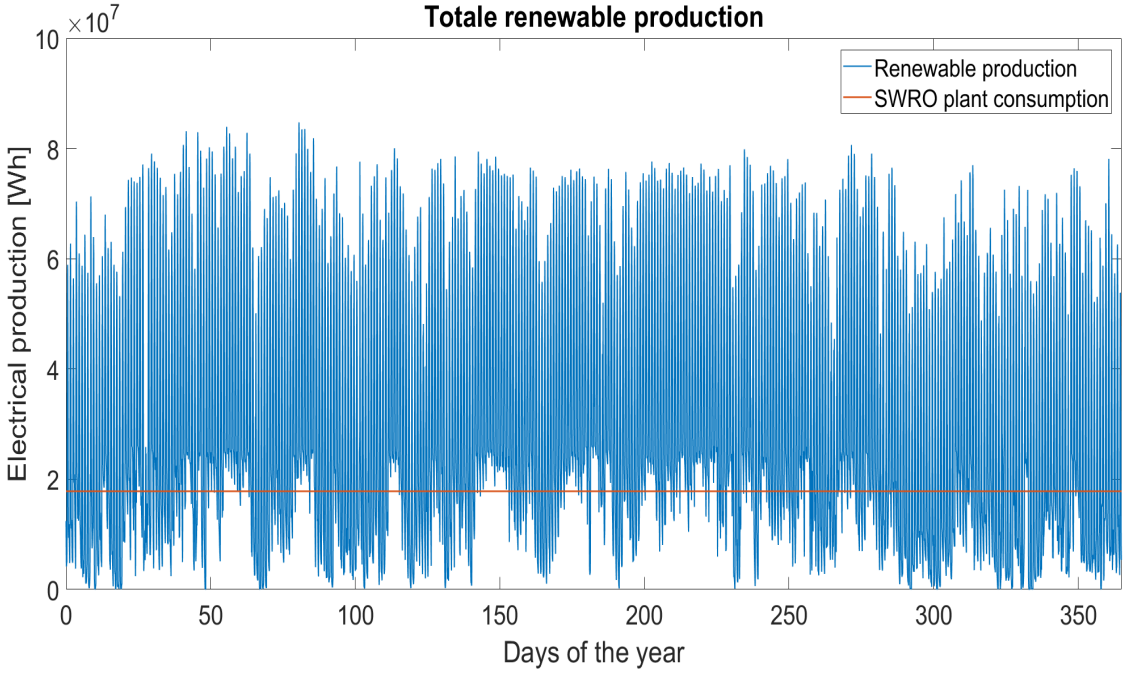


Figure 4.8: Electrical production and consumption 2014

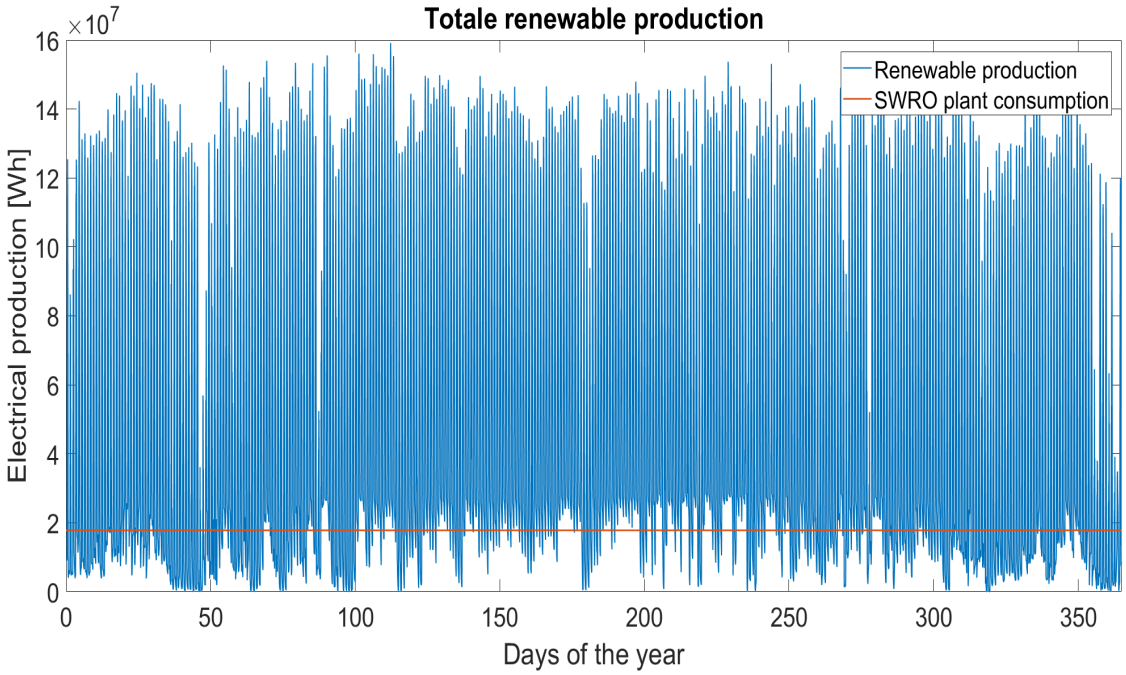


Figure 4.9: Electrical production and consumption 2008

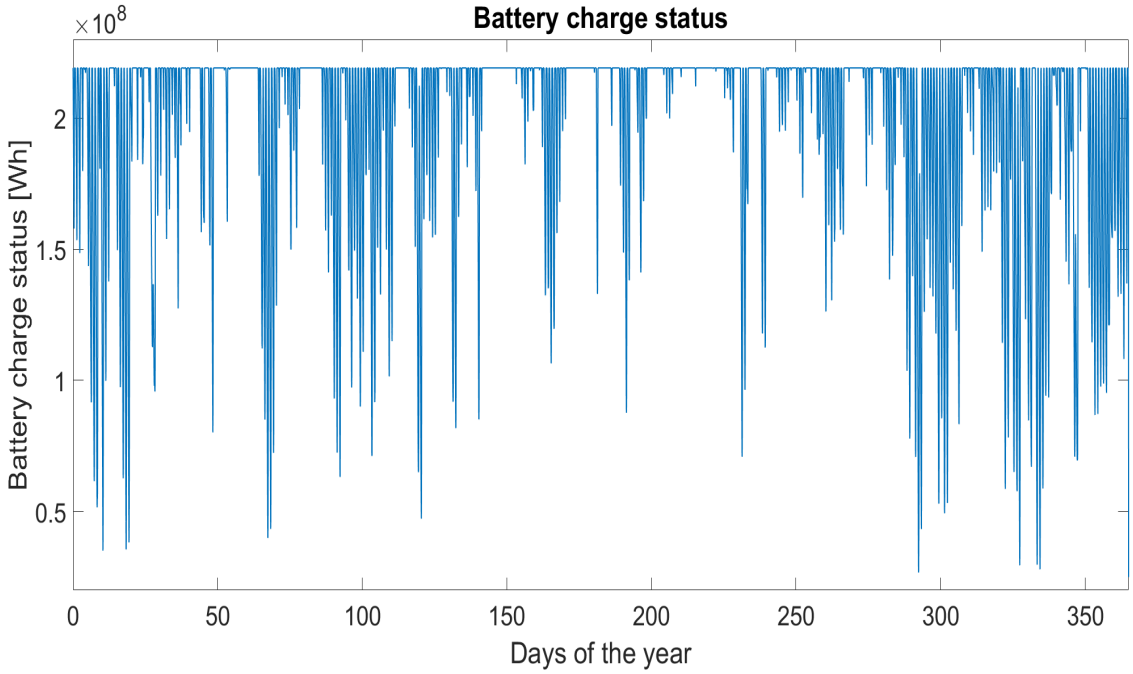


Figure 4.10: Battery charge status 2014

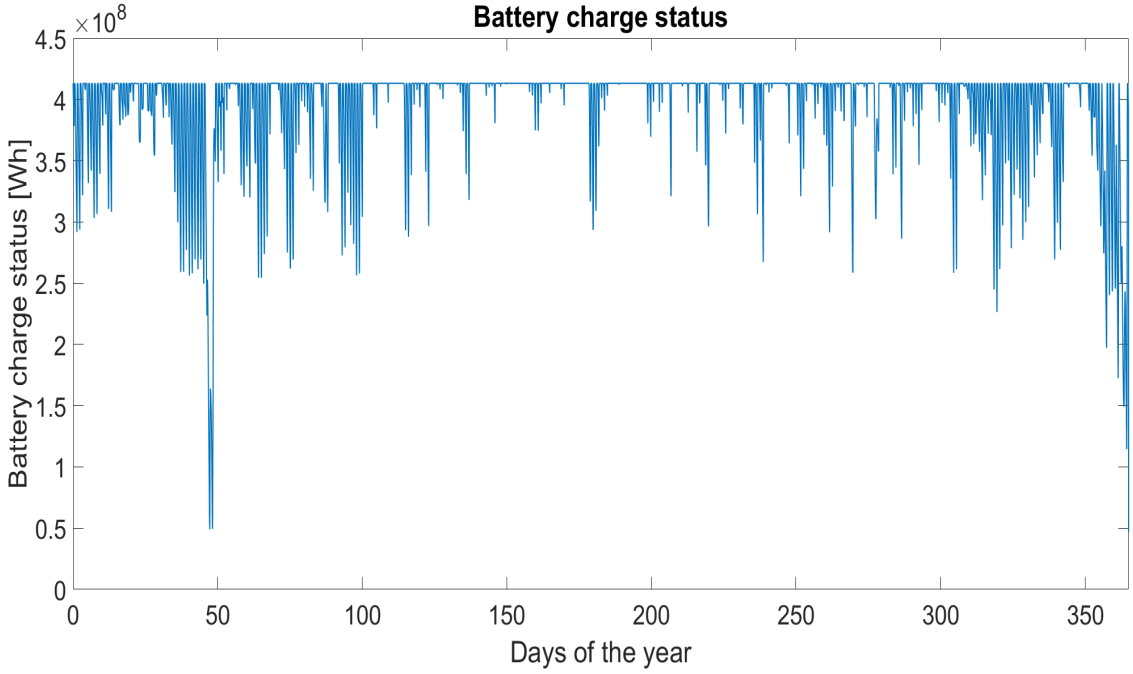


Figure 4.11: Battery charge status 2008

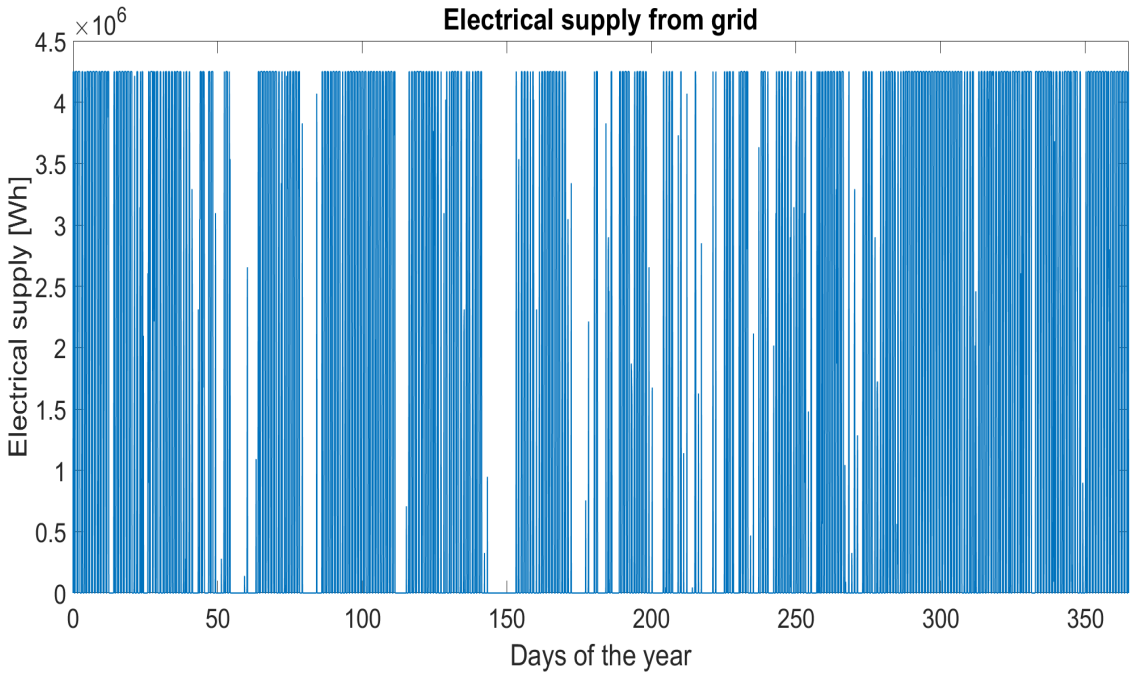


Figure 4.12: Supply by the grid 2014

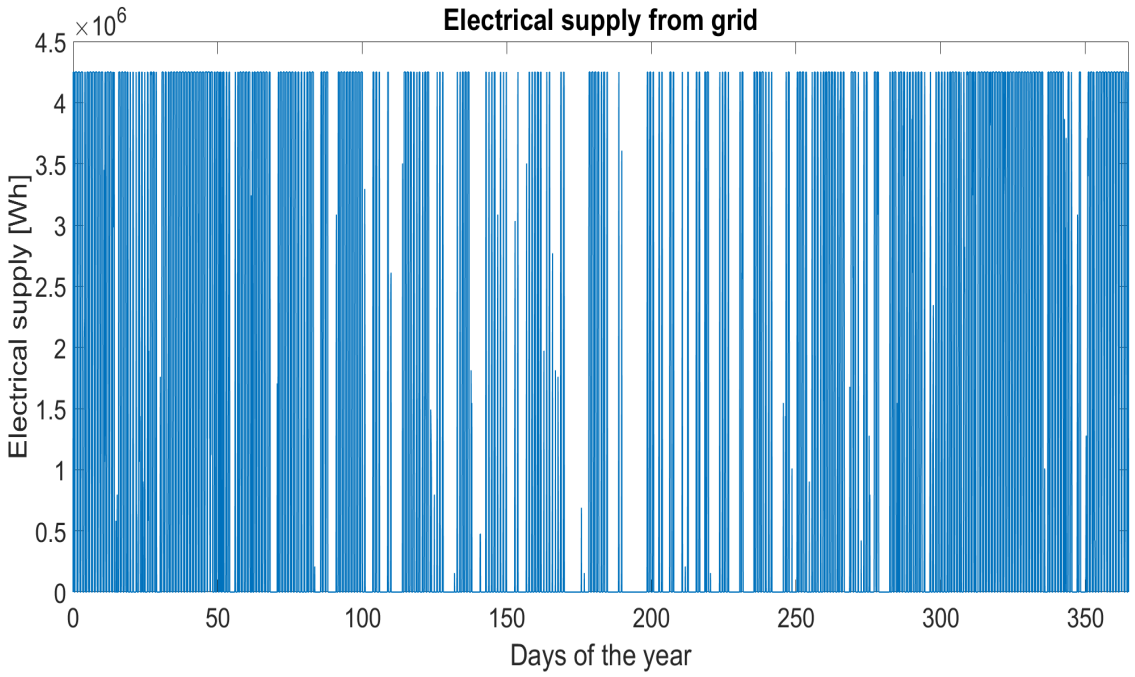


Figure 4.13: Supply by the grid 2008

4.2.3 Interpretation

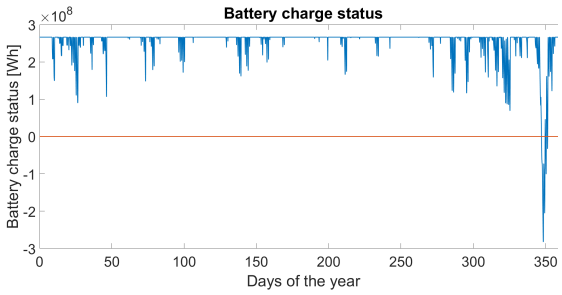
By adding the connection to the grid with an electricity purchase cost of 0.09 [$/kWh], we notice that the LCOW decreases while remaining always higher than 1 [$/$m^3$]. In this model, the fixed tilt PVs also show better results than the dual axis tracking for most years (except 2016). We will therefore analyze the results of the fixed tilt PVs.

The best and worst years remain the same, 2014 and 2008 respectively. The PV/WT ratio is slightly

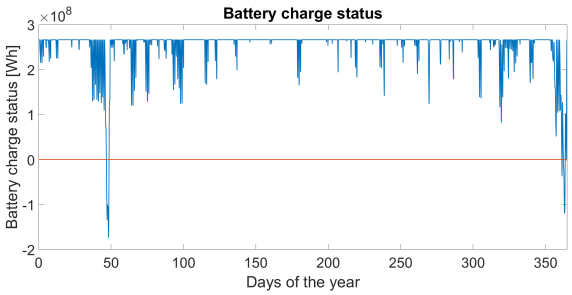
different(FF : 0.5 vs 0.3). The real difference comes from the multiplying factor N (1.7 vs 2.7). In the same way as for the previous model, renewable production is over-sized for the year 2008. Once again, we note that the batteries are much more used in 2014 than in 2008. While the latter have very high values(413.23MWh) of storage twice in the year (around the 50th day and the last ten days of the year). With two forced shutdowns of the desalination plant, the capacity of the storage facility could again be halved for the year 2008.
In addition, the LCOW values are expected to decrease further when considering more realistic purchasing electricity costs from the grid. Indeed, the price depends on the time of day : it is known to be cheaper during the night when the plant needs it more due to the fact that the production of PV panels is null. Finally, the LCOE has decreased compared to the previous model but is still well above market values.

4.2.4 Final configuration choice

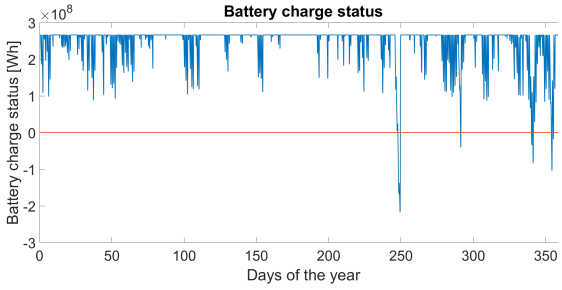
As we can see in the table 4.3, fixed tilt PV panels give better results. As for the previous model, 2009 has an interesting optimal configuration. Indeed, the ratio between PV in WT is well balanced (FF=0.6), the installations are not too oversized (N=2.4) and the storage is not too large (266.37MWh). Of the eleven years, there are five that are more critical (2007, 2008, 2010, 2013, 2016) as can be seen in the battery status below.



