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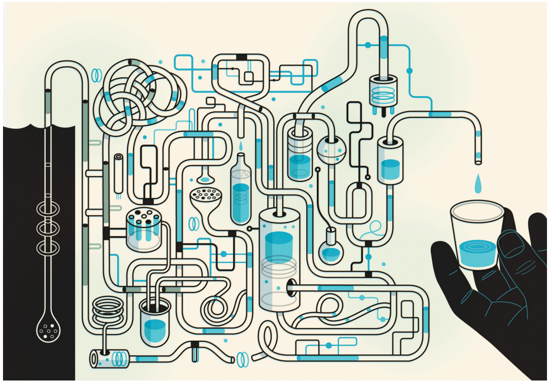

Is RES powered desalination a viable solution for water stressed regions? A case study in Algarve, Portugal

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Mechanical Engineering

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To my parents

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Resumo

O abastecimento de água potável é por vezes problemático em Portugal devido à forte concentração sazonal das precipitações, à desigualdade da disponibilidade dos recursos hídricos e às secas frequentes no país. Prevê-se que as alterações climáticas venham piorar esta situação, e urge encontrar uma solução que possa simultaneamente aliviar a pressão exercida sobre os recursos hídricos e garantir água de qualidade às populações. A dessalinização de água tem vindo a afirmar-se como uma das melhores opções para combater a escassez de água, mas o elevado consumo energético associado às tecnologias de dessalinização e os custos de produção que daí resultam tornam a sua implementação complicada. Este trabalho procura determinar se a dessalinização de água alimentada por energias renováveis pode ser uma solução viável para garantir um abastecimento de água robusto e sustentável. A região do Algarve foi escolhida como caso de estudo por ser particularmente ameaçada em termos de recursos hídricos, e pelo desafio que o fluxo turístico sazonal representa para a rede de distribuição de água. Duas estratégias são consideradas: optar por uma central de dessalinização de grandes dimensões que abastece toda a região do Algarve (centralizado), ou optar por duas centrais mais pequenas, cada uma responsável pelo abastecimento da sua respectiva sub-região (descentralizado). É feita uma análise de custos de forma a estimar o custo de produção da água dessalinizada, considerando a procura de água potável na região considerada, assim como os perfis horários do consumo eléctrico e da produção eléctrica por energias renováveis. Foram desenvolvidos dois modelos para a estimação do custo de produção: um modelo em folha de cálculo, e subsequentemente um modelo de optimização de forma a minimizar os custos eléctricos. O custo unitário de produção obtido para o cenário descentralizado (0.7266 EUR/m^3) está dentro do padrão do sector, mas representa um custo 61.3% mais elevado do que o valor estimado para a água obtida por meios convencionais. É preciso financiamento externo para poder reduzir os custos de capital de uma central de dessalinização, de forma a viabilizar o projecto e torná-lo competitivo.

Abstract

With a severe seasonal concentration of precipitation, unevenly distributed water resources and frequent droughts and floods, the water supply in Portugal is under stress, and the problem is expected to increase with climate change. Water desalination is increasingly becoming the preferred solution to fight water scarcity but, being energy-intensive, the underlying costs and sustainability concerns over the power sources chosen remain a challenge to its implementation. This study aims to assess if the introduction of renewable energy sources (RES) powered seawater desalination in mainland Portugal could allow for the flexibility needed to guarantee water security through a viable model. The Algarve Region was chosen as a case study because it is particularly water stressed and subject to highly varying demographics depending on the season. Two strategies are considered: either one large plant supplies the whole region (centralised) or two smaller ones supply their respective sub-regions (decentralised). Taking the region's freshwater demand, hourly RES production and electricity consumption profiles, a cost analysis is performed in order to obtain an estimation for the produced levelised cost of water (LCOW). Two models were developed to estimate the LCOW: a spreadsheet model and a subsequent optimisation model, minimising electricity costs. The resulting 0.7266 EUR/m^3 of desalinated water, obtained for the decentralised solution, fits within the industry standard rate although being 61.3% higher than the estimated conventional water supply production cost. Finding external financing through European or national funding could further lower CAPEX and get desalination on par with the current market price of water.

Keywords:

Seawater desalination, Renewable Energy Sources, Water-Energy nexus.

Contents

List of Figures

List of Tables

List of Acronyms

RES : Renewable Energy Source
RO : Reverse Osmosis
$SWRO$: Seawater Reverse Osmosis
$LCOW$: Levelised Cost Of Water
PV : Photovoltaic
WT : Wind Turbines
$CAPEX$: Capital Expenditures
CRF : Capital Recovery Factor
$OPEX$: Operational Expenditures
TWP : Total Water Produced
EC : Electricity Costs
SEC : Specific Energy Consumption
USD : United States Dollar
EUR : Euro
AdA : Aguas do Algarve
$MILP$: Mixed Integer Linear Programming

List of Variables

$CAPEX_{annual}$	: total annualised CAPEX (EUR/year)
$OPEX^{y}$	: total yearly OPEX (EUR/year)
EC^{y}	: total yearly electricity costs (EUR/year)
TWP^{y}	: total water produced in a year (m^3/year)
$Demand^{d}$	: fresh water demand (m^3/day)
$Demand^{m}$	: fresh water demand (m^3/month)
$DaysPerMonth$	: number of days in each given month
$DaysPerSeason$	: number of days in each given season of the year
$SeasonDemand$	: total water demand for each season of the year (m^3/season)
TWD^{y}	: total water demand (m^3/year)
TWP^{y}	: total water to be produced (m^3/year)
$DesalPlant_{CAPEX}$	: CAPEX for the Desalination Plant (EUR)
$WaterSupply_{CAPEX}$	: CAPEX for the systems related to Water Supply (EUR)
$PowerLine_{CAPEX}$	: CAPEX for the Power Line connection (EUR)
RES_{CAPEX}	: CAPEX for the installed capacity of RES (EUR)
$PlantOutput^{d}$	: maximum real capacity of desalination output (m^3/day)
$NominalPlantCapacity^{d}$	: maximum nominal capacity of desalination output (m^3/day)
$ReferenceCost$	: desalination plant CAPEX cost (EUR/m^3/day)
$Pipeline_{CAPEX}$	: CAPEX for the Pipeline (EUR)
$PumpConstr_{CAPEX}$	: CAPEX for the pumping station construction (EUR)
$PumpEquip_{CAPEX}$	: CAPEX for the pumping station equipment (EUR)
Q_{max}	: maximum flow rate of pipeline (l/s)
H	: pumping head (m)
V_{max}	: maximum flow velocity (m/s)
D	: pipeline diameter (m)
$Pipeline_{length}$	: length of the water pipeline (m)
$CostPerMetre_{D}$	: cost of the water pipeline, according to its diameter (EUR/m)
$PowerConsumption$	: peak power consumption for desalination (kW)
SEC_{desal}	: Specific Energy Consumption for desalination (kWh/m^3)
PV_{CAPEX}	: CAPEX of Photovoltaic panels (EUR/kWp)
$Wind_{CAPEX}$	: CAPEX of Wind Turbines (EUR/kW)
i	: weighted average capital cost (%)
n	: project lifetime (years)
$DesalPlant_{OPEX}$	: OPEX of the desalination plant (EUR/year)
$WaterSupply_{OPEX}$	: OPEX of the water supply system (EUR/year)
RES_{OPEX}	: OPEX of the RES capacity installed on site (EUR/year)
$Labor$	: labor costs (EUR/m^3)