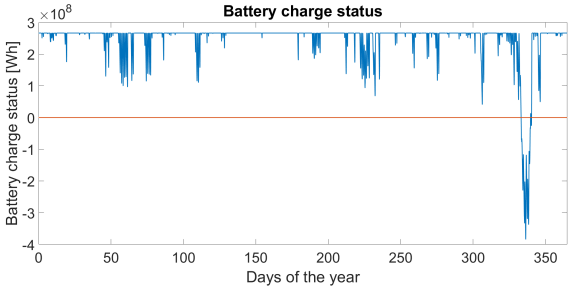
(a) 2007 battery charge state with 2009 configuration



(b) 2008 battery charge state with 2009 configuration



(a) 2010 battery charge state with 2009 configuration



(b) 2013 battery charge state with 2009 configuration

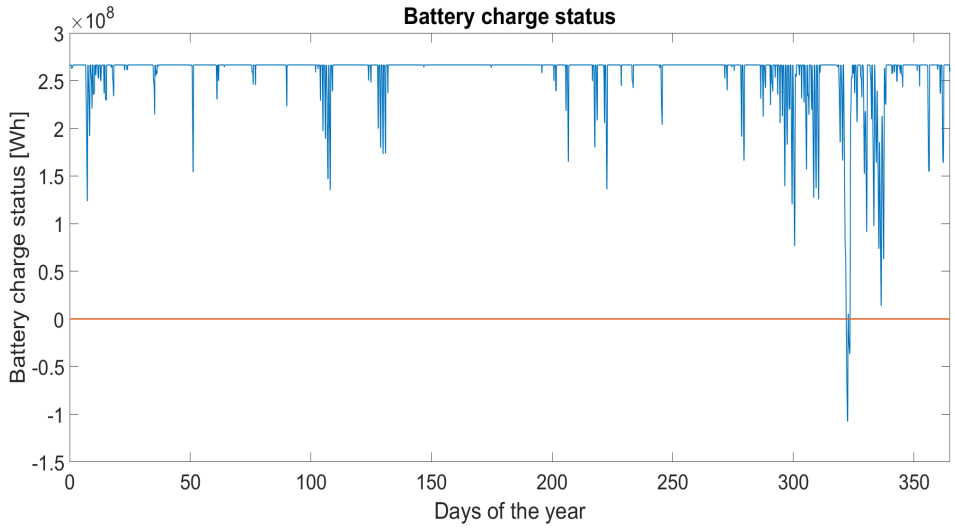


Figure 4.16: 2016 battery charge state with 2009 configuration

The results are similar to the previous model. The same 5 years create some concerns. The years 2007, 2008, 2010, and 2016 respectively require 1, 2, 4, and 1 shutdowns of relatively limited duration, which is therefore manageable for the plant operators but still requires preparation of the consumers to avoid problems.
2013 is still a tricky year since it requires a rather long shutdown (around 10 days), it will still be necessary to find an external solution to supply consumers for such a long time. If the final use is for industry or agriculture, this should not be too problematic since these sectors generally have their own water reserves to cope with this kind of situation.
In the 6 others years, forced shutdowns are less than 3 per year and of very short duration (max 1 days). They therefore seem to be quite viable for both the consumers and the plant, provided some individual water reserve exist.
This choice thus induces some rather hard constraints for some rare periods but makes it possible to avoid oversizing the renewable electricity production installations. As we cans see in table 4.4, it possible to keep a LCOW close to 1.364[$/$m^3$] over all the years. This value remains however higher than the market value. As a conclusion, this model does not seem viable to compete with conventional SWRO desalination plants.

Year	**2006**	**2007**	**2008**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
LCOW [$/$m^3$]	1.367	1.376	1.373	1.377	1.364	1.364	1.390	1.364	1.364	1.365

Table 4.4: LCOW with the 2009 configuration, taking into account the shutdowns

4.3 Model 3

Combining renewable production with water storage provided the following results :

4.3.1 Results

Year	FF[-]	PV[ha]	WT[-]	Bat[MWh]	Tank[m^3]	N[-]	LCOW[$/$m^3$]	LCOE[$/$kWh$]
2006	0.8	14.739	24.10	/	70 400	2	**0.909**	0.069
	0.8	11.561	24.1	/	67 048	2	**0.904**	0.069
2007	0.8	13.112	21.07	/	161 360	1.8	**0.903**	0.062
	0.8	10.257	21.07	/	161 360	1.8	**0.898**	0.062
2008	0.8	15.965	25.1	/	120 410	2.1	**0.919**	0.072
	0.8	12.676	25.1	/	132 750	2.1	**0.917**	0.072
2009	0.8	14.011	24.04	/	126 430	1.9	**0.943**	0.071
	0.7	16.613	21.04	/	43 219	1.9	**0.939**	0.072
2010	0.8	14.115	25.09	/	104 010	1.9	**1.009**	0.078
	0.7	17.657	23.11	/	94 343	2	**1.005**	0.081
2011	0.9	6.616	23.07	/	85 572	1.8	**0.91**	0.062
	0.8	10.439	20.5	/	50 032	1.8	**0.905**	0.062
2012	0.8	14.846	23.08	/	77 616	2	**0.919**	0.069
	0.8	11.801	23.08	/	85 572	2	**0.916**	0.068
2013	0.8	14.359	21.03	/	227 050	1.9	**0.907**	0.063
	0.8	11.416	21.03	/	238 400	1.9	**0.904**	0.063
2014	0.8	15.453	23.07	/	33 864	2.1	**0.895**	0.068
	0.8	12.204	23.07	/	32 251	2.1	**0.89**	0.067
2015	0.8	15.747	22.04	/	99 060	2.1	**0.882**	0.065
	0.8	12.509	22.04	/	114 670	2.1	**0.88**	0.064
2016	0.8	14.809	19.15	/	99 060	1.8	**0.866**	0.059
	0.8	11.334	19.15	/	89 850	1.8	**0.861**	0.058

Table 4.5: Best configuration year per year.

4.3.2 Graphs Worst vs best year

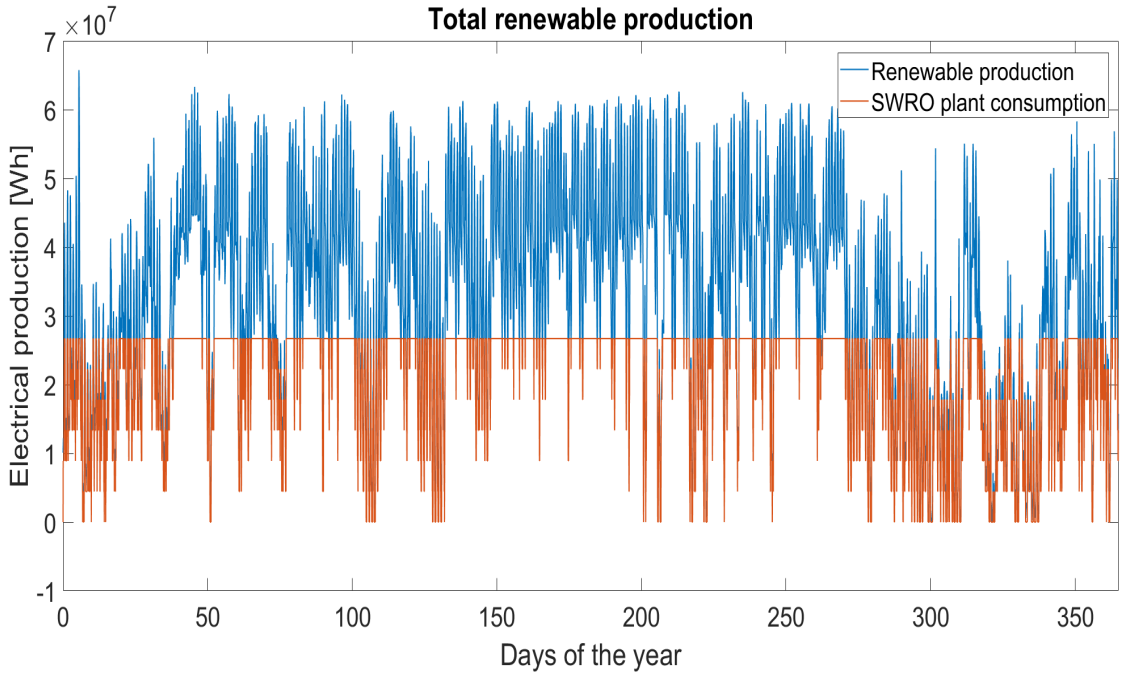


Figure 4.17: Electrical production and consumption 2016

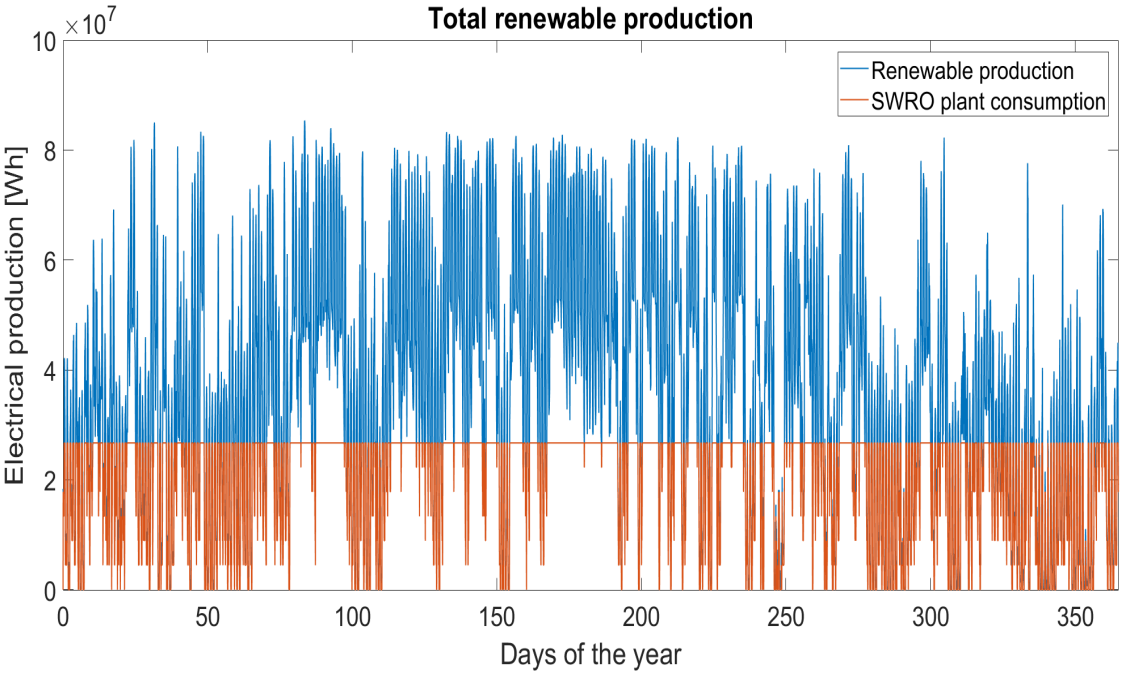


Figure 4.18: Electrical production and consumption 2010

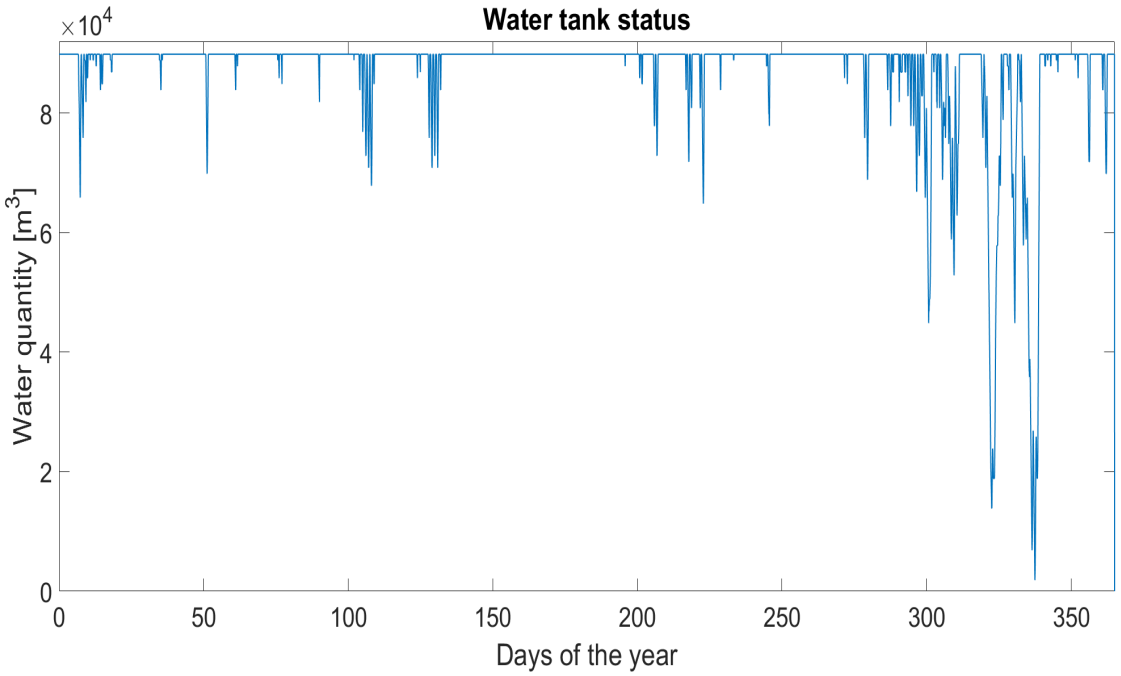


Figure 4.19: Water tank status 2016

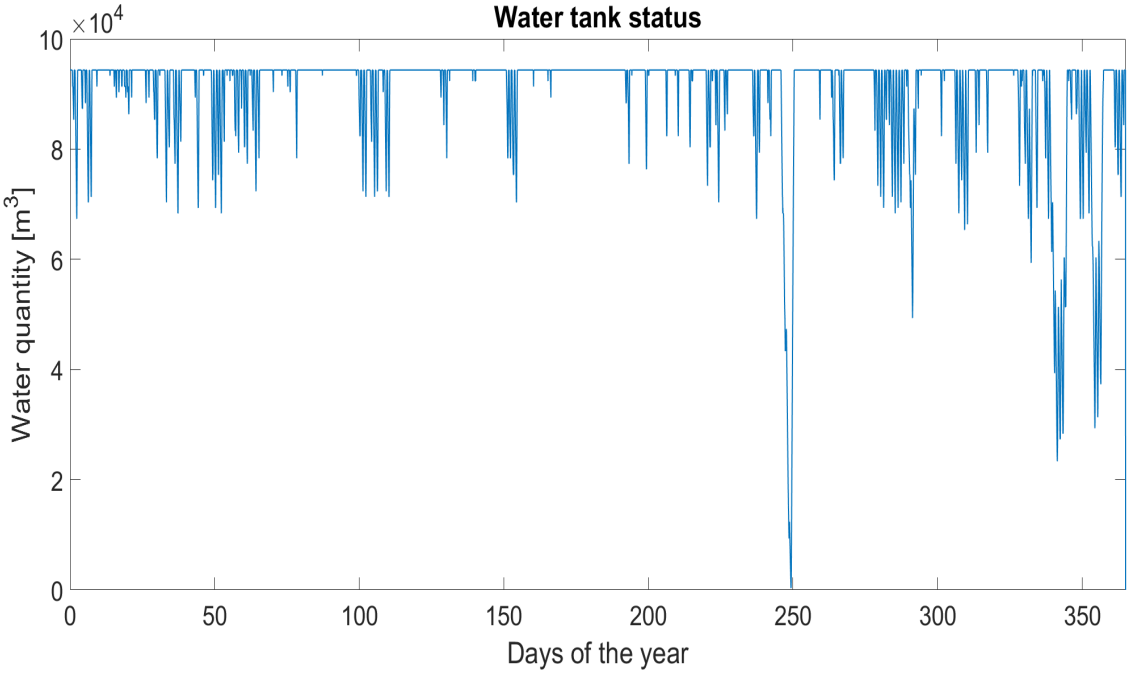


Figure 4.20: Water tank status 2010

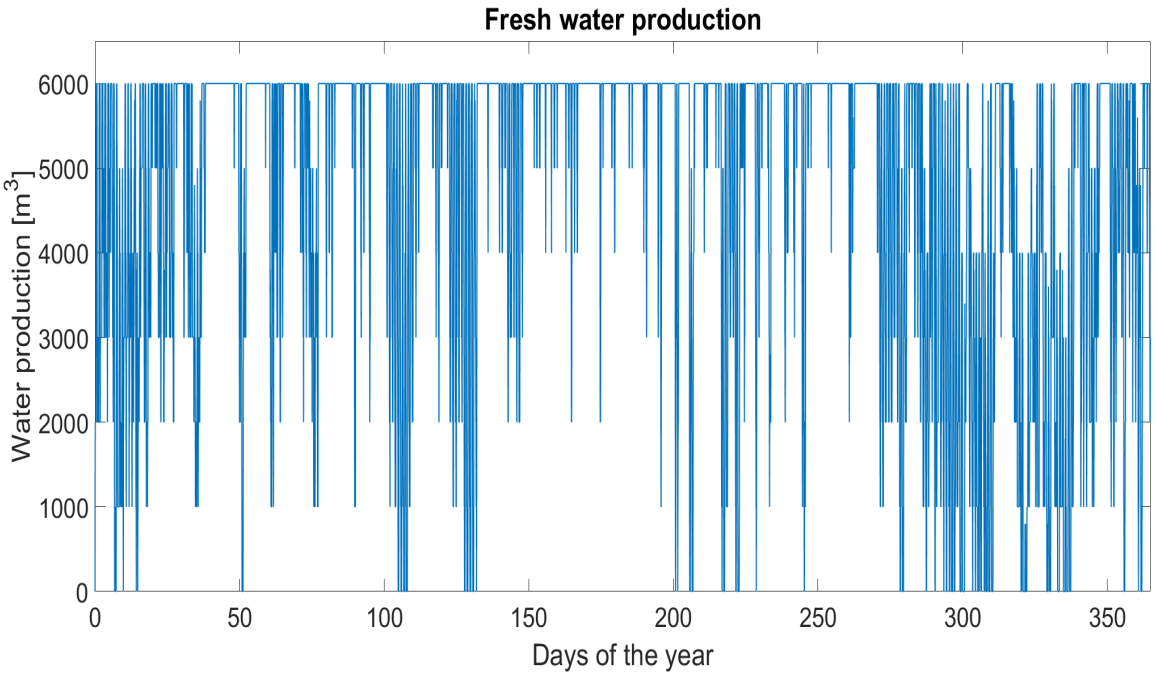


Figure 4.21: Water production 2016

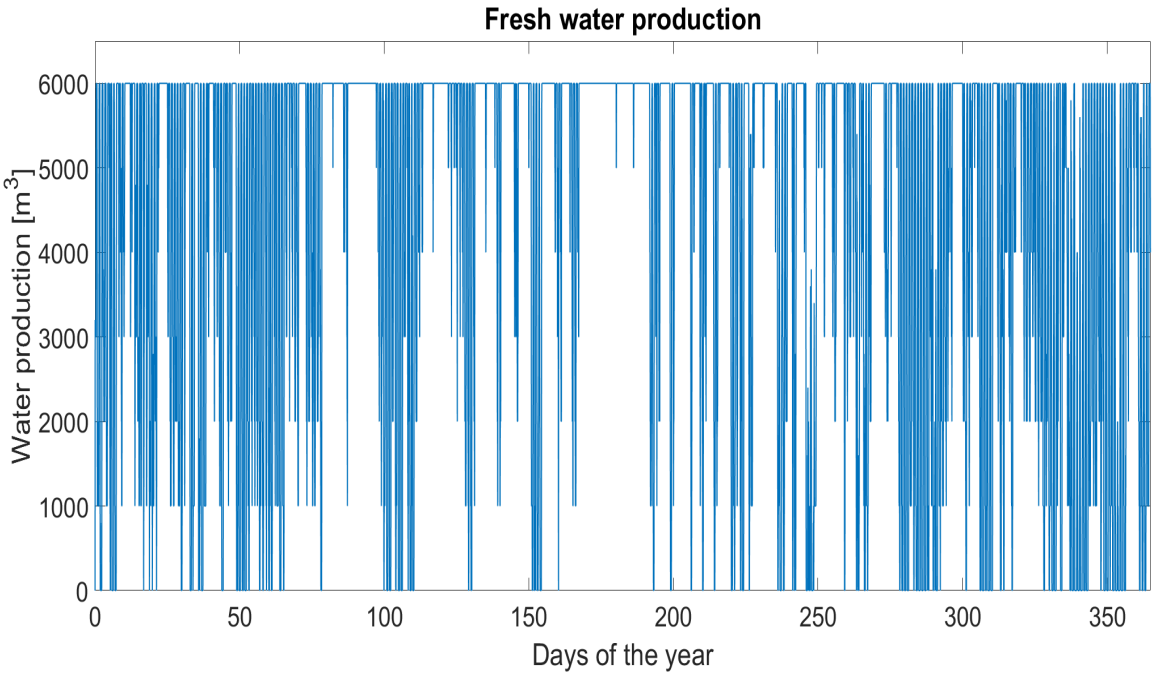


Figure 4.22: Water production 2010

4.3.3 Interpretation

As explained earlier in the report, the constraint for the flexible model is that the output must always be at least equal to half output of the constant models so 2000$[m^3/h]$, to avoid a significant over-production of water. To achieve this, the battery storage is replaced by a desalinated water storage. Considering a plant with 6 trains instead of 4 (144 000$[m^3/day]$), the final water production will obviously be higher than in the two previous models. To calculate the LCOW, the assumption is

made that all the water produced has the same market value.
Observing results of table 4.5, we notice that the installation with dual axis tracking PV allows a small gain for each year. We will then consider this technology for this model. We also can notice that each configuration is balanced for the factor FF and N.
On the other hand the water storage capacity varies significantly with the year and the configuration (from 32251 to 238400[m^3]). This is obviously linked to the total production of electricity. If we look at the LCOW, the worst year is 2010 and the best 2016. The electricity production in year 2010 is oversized and larger renewable installations are needed. We also note that the storage of desalinated water is not used much for either one. The water tank is emptied just two or three times in the year (around the 325th and 335th day for 2016 and around the 250th,340th and 360th day of 2010).

In this model, with the hypotheses considered, we arrive at a LCOW cheaper than 1[$\$/m^3$]. It is important to note that the LCOE also lowers to less than the market price of electricity. This shows the interest of trying to develop this flexible plant configuration plant that provide a good match with the variable renewable production.

4.3.4 Final configuration choice

In model 3, as explained above, installations using dual axis tracking PV panels give better results than fixed PV, so we select this technology. Furthermore, referring to table 4.5, all configurations are very close from each other (N between 1.8-2.1 and FF between 0.7-0.8)
It will be assumed that the plant will be specifically designed for flexible operation and therefore maintenance and cleaning of the various trains can be carried out continuously during the year without having to shut down the whole plant. For example, the order in which the different trains are switched on will be changed during the year to be able to equalize trains use and ensure a continuous maintenance on all trains. So we will limit as much as possible the number of forced shutdowns in the plant, if any.
The configuration of the year 2007 is chosen, as the size of the installations as well as their relatively large storage allows to operate the plant over the eleven years except for three shortages spread over three distinct years(2008, 2009, 2013).

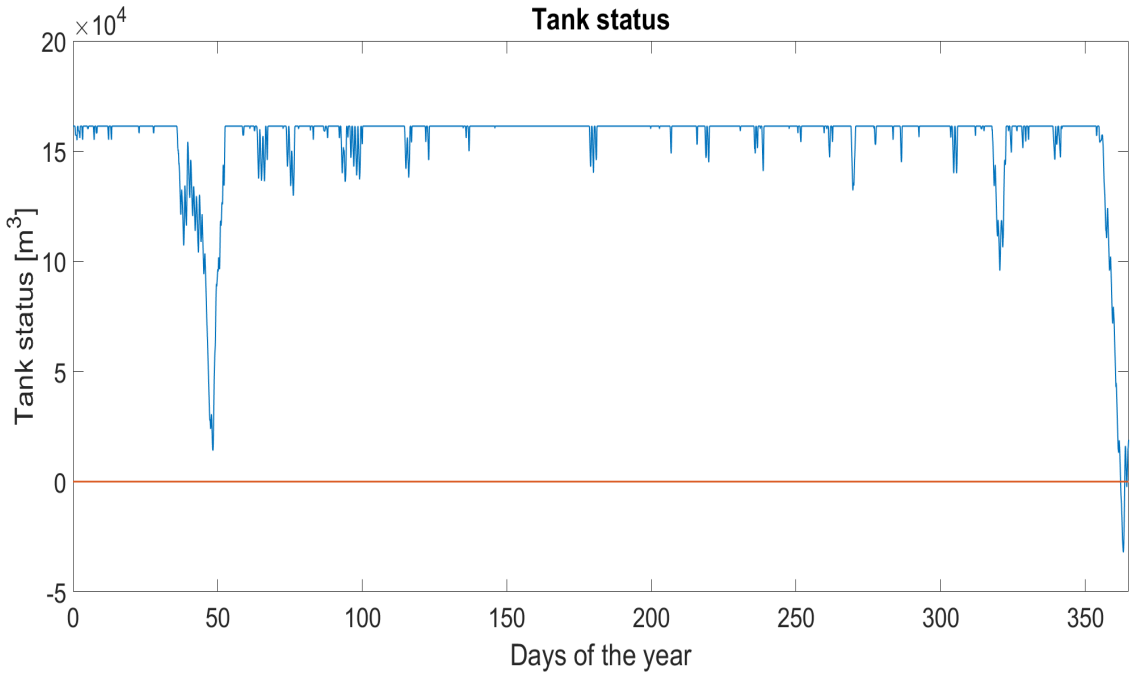


Figure 4.23: 2008 water reserve with 2007 configuration

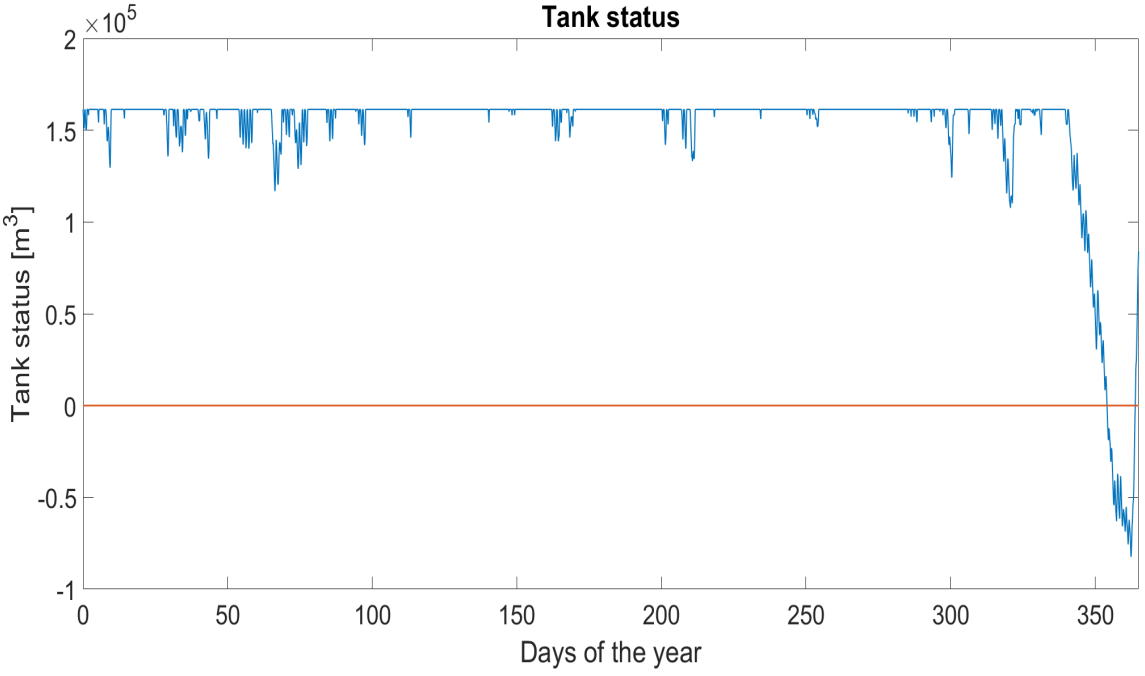


Figure 4.24: 2009 water reserve with 2007 configuration

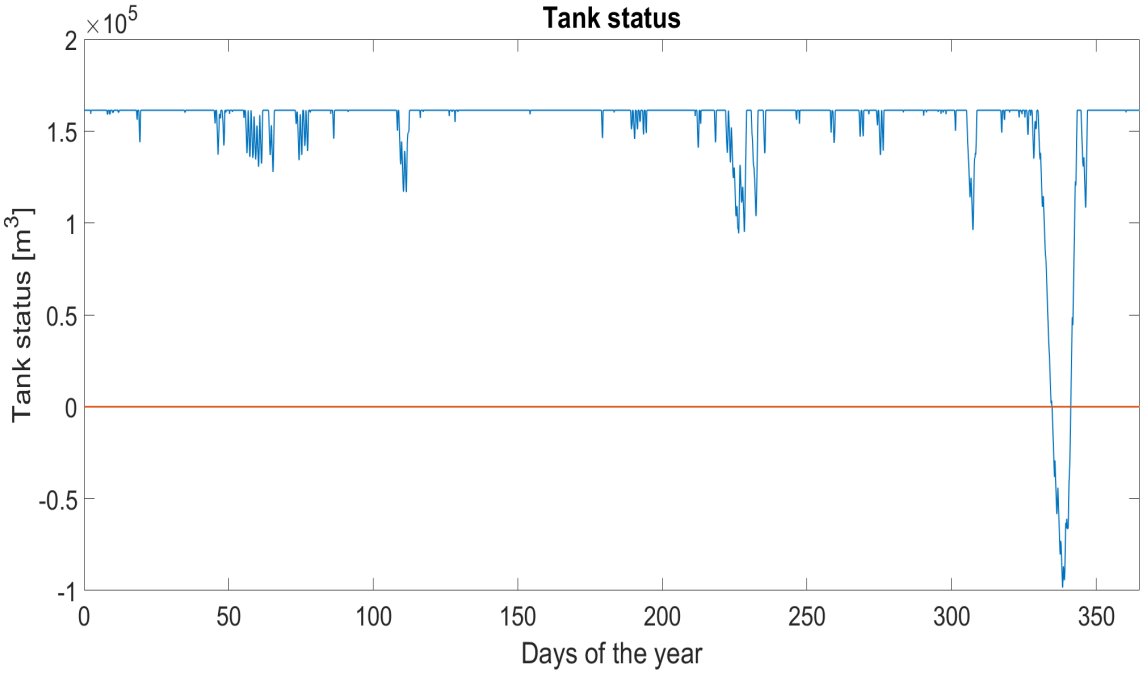


Figure 4.25: 2013 water reserve with 2007 configuration

As can be seen, the shortage in 2008 is very light and a small additional water storage would avoid having to shut down the SWRO plant.
On the other hand for the years 2009 and 2013, we still have this big dip around day 355 and 340 respectively, which will force the complete shutdown of the plant supply for about ten to fifteen days. However, the overall results are encouraging, with only two forced shutdown in 11 years. The resulting LCOW with the 2007 configuration which takes into account the shutdown losses, shown in table 4.6 gives good results with only one year above 1[$\$/m^3$].
It has to be noted that additional costs might be exposed when maintaining a drinkable water reserve. Precautions have to be taken to ensure the water sanitary quality (chemically and bacteriologically). Similarly, the security around the water tank will have be provided . Both could lead to some additional capex and opex, which we have not been able to quantify. The amount might however stay low in comparison to the overall plant costs.

Year	**2006**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
LCOW [$\$/m^3$]	0.912	0.920	0.958	1.015	0.909	0.922	0.903	0.896	0.881	0.8651

Table 4.6: LCOW with the 2007 configuration, taking into account the shutdowns

4.4 Model 4

Combining renewable production with battery and water storage provided the following results :

4.4.1 Results

Year	FF[-]	PV[ha]	WT[-]	Bat[MWh]	Tank[m^3]	N[-]	LCOW[$/$m^3$]	LCOE[$/$kWh$]
2006	0.8	14.739	24.1	8.732	47 649	2	**0.894**	0.068
	0.8	11.561	24.1	8.732	50 032	2	**0.889**	0.068
2007	0.8	13.112	21.07	8.732	120 410	1.8	**0.884**	0.063
	0.8	10.257	21.07	8.732	126 430	1.8	**0.879**	0.063
2008	0.8	15.965	25.1	7.183	70 400	2.1	**0.901**	0.072
	0.8	10.262	20.32	8.732	126 432	1.7	**0.9**	0.063
2009	0.8	14.011	24.04	8.732	60 814	1.9	**0.920**	0.07
	0.8	11.076	24.04	8.316	60 814	1.9	**0.915**	0.069
2010	0.8	14.115	25.1	9.168	81 497	1.9	**0.988**	0.077
	0.7	14.126	18.49	9.627	99 060	1.6	**0.982**	0.069
2011	0.8	11.762	18.23	6.516	47 649	1.6	**0.889**	0.057
	0.8	9.279	18.23	6.205	50 032	1.6	**0.885**	0.057
2012	0.8	14.846	23.08	6.205	60 814	2	**0.901**	0.068
	0.8	11.801	23.08	6.205	67 048	2	**0.898**	0.068
2013	0.8	14.359	21.03	9.168	177 900	1.9	**0.89**	0.065
	0.8	11.416	21.03	9.168	205 940	1.9	**0.888**	0.065
2014	0.9	6.255	21.01	6.516	67 048	1.7	**0.874**	0.056
	0.9	4.94	21.008	6.516	67 048	1.7	**0.873**	0.056
2015	0.8	15.747	22.04	7.183	60 814	2.1	**0.866**	0.064
	0.8	12.509	22.04	7.183	73 920	2.1	**0.864**	0.064
2016	0.8	13.986	18.085	6.841	81 497	1.7	**0.849**	0.056
	0.8	11.334	19.15	6.205	67 048	1.8	**0.843**	0.057

Table 4.7: Best configuration year per year.