$CFactor$: correcting factor, US to local average salary
$Chemical$: OPEX in chemicals (EUR/m^3)
$MembraneExchange$: OPEX for membrane exchanges (EUR/m^3)
$Maintenance$: OPEX for general maintenance (EUR/m^3)
$Pipeline_{OPEX}$: OPEX for the Pipeline (EUR/m^3)
$PumpConstr_{OPEX}$: OPEX for the pumping station construction (EUR/m^3)
$PumpEquip_{OPEX}$: OPEX for the pumping station equipment (EUR/m^3)
PV_{OPEX} : OPEX of Photovoltaic panels (EUR/year)
$Wind_{OPEX}$: OPEX of Wind Turbines (EUR/year)
EC^{y}_{total} : total yearly electricity costs (EUR/year)
$EC^{d,s}_{total}$: total electricity costs for each representative day (EUR/day)
$OwnRES^{h,s}_{exp.}$: expenses related to Own production RES (EUR)
$SurplusRES^{h,s}_{exp.}$: expenses related to Surplus RES (EUR)
$Grid^{h,s}_{exp.}$: expenses related to grid power (EUR)
$Pumping^{h,s}_{exp.}$: expenses related to water pumping (EUR)
$OwnRES^{h,s}_{consump.}$: energy consumption of Own production RES (kWh)
$SurplusRES^{h,s}_{consump.}$: energy consumption of Surplus RES (kWh)
$Grid^{h,s}_{consump.}$: energy consumption of grid power (kWh)
$Pumping^{h,s}_{consump.}$: energy consumption for water pumping (kWh)
$OwnRES^{h,s}_{cost}$: unitary cost of Own RES power (EUR/kWh)
$SurplusRES^{h,s}_{cost}$: unitary cost of Surplus RES power (EUR/kWh)
$Grid^{h,s}_{varcost}$: variable cost of grid power (EUR/kWh)
$Grid^{h,s}_{fixedcost}$: fixed cost of grid power (EUR)
$Pumping^{h,s}_{varcost}$: variable cost of power used for water pumping (EUR/kWh)
$Pumping^{h,s}_{fixedcost}$: fixed cost of power used for water pumping (EUR)
$SEC_{pumping}$: Specific Energy Consumption for water pumping (kWh/m^3)
$PowerCons^{h,s}_{desal}$: total power consumption for desalination (kWh)
$Factor_{RESpenetr.}$: share of electricity demand supplied by regional RES production (%)
$ElectricityDemand^{h,s}_{region}$: hourly electricity demand of the region considered (kWh)
$RegionalRES^{h,s}_{prod.}$: hourly RES power production in the region considered (kWh)
$PriceFactor$: discount factor (%)
$MarketPrice^{h,s}$: average hourly market price of electricity (EUR/kWh)
$Flag_{total}$: sum of total Flag values in a day
$Flag^{d,s}_{sum}$: sum of Flag values for hour t
$Flag^{t,s}_{C1}$: binary variable flagging the activation of module 1
$Factor_{module}$: factor connecting the number of modules to the output capacity
$GridSupplier_{tariff}$: electricity tariff of the local grid supplier (EUR/kWh)
$Q^{m^3/h}_{max}$: maximum flow rate of pipeline (m^3/h)
$Desalination^{h,s}_{volume}$: volume of water produced (m^3)
$Pumping^{h,s}_{volume}$: volume of water pumped (m^3)
$StorageTank_{capacity}$: volume available for water storage (m^3)

Chapter 1

Introduction

1.1 Context and Motivation

Water scarcity has been listed by the World Economic Forum as the biggest threat to the world's economies, environment and people [1], and it is becoming a major concern for water resource policy makers. The oceans cover roughly 71% of the surface of our planet, but a mere 0.014% of all water on Earth is both fresh and easily accessible. Nonetheless, fresh water resources should technically be sufficient to meet demand at a global level, but the temporal and geographic mismatch between water availability and demand are responsible for putting four billion people under conditions of severe water scarcity, at least one month per year [2]. Unsatisfied demand in freshwater comes with added risks besides the sanitary threat: it slows economic growth, creates disputes between its users (sometimes spurring water conflicts [3]), and it can lead to irreversible depletion of groundwater resources. Variations in water availability are a part of the natural hydrological cycle, but the situation is aggravated by human interference through poor management approaches, increasing demographic pressures, urbanisation and pollution rates [4].

An increasingly important driver of change for the water cycle is climate change [5]. Although water scarcity has mostly threatened semi-arid and arid regions in the past, there are growing concerns for previously unaffected regions. Projections on the impact of climate change point to a global rise in temperatures, localised reductions in precipitation and an increase in drought and flooding frequencies. A severe reduction in river runoff and aquifer recharge is namely expected to occur in the entire Mediterranean basin [4], and there are growing concerns over the desertification of southern Europe [6][7].

Mainland Portugal has an uneven distribution of water resources, despite having water availability within the European average[8]: water is abundant north of the Tagus, but the southern regions have a negative hydrologic budget (i.e. more water outflows than inflows). The country is characterised by a severe seasonal concentration of precipitation, with 79% of total precipitation occurring between October and March, and by increasingly frequent extreme weather events such as droughts and floods [9], making water resource management a challenge. In response to these concerns Portugal has established a National Strategy for Adaptation to Climate Change (ENAAC in Portuguese) in which it states water resource diversification as one of its strategic objectives [10].

The hydrologic regions of Sado e Mira, Guadiana and Algarve have been identified as being water stressed (with water exploitation indexes above 25%), and the latter as having over-exploited groundwater resources [11]. Portugal's water distribution system is also inefficient: according to the country's water regulation authority (ERSAR in Portuguese), 29.8% of the total supplied drinking water was wasted within the water supply network in 2016 [12]. Considering the expected advancement of desertification and the water inflow reduction previously mentioned, the region of Algarve, Portugal, fits within the situation described above.