4.4.2 Graphs worst vs best year

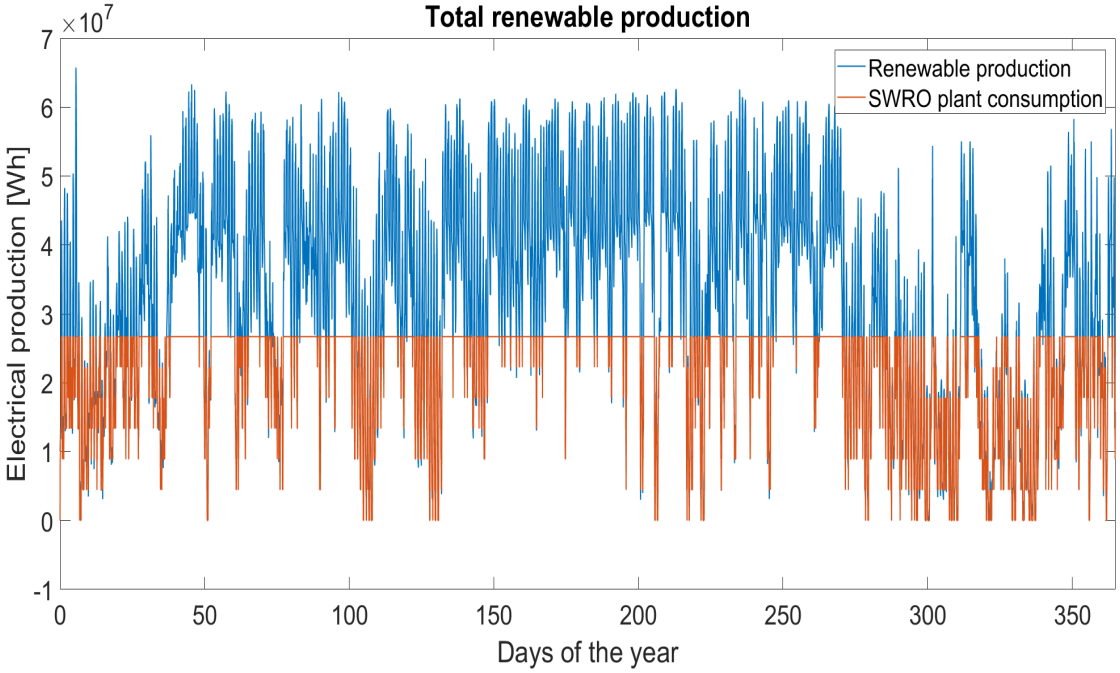


Figure 4.26: Electrical production and consumption 2016

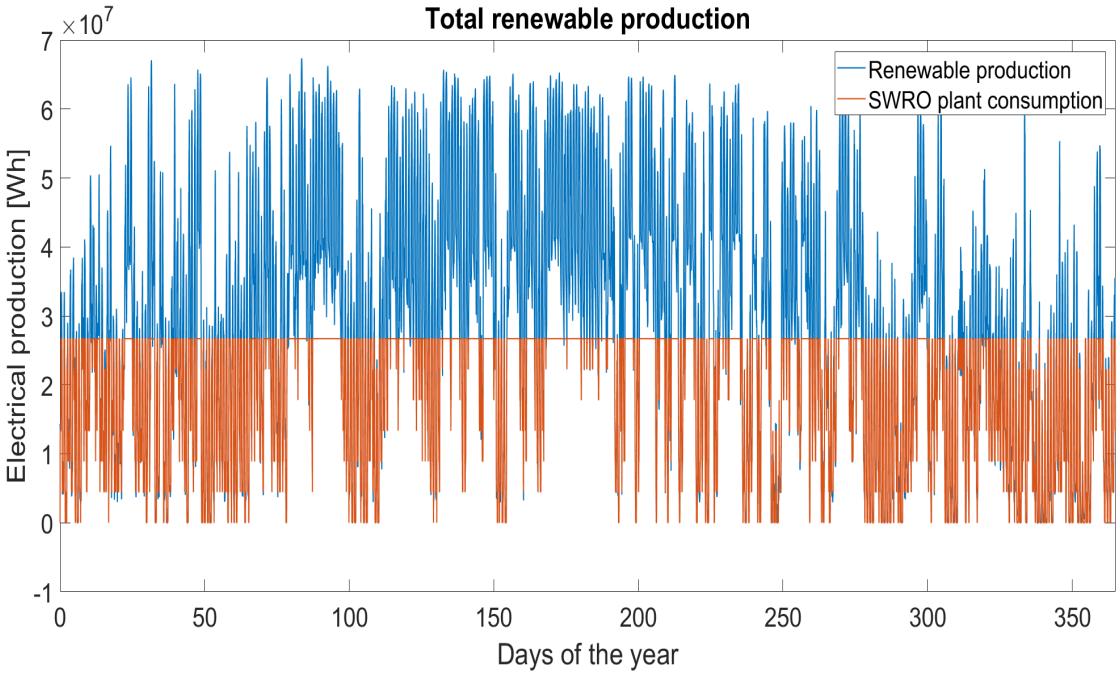


Figure 4.27: Electrical production and consumption 2010

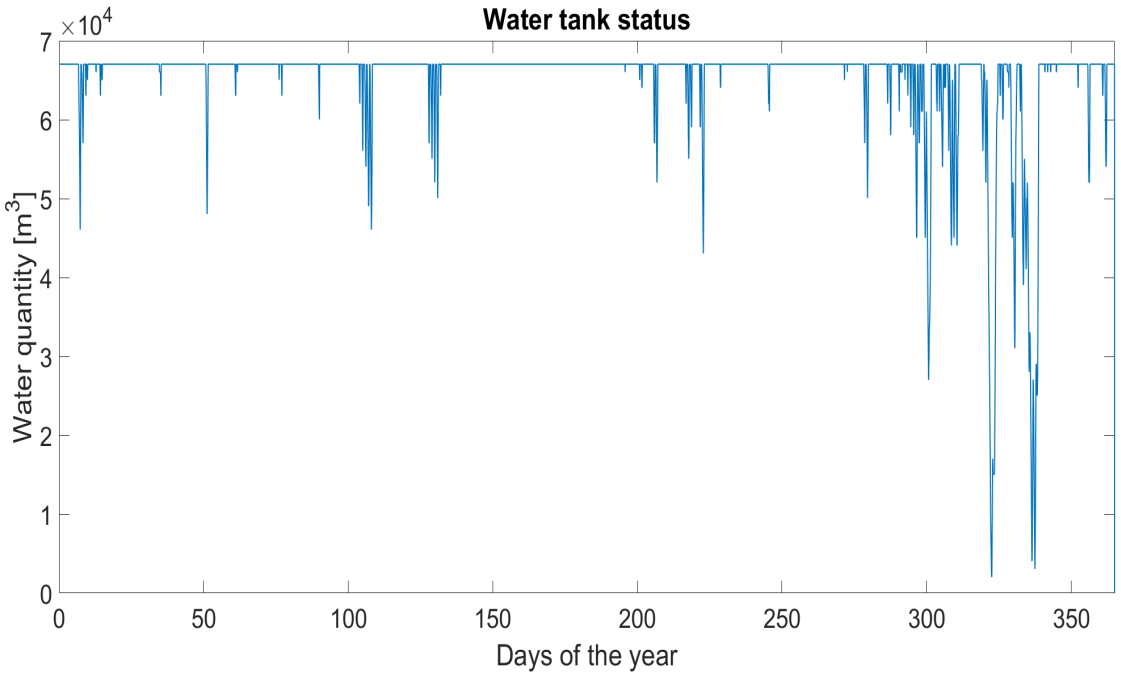


Figure 4.28: Water tank status 2016

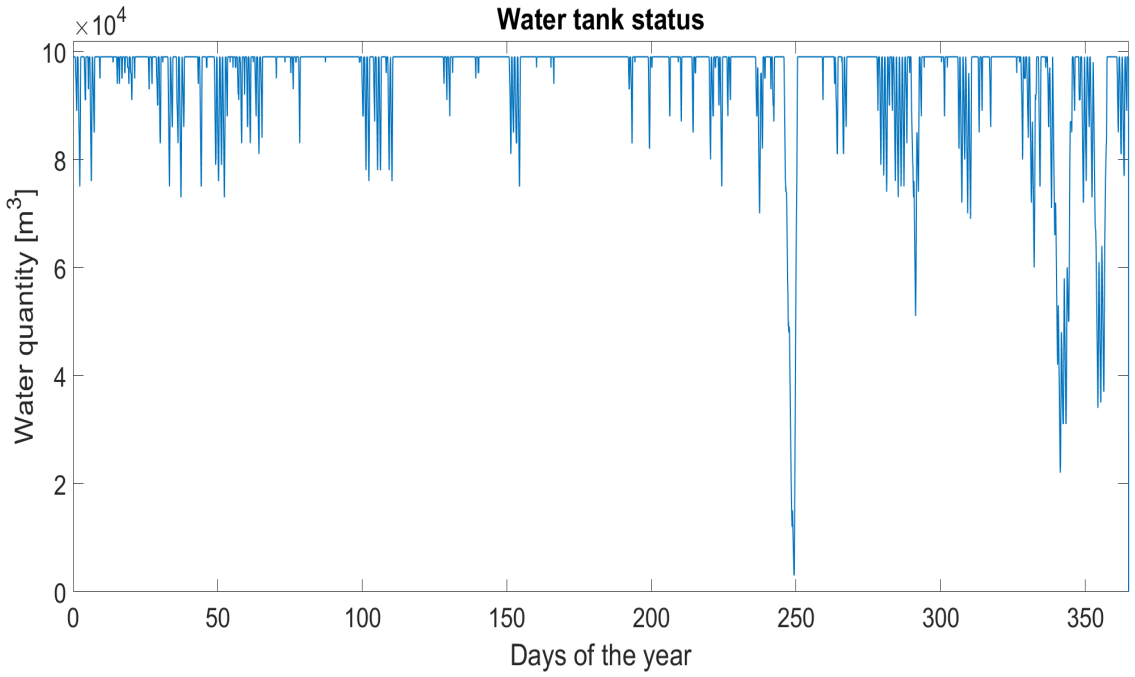


Figure 4.29: Water tank status 2010

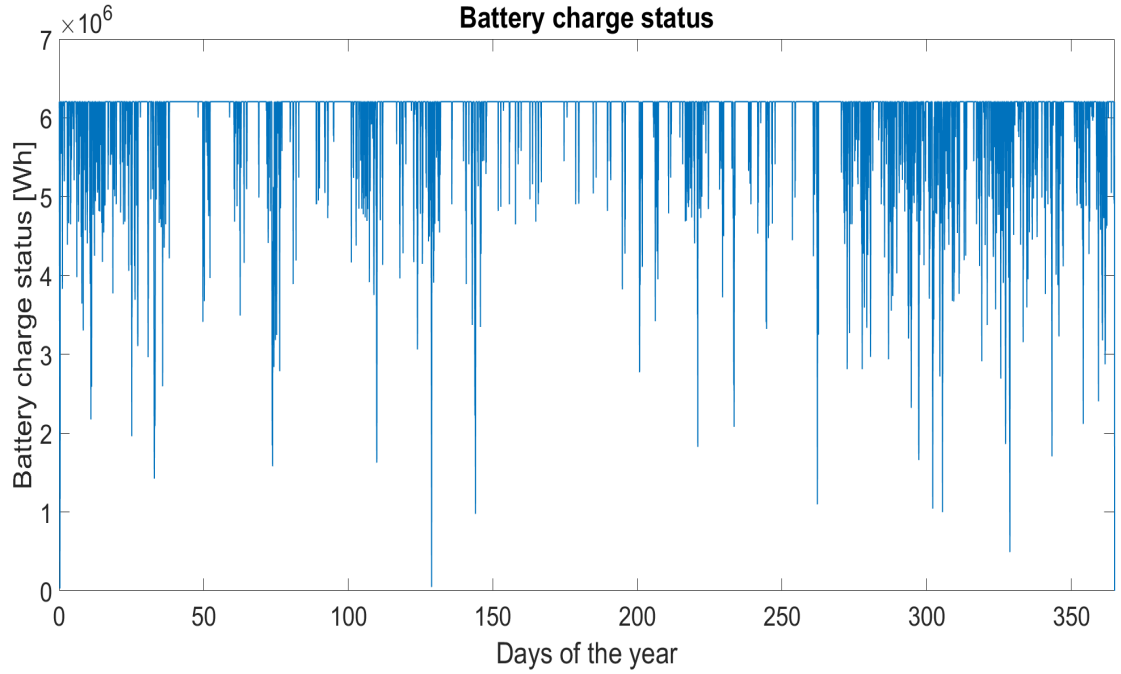


Figure 4.30: Battery charge status 2016

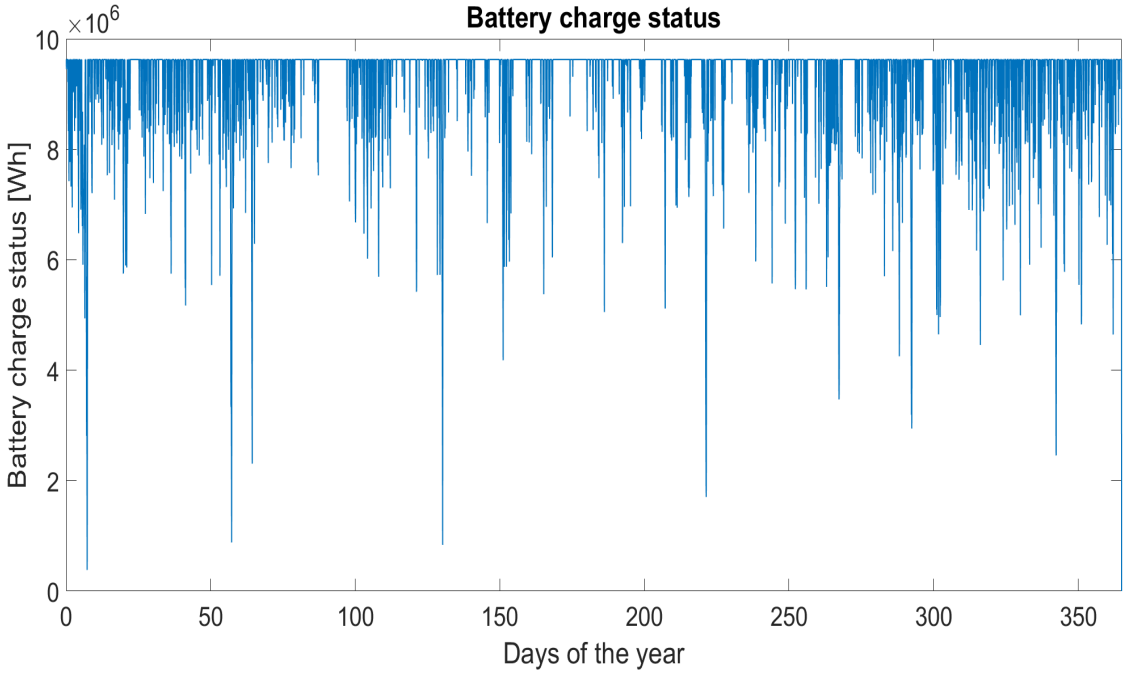


Figure 4.31: Battery charge status 2010

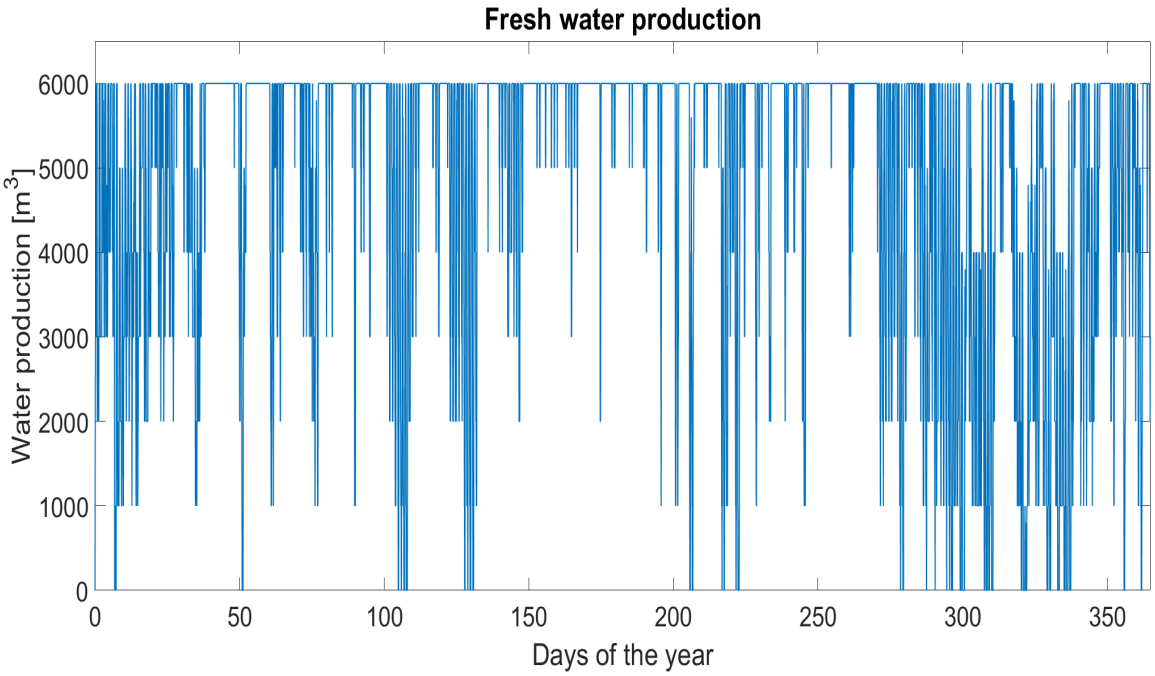


Figure 4.32: Water production 2016

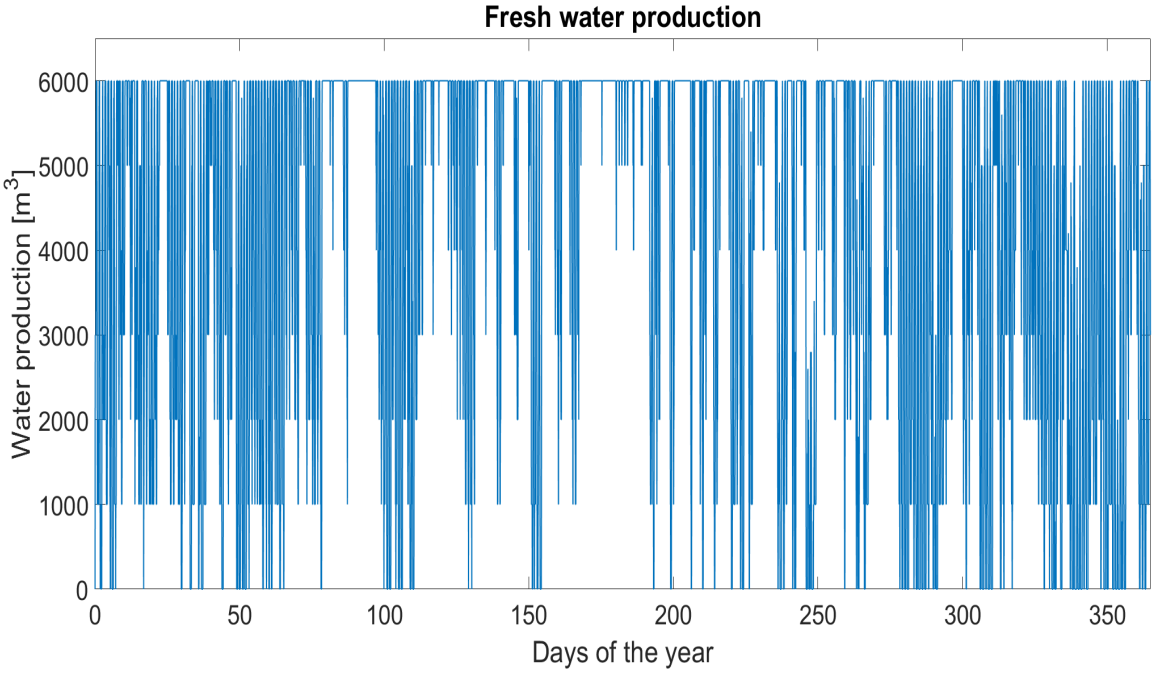


Figure 4.33: Water production 2010

4.4.3 Interpretation

It can be seen in the table 4.7 that the addition of batteries to improve the efficiency of the installations works. Indeed, the LCOW is on average 0.0178[$/$m^3$] and 0.0184[$/m^3] (respectively for fixed and dual axis tracking) lower than that of model 3. The graphs are similar with also two and three peaks (resp. 2016 and 2008) where the fresh water storage empties. Batteries are regularly used, which proves their usefulness to improve installations efficiency. The gain it brings on the LCOW

remains relatively small, as can be seen from the values calculated above. However, over the lifetime of the desalination plant this can make a big difference.
Overall, the results of Models 3 and 4 are encouraging.
In contrast to the constantly running models of the desalination plant, when the desalination plant operates flexibly, wind turbines are largely dominant over PV panels for power generation.
The LCOE also becomes lower than the market price of electricity in this model.

4.4.4 Final configuration choice

We will also consider here a configuration with a dual axis tracking PV panels installation since it gives globally lower LCOWs. The assumptions are the same as for model 3, with the addition of the battery installations. We will consider that the batteries cannot stay discharged more than one day.
The 2007 configuration works well: the size of the installations are reasonable (N=1.8), the battery storage relatively low compared to the other configurations (8.732MWh), and the water storage quite large but not the largest values(126430m^3).