Algarve is the southernmost region of Portugal, extending south of the Tagus valley to the southern coast of the Iberian Peninsula. It has a surface of 4997 km^2 and a resident population of about 450,000 inhabitants. The region's mild climate and numerous beaches make it the country's most important touristic destination and one of Europe's most popular, having received an estimated total of 7.1 million tourists in 2017 [13]. This large inflow leads to an estimated tripling of its population in peak holiday season, which coincides with its driest season. The resulting large variations in freshwater demand [14] contribute to making the management of water resources particularly challenging in Algarve.

1.2 Problem statement

Water scarcity is a global concern. The solutions to tackle it are usually divided into two categories: either demand management or supply enhancement. Demand management refers to actions that try to curb freshwater consumption, whether by encouraging users to reduce water usage or by improving the efficiency of water distribution systems. On the other hand, supply enhancement solutions focus on increasing the availability of freshwater either through construction of water infrastructure and groundwater development or through development of non-conventional sources of water such as water reuse and seawater desalination.

Efficiently creating drinking water from the ocean is one of modern society's big technological challenges [15]. Water desalination technologies have matured in the last decade from being a last resort solution to becoming strong candidates in water resource diversification [16]. However, they are still energy-intensive, which sets a challenge when it comes to sustainably sourcing the power needed for the process.

The most recent trend in the quest for sustainable desalination has been in pairing seawater reverse osmosis (SWRO) with renewable energies, both for their low carbon footprint and their widespread availability. The installed capacity of renewable energy sources (RES) is steadily increasing worldwide (with solar and wind energy accounting for 84% of growth in 2018), and it now represents a third of global power capacity [17]. The main difficulty in designing a desalination project purely powered by RES comes from the intermittency of power sources such as solar and wind energy, which imposes an upper limit on how much of the produced power can be effectively exploited. A quantitative analysis of the problem is needed in order to address these issues.

Figure 1.1 shows a SWRO plant powered by a combination of photovoltaic solar panels and wind turbines: this is the layout that will be considered in this work.

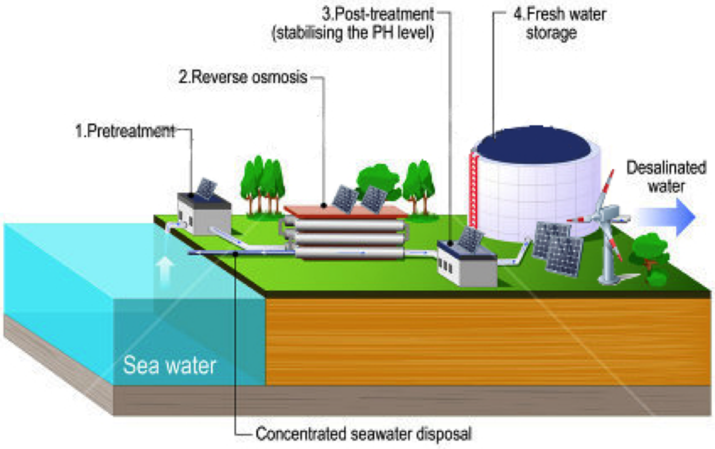


Figure 1.1: Layout of a sea water Reverse Osmosis desalination plant powered by renewable energies (adapted from [18])

1.3 Objectives of study

The main purpose of this study is to figure out how RES powered desalination could become a viable solution for water stressed regions such as Algarve.

The first objective is to determine which criteria are used in assessing the project's feasibility. This work mainly focuses on the economic criterion: the goal is to produce an estimation of the levelised cost of water (LCOW) of different desalination setups and then compare it to the reference cost of the region's conventional water supplier. Environmental criteria are also briefly assessed by comparing the carbon footprint of each proposed scenario, and by computing the share of RES in their respective power consumptions.

The next step is to analyse Algarve's endogenous energy resources in order to produce an estimation of the RES potential, and to characterise the region's water and electricity consumption profiles. This information is then applied in establishing three different scenarios for which we estimate the resulting LCOWs:

- a Baseline scenario where one plant supplies the whole Algarve, powered exclusively by the grid;
- a Centralised scenario where one plant supplies the whole Algarve, powered by three different power sources (excess RES, own production RES and grid power as backup);
- a Decentralised scenario where two plants supply their respective sub-regions of Algarve, powered by three different power sources (excess RES, own production RES and grid power as backup).

In order to ensure sustainability, the models are designed so that, except for the Baseline scenario, the power consumed comes from three different sources, two of them entirely renewable.

To estimate the LCOW, two desalination plant models are built: a spreadsheet model with a constant hourly output and a subsequent optimisation model to find the operational strategy that minimises electricity costs. Once the resulting LCOWs are obtained, a comparative analysis of the various scenarios is made in order to conclude on the project's viability and to advise on which setup to choose.

1.4 Present contribution

The main contributions of this work are as follows:

1. Establishing three scenarios of desalination integration into the existing water supply network;
2. Evaluating the region's RES potential and introducing a novel cost structure, using excess RES, that allows for both a reduction of LCOW and an increase in RES exploitation;
3. Presenting and discussing measures that may lead, in the long run, to a new water supply paradigm.

1.5 Thesis outline

This thesis is divided into six chapters, starting with the introduction: this first chapter presents the motivation for the study, the problem to be addressed, the set objectives and the contribution of this work. Chapter 2 presents an overview of relevant work published in the literature relating to water desalination powered by renewable energy sources. Chapter 3 describes the methods used in assessing the economic viability of RES powered desalination plants, and in optimising the electricity costs of plant operation. Chapter 4 characterises the region of Algarve, including its fresh water consumption and available renewable energy resources; it then details the application of the methods described in Chapter 3 to the chosen case study region. Chapter 5 presents and discusses the results of the three scenarios proposed, as well as a sensitivity analysis to identify the key variables of the model. It also discusses four guidelines that could help change the water supply paradigm in Portugal. Finally, Chapter 6 summarises the main conclusions of this thesis and presents ideas that might lead to further research.

Chapter 2

Literature review

2.1 Desalination technologies

The first record of desalination technology being used came from the writings of Aristotle, a Greek philosopher who lived during the fourth century BC. Ancient Romans also used evaporation to remove the salt from water to make it potable. Since then, desalination technology has become much more sophisticated, although some of the underlying principles remain sensibly unchanged. Seawater desalination technologies are classified into two major groups according to which of these underlying principles they are based on:

1. Thermal (phase-change) processes;
2. Membrane (non phase-change) processes.

Thermal processes led the desalination industry up until 2005, but Table 2.1 shows that they have now been surpassed by membrane processes (80% of today's global desalination capacity) in terms of energy efficiency and total operating costs [19].

Seawater desalination technology	Cost of water (USD/m^3)	Energy use (kWh_e/m^3)
Multi-Stage Flash	0.56-1.76	50-80
Multiple Effect Distillation	0.52-1.02	15-58
Membrane Distillation	1.2-2.0	10-43
Electro Dialysis	non cost effective	17
Reverse Osmosis	0.3-1.0	2-4

Table 2.1: Predominant desalination technologies and respective energy use (kWh_e is the electric equivalent energy use) [19, 20]

Desalination technologies have matured in the last two decades from being an expensive last resort solution to becoming strong candidates in water resource diversification [16]. Technical innovations such as Energy Recovery Devices and high-permeability membranes have made this possible by bringing down desalination's energy consumption, its main drawback, to around 3.0 kWh/m^3 for its most energy efficient technology, Reverse Osmosis (RO). RO consists in producing freshwater by forcing a briny feed through a semipermeable membrane in order to filter out ions, molecules and particles. The main energy requirement of RO is for pressuring the feed water and overcoming osmotic pressure. Although some ongoing research, on nano-structured membranes for instance, might lead to further reductions in energy consumption, no revolutionary breakthrough is expected in the next few years [21].

The energy consumption being bounded at around 0.7 kWh/m^3 by the theoretical limit of reverse osmosis [22], the focus has now shifted from technological developments to:

- Reducing desalination's carbon footprint;
- Optimising operations and scheduling of desalination plants in order to minimise electricity costs;
- Reducing desalination's environmental impact.

The carbon footprint of a desalination plant mainly comes from its large power consumption. In order to reduce the environmental impact of a desalination project, the main power source chosen must be sustainable and as non-polluting as possible.

2.2 Desalination powered by Renewable Energy Sources

Large capacity SWRO plants have historically been powered by non-renewable sources [23]. The main recent developments have been in replacing conventional power with renewable energy sources (RES) and in dealing with their intermittency. According to Abderlkareem et al. [24] and Caldera et al. [25] solar photovoltaic (PV) and wind turbines (WT) are two of the strongest candidates in powering low-carbon membrane desalination.

To determine the best performing energy supply setups for desalination plants, various studies have considered combinations of PV, WT, batteries, diesel generators and grid connections. Carta et al. [26] showed the difficulty in synchronising WT generated power and SWRO power consumption, making it impossible to maintain constant permeate recovery by relying exclusively on WT. Joyce et al. [27] and Masson et al. [28] have both been successful in designing small capacity RO installations relying entirely on PV, but the restricted time window of operation make it an unsuitable solution for desalination plants that need to consistently produce large outputs. The individual shortcomings of PV and WT can, however, be overcome by combining both technologies, providing a smoother operation capable of driving the desalination process round the clock [29]. An example of a small scale PV and WT hybrid application is given by Mentis et al. [30], who studied the arid islands in the Aegean Sea: they dimensioned the desalination plant, the WT and PV installed capacities needed to supply 100% of local water demand. The obtained production cost of water suggests that RES powered desalination is a suitable alternative to the expensive and polluting solution of water transportation from the mainland [30].

To the best of our knowledge, only small scale SWRO plants powered by RES have been successful off-grid. The general consensus is that a backup energy supplier is needed for a continuous operation, with battery and grid-tied solutions being the most popular (purposefully excluding diesel generators, for sustainability reasons). Fornarelli et al. [31] compared seven energy configurations (consisting of centralised or decentralised PV, WT and a connection to the grid) to determine the most cost-effective solution to power a Brackish Water RO plant dimensioned to supply a rural community in the coastal town of Denmark, Australia. RES intermittency was accounted for by allowing the plant feed flow rate and operating pressure to vary within admissible limits [31]. Ghenai et al. showed that a solar PV/Grid/Inverter setup compared favourably to a PV/Diesel generator/Batteries setup, both in terms of levelised cost of energy and in sustainability [32].

2.3 Operational optimisation to reduce levelised costs

The second major theme developed in the literature is connected to the operational strategy of desalination plants and the impact it might have on water production costs.

There are other factors influencing the resulting water production costs of a desalination project besides the chosen technologies to be used. Project planning and operational plant strategy have a major impact on total costs, which are generally divided into two cost categories: capital costs and operation and maintenance costs [23].

When planning for the water demand of metropolitan areas, Shahabi et al. [33] showed that opting for two complementary desalination plants instead of a large one could result in both lower levelised costs and environmental impact. Economies of scale of a single, larger plant are outweighed by its higher water transfer construction and operational expenses. In a later work [34], Shahabi et al. incorporated the desalination planning decisions into a Mixed Integer Linear programming (MILP) optimisation model, targeting environmental and economical objectives under case specific constraints for the city of Perth, Australia.

Mokheimer et al. [35] compared two operational strategies (either 12h or 24h/day) and several configurations of RES installed capacity in order to plan a PV/WT hybrid RO plant in Dhahran, Saudi Arabia. They modelled the plant and optimised the planning decisions for lowest cost per cubic meter of desalinated water, allowing them to estimate water production costs.

In a series of studies, Vakilifard et al. [36, 37, 38] proposed a comprehensive planning model for urban water and energy management and applied it to the metropolitan area of Perth, Australia. Their model considers a desalination-based water supply network driven by a combination of surplus output from residential PV installations and grid power. The plant's hourly operation scheduling is a function of energy related input parameters (local grid tariffs, PV output and electricity demand profiles) and water supply related parameters (desalination, storage tank and pumping/pipeline capacities). A MILP optimisation was then performed in order to minimise costs, and the various obtained results where compared to a grid driven base scenario. Vakilifard et al. first showed that the desalination output was inversely correlated to the grid tariffs, with peak production and pumping coinciding with off-peak electricity demand periods [36] ; in terms of optimal planning, they later found that working on an operational time-scale of hours lead to lower costs when compared to seasonal or yearly operational strategies[37]. Finally, their most recent study reinstated the need to consider both centralised and decentralised scenarios in the planning phase, as different values of operational parameters could lead to having either one of the scenarios being the optimal solution [38].