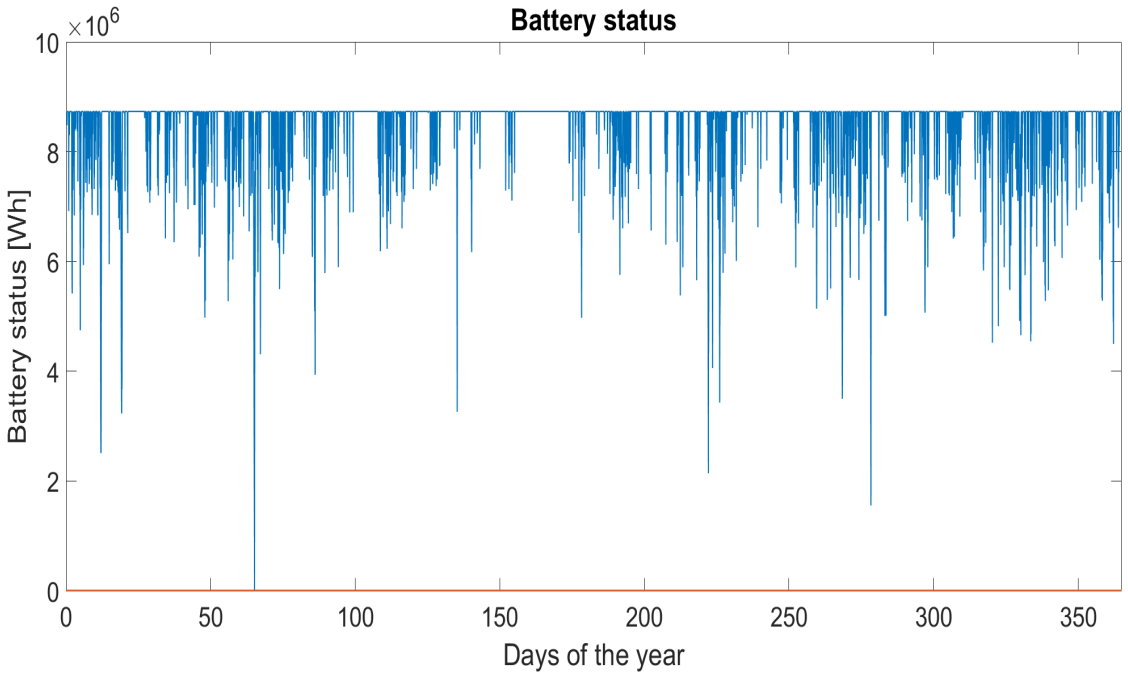


Figure 4.34: 2013 battery charge state with 2007 configuration

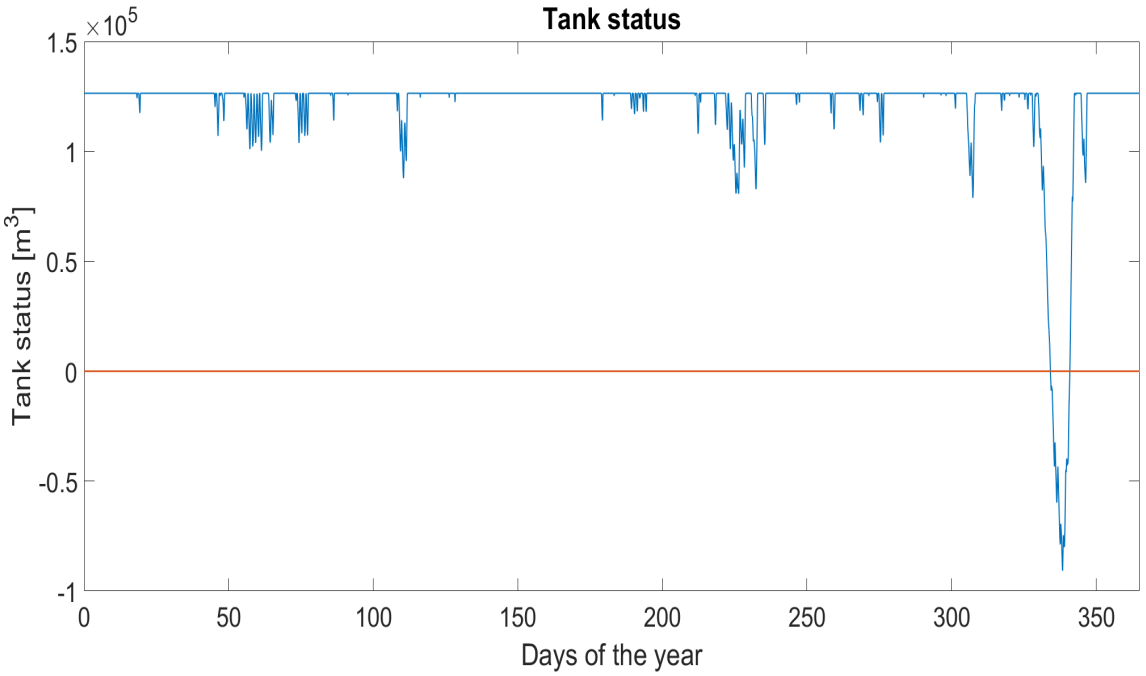


Figure 4.35: 2013 tank status with 2007 configuration

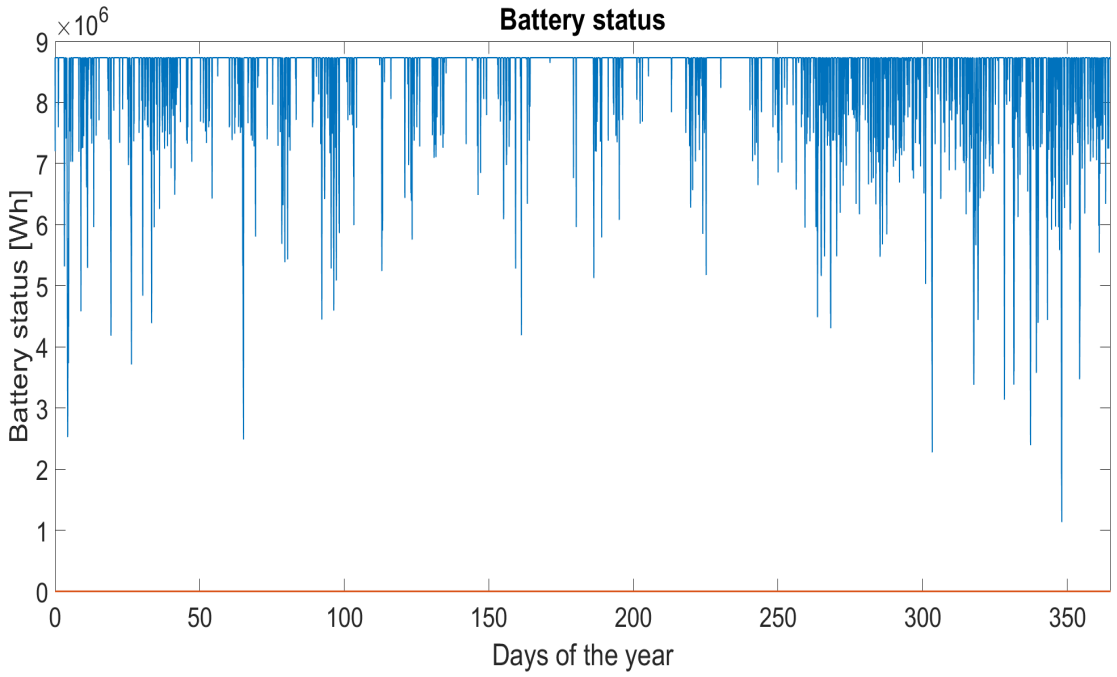


Figure 4.36: 2015 battery charge state with 2007 configuration

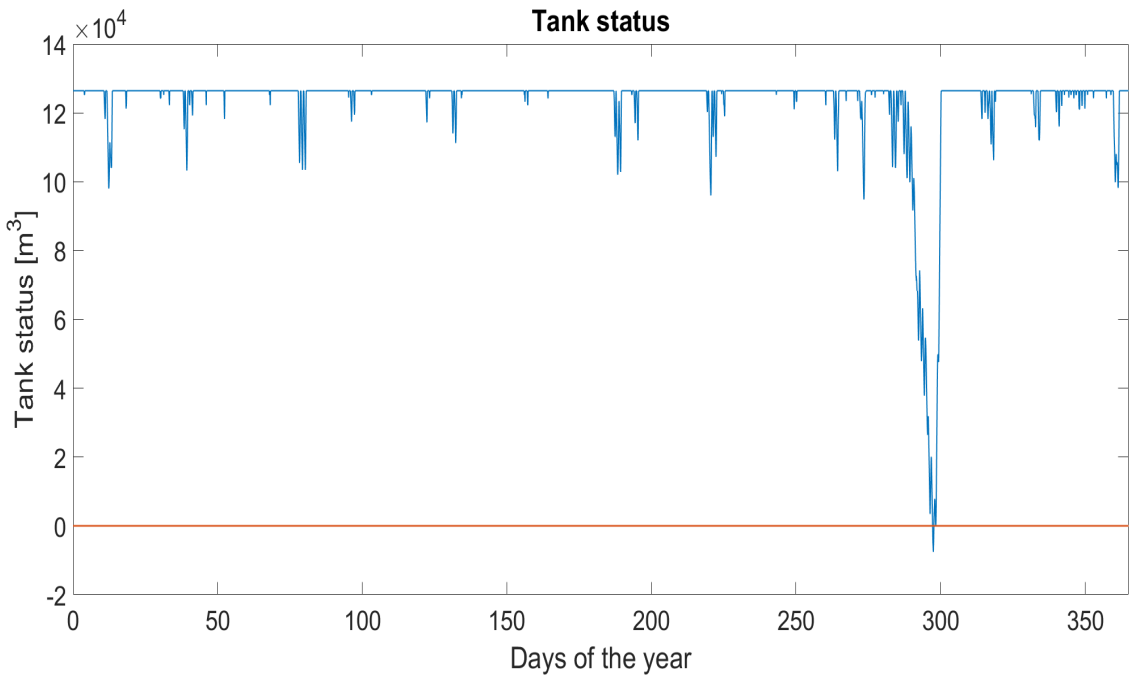


Figure 4.37: 2015 tank status state with 2007 configuration

Here again, the water storage gets problematically low at 2 occasions (2013 and 2015). In 2013, as for the previous model, the shortage is important and the plant will have to be shutdown for about ten days. Also solutions outside the plant will have to be found.
In 2015, there is a very slight shortage that should not require the shutdown of the plant and a simple slightly larger water storage would allow to overcome this situation. With this configuration we get the LCOWs shown in table 4.8. It should be noted that for the years where we consider no shutdown of the desalination plant, the LCOW will always be slightly higher than what is shown in the table 4.7. Indeed, these results are the minimum values of LCOW for each year without considering any shutdown.

Year	**2006**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
LCOW [$/$m^3$]	0.891	0.897	0.92	0.984	0.891	0.901	0.885	0.879	0.864	0.85

Table 4.8: LCOW with the 2007 configuration, taking into account the shutdowns

Chapter 5

Conclusion

This master thesis objective was to develop a methodology as well as an optimization scheme to produce desalinated water at the lowest cost possible while maximizing the use of renewable energy. The geographic location allowed to consider both photovoltaic and wind turbine processes without space constraint. The goal needed a right sizing (as low as possible) of the investment while ensuring a given desalinized water volume well distributed over the seasons.
The challenges to obtain relevant data for renewable energy production equipment costs as well as reverse osmosis equipment performances led to formulating work hypothesis. I believe they remained realistic and do not impair the obtained results.
On the other hand, the natural resources data (wind and sun irradiance) being available in a discrete for more than 10 years, an iterative calculation technique was developed. It allowed to determine optimum configurations on a yearly basis and from there extrapolate to the whole period to verify relevance of the proposed solutions. The approach was applied to configurations of increasing complexity until reaching realistic cost per liter of water.

The corresponding results obtained for the different models are encouraging. Starting with a setup with 100% renewable operation, the most expensive cost per liter is calculated. It highlights the classic problem of renewable energies which are diffuse by definition and are not very efficient at supplying a constant load. It results in a necessary over-sizing of the electrical installations as well as a oversized storage. In addition, some rare periods of very low energy production endanger the good functioning of a plant reasonably sized (i.e. with constrained storage capacity). This solution is therefore unlikely, even with a significant drop in the price of renewable electricity generation facilities in the coming years, because it will never be optimal for a company seeking to maximize its revenues.
The relatively low kWh_e prices allow slightly better results for model 2, which uses the grid as a buffer, up to 23.9% of the plant consumption. However, this is not enough for the plant to be competitive in the market. As, with the imposed limitation of max 23.9% of the power being supplied by the MV grid connection, this last does not allow to avoid holes in the renewable production, the storage must also be oversized, with its corresponding investment costs.

Both models with flexible water production are very encouraging, even considering several constraints

that had to be imposed. Firstly, the desalination plant must be oversized compared to the constant production cases. The minimum water quantity supplied in hours per hour is half of the constant case. This could therefore have negative consequences on consumers and will imply a good management of the water distribution. Second, there will also be overproduction at times, so it will be necessary to find a useful use for this water when this happens. Flexible operation increases plant management complexity as well as the plant design. This complexity will have a cost that could not be estimated in this report. It remains that the results obtained correspond to the market values of the drinking water production, and considering that the prices of renewable installations will continue to fall in the coming years. This solutions really seems the way forward.

The results show that this flexible operation blends much better with renewable electricity production, thus avoiding major over-sizing. Moreover, the alternative of water storage to battery storage allows a significant cost reduction with a much simpler installation.

The combination of water and battery storage as defined in Model 4 to maximize water production also has the advantage of being completely off-grid and allows the implementation of this type of plant in arid regions with no electricity grid.

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Chapter 6

Annexes

6.1 Codes

6.1.1 Model 1

```
close all;

%% premier mod le 100% renouvelable avec PV, wind turbine and batteries
%% consomation de l'usine de d salement variable avec la temperature de
    l'eau (par saison)
Conso_tot = sum(Conso_syst); % en MWh
%% Wind turbine production with Enercon E- 44-92 800kW-2350kW

% power curve

cut_in_speed = 3; %m/s
cut_out_speed = 28;

wind = [1 : 25];
% en kW
power_44 = [0 0 4 20 50 96 156 238 340 466 600 710 790 850 880 905 910
    910 910 910 910 910 910 910 910];% 900kW
power_48 = [0 0 5 25 60 110 180 275 400 555 671 750 790 810 810 810 810
    810 810  810 810 810 810 810 810];% 800kW
power_53 = [0 2 14 38 77 141 228 336 480 645 744 780 810 810 810 810 810
    810 810 810 810 810 810 810 810]; % 800kW
power_70 = [0 2 18 56 127 240 400 626 892 1223 1590 1900 2080 2230 2300
    2310 2310 2310 2310 2310 2310 2310 2310 2310 2310]; % 2300kW
power_82 = [0 3 25 82 174 321 532 815 1180 1580 1810 1980 2050 2050 2050
    2050 2050 2050 2050 2050 2050 2050 2050 2050 2050]; % 2000kW
power_82_2 = [0 3 25 82 174 321 532 815 1180 1580 1890 2100 2250 2350
    2350 2350 2350 2350 2350 2350 2350 2350 2350 2350]; % 2300kW
```

```
21 power_92 = [0 3.6 29.9 98.2 208.3 384.3 637 975.8 1403.6 1817.8 2088.7
       2237 2300 2350 2350 2350 2350 2350 2350 2350 2350 2350 2350 2350
       2350]; % 2350kW
22
23 xx = 0:.01:25;
24 % on calcule les diff rentes power curve des diff rentes   oliennes
       Enercon
25 yy_44 = spline(wind,power_44,xx); %cubic polynomial interpolation
26 yy_48 = spline(wind,power_48,xx);
27 yy_53 = spline(wind,power_53,xx);
28 yy_70 = spline(wind,power_70,xx);
29 yy_82 = spline(wind,power_82,xx);
30 yy_82_2 = spline(wind,power_82_2,xx);
31 yy_92 = spline(wind,power_92,xx);
32
33
34 %calcul de la production de chaque eolienne avec les data de vent a
       Dakhla.
35 L = length(Wind_speed);
36 Z0 = 0.0024;
37 Z = 150; %hauteur de l eolienne
38 Z_ref = 10; %hauteur a laquelle le vent est mesurer
39 prod_windTurbine_44 = zeros(L,1);
40 prod_windTurbine_48 = zeros(L,1);
41 prod_windTurbine_53 = zeros(L,1);
42 prod_windTurbine_70 = zeros(L,1);
43 prod_windTurbine_82 = zeros(L,1);
44 prod_windTurbine_82_2 = zeros(L,1);
45 prod_windTurbine_92 = zeros(L,1);
46 for i=1:L
47     Wind_speed_corr(i) = Wind_speed(i)*log(Z/Z0)/log(Z_ref/Z0);
48     a = fix(Wind_speed_corr(i));
49     b = mod(Wind_speed_corr(i),a);
50     c = 100*a + 100*b;
51     prod_windTurbine_44(i) = yy_44(fix(c)); % en kW
52     prod_windTurbine_48(i) = yy_48(fix(c));
53     prod_windTurbine_53(i) = yy_53(fix(c));
54     prod_windTurbine_70(i) = yy_70(fix(c));
55     prod_windTurbine_82(i) = yy_82(fix(c));
56     prod_windTurbine_82_2(i) = yy_82_2(fix(c));
57     prod_windTurbine_92(i) = yy_92(fix(c));
58 end
59 %production totale sur l annee
```

```
60 prod_tot_44 = sum(prod_windTurbine_44);
61 prod_tot_48 = sum(prod_windTurbine_48);
62 prod_tot_53 = sum(prod_windTurbine_53);
63 prod_tot_70 = sum(prod_windTurbine_70);
64 prod_tot_82 = sum(prod_windTurbine_82);
65 prod_tot_82_2 = sum(prod_windTurbine_82_2);
66 prod_tot_92 = sum(prod_windTurbine_92);
67 prod_tot = [ prod_tot_44/900 prod_tot_48/800 prod_tot_53/800 prod_tot_70
       /2300 prod_tot_82/2000 prod_tot_82_2/2300 prod_tot_92/2350];
68
69 %% PV panels
70
71 % fixed tilt
72 Pn_PV = 442.8; % en watt
73 Area_unit_PV = 2.113; % en m^2
74 eta_n_PV = 0.2093;
75 Pn_per_m2 = Pn_PV/Area_unit_PV; %Watt/m^2
76
77 % dual axis
78 % Pn_PV = 415.8; % en watt
79 % Area_unit_PV = 2.113; % en m^2
80 % eta_n_PV = 0.1966;
81 % Pn_per_m2 = Pn_PV/Area_unit_PV; %Watt/m^2
82
83 % pertes
84 eta_SDF = 0.98; % system derate factor
85 eta_inverter = 0.95;
86 eta_temp = 0.88;
87 eta_wire = 0.98;
88 eta_PV = eta_n_PV*eta_SDF*eta_inverter*eta_temp*eta_wire;
89
90 % dimmensionnement
91 G = sum(G_i);
92
93
94 %% Conso systeme
95 %consomation de lusine en Wh (heure par heure)
96 Conso_syst_Wh = 1e6.*Conso_syst; % en Wh
97
98
99 %% Costs
100
101 % Wind turbine (prise sur internet)
```

```
C_WT = 3.34e6; % cout pour une E-92 : achat, installation et maintenance sur 20 ans
O_WT = 101e3;
% Pv panels
C_PV = 840; % /kWh : achat installation et maintenance sur 25 ans
O_PV = 16.8;
% C_PV = 1120; %pour dual axis tracking
% O_PV = 22.4;
% batteries
C_bat = 420; % /kwh : achat installation et maintenance sur 20 ans
O_bat = 12;
% plant
C_plant = 96*1.2625e6;
O_plant = 96*1.1e6/20;
%% optimisation
ff = [0:0.1:1]; % on va regarder quelle repartition PV/WT est la meilleures
%N = 2.2; % cmb de fois la production minimale est le meilleur compromis pour diminuer les couts (cout des batteries tres cher pour N=1)
L2 = length(ff);
N0 = 1; % a changer si on change la valeur de d but du N dans la boucle for
% batterie
eta_bat = 0.886;

iter = 1;
for N=1:0.1:5
    % PV
    Area_PV_opt = N*(1-ff).*Conso_tot.*1e6./(eta_PV.*G); %vecteur de 11 colonnes avec les surface de panneaux necessaire dans chaque cas
    %WT
    Number_WT_opt = N*ff.*Conso_tot.*1e3./prod_tot_92;

    Area_PV_opt_tab(iter,:) = Area_PV_opt; % pour stocker dans un tableau toute les valeurs des aire des panneaux
    Number_WT_opt_tab(iter,:) = Number_WT_opt;
    % calcul de chaque quantite d energie produite ensuite dimensionnement avec
    % batterie jamais prise en d faut ( un gros d ficit survient en fin d annee
    % peut etre on peut prevoir une fermeture annuelle de maintenance de 20
    % jours ?)
```

```
136     for k=1:L2
137         E_gen_PV_opt(k,:) = eta_PV*Area_PV_opt(k).*G_i;
138         E_gen_WT_opt(k,:) = 1000.*(fix(Number_WT_opt(k))+1).*
                prod_windTurbine_92;
139         E_gen_tot_opt = E_gen_PV_opt(k,:) + E_gen_WT_opt(k,:);
140         E_gen_tot_opt_2(k,:) = E_gen_tot_opt;
141         [C2,E2] = batterie(Conso_syst_Wh,E_gen_tot_opt,L);
142         Cap_bat(iter,k) = C2/eta_bat;
143         E_bat_opt(k,:) = E2 + (C2/eta_bat - C2); % la paranthese en plus
                c'est pour consid rer le rendement des batteries
144
145         % stocker toute les valeurs pour pouvoir replotter les graphes.
146         E_gen_PV_tab(iter,k,:) = E_gen_PV_opt(k,:);
147         E_gen_WT_tab(iter,k,:) = E_gen_WT_opt(k,:);
148         E_gen_tot_tab(iter,k,:) = E_gen_tot_opt_2(k,:);
149         E_bat_tab(iter,k,:) = E_bat_opt(k,:);
150
151     end
152     iter = iter+1;
153 end
154
155
156
157 %% calculs costs % NB : a integrer dans les cout le rendement des
        batterie qui est pas encore pris en compte
158 DR = 0.07; % discount rate 7%
159 CRF = (DR*(1+DR)^20)/((1+DR)^20-1);
160
161 C_WT_tot = Number_WT_opt_tab.*C_WT; % vecteur de 10 en fonction de ff
162 C_PV_tot = Pn_per_m2.*Area_PV_opt_tab.*C_PV./1000;
163 C_bat_tot = Cap_bat.*C_bat./1000;
164 O_WT_tot = Number_WT_opt_tab.*O_WT; % vecteur de 10 en fonction de ff
165 O_PV_tot = Pn_per_m2.*Area_PV_opt_tab.*O_PV./1000;
166 O_bat_tot = Cap_bat.*O_bat./1000;
167
168 Capex_tot = C_WT_tot + C_PV_tot + C_bat_tot + C_plant; % a minimiser au
        final.
169 Opex_tot = O_WT_tot + O_PV_tot + O_bat_tot + O_plant;
170 Capex_tot2 = C_WT_tot + C_PV_tot + C_bat_tot;
171 Opex_tot2 = O_WT_tot + O_PV_tot + O_bat_tot;
172
173 LCOW = (Capex_tot.*CRF + Opex_tot)./96000./365;
174 LCOE = (Capex_tot2.*CRF + Opex_tot2)./96./4157./365;
```

```
175 %TROUVER LA MEILLEURE CONFIG
176 minimum = min(min(LCOW));
177 [ind_ligne,ind_colonne] = find(LCOW==minimum);
178
179 %% Output + Graphes
180 opt_N = N0 + (ind_ligne-1)*0.1 % attention au pas 0.1 si on veut le
        changer dans l'opti
181 opt_FF = ff(1) + (ind_colonne-1)*0.1
182 LCOW2 = LCOW(ind_ligne,ind_colonne)
183 LCOE2 = LCOE(ind_ligne,ind_colonne)
184 AirePV = Area_PV_opt_tab(ind_ligne,ind_colonne)
185 NombreWT = Number_WT_opt_tab(ind_ligne,ind_colonne)
186 Capcite_batterie = Cap_bat(ind_ligne,ind_colonne)
187 % val = Capex_tot(ind_ligne,ind_colonne)*CRF + Opex_tot(ind_ligne,
        ind_colonne)
188
189 plot_PV = squeeze(E_gen_PV_tab(ind_ligne,ind_colonne,:));
190 plot_WT = squeeze(E_gen_WT_tab(ind_ligne,ind_colonne,:));
191 plot_tot = squeeze(E_gen_tot_tab(ind_ligne,ind_colonne,:));
192 plot_bat = squeeze(E_bat_tab(ind_ligne,ind_colonne,:));
193
194 [workingBat,prod_wat2] = fixedConfig(Conso_syst_Wh,30.37,4.7197e5,2.9646
        e8,prod_windTurbine_92,G_i,eta_PV,L);
195 LCOW3 = (5.4178e7)/prod_wat2
196
197 heure = linspace(0,365,L);
198 zero_droite = zeros(L,1);
199 % plot(heure,plot_PV)
200 % title('production PV panels')
201 % xlabel('jour annee')
202 % ylabel('Production PV en Wh')
203 %
204 % figure;
205 % plot(heure,plot_WT)
206 % title('Production eolienne')
207 % xlabel('jour annee')
208 % ylabel('production eolienne en Wh')
209
210 figure;
211 plot(heure,plot_tot,heure,Conso_syst_Wh)
212 xlim([0 365])
213 title('Total renewable production')
214 xlabel('Days of the year')
```

```
215 ylabel('Electrical production Wh')
216 legend('Renewable production','SWRO plant consumption')
217
218 figure;
219 plot(heure,plot_bat)
220 xlim([0 365])
221 title('Battery charge status')
222 xlabel('Days of the year')
223 ylabel('Battery charge status [Wh]')
224 %
225 % figure;
226 % plot(heure,Conso_syst_Wh)
227 % title('Consomation system')
228
229 figure;
230 plot(heure,workingBat,heure,zero_droite)
231 xlim([0 365])
232 title('Battery charge status2')
233 xlabel('Days of the year')
234 ylabel('Battery charge status [Wh]')
235 %% functions
236 function [Capacite_bat,E_bat] = batterie(conso_RO,Energie_produite,L) %
237 E_bat = zeros(L,1);
238 E_bat(1) = 50e6;
239 i=2;
240 while i<L % cette fonction sort une valeur de la batterie necessaire pour
        qu'elle ne soit jamais vide
241     if E_bat(i-1)<0
242         E_bat(1) = E_bat(1)*1.05;
243         i=2;
244     else
245         if conso_RO(i) > Energie_produite(i)
246             E_bat(i) = E_bat(i-1)-(conso_RO(i)-Energie_produite(i));
247         else
248             E_bat(i) = E_bat(i-1)+(Energie_produite(i)-conso_RO(i));
249         end
250         if E_bat(i)>E_bat(1)
251             E_bat(i) = E_bat(1);
252         end
253         i=i+1;
254     end
255 end
256 Capacite_bat = E_bat(1);
```

```
257 end
258
259 function [workinBat,prod_wat2] = fixedConfig(conso_RO,configWT,configPV,
        configBat,windDataProd,irrData,eta_PV,L)% windDataProd ce que 1
          olienne    produit en fct des data de vents
260
261 Elec_gen_PV = configPV.*eta_PV.*irrData;
262 Elec_gen_WT = configWT.*windDataProd.*1e3;
263 Elec_gen_tot = Elec_gen_PV + Elec_gen_WT;
264
265 prod_wat = zeros(L,1);
266 Elec_bat = zeros(L,1);
267 Elec_bat(1) = configBat; % capacite de la batterie
268
269 for i=2:L
270     if Elec_gen_tot(i) - conso_RO(i) < 0
271         Elec_bat(i) = Elec_bat(i-1) + (Elec_gen_tot(i) - conso_RO(i));
272     else
273          Elec_bat(i) = Elec_bat(i-1) + (Elec_gen_tot(i) - conso_RO(i));
274     end
275     if Elec_bat(i)>Elec_bat(1)
276         Elec_bat(i)=Elec_bat(1);
277     end
278 end
279 workinBat = Elec_bat;
280 for ii=1:L
281     if Elec_bat(ii) < 0
282         prod_wat(ii) = 0;
283     else
284         prod_wat(ii) = 4000;
285     end
286 end
287 prod_wat2 = sum(prod_wat);
288 end
```

6.1.2 Model 2

```
1 close all;
2
3 %% premier mod le 100% renouvelable avec PV, wind turbine and batteries
      et grid
4 %% consomation de l'usine de d salement variable avec la temperature de
      l'eau (par saison)
5 Conso_tot = sum(Conso_syst); % en MWh
```

```
%% Wind turbine production with Enercon E- 44-92 800kW-2350kW

% power curve

cut_in_speed = 3; %m/s
cut_out_speed = 28;

wind = [1 : 25];
% en kW
power_44 = [0 0 4 20 50 96 156 238 340 466 600 710 790 850 880 905 910
    910 910 910 910 910 910 910 910];% 900kW
power_48 = [0 0 5 25 60 110 180 275 400 555 671 750 790 810 810 810 810
    810 810  810 810 810 810 810 810];% 800kW
power_53 = [0 2 14 38 77 141 228 336 480 645 744 780 810 810 810 810 810
    810 810 810 810 810 810 810 810]; % 800kW
power_70 = [0 2 18 56 127 240 400 626 892 1223 1590 1900 2080 2230 2300
    2310 2310 2310 2310 2310 2310 2310 2310 2310]; % 2300kW
power_82 = [0 3 25 82 174 321 532 815 1180 1580 1810 1980 2050 2050 2050
    2050 2050 2050 2050 2050 2050 2050 2050 2050]; % 2000kW
power_82_2 = [0 3 25 82 174 321 532 815 1180 1580 1890 2100 2250 2350
    2350 2350 2350 2350 2350 2350 2350 2350 2350 2350]; % 2300kW
power_92 = [0 3.6 29.9 98.2 208.3 384.3 637 975.8 1403.6 1817.8 2088.7
    2237 2300 2350 2350 2350 2350 2350 2350 2350 2350 2350 2350 2350
    2350]; % 2350kW

xx = 0:.01:25;
% on calcule les diff rentes power curve des diff rentes   oliennes
    Enercon
yy_44 = spline(wind,power_44,xx); %cubic polynomial interpolation
yy_48 = spline(wind,power_48,xx);
yy_53 = spline(wind,power_53,xx);
yy_70 = spline(wind,power_70,xx);
yy_82 = spline(wind,power_82,xx);
yy_82_2 = spline(wind,power_82_2,xx);
yy_92 = spline(wind,power_92,xx);


%calcul de la production de chaque eolienne avec les data de vent a
    Dakhla.
L = length(Wind_speed);
Z0 = 0.0024;
Z = 150; %hauteur de l eolienne
Z_ref = 10; %hauteur a laquelle le vent est mesurer
```

```
prod_windTurbine_44 = zeros(L,1);
prod_windTurbine_48 = zeros(L,1);
prod_windTurbine_53 = zeros(L,1);
prod_windTurbine_70 = zeros(L,1);
prod_windTurbine_82 = zeros(L,1);
prod_windTurbine_82_2 = zeros(L,1);
prod_windTurbine_92 = zeros(L,1);
for i=1:L
    Wind_speed_corr(i) = Wind_speed(i)*log(Z/Z0)/log(Z_ref/Z0);
    a = fix(Wind_speed_corr(i));
    b = mod(Wind_speed_corr(i),a);
    c = 100*a + 100*b;
    prod_windTurbine_44(i) = yy_44(fix(c)); % en kW
    prod_windTurbine_48(i) = yy_48(fix(c));
    prod_windTurbine_53(i) = yy_53(fix(c));
    prod_windTurbine_70(i) = yy_70(fix(c));
    prod_windTurbine_82(i) = yy_82(fix(c));
    prod_windTurbine_82_2(i) = yy_82_2(fix(c));
    prod_windTurbine_92(i) = yy_92(fix(c));
end
%production totale sur l annee
prod_tot_44 = sum(prod_windTurbine_44);
prod_tot_48 = sum(prod_windTurbine_48);
prod_tot_53 = sum(prod_windTurbine_53);
prod_tot_70 = sum(prod_windTurbine_70);
prod_tot_82 = sum(prod_windTurbine_82);
prod_tot_82_2 = sum(prod_windTurbine_82_2);
prod_tot_92 = sum(prod_windTurbine_92);
prod_tot = [ prod_tot_44/900 prod_tot_48/800 prod_tot_53/800 prod_tot_70
    /2300 prod_tot_82/2000 prod_tot_82_2/2300 prod_tot_92/2350];

%% PV panels

% fixed tilt
Pn_PV = 442.8; % en watt
Area_unit_PV = 2.113; % en m^2
eta_n_PV = 0.2093;
Pn_per_m2 = Pn_PV/Area_unit_PV; %Watt/m^2

% dual axis
% Pn_PV = 415.8; % en watt
% Area_unit_PV = 2.113; % en m^2
% eta_n_PV = 0.1966;
```

```
81 % Pn_per_m2 = Pn_PV/Area_unit_PV; %Watt/m^2
82
83 % pertes
84 eta_SDF = 0.98; % system derate factor
85 eta_inverter = 0.95;
86 eta_temp = 0.88;
87 eta_wire = 0.98;
88 eta_PV = eta_n_PV*eta_SDF*eta_inverter*eta_temp*eta_wire;
89
90 % dimmensionnement
91 G = sum(G_i);
92
93
94 %% Conso systeme
95 %consomation de lusine en Wh (heure par heure)
96 Conso_syst_Wh = 1e6.*Conso_syst; % en Wh
97
98
99 %% Costs
100
101 % Wind turbine (prise sur internet)
102 C_WT = 3.34e6; % cout pour une E-92 : achat, installation et maintenance
       sur 20 ans
103 O_WT = 101e3;
104 % Pv panels
105 C_PV = 840; % /kWh : achat installation et maintenance sur 25 ans
106 O_PV = 16.8;
107 % C_PV = 1120; %pour dual axis tracking
108 % O_PV = 22.4;
109 % batteries
110 C_bat = 420; % /kwh : achat installation et maintenance sur 20 ans
111 O_bat = 12;
112 % plant
113 C_plant = 96*1.2625e6;
114 O_plant = 96*1.1e6/20;
115
116 %% optimisation
117 ff = [0:0.1:1]; % on va regarder quelle repartition PV/WT est la
       meilleures
118 %N = 2.2; % cmb de fois la production minimale est le meilleur compromis
       pour diminuer les couts (cout des batteries tres cher pour N=1)
119 L2 = length(ff);
120 N0 = 1; % a changer si on change la valeur de d but du N dans la boucle
```

```
    for
% batterie
eta_bat = 0.886;

iter = 1;
for N=1:0.1:5
    % PV
    Area_PV_opt = N*(1-ff).*Conso_tot.*1e6./(eta_PV.*G); %vecteur de 11
        colonnes avec les surface de panneaux necessaire dans chaque cas
    %WT
    Number_WT_opt = N*ff.*Conso_tot.*1e3./prod_tot_92;

    Area_PV_opt_tab(iter,:) = Area_PV_opt; % pour stocker dans un tableau
        toute les valeurs des aire des panneaux
    Number_WT_opt_tab(iter,:) = Number_WT_opt;
    % calcul de chaque quantite d energie produite ensuite
        dimensionnement avec
    % batterie jamais prise en d faut ( un gros d ficit survient en fin
        d annee
    % peut etre on peut prevoir une fermeture annuelle de maintenance de
        20
    % jours ?)
    for k=1:L2
        E_gen_PV_opt(k,:) = eta_PV*Area_PV_opt(k).*G_i;
        E_gen_WT_opt(k,:) = 1000.*(fix(Number_WT_opt(k))).*
            prod_windTurbine_92;
        E_gen_tot_opt = E_gen_PV_opt(k,:) + E_gen_WT_opt(k,:);
        E_gen_tot_opt_2(k,:) = E_gen_tot_opt;
        [C2,E2,E_gen_grid] = batterie(Conso_syst_Wh,E_gen_tot_opt,L);
        Cap_bat(iter,k) = C2/eta_bat;
        E_bat_opt(k,:) = E2 + (C2/eta_bat - C2); % la paranthese en plus
            c'est pour consid rer le rendement des batteries
        E_gen_tot_grid(iter,k) = sum(E_gen_grid);

        % stocker toute les valeurs pour pouvoir replotter les graphes.
        E_gen_PV_tab(iter,k,:) = E_gen_PV_opt(k,:);
        E_gen_WT_tab(iter,k,:) = E_gen_WT_opt(k,:);
        E_gen_tot_tab(iter,k,:) = E_gen_tot_opt_2(k,:);
        E_bat_tab(iter,k,:) = E_bat_opt(k,:);
        E_gen_grid_tab(iter,k,:) = E_gen_grid;
    end
    iter = iter+1;
end
```

```
156
157
158 %% calculs costs % NB : a integrer dans les cout le rendement des
        batterie qui est pas encore pris en compte
159 DR = 0.07; % discount rate 7%
160 CRF = (DR*(1+DR)^20)/((1+DR)^20-1);
161
162 C_WT_tot = Number_WT_opt_tab.*C_WT; % vecteur de 10 en fonction de ff
163 C_PV_tot = Pn_per_m2.*Area_PV_opt_tab.*C_PV./1000;
164 C_bat_tot = Cap_bat.*C_bat./1000;
165 C_tot_grid = E_gen_tot_grid.*0.09./1000;
166 O_WT_tot = Number_WT_opt_tab.*O_WT; % vecteur de 10 en fonction de ff
167 O_PV_tot = Pn_per_m2.*Area_PV_opt_tab.*O_PV./1000;
168 O_bat_tot = Cap_bat.*O_bat./1000;
169
170 Capex_tot = C_WT_tot + C_PV_tot + C_bat_tot + C_plant;
171 Opex_tot = O_WT_tot + O_PV_tot + O_bat_tot + C_tot_grid + O_plant;
172 Capex_tot2 = C_WT_tot + C_PV_tot + C_bat_tot;
173 Opex_tot2 = O_WT_tot + O_PV_tot + O_bat_tot;
174
175 LCOW = (Capex_tot.*CRF + Opex_tot)./96000./365; % a minimiser au final
176 LCOE = (Capex_tot.*CRF + Opex_tot)./(96*4157*365 - E_gen_tot_grid./1000);
177 %TROUVER LA MEILLEURE CONFIG
178 minimum = min(min(LCOW));
179 [ind_ligne,ind_colonne] = find(LCOW==minimum);
180
181 %% Output + Graphes
182 opt_N = N0 + (ind_ligne-1)*0.1 % attention au pas 0.1 si on veut le
        changer dans l'opti
183 opt_FF = ff(1) + (ind_colonne-1)*0.1
184 LCOW2 = LCOW(ind_ligne,ind_colonne)
185 LCOE2 = LCOE(ind_ligne,ind_colonne)
186 AirePV = Area_PV_opt_tab(ind_ligne,ind_colonne)
187 NombreWT = Number_WT_opt_tab(ind_ligne,ind_colonne)
188 Capacite_Batterie = Cap_bat(ind_ligne,ind_colonne)
189 % val = Capex_tot(ind_ligne,ind_colonne)*CRF + Opex_tot(ind_ligne,
        ind_colonne)
190
191 plot_PV = squeeze(E_gen_PV_tab(ind_ligne,ind_colonne,:));
192 plot_WT = squeeze(E_gen_WT_tab(ind_ligne,ind_colonne,:));
193 plot_tot = squeeze(E_gen_tot_tab(ind_ligne,ind_colonne,:));
194 plot_bat = squeeze(E_bat_tab(ind_ligne,ind_colonne,:));
195 plot_grid = squeeze(E_gen_grid_tab(ind_ligne,ind_colonne,:));
```

```
196
197 [workingBat,prod_wat2] = fixedConfig(Conso_syst_Wh,22.78,3.5397e5,2.6637
        e8,prod_windTurbine_92,G_i,eta_PV,Conso_syst_Wh(1)*0.2388,L);
198 LCOW3 = (4.7785e7)/prod_wat2
199 %
200 heure = linspace(0,365,L);
201 zero_droite = zeros(L,1);
202 %
203 % plot(heure,plot_PV)
204 % title('production PV panels')
205 % xlabel('jour annee')
206 % ylabel('Production PV en Wh')
207 %
208 % figure;
209 % plot(heure,plot_WT)
210 % title('Production eolienne')
211 % xlabel('jour annee')
212 % ylabel('production eolienne en Wh')
213 %
214 figure;
215 plot(heure,plot_tot,heure,Conso_syst_Wh)
216 xlim([0 365])
217 title('Totale renewable production')
218 xlabel('Days of the year')
219 ylabel('Electrical production [Wh]')
220 legend('Renewable production','SWRO plant consumption')
221
222 figure;
223 plot(heure,plot_bat)
224 xlim([0 365])
225 title('Battery charge status')
226 xlabel('Days of the year')
227 ylabel('Battery charge status [Wh]')
228 %
229 % figure;
230 % plot(heure,Conso_syst_Wh)
231 % title('Consomation system')
232
233 figure;
234 plot(heure,plot_grid)
235 xlim([0 365])
236 title('Electrical supply from grid')
237 xlabel('Days of the year')
```

```
238 ylabel('Electrical supply [Wh]')
239
240 figure;
241 plot(heure,workingBat,heure,zero_droite)
242 xlim([0 365])
243 title('Battery charge status2')
244 xlabel('Days of the year')
245 ylabel('Battery charge status [Wh]')
246 %% functions
247 function [Capacite_bat,E_bat,E_grid] = batterie(conso_RO,Energie_produite
    ,L) %
248 E_bat = zeros(L,1);
249 E_bat(1) = 50e5;
250 E_grid = zeros(L,1);
251 i=2;
252 E_max_grid = conso_RO(1)*0.2388;
253 while i<L % cette fonction sort une valeur de la batterie necessaire pour
    qu'elle ne soit jamais vide
254     if E_bat(i-1)<0
255         E_bat(1) = E_bat(1)*1.05;
256         i=2;
257     else
258         if (conso_RO(i) > Energie_produite(i)) && (conso_RO(i)-
            Energie_produite(i)<=E_max_grid)
259
260             E_grid(i) = conso_RO(i)-Energie_produite(i);
261             E_bat(i) = E_bat(i-1);
262         elseif (conso_RO(i) > Energie_produite(i)) && (conso_RO(i)-
            Energie_produite(i)>E_max_grid)
263             E_grid(i) = E_max_grid;
264             E_bat(i) = E_bat(i-1)-(conso_RO(i)-Energie_produite(i)-
                E_max_grid);
265         else
266             E_bat(i) = E_bat(i-1)+(Energie_produite(i)-conso_RO(i));
267         end
268         if E_bat(i)>E_bat(1)
269             E_bat(i) = E_bat(1);
270         end
271         i=i+1;
272     end
273 end
274 Capacite_bat = E_bat(1);
275 end
```

```
276
277 function [workinBat,prod_wat2] = fixedConfig(conso_RO,configWT,configPV,
    configBat,windDataProd,irrData,eta_PV,grid_capacity,L)% windDataProd
    ce que 1   olienne   produit en fct des data de vents
278
279 Elec_gen_PV = configPV.*eta_PV.*irrData;
280 Elec_gen_WT = configWT.*windDataProd.*1e3;
281 Elec_gen_tot = Elec_gen_PV + Elec_gen_WT;
282
283 prod_wat = zeros(L,1);
284 Elec_bat = zeros(L,1);
285 Elec_bat(1) = configBat; % capacite de la batterie
286 for i=2:L
287     if Elec_gen_tot(i) - conso_RO(i) + grid_capacity < 0
288         Elec_bat(i) = Elec_bat(i-1) + (Elec_gen_tot(i) - conso_RO(i) +
              grid_capacity);
289     elseif Elec_gen_tot(i) - conso_RO(i) > 0
290          Elec_bat(i) = Elec_bat(i-1) + (Elec_gen_tot(i) - conso_RO(i));
291     else
292         Elec_bat(i) = Elec_bat(i-1);
293     end
294     if Elec_bat(i) > Elec_bat(1)
295         Elec_bat(i) = Elec_bat(1);
296     end
297 end
298 workinBat = Elec_bat;
299 for ii=1:L
300     if Elec_bat(ii) < 0
301         prod_wat(ii) = 0;
302     else
303         prod_wat(ii) = 4000;
304     end
305 end
306 prod_wat2 = sum(prod_wat);
307 end
```