Chapter 3

Methods

To estimate the LCOW, two desalination plant models are built: a preliminary spreadsheet model with a constant hourly output and a subsequent optimisation model to find the operational strategy that minimises electricity costs. This section first defines the main parameter to be evaluated (LCOW). It then takes each model (first the spreadsheet and later the optimisation model) and sets the respective modelling assumptions, their specific parameters and equations.

3.1 Economic analysis

According to the literature, the main evaluation parameter to enter the water supply market is the Levelised Cost Of Water i.e. the cost per cubic metre produced given by equation 3.1.

$$LCOW = \frac{CAPEX_{annual} \times CRF + OPEX^{y} + EC^{y}}{TWP^{y}} \tag{3.1}$$

Where $CAPEX$ are the Capital Expenditures, money spent on fixed assets (over the project's lifetime); CRF is the Capital Recovery Factor annualising the $CAPEX$, $OPEX^{y}$ are the annual Operational Expenditures, the ongoing expenses inherent to the desalination plant operation ; EC^{y} are the electricity costs of the process over a year; TWP^{y} is the total volume of water produced in a year. The LCOW will be compared to the estimated cost of production of the conventional water supplier of the region.

3.2 Carbon footprint of power consumption

Powering desalination with RES helps decrease the total carbon footprint of water desalination. The carbon footprint of the Baseline scenario is estimated by taking the total grid power consumed in a year and converting it using the grid supplier's average emission of 256 tCO_2/GWh [39]. The same method is then used to estimate the CO_2 emissions of both the Centralised and Decentralised scenarios, and the emission savings are computed referring to the Baseline scenario's emissions.

3.3 General model assumptions

The exact parameters chosen for this study depend heavily on how the project is modelled. Assumptions are made for water dispatching, time sampling, power consumption, RES power production and the region's electricity demand.

The main assumption concerning the connection between the desalination plant and the local water supply network is that:

- the water supply network is capable of absorbing all the water produced (no limitation on water flow at the connection point).

The assumptions for time sampling are:

- a year is broken into 4 seasons, each represented by one average day repeated for the number of days in the season;
- representative days are made of 24 blocks of one hour, from 00:00 to 23:00.

Finally, the assumptions related to power consumption are:

- power used for desalination comes from three sources: first priority is given to the plant's own RES power production, followed by the region's RES excess output and lastly the local power grid;
- the region's RES production is first used to fulfil 80% of the total residential power consumption (the considered share of RES in the grid's power mix);
- the remaining power (called surplus) produced by the region's RES plants is used for desalination. It is bought at 75% of the hourly market price as it represents a local, predictable and large power demand;
- grid power is bought at the hourly tariff of the local power supplier, including both variable and fixed prices.

3.4 Spreadsheet project modelling

The main difference between the two models built is in how water production is managed. For the spreadsheet model, the guiding assumptions are:

- the plant has a constant desalination output throughout the day;
- the plant instantly pumps the water it is producing, without using any storage tank;
- power consumption for pumping is strictly from the local power grid, as a simplification.

Once the assumptions are set, we build an Excel spreadsheet with all the relevant input data in order to compute the LCOW. Excel was chosen because the data set is relatively complex, but the algebra is straightforward which means that it is more important to have a clear overview of the data than that of the formulae. The data set is then manipulated to compute each component of the LCOW. Figure 2.1 decomposes the LCOW into each of its components: the purpose of this diagram is to serve as a visual aid to the reader while going through the methodology. The components appear in the diagram (from left to right and from the top down) in the same order as they are developed in the following subsections.

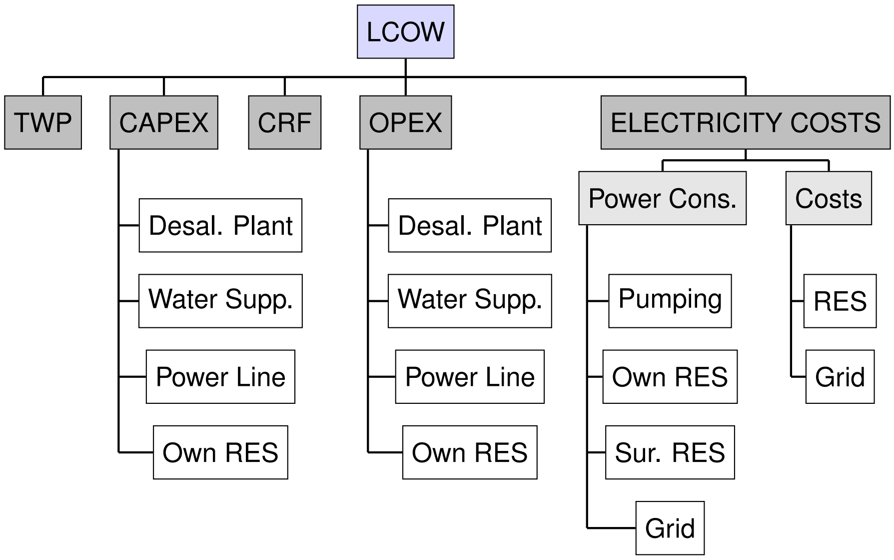


Figure 3.1: Diagram of LCOW components

3.4.1 Total Water Produced (TWP)

The desalination plant is dimensioned so that the total desalinated water covers the region's fresh water demand. The calculations are based on the local water supplier's published data, namely the monthly water demand.

We start by computing the daily water demand for each month of the year, given by eq. 3.2:

$$Demand^d = \frac{Demand^m}{DaysPerMonth} \tag{3.2}$$

The daily demand in a season is estimated by taking the average daily demand over the 3 months in each season, given by eq. 3.3:

$$SeasonDemand = \frac{\sum Demand^d}{3} \tag{3.3}$$

A year is modelled by taking one representative day for each of the four seasons, as shown by Table 3.1

Season	Months	Number of days
Winter	December, January and February	90
Spring	March, April and May	92
Summer	June, July and August	92
Autumn	September, October and November	91

Table 3.1: Groupings used for representative days of each season

The total water demand in a year is given by eq. 3.4:

$$TWD^y = \sum_{s=1}^{4}(SeasonDemand \times DaysPerSeason^s) \tag{3.4}$$

We then set the total water to be produced, TWP^y, equal to TWD^y.

3.4.2 Capital Expenditures (CAPEX)

The Capital Expenditures, given by eq. 3.5, include the construction costs of the desalination plant, the pumping facility, the power line connection and the PV panels and wind turbines installed.

$$CAPEX_{total} = DesalPlant_{CAPEX} + WaterSupply_{CAPEX} + PowerLine_{CAPEX} + RES_{CAPEX} \quad (3.5)$$

Each of the terms in Equation 3.5 will be defined in the following sections.