6.1.3 Model 3

```
1 close all;
2
3 %% Estimation conso syst me
4 Conso_tot = sum(Conso_syst); % en MWh
5 prod_nom = 2000; % production nominale eau dans le cas fonctionnement
    constant
```

```
%% conso RO
conso_train = 4.45; % en MWh pour un train de 1000m^3/h
Nbre_train = 6;
for ii=1:Nbre_train
    conso_step_RO(ii) = ii*conso_train*1e6; % en Wh
end

%% Wind turbine Enercon 92
wind = [1 : 25];

power_92 = [0 3.6 29.9 98.2 208.3 384.3 637 975.8 1403.6 1817.8 2088.7
    2237 2300 2350 2350 2350 2350 2350 2350 2350 2350 2350 2350
    2350]; % 2350kW
xx = 0:.01:25;
yy_92 = spline(wind,power_92,xx);


L = length(Wind_speed);
Z0 = 0.0024;
Z = 150; %hauteur de l eolienne
Z_ref = 10; %hauteur a laquelle le vent est mesurer
prod_windTurbine_92 = zeros(L,1);
for i=1:L
    Wind_speed_corr(i) = Wind_speed(i)*log(Z/Z0)/log(Z_ref/Z0);
    a = fix(Wind_speed_corr(i));
    b = mod(Wind_speed_corr(i),a);
    c = 100*a + 100*b;
    prod_windTurbine_92(i) = yy_92(fix(c)); % en kWh
end
prod_tot_92 = sum(prod_windTurbine_92);

%% PV panels

% fixed tilt
% Pn_PV = 442.8; % en watt
% Area_unit_PV = 2.113; % en m^2
% eta_n_PV = 0.2093;
% Pn_per_m2 = Pn_PV/Area_unit_PV; %Watt/m^2

% dual axis
Pn_PV = 415.8; % en watt
Area_unit_PV = 2.113; % en m^2
eta_n_PV = 0.1966;
```

```
47 Pn_per_m2 = Pn_PV/Area_unit_PV; %Watt/m^2
48
49 % pertes
50 eta_SDF = 0.98; % system derate factor
51 eta_inverter = 0.95;
52 eta_temp = 0.88;
53 eta_wire = 0.98;
54 eta_PV = eta_n_PV*eta_SDF*eta_inverter*eta_temp*eta_wire;
55
56 % dimmensionnement
57 G = sum(G_i);
58
59
60 %% optimisation
61
62 ff = [0:0.1:1]; % on va regarder quelle repartition PV/WT est la
       meilleures
63 %N = 2.2; % cmb de fois la production minimale est le meilleur compromis
       pour diminuer les couts (cout des batteries tres cher pour N=1)
64 L2 = length(ff);
65 N0 = 0.2; % a changer si on change la valeur de d but du N dans la
       boucle for
66 % batterie
67 eta_bat = 0.886;
68 L3 = length(conso_step_RO);
69 iter = 1;
70 for N=0.2:0.1:3
71     % PV
72     Area_PV_opt = N*(1-ff).*Conso_tot.*1e6./(eta_PV.*G); %vecteur de 11
           colonnes avec les surface de panneaux necessaire dans chaque cas
73     %WT
74     Number_WT_opt = N*ff.*Conso_tot.*1e3./prod_tot_92;
75
76     Area_PV_opt_tab(iter,:) = Area_PV_opt; % pour stocker dans un tableau
           toute les valeurs des aire des panneaux
77     Number_WT_opt_tab(iter,:) = Number_WT_opt;
78     % calcul de chaque quantite d energie produite ensuite
           dimensionnement avec
79     % batterie jamais prise en d faut ( un gros d ficit survient en fin
           d annee
80     % peut etre on peut prevoir une fermeture annuelle de maintenance de
           20
81     % jours ?)
```

```
82      for k=1:L2
83          E_gen_PV_opt(k,:) = eta_PV*Area_PV_opt(k).*G_i;
84          E_gen_WT_opt(k,:) = 1000.*(fix(Number_WT_opt(k))).*
                prod_windTurbine_92;
85          E_gen_tot_opt = E_gen_PV_opt(k,:) + E_gen_WT_opt(k,:);
86          E_gen_tot_opt_2(k,:) = E_gen_tot_opt;
87
88          % stocker toute les valeurs pour pouvoir replotter les graphes.
89          E_gen_PV_tab(iter,k,:) = E_gen_PV_opt(k,:);
90          E_gen_WT_tab(iter,k,:) = E_gen_WT_opt(k,:);
91          E_gen_tot_tab(iter,k,:) = E_gen_tot_opt_2(k,:);
92  %           E_gen_tot_sum(iter,k) = sum(E_gen_tot_tab(iter,k,:));
93
94          % trouver la conso de la RO
95          E_cons_tot_tab(iter,k,1) = 0;
96          water_prod(iter,k,1) = 0;
97          indice_train(iter,k,1) = 0;
98          for y =2:L
99              iii = 2;
100             while iii<=L3
101                 if E_gen_tot_tab(iter,k,y)<conso_step_RO(1)
102                     E_cons_tot_tab(iter,k,y) = 0;
103                     water_prod(iter,k,y) = 0;
104                     indice_train(iter,k,y) = 0;
105                     iii=L3+1;
106                 elseif (E_gen_tot_tab(iter,k,y)<conso_step_RO(iii)) && (
                        E_gen_tot_tab(iter,k,y)>=conso_step_RO(iii-1))
107                     indice_train(iter,k,y) = iii-1;
108                     if indice_train(iter,k,y) > indice_train(iter,k,y-1)
                            % si des trains doivent s'allumer on perd de la
                            prod pendant l'allumage
109                         E_cons_tot_tab(iter,k,y) = conso_step_RO(iii-1);
110                         water_prod(iter,k,y) = (iii-1)*1000 - (
                                indice_train(iter,k,y)-indice_train(iter,k,y
                                -1))*1000*0.1998; % car 1000 m3 par train
111                         iii=L3+1; % on break la boucle car la valeur de
                                conso est attribu e
112                     else
113                         E_cons_tot_tab(iter,k,y) = conso_step_RO(iii-1);
114                         water_prod(iter,k,y) = (iii-1)*1000; % car 1000
                                m3 par train
115                         iii=L3+1; % on break la boucle car la valeur de
                                conso est attribu e
```

```
116                     end
117                 elseif (E_gen_tot_tab(iter,k,y)>conso_step_RO(L3))
118                     indice_train(iter,k,y) = L3;
119                     if indice_train(iter,k,y) > indice_train(iter,k,y-1)
120                         E_cons_tot_tab(iter,k,y) =  conso_step_RO(L3);
121                         water_prod(iter,k,y) = (L3)*1000 - (indice_train(
                                iter,k,y)-indice_train(iter,k,y-1))
                                *1000*0.1998; % car 1000 m3 par train
122                         iii=L3+1;
123                     else
124                         E_cons_tot_tab(iter,k,y) =  conso_step_RO(L3);
125                         water_prod(iter,k,y) = (L3)*1000; % car 1000 m3
                                par train
126                         iii=L3+1;
127                     end
128                 else
129                    iii=iii+1;
130                 end
131             end
132         end
133 %          E_cons_var(iter,k) = sum(E_cons_tot_tab(iter,k,:));
134         Water_prod_totale(iter,k) = sum(water_prod(iter,k,:));
135         [water_storage_tot,water_storage] = water(E_cons_tot_tab(iter,k
                ,:),prod_nom,L);
136         water_storage_tot_tab(iter,k) = water_storage_tot;
137         water_storage_tab(iter,k,:) = water_storage;
138     end
139     iter = iter+1;
140 end
141
142 %% costs
143
144 % Wind turbine (prise sur internet)
145 C_WT = 3.34e6; % cout pour une E-92 : achat, installation et maintenance
      sur 20 ans
146 O_WT = 101e3;
147 % Pv panels
148 % C_PV = 840; % /kWh : achat installation et maintenance sur 25 ans
149 % O_PV = 16.8;
150 C_PV = 1120; %pour dual axis tracking
151 O_PV = 22.4;
152 % plant
153 C_plant = Nbre_train*24*1.2625e6;
```

```
154 O_plant = Nbre_train*24*1.1e6/20;
155 % water
156 C_wat = 40; % /m3 : achat installation et maintenance sur 20 ans
157
158 %%
159 DR = 0.07; % discount rate 7%
160 CRF = (DR*(1+DR)^20)/((1+DR)^20-1);
161
162 C_WT_tot = Number_WT_opt_tab.*C_WT; % vecteur de 10 en fonction de ff
163 C_PV_tot = Pn_per_m2.*Area_PV_opt_tab.*C_PV./1000;
164 C_wat_tot = water_storage_tot_tab.*C_wat;
165 O_WT_tot = Number_WT_opt_tab.*O_WT; % vecteur de 10 en fonction de ff
166 O_PV_tot = Pn_per_m2.*Area_PV_opt_tab.*O_PV./1000;
167
168 Capex_tot = C_WT_tot + C_PV_tot + C_wat_tot + C_plant; % a minimiser au
      final
169 Opex_tot = O_WT_tot + O_PV_tot + O_plant;
170 Capex_tot2 = C_WT_tot + C_PV_tot; % a minimiser au final
171 Opex_tot2 = O_WT_tot + O_PV_tot;
172
173 LCOW = (Capex_tot.*CRF + Opex_tot)./Water_prod_totale; % a minimiser au
      final
174 LCOE = (Capex_tot2.*CRF + Opex_tot2)./(Water_prod_totale.*4.45);
175
176 %TROUVER LA MEILLEURE CONFIG
177 minimum = min(min(LCOW));
178 [ind_ligne,ind_colonne] = find(LCOW==minimum);
179
180 %% Output + graphe
181 % ind_ligne
182 % ind_colonne
183 opt_N = N0 + (ind_ligne-1)*0.1 % attention au pas 0.1 si on veut le
      changer dans l'opti
184 opt_FF = ff(1) + (ind_colonne-1)*0.1
185 LCOW2 = LCOW(ind_ligne,ind_colonne)
186 LCOE2 = LCOE(ind_ligne,ind_colonne)
187 Surface_PV = Area_PV_opt_tab(ind_ligne,ind_colonne)
188 Nombre_WT = Number_WT_opt_tab(ind_ligne,ind_colonne)
189 Stockage_eau = water_storage_tot_tab(ind_ligne,ind_colonne)
190 quant_eau_produite = Water_prod_totale(ind_ligne,ind_colonne)
191 % val = Capex_tot(ind_ligne,ind_colonne)*CRF + Opex_tot(ind_ligne,
      ind_colonne)
192
```

```
193
194 plot_PV = squeeze(E_gen_PV_tab(ind_ligne,ind_colonne,:));
195 plot_WT = squeeze(E_gen_WT_tab(ind_ligne,ind_colonne,:));
196 plot_prod_tot = squeeze(E_gen_tot_tab(ind_ligne,ind_colonne,:));
197 plot_conso_tot = squeeze(E_cons_tot_tab(ind_ligne,ind_colonne,:));
198 plot_wat_sto = squeeze(water_storage_tab(ind_ligne,ind_colonne,:));
199 plot_wat = squeeze(water_prod(ind_ligne,ind_colonne,:));
200
201 [workinWat,prod_wat3] = fixedConfig(conso_step_RO,21.07,1.0257e5,161360,
      prod_windTurbine_92,G_i,eta_PV,L,Nbre_train,prod_nom);
202 LCOW3 = (3.7048e7)/prod_wat3
203
204 heure = linspace(0,365,L);
205 zero_droite = zeros(L,1);
206
207 figure;
208 plot(heure,plot_wat)
209 xlim([0 365])
210 title('Fresh water production')
211 xlabel('Days of the year')
212 ylabel('Water production [m^3]')
213
214 figure;
215 plot(heure,plot_wat_sto)
216 xlim([0 365])
217 title('Water tank status')
218 xlabel('Days of the year')
219 ylabel('Water quantity [m^3]')
220
221 % figure;
222 % plot(heure,plot_conso_tot)
223 % title('Consomation RO')
224 % xlabel('jour annee')
225 % ylabel('Consomation en Wh')
226
227 figure;
228 plot(heure,plot_prod_tot,heure,plot_conso_tot)
229 xlim([0 365])
230 title('Total renewable production')
231 xlabel('Days of the year')
232 ylabel('Electrical production [Wh]')
233 legend('Renewable production','SWRO plant consumption')
234
```

```
235 figure;
236 plot(heure,workinWat,heure,zero_droite)
237 xlim([0 365])
238 title('Tank status2')
239 xlabel('Days of the year')
240 ylabel('Tank status [m^3]')
241 %% stockage eau
242 function [water_sto_tot,water_sto] = water(conso_RO,prod_nominale,L) %
243 water_sto = zeros(L,1);
244 water_sto(1) = 10000; % en m3
245 i=2;
246 while i<L % cette fonction sort une valeur de la batterie necessaire pour
      qu'elle ne soit jamais vide
247     water_instant = conso_RO(i)/4.45e6*1000; %*1000 car chaque train
        produisent 1000m3/heure
248     if water_sto(i-1)<0
249         water_sto(1) = water_sto(1)*1.05;
250         i=2;
251     else
252         if (water_instant > prod_nominale) % car 4000 m3/heure en vitesse
              nominale constante
253             water_sto(i) = water_sto(i-1)+(water_instant-prod_nominale);
254         elseif (water_instant <= prod_nominale)
255             water_sto(i) = water_sto(i-1)-(prod_nominale-water_instant);
256         end
257         if water_sto(i) > water_sto(1)
258             water_sto(i) = water_sto(1);
259         end
260         i=i+1;
261     end
262 end
263 water_sto_tot = water_sto(1);
264 end
265
266 function [workinWat,prod_wat3] = fixedConfig(conso_step_RO,configWT,
    configPV,configWat,windDataProd,irrData,eta_PV,L,k,minimum_prod)%
    windDataProd ce que 1   olienne   produit en fct des data de vents, k
    est Nbre_train
267
268 Elec_gen_PV = configPV.*eta_PV.*irrData;
269 Elec_gen_WT = configWT.*windDataProd.*1e3;
270 Elec_gen_tot = Elec_gen_PV + Elec_gen_WT;
271
```

```
272 prod_wat = zeros(L,1);
273 prod_wat2 = zeros(L,1);
274 Tank_cap = zeros(L,1);
275 Tank_cap(1) = configWat; % capacite du stockage d'eau
276 indice_trains = zeros(L,1);
277
278 ii=2;
279 for i=2:L
280     while ii<=k
281         if Elec_gen_tot(i) < conso_step_RO(1)
282             prod_wat(i) = 0;
283             Tank_cap(i) = Tank_cap(i-1) - minimum_prod;
284              ii=k+1;
285         elseif Elec_gen_tot(i) >= conso_step_RO(ii-1) && Elec_gen_tot(i) <
                conso_step_RO(ii)
286             indice_trains(i) = (ii-1);
287             if indice_trains(i) > indice_trains(i-1)
288                 prod_wat(i) = 1000*(ii-1) - (indice_trains(i)-
                        indice_trains(i-1))*1000*0.1998;
289                 Tank_cap(i) = Tank_cap(i-1) + (prod_wat(i) - minimum_prod
                        );
290                 ii=k+1;
291             else
292                 prod_wat(i) = 1000 * (ii-1);
293                 Tank_cap(i) = Tank_cap(i-1) + (prod_wat(i) - minimum_prod
                        );
294                 ii=k+1;
295             end
296         elseif Elec_gen_tot(i) > conso_step_RO(k)
297             indice_trains(i) = k;
298             if indice_trains(i) > indice_trains(i-1)
299                 prod_wat(i) = 1000*k - (indice_trains(i)-indice_trains(i
                        -1))*1000*0.1998;
300                 Tank_cap(i) = Tank_cap(i-1) + (prod_wat(i) - minimum_prod
                        );
301                 ii=k+1;
302             else
303                 prod_wat(i) = 1000 * k;
304                 Tank_cap(i) = Tank_cap(i-1) + (prod_wat(i) - minimum_prod
                        );
305                 ii=k+1;
306             end
307         else
```

```
            ii=ii+1;
        end
    end
     if Tank_cap(i) > Tank_cap(1)
            Tank_cap(i) = Tank_cap(1);
     end
     ii = 2;
end
workinWat = Tank_cap;
for iii = 1:L % pour prendre en compte les arrets pour le LCOW avec
    config fixe
     if (Tank_cap(iii) < 0)
         prod_wat2(iii) = 0;
     else
         prod_wat2(iii) = prod_wat(iii);
     end
end
prod_wat3 = sum(prod_wat2);
end
```

6.1.4 Model 4

```
close all;

%% Estimation conso syst me
Conso_tot = sum(Conso_syst); % en MWh
prod_nom = 2000; % production nominale eau dans le cas fonctionnement
    constant
%% conso RO
conso_train = 4.45; % en MWh
Nbre_train = 6;
for ii=1:Nbre_train
     conso_step_RO(ii) = ii*conso_train*1e6; % en Wh
end

%% Wind turbine Enercon 92
wind = [1 : 25];

power_92 = [0 3.6 29.9 98.2 208.3 384.3 637 975.8 1403.6 1817.8 2088.7
    2237 2300 2350 2350 2350 2350 2350 2350 2350 2350 2350 2350
    2350]; % 2350kW
xx = 0:.01:25;
yy_92 = spline(wind,power_92,xx);