Desalination plant CAPEX

The desalination plant cost depends on its nominal plant capacity. The project intends to supply 100% of the water demand, so the desalination plant output needed is determined by the highest seasonal water demand, given by eq. 3.6.

$$PlantOutput^d = \max\ SeasonDemand \quad (3.6)$$

The nominal plant capacity needed, $NominalPlantCapacity^d$, is obtained by applying a plant factor to $PlantOutput^d$ in order to account for the time when the plant will be stopped for maintenance work and unforeseen shutdowns. Using the $ReferenceCost$ in EUR/m^3/year we have then the desalination plant CAPEX given by eq. 3.7:

$$DesalPlant_{CAPEX} = 365 \times NominalPlantCapacity^d \times ReferenceCost \quad (3.7)$$

Water Supply CAPEX

The total Water Supply CAPEX is given by eq. 3.8:

$$WaterSupply_{CAPEX} = Pipeline_{CAPEX} + PumpConstr_{CAPEX} + PumpEquip_{CAPEX} \quad (3.8)$$

where the pumping construction and equipment costs are given by[40] (costs in EUR), given by eqs. 3.9 and 3.10:

$$PumpConstr_{CAPEX} = 39904 + 374 \times Q_{max} + 0.15 \times Q_{max} \times H \quad (3.9)$$

$$PumpEquip_{CAPEX} = 1317 \times Q_{max}^{0.769} \times H^{0.184} + 2092 \times (Q_{max} \cdot H)^{0.466} \quad (3.10)$$

where H is the pumping head in m and Q_{max} is in L/s. The pumping capacity is defined as the altitude difference between the desalination plant and the water supply connection point, computed with a Geospatial tool such as Google Maps.

The pumping capacity (Q_{max}) must be dimensioned to be as close as possible to the plant output to avoid any bottleneck situations.

The pumping pipeline diameter is found solving the following equation for D, assuming a maximum flow velocity of V_{max} in m/s, as shown by eq. 3.11:

$$Q_{max} = 24 \times 3600 \times V_{max} \times \pi \times \frac{D^2}{4} \simeq PlantOutput \tag{3.11}$$

The pipeline cost is a function of its diameter and total length, given by eq. 3.12:

$$Pipeline_{CAPEX} = Pipeline_{length} \times CostPerMetre_D \tag{3.12}$$

where $Pipeline_{length}$ is the distance from the desalination plant to the water supply connection point in metres and $CostPerMetre_D$ is the cost of the pipeline in EUR/m according to its diameter D.

Power Line CAPEX

A regular, residential connection to the grid is not an adequate solution due to the high power consumption of desalination plants.

The cost of a high voltage connection to the grid is calculated based on the grid supplier's pricing tariff, and is a function of two factors:

- Power rating;
- Distance between the desalination plant and the grid connection point.

To estimate the plant's power consumption, we take the peak energy consumed during one hour, as given by eq. 3.13:

$$PowerConsumption = \frac{PlantOutput^d \times SEC_{desal}}{Time} \tag{3.13}$$

in kW, where SEC_{desal} is the Specific Energy Consumption of the desalination process chosen in kWh/m^3. This allows, if needed, the desalination plant to guarantee its intended water output with power coming exclusively from the grid.

The distance to the grid connection point is computed using the same Geospatial tool as for the pumping head.

Own production of RES CAPEX

Installing photovoltaic panels and wind turbines on site leads to savings in electricity costs of operation. The capacity installed depends on the available area and topography of the plant's location. Rooftop PV panels cover the buildings of the plant, complemented by both a PV and wind turbine farm. The respective capital costs used in the literature are given by Table 3.2:

Type of RES	CAPEX
Rooftop PV panels	550 EUR/kWp
PV panels farm	550 EUR/kWp
Wind turbine	1 000 EUR/kW

Table 3.2: CAPEX of RES for own production[41]

The total CAPEX of the RES capacity installed for own production is given by eq. 3.14:

$$RES_{CAPEX} = PV_{CAPEX} + Wind_{CAPEX} \tag{3.14}$$

3.4.3 Capital Recovery Factor (CRF)

Capital expenditures are amortised over the lifetime of their respective assets. Annualised capital expenditures are computed with eq. 3.15:

$$CAPEX_{annual} = CRF \times CAPEX_{total} \tag{3.15}$$

where CRF is the Capital Recovery Factor given by eq. 3.16:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{3.16}$$

where i is the weighted average capital cost and n is the project lifetime in years.

3.4.4 Operational Expenditures (OPEX)

The operational expenditures are given by eq. 3.17:

$$OPEX^y = DesalPlant_{OPEX} + WaterSupply_{OPEX} + RES_{OPEX} \tag{3.17}$$

The three terms in this equation will be presented in the following sections.

Desalination plant OPEX

The operational costs of the desalination plant are given by eq. 3.18:

$$DesalPlant_{OPEX} = TWP^y \times (Labor \times CFactor + Chemical + MembraneExchange + Maintenance) \tag{3.18}$$

where $Labor$, $Chemical$, $MembraneExchange$ and $Maintenance$ costs are in EUR/m^3. $Labor$ costs are corrected with $CFactor$ in order to account for differences in standards of living: $CFactor$ is the ratio between the local average salary and the one in the US, since the values taken from the literature are from an american case.

Water Supply OPEX

The yearly pumping OPEX and maintenance costs are given by eq. 3.19:

$$WaterSupply_{OPEX} = Pipeline_{OPEX} + PumpConstr_{OPEX} + PumpEquip_{OPEX} \tag{3.19}$$

where its components are given by eqs. 3.20, 3.21 and 3.22 [40]:

$$Pipeline_{OPEX} = 0.75\% \times Pipeline_{CAPEX} \tag{3.20}$$

$$PumpConstr_{OPEX} = 1\% \times PumpConstr_{CAPEX} \tag{3.21}$$

$$PumpEquip_{OPEX} = 2.5\% \times PumpEquip_{CAPEX} \tag{3.22}$$

Power Line OPEX

The operational expenditures of the power line connecting the desalination plant to the grid are considered to be included in the CAPEX.

Own production of RES OPEX

The operational expenditures of the own plant RES consider both PV and WT installed is given by eq. 3.23:

$$RES_{OPEX} = PV_{OPEX} + Wind_{OPEX} \tag{3.23}$$

where its components are respectively given by eqs. 3.24 and 3.25 [41]:

$$PV_{OPEX} = 1.5\% \times PV_{CAPEX} \tag{3.24}$$

$$Wind_{OPEX} = 2\% \times Wind_{CAPEX} \tag{3.25}$$

3.4.5 Electricity costs (EC)

The total electricity expense over a year is given by the sum of the 4 seasons costs (in EUR), as shown in eq. 3.26:

$$EC^{y}_{total} = \sum_{s=1}^{4}(EC^{d,s}_{total} \times DaysPerSeason^{s}) \tag{3.26}$$

In terms of time scale, the building blocks in computing the energy costs is one hour. Adding the electricity costs of each of the 24 time blocks in a representative day, we have the total electricity costs as given by eq. 3.27:

$$EC^{d,s}_{total} = \sum_{h=0}^{23}(OwnRES^{h,s}_{exp.} + SurplusRES^{h,s}_{exp.} + Grid^{h,s}_{exp.} + Pumping^{h,s}_{exp.}) \tag{3.27}$$

with each hourly expense given by eqs. 3.28, 3.29, 3.30 and 3.31:

$$OwnRES^{h,s}_{exp.} = OwnRES^{h,s}_{consump.} \times OwnRES^{h,s}_{cost} \tag{3.28}$$

$$SurplusRES^{h,s}_{exp.} = SurplusRES^{h,s}_{consump.} \times SurplusRES^{h,s}_{cost} \tag{3.29}$$

$$Grid^{h,s}_{exp.} = Grid^{h,s}_{consump.} \times Grid^{h,s}_{varcost} + Grid^{h}_{fixedcost} \tag{3.30}$$

$$Pumping^{h,s}_{exp.} = Pumping^{h,s}_{consump.} \times Pumping^{y}_{varcost} + Grid^{h}_{fixedcost} \tag{3.31}$$

The electricity expense of using a power source is, essentially, a function of the power consumption of that particular source and the costs it entails.

3.4.5.1 Power consumption

Pumping power consumption The water is assumed to be pumped at a constant rate to match the constant desalination output.The pumping power consumption is given by eq. 3.32:

$$Pumping^{h,s}_{consump.} = \frac{SeasonDemand}{24} \times SEC_{pumping} \tag{3.32}$$

where $SEC_{pumping}$ is the Specific Energy Consumption of pumping in kWh/m^3

Desalination power consumption For each hour of the day, the power demand for desalination must be met by a proportion of own production RES, surplus RES and grid power consumption, as given by eq. 3.33:

$$PowerCons^{h,s}_{desal} = OwnRES^{h,s}_{consump.} + SurplusRES^{h,s}_{consump.} + Grid^{h,s}_{consump.} \tag{3.33}$$

where the power consumption for desalination is given by eq. 3.34:

$$PowerCons^{h,s}_{desal} = Demand^{h,s} \times SEC_{desal} \tag{3.34}$$

with the each hourly water demand given by eq. 3.35:

$$Demand^{h,s} = \frac{SeasonDemand}{24} \tag{3.35}$$

The consumption proportions between the three different power sources are governed by the model assumptions: first priority is given to the plant's own RES power production, followed by the region's RES excess output and lastly the local power grid. The constraint imposed on own production RES is that the whole power production of the PV panels and Wind turbines installed on the plant must be consumed. The constraint on surplus RES consumption is that the surplus power available for desalination is subject to the curtailment of RES production in the region, as shown by eq. 3.36:

$$SurplusRES^{h,s}_{consump.} \leq RegionalRES^{h,s}_{prod.} - Factor_{RESpenetr.} \times ElectricityDemand^{h,s}_{region} \tag{3.36}$$

where $Factor_{RESpenetr.}$ is the the percentage of the electricity demand in the region, $ElectricityDemand^{h,s}_{region}$, that is supplied by the RES production $RegionalRES^{h,s}_{prod.}$

To compute RES power consumption ($OwnRES^{h,s}_{consump.}$ and $SurplusRES^{h,s}_{consump.}$), RES power production must be estimated.

RES power production estimation The method used to estimate the power production was the same for both the RES producers in the region ($RegionalRES^{h,s}_{prod.}$) and the RES capacity installed on the desalination plant ($OwnRES^{h,s}_{prod.}$).

The production of each Photovoltaic plant is estimated using:

- installed capacity and coordinates of each known PV plant;
- 10% system loss;
- 35º Tilt and 180º Azimuth;

- CM-SAF SARAH database.

The production of each Wind farm is estimated using:

- installed capacity and coordinates of each known wind farm;
- turbine model installed at each location, whenever specified;
- hub height of 80m;
- MERRA-2 database.

The data was recovered through the Renewables.ninja simulation tool[42, 43] (parameters such as the system losses, tilt and azimuth angles or hub height are set to the tool's standard values). For wind energy, and because it is particularly unpredictable, the hourly power production estimation is averaged over three years of data.

3.4.5.2 Power costs

Having computed the power consumption values, the next step in order to obtain the power expenses is to determine their costs per unit of power.

RES power costs $OwnRES_{cost}^{h,s}$, the power produced by the desalination plant's own capacity is considered to have no variable cost (only CAPEX and maintenance OPEX apply). Surplus RES power is valued according to the average hourly market price of the kWh in the region as given by eq. 3.37:

$$SurplusRES_{cost}^{h,s} = PriceFactor \times MarketPrice^{h,s} \tag{3.37}$$

where $PriceFactor$ is the discount factor assumed.

Grid power costs $Grid_{varcost}^{h,s}$ and $Grid_{fixedcost}$ are respectively the variable tariff and fixed costs imposed by the power supplier. It is assumed that pumping is exclusively powered by grid power, at a variable cost $Pumping_{varcost}^{y}$ that is equal to the yearly average of $Grid_{varcost}^{h,s}$, as given by eq. 3.38:

$$Pumping_{varcost}^{y} = \frac{1}{4} \times \sum_{s=1}^{4} \left(\frac{\sum_{h=0}^{23} Grid_{varcost}^{h,s}}{24} \right) \tag{3.38}$$

3.5 Electricity cost optimisation model

As previously mentioned, SWRO desalination is a very energy intensive technology. According to [16], energy expenses for the SWRO process alone represent between 25 to 40% of the LCOW, making it its largest contributor. Besides, SWRO systems contribute to between 65 to 80% of total energy consumption of a desalination plant (to which we must add the energy needed for pumping for example). Managing energy expenses correctly is therefore crucial for the economical viability of a desalination plant.

Some strong assumptions are made in the spreadsheet model with respect to power consumption (Section 3.4). The desalination plant's capacity is dimensioned according to the yearly peak demand, which means that it is over-dimensioned the rest of the year. The plant could then have the flexibility to be desalinating at a higher (lower) output than the hourly average demand at an hour of the day where the energy is cheapest (costly). By imposing a constant desalination output throughout the day, the spreadsheet model cannot take advantage of this flexibility.