```

```
20
21 L = length(Wind_speed);
22 Z0 = 0.0024;
23 Z = 150; %hauteur de l eolienne
24 Z_ref = 10; %hauteur a laquelle le vent est mesurer
25 prod_windTurbine_92 = zeros(L,1);
26 for i=1:L
27     Wind_speed_corr(i) = Wind_speed(i)*log(Z/Z0)/log(Z_ref/Z0);
28     a = fix(Wind_speed_corr(i));
29     b = mod(Wind_speed_corr(i),a);
30     c = 100*a + 100*b;
31     prod_windTurbine_92(i) = yy_92(fix(c)); % en kWh
32 end
33 prod_tot_92 = sum(prod_windTurbine_92);
34
35 %% PV panels
36
37 % fixed tilt
38 % Pn_PV = 442.8; % en watt
39 % Area_unit_PV = 2.113; % en m^2
40 % eta_n_PV = 0.2093;
41 % Pn_per_m2 = Pn_PV/Area_unit_PV; %Watt/m^2
42
43 % dual axis
44 Pn_PV = 415.8; % en watt
45 Area_unit_PV = 2.113; % en m^2
46 eta_n_PV = 0.1966;
47 Pn_per_m2 = Pn_PV/Area_unit_PV; %Watt/m^2
48
49 % pertes
50 eta_SDF = 0.98; % system derate factor
51 eta_inverter = 0.95;
52 eta_temp = 0.88;
53 eta_wire = 0.98;
54 eta_PV = eta_n_PV*eta_SDF*eta_inverter*eta_temp*eta_wire;
55
56 % dimmensionnement
57 G = sum(G_i);
58
59
60 %% optimisation
61
62 ff = [0:0.1:1]; % on va regarder quelle repartition PV/WT est la
```

```
    meilleures
%N = 2.2; % cmb de fois la production minimale est le meilleur compromis
    pour diminuer les couts (cout des batteries tres cher pour N=1)
L2 = length(ff);
N0 = 0.2; % a changer si on change la valeur de d but du N dans la
    boucle for
% batterie
eta_bat = 0.886;
L3 = length(conso_step_RO);
iter = 1;
for N=0.2:0.1:3
    % PV
    Area_PV_opt = N*(1-ff).*Conso_tot.*1e6./(eta_PV.*G); %vecteur de 11
        colonnes avec les surface de panneaux necessaire dans chaque cas
    %WT
    Number_WT_opt = N*ff.*Conso_tot.*1e3./prod_tot_92;

    Area_PV_opt_tab(iter,:) = Area_PV_opt; % pour stocker dans un tableau
        toute les valeurs des aire des panneaux
    Number_WT_opt_tab(iter,:) = Number_WT_opt;
    % calcul de chaque quantite d energie produite ensuite
        dimensionnement avec
    % batterie jamais prise en d faut ( un gros d ficit survient en fin
        d annee
    % peut etre on peut prevoir une fermeture annuelle de maintenance de
        20
    % jours ?)
    for k=1:L2
        E_gen_PV_opt(k,:) = eta_PV*Area_PV_opt(k).*G_i;
        E_gen_WT_opt(k,:) = 1000.*(fix(Number_WT_opt(k))).*
            prod_windTurbine_92;
        E_gen_tot_opt = E_gen_PV_opt(k,:) + E_gen_WT_opt(k,:);
        E_gen_tot_opt_2(k,:) = E_gen_tot_opt;

        % stocker toute les valeurs pour pouvoir replotter les graphes.
        E_gen_PV_tab(iter,k,:) = E_gen_PV_opt(k,:);
        E_gen_WT_tab(iter,k,:) = E_gen_WT_opt(k,:);
        E_gen_tot_tab(iter,k,:) = E_gen_tot_opt_2(k,:);
%         E_gen_tot_sum(iter,k) = sum(E_gen_tot_tab(iter,k,:));

        E_cons_tot_tab(iter,k,1) = 0;
        water_prod(iter,k,1) = 0;
        indice_train(iter,k,1) = 0;
```

```
97          E_bat(iter,k,1) = E_gen_tot_tab(iter,k,1);
98          % trouver la conso de la RO
99          for y =2:L
100             iii = 2;
101             while iii<=L3
102                 if (E_gen_tot_tab(iter,k,y)<conso_step_RO(1)*0.65)
103                     E_cons_tot_tab(iter,k,y) = 0;
104                     water_prod(iter,k,y) = 0;
105                     indice_train(iter,k,y) = 0;
106                     E_bat(iter,k,y) = E_gen_tot_tab(iter,k,y);
107                     iii=L3+1;
108                 elseif (E_gen_tot_tab(iter,k,y)>=conso_step_RO(1)*0.65)
                        && (E_gen_tot_tab(iter,k,y)<conso_step_RO(1))
109                     E_cons_tot_tab(iter,k,y) = conso_step_RO(1);
110                     indice_train(iter,k,y) = 1;
111                     E_bat(iter,k,y) = E_gen_tot_tab(iter,k,y)-
                            conso_step_RO(1);
112                     if indice_train(iter,k,y)>indice_train(iter,k,y-1)
113                         water_prod(iter,k,y) = 1000*0.8002; % si le
                                train d marre
114                     else
115                         water_prod(iter,k,y) = 1000; % si le train est
                                d ja allum
116                     end
117                     iii=L3+1;
118                 elseif (E_gen_tot_tab(iter,k,y)<conso_step_RO(iii)-4.45e6
                        *0.35) && (E_gen_tot_tab(iter,k,y)>conso_step_RO(iii
                        -1))
119                     E_cons_tot_tab(iter,k,y) = conso_step_RO(iii-1);
120                     indice_train(iter,k,y) = iii-1;
121                     E_bat(iter,k,y) = E_gen_tot_tab(iter,k,y) -
                            conso_step_RO(iii-1);
122
123                     if indice_train(iter,k,y)>indice_train(iter,k,y-1)
124                         water_prod(iter,k,y) = (iii-1)*1000 - (
                                indice_train(iter,k,y)-indice_train(iter,k,y
                                -1))*1000*0.1998; % si le train d marre
125                     else
126                         water_prod(iter,k,y) = (iii-1)*1000; % si le
                                train est d ja allum
127                     end
128
129                     iii=L3+1; % on break la boucle car la valeur de conso
```

```
                    est attribu e
130                 elseif (E_gen_tot_tab(iter,k,y)>=conso_step_RO(iii)-4.45
                        e6*0.35) && (E_gen_tot_tab(iter,k,y)<=conso_step_RO(
                        iii))
131                     E_cons_tot_tab(iter,k,y) = conso_step_RO(iii);
132                     indice_train(iter,k,y) = iii;
133                     E_bat(iter,k,y) =  E_gen_tot_tab(iter,k,y)-
                            conso_step_RO(iii);
134
135                     if indice_train(iter,k,y)>indice_train(iter,k,y-1)
136                         water_prod(iter,k,y) = (iii)*1000 - (
                                indice_train(iter,k,y)-indice_train(iter,k,y
                                -1))*1000*0.1998; % si le train d marre
137                      else
138                         water_prod(iter,k,y) = (iii)*1000; % si le train
                                est d ja allum
139                     end
140
141                     iii=L3+1; % on break la boucle car la valeur de conso
                            est attribu e
142                 elseif (E_gen_tot_tab(iter,k,y)>conso_step_RO(L3))
143                     E_cons_tot_tab(iter,k,y) =  conso_step_RO(L3);
144                     indice_train(iter,k,y) = L3;
145                     E_bat(iter,k,y) =  E_gen_tot_tab(iter,k,y)-
                            conso_step_RO(L3);
146
147                     if indice_train(iter,k,y)>indice_train(iter,k,y-1)
148                         water_prod(iter,k,y) = (L3)*1000 - (indice_train
                                (iter,k,y)-indice_train(iter,k,y-1))
                                *1000*0.1998; % si le train d marre
149                      else
150                         water_prod(iter,k,y) = (L3)*1000; % si le train
                                est d ja allum
151                     end
152
153                     iii=L3+1;
154                 else
155                     iii=iii+1;
156                 end
157             end
158         end
159 %          E_cons_var(iter,k) = sum(E_cons_tot_tab(iter,k,:));
160         Water_prod_totale(iter,k) = sum(water_prod(iter,k,:));
```

```
161             [water_storage_tot,water_storage] = water(E_cons_tot_tab(iter,k
                    ,:),prod_nom,L);
162             water_storage_tot_tab(iter,k) = water_storage_tot;
163             water_storage_tab(iter,k,:) = water_storage;
164             [Capacite_bat,E_batterie] = batterie2(E_bat(iter,k,:),L);
165             Capacite_bat_tab(iter,k) = Capacite_bat;
166             E_batterie_tab(iter,k,:) = E_batterie;
167         end
168         iter = iter+1;
169     end
170
171     %% costs
172     % Wind turbine (prise sur internet)
173     C_WT = 3.34e6; % cout pour une E-92 : achat, installation et maintenance
            sur 20 ans
174     O_WT = 101e3;
175     % Pv panels
176     % C_PV = 840; % /kWh : achat installation et maintenance sur 25 ans
177     % O_PV = 16.8;
178     C_PV = 1120; %pour dual axis tracking
179     O_PV = 22.4;
180     % batteries
181     C_bat = 420; % /kwh : achat installation et maintenance sur 20 ans
182     O_bat = 12;
183     % water
184     C_wat = 40; % /m3 : achat installation et maintenance sur 20 ans
185     % plant
186     C_plant = Nbre_train*24*1.2625e6;
187     O_plant = Nbre_train*24*1.1e6/20;
188
189
190     %%
191     DR = 0.07; % discount rate 7%
192     CRF = (DR*(1+DR)^20)/((1+DR)^20-1);
193
194     C_WT_tot = Number_WT_opt_tab.*C_WT; % vecteur de 10 en fonction de ff
195     C_PV_tot = Pn_per_m2.*Area_PV_opt_tab.*C_PV./1000;
196     C_wat_tot = water_storage_tot_tab.*C_wat;
197     C_bat_tot = Capacite_bat_tab.*C_bat./1000;
198     O_WT_tot = Number_WT_opt_tab.*O_WT; % vecteur de 10 en fonction de ff
199     O_PV_tot = Pn_per_m2.*Area_PV_opt_tab.*O_PV./1000;
200     O_bat_tot = Capacite_bat_tab.*O_bat./1000;
201
```

```
202 Capex_tot = C_WT_tot + C_PV_tot + C_wat_tot + C_bat_tot + C_plant; % a
        minimiser au final
203 Opex_tot = O_WT_tot + O_PV_tot + O_bat_tot + O_plant;
204 Capex_tot2 = C_WT_tot + C_PV_tot + C_wat_tot; % a minimiser au final
205 Opex_tot2 = O_WT_tot + O_PV_tot;
206
207 LCOW = (Capex_tot.*CRF + Opex_tot)./Water_prod_totale; % a minimiser au
        final
208 LCOE = (Capex_tot2.*CRF + Opex_tot2)./(Water_prod_totale.*4.45);
209
210
211 %TROUVER LA MEILLEURE CONFIG
212 minimum = min(min(LCOW));
213 [ind_ligne,ind_colonne] = find(LCOW==minimum);
214
215 %% Output + graphe
216
217 opt_N = N0 + (ind_ligne-1)*0.1 % attention au pas 0.1 si on veut le
        changer dans l'opti
218 opt_FF = ff(1) + (ind_colonne-1)*0.1
219 LCOW2 = LCOW(ind_ligne,ind_colonne)
220 LCOE2 = LCOE(ind_ligne,ind_colonne)
221 Surface_PV = Area_PV_opt_tab(ind_ligne,ind_colonne)
222 Nombre_WT = Number_WT_opt_tab(ind_ligne,ind_colonne)
223 Stockage_eau = water_storage_tot_tab(ind_ligne,ind_colonne)
224 Stockage_bat = Capacite_bat_tab(ind_ligne,ind_colonne)
225 quant_eau_produite = Water_prod_totale(ind_ligne,ind_colonne)
226 % val = Capex_tot(ind_ligne,ind_colonne)*CRF + Opex_tot(ind_ligne,
        ind_colonne)
227
228 plot_PV = squeeze(E_gen_PV_tab(ind_ligne,ind_colonne,:));
229 plot_WT = squeeze(E_gen_WT_tab(ind_ligne,ind_colonne,:));
230 plot_prod_tot = squeeze(E_gen_tot_tab(ind_ligne,ind_colonne,:));
231 plot_conso_tot = squeeze(E_cons_tot_tab(ind_ligne,ind_colonne,:));
232 plot_wat_sto = squeeze(water_storage_tab(ind_ligne,ind_colonne,:));
233 plot_wat = squeeze(water_prod(ind_ligne,ind_colonne,:));
234 plot_bat = squeeze(E_batterie_tab(ind_ligne,ind_colonne,:));
235
236 [workinWat,workinBat,prod_wat3] = fixedConfig(conso_step_RO,21.07,1.0257
        e5,126430,8.732e6,prod_windTurbine_92,G_i,eta_PV,L,Nbre_train,prod_nom
        );
237 LCOW3 = (3.7367e7)/prod_wat3
238
```

```
239 heure = linspace(0,365,L);
240 zero_droite = zeros(L,1);
241
242 figure;
243 plot(heure,plot_wat)
244 xlim([0 365])
245 title('Fresh water production')
246 xlabel('Days of the year')
247 ylabel('Water production [m^3]')
248
249 figure;
250 plot(heure,plot_wat_sto)
251 xlim([0 365])
252 title('Water tank status')
253 xlabel('Days of the year')
254 ylabel('Water quantity [m^3]')
255
256 figure;
257 plot(heure,plot_bat)
258 xlim([0 365])
259 title('Battery charge status')
260 xlabel('Days of the year')
261 ylabel('Battery charge status [Wh]')
262
263 % figure;
264 % plot(heure,plot_conso_tot)
265 % title('Consomation RO')
266 % xlabel('jour annee')
267 % ylabel('Consomation en Wh')
268
269 figure;
270 plot(heure,plot_prod_tot,heure,plot_conso_tot)
271 xlim([0 365])
272 title('Total renewable production')
273 xlabel('Days of the year')
274 ylabel('Electrical production [Wh]')
275 legend('Renewable production','SWRO plant consumption')
276
277 figure;
278 plot(heure,workinWat,heure,zero_droite)
279 xlim([0 365])
280 title('Tank status2')
281 xlabel('Days of the year')
```

```
282 ylabel('Tank status [m^3]')
283
284 figure;
285 plot(heure,workinBat,heure,zero_droite)
286 xlim([0 365])
287 title('battery status2')
288 xlabel('Days of the year')
289 ylabel('Battery status [Wh]')
290 %% stockage eau
291 function [water_sto_tot,water_sto] = water(conso_RO,prod_nominale,L) %
292 water_sto = zeros(L,1);
293 water_sto(1) = 10000; % en m3
294 i=2;
295 while i<L % cette fonction sort une valeur de la batterie necessaire pour
      qu'elle ne soit jamais vide
296     water_instant = conso_RO(i)/4.45e6*1000; %*1000 car chaque train
        produisent 1000m3/heure
297     if water_sto(i-1)<0
298         water_sto(1) = water_sto(1)*1.05;
299         i=2;
300     else
301         if (water_instant > prod_nominale) % car 4000 m3/heure en vitesse
              nominale constante
302             water_sto(i) = water_sto(i-1)+(water_instant-prod_nominale);
303         elseif (water_instant <= prod_nominale)
304             water_sto(i) = water_sto(i-1)-(prod_nominale-water_instant);
305         end
306         if water_sto(i) > water_sto(1)
307             water_sto(i) = water_sto(1);
308         end
309         i=i+1;
310     end
311 end
312 water_sto_tot = water_sto(1);
313 end
314
315 function [Capacite_bat,E_batterie] = batterie2(E_bat,L) %
316 E_batterie = zeros(L,1);
317 E_batterie(1) = 4e6;
318 i=2;
319 while i<L % cette fonction sort une valeur de la batterie necessaire pour
      qu'elle ne soit jamais vide
320     if E_batterie(i-1)<0
```

```
321             E_batterie(1) = E_batterie(1)*1.05;
322             i=1;
323         else
324             E_batterie(i) = E_batterie(i-1) + E_bat(i);
325         end
326         if E_batterie(i)>E_batterie(1)
327                 E_batterie(i) = E_batterie(1);
328         end
329         i=i+1;
330 end
331 Capacite_bat = E_batterie(1);
332 end
333
334 function [workinWat,workinBat,prod_wat3] = fixedConfig(conso_step_RO,
        configWT,configPV,configWat,configBat,windDataProd,irrData,eta_PV,L,k,
        minimum_prod)% windDataProd ce que 1 olienne produit en fct des data
         de vents, k est Nbre_train
335
336 Elec_gen_PV = configPV.*eta_PV.*irrData;
337 Elec_gen_WT = configWT.*windDataProd.*1e3;
338 Elec_gen_tot = Elec_gen_PV + Elec_gen_WT;
339
340 prod_wat = zeros(L,1);
341 prod_wat2 = zeros(L,1);
342 Tank_cap = zeros(L,1);
343 Tank_cap(1) = configWat; % capacite du stockage d'eau
344
345 Elec_bat = zeros(L,1);
346 Elec_bat(1) = configBat;
347 indice_trains = zeros(L,1);
348
349 ii=2;
350 for i=2:L
351     while ii<=k
352         if Elec_gen_tot(i) < 0.65*conso_step_RO(1)
353             prod_wat(i) = 0;
354             Tank_cap(i) = Tank_cap(i-1) - minimum_prod;
355             Elec_bat(i) = Elec_bat(i-1) + Elec_gen_tot(i);
356              ii=k+1;
357
358         elseif Elec_gen_tot(i) >= 0.65*conso_step_RO(1) && Elec_gen_tot(i)
                < conso_step_RO(1)
359
```

```
360
361             Elec_bat(i) = Elec_bat(i-1) - (conso_step_RO(1)-Elec_gen_tot(i
                    ));
362             indice_trains(i) = 1;
363             if indice_trains(i) > indice_trains(i-1)
364                 prod_wat(i) = 1000*0.8002;
365             else
366                  prod_wat(i) = 1000;
367             end
368              Tank_cap(i) = Tank_cap(i-1) - minimum_prod + prod_wat(i);
369             ii=k+1;
370
371         elseif Elec_gen_tot(i) >= conso_step_RO(ii-1) && Elec_gen_tot(i) <
                (0.65*conso_step_RO(1)+conso_step_RO(ii-1))
372
373
374              Elec_bat(i) = Elec_bat(i-1) + (Elec_gen_tot(i) -
                    conso_step_RO(ii-1));
375              indice_trains(i) = ii-1;
376              if indice_trains(i) > indice_trains(i-1)
377                 prod_wat(i) = 1000 * (ii-1) - (indice_trains(i)-
                        indice_trains(i-1))*1000*0.1998;
378             else
379                  prod_wat(i) = 1000 * (ii-1);
380              end
381              Tank_cap(i) = Tank_cap(i-1) + (prod_wat(i) - minimum_prod);
382             ii=k+1;
383
384         elseif Elec_gen_tot(i) >= (0.65*conso_step_RO(1)+conso_step_RO(ii
                -1)) && Elec_gen_tot(i) < conso_step_RO(ii)
385
386
387             Elec_bat(i) = Elec_bat(i-1) - (conso_step_RO(ii) -
                    Elec_gen_tot(i));
388             indice_trains(i) = ii;
389              if indice_trains(i) > indice_trains(i-1)
390                 prod_wat(i) = 1000 * (ii) - (indice_trains(i)-
                        indice_trains(i-1))*1000*0.1998;
391             else
392                  prod_wat(i) = 1000 * (ii);
393              end
394             Tank_cap(i) = Tank_cap(i-1) + (prod_wat(i) - minimum_prod);
395             ii=k+1;
```

```
396
397         elseif Elec_gen_tot(i) > conso_step_RO(k)
398
399
400             Elec_bat(i) = Elec_bat(i-1) + (Elec_gen_tot(i) -
                    conso_step_RO(k));
401             indice_trains(i) = k;
402              if indice_trains(i) > indice_trains(i-1)
403                prod_wat(i) = 1000 * k - (indice_trains(i)-indice_trains(i
                       -1))*1000*0.1998;
404             else
405                  prod_wat(i) = 1000 * k;
406               end
407             Tank_cap(i) = Tank_cap(i-1) + (prod_wat(i) - minimum_prod);
408             ii=k+1;
409
410         else
411             ii=ii+1;
412         end
413     end
414      if Tank_cap(i) > Tank_cap(1)
415             Tank_cap(i) = Tank_cap(1);
416      end
417      if Elec_bat(i) > Elec_bat(1)
418          Elec_bat(i) = Elec_bat(1);
419      end
420      ii = 2;
421 end
422 workinWat = Tank_cap;
423 workinBat = Elec_bat;
424 for iii = 1:L % pour prendre en compte les arrets pour le LCOW avec
       config fixe
425      if (Tank_cap(iii) < 0)
426          prod_wat2(iii) = 0;
427      else
428          prod_wat2(iii) = prod_wat(iii);
429      end
430 end
431 prod_wat3 = sum(prod_wat2);
432 end
```

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