The second step in estimating the LCOW for this project is to search for the optimal operational scheduling of the plant so that the total electricity costs are minimised.

3.5.1 Optimisation assumptions

The main difference between the optimisation model and the model presented in section 3.4 is that the desalination output is now an optimisation variable and is therefore no longer fixed. This change leads to some added considerations: the general model assumptions presented in section 3.3 still apply, to which a set of new ones is added.

SWRO plants were historically designed to work at a constant capacity. A reduction in the pressure vessels needed for an output lower than full capacity meant that pumps would work less efficiently, and that membrane fouling problems appeared with lower flow rates. Constant output was not a problem as long as the desalination water produced represented a small fraction of the fresh water consumption of the region it supplied. As SWRO got more cost effective, desalinated water became a viable primary supplier and desalination plants now need the ability to mirror demand fluctuations in their output capacity. This is made possible by using a “pressure centre” design as shown by Figure 3.2: the three components of a traditional single reverse osmosis unit (pressure pump, membrane rack and energy recovery system) are split between three centralised centres working for all the units, while connecting all the components to one common piping system[44, 45]. According to the production capacity needed, the plant can then operate with between 1 and 4 high pressure pumps, while maintaining pumping efficiencies around 90% and reducing SEC during low demand season.

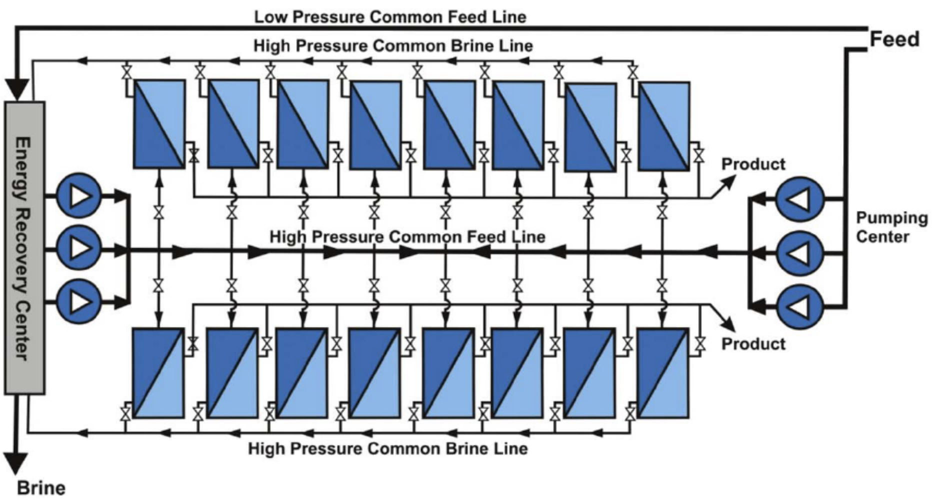


Figure 3.2: Layout of a SWRO plant with pressure centre design[16]

The assumptions related to the plant modular capacity are:

- the nominal output capacity is evenly split into 4 modules;
- the modules are activated according to the capacity needed to desalinate the optimal volume for each hour block;

- modules are ordered and their operation is cumulative: for example, for module 3 to be activated, modules 1 and 2 must also be activated;
- to simulate the time constant of the system, the activation and de-activation of the modules have a rigidity constraint: between two consecutive hour blocks, only one module can be either added or removed;

The general water production and management assumptions are:

- the plant has a variable desalination output throughout the day;
- the total output volume in a day must match the daily water demand;
- the total output volume in a day must be pumped to the water supply network by the end of the day;
- the usage of storage tanks is considered;
- the storage tanks must be empty at the start and at the end of the day: because seasons are modelled by a repetition of strictly identical days, allowing for overnight water storage would become problematic on inter-seasonal transitions;
- power consumption for pumping is from the same three sources as the power used for desalination.

3.5.2 Optimisation formulation

The goal of this optimisation model is to minimise the total electricity costs: the yearly electricity costs, as defined in equations 3.26 and 3.27 in section 3.4.5, are given by a linear function.

Linear programming problems can be expressed in canonical form as:

$$\begin{aligned} x^* &= \text{Argmax } c^T x \\ Ax &\leq b \\ x &\geq 0 \end{aligned}$$

that is find the optimal value x^* so that the objective function $c^T x$ (where c is a vector of known coefficients and x is a vector of variables) is maximised. With regard to constraints on the variables, A is a matrix and b is a vector, both of known coefficients. Two optimisations are performed: minimisation of total electricity costs and minimisation of number of plant modules used.

The optimisation variables in this model are:

- the power consumption from each one of the three sources, for desalination purposes (3 variables);
- the power consumption from each one of the three sources, for pumping purposes (3 variables);
- which plant modules are in use (4 variables).

According to our time modelling assumptions, the dimension of the vector space x is 10×24: from 0h to 23h, for the 10 optimisation variables.

Although the power consumption variables are Real numbers, the operation of the plant's modules is modelled by a binary variable: their value is "1" if activated and "0" if not. Seeing that some variables are Real numbers and others are Integers, the problem at hand is classified as being a Mixed Integer Linear Program (MILP). The cost functions and the constraints imposed on the variables of both optimisation problems are developed in the following sections.

3.5.2.1 Modularity

Objective function

The goal of the secondary optimisation is to ensure that the plant is only activating the modules it strictly needs to produce the optimal volume set by the main optimisation (electricity costs minimisation). The activation of each module is modelled by a binary variable, and the objective function to minimise is given by eq. 3.39:

$$Flag_{total} = \sum_{s=1}^{4}\sum_{t=0}^{23}(Flag_{sum}^{t,s} \times DaysPerSeason^{s}) \tag{3.39}$$

with $Flag_{sum}^{t,s}$ defined in eq. 3.40:

$$Flag_{sum}^{t,s} = Flag_{C1}^{t,s} + Flag_{C2}^{t,s} + Flag_{C3}^{t,s} + Flag_{C4}^{t,s} \tag{3.40}$$

where $Flag_{C1}^{t,s}$ is a flag variable representing the activation of module 1, the first quarter of total capacity.

Constraints

Constraint 1.1 To ensure that the operation of modules is cumulative, we set eqs. 3.41:

$$\begin{cases} Flag_{C3}^{t,s} = Flag_{C2}^{t,s} = Flag_{C1}^{t,s} = 1 \text{ , if } Flag_{C4}^{t,s} = 1 \\ Flag_{C2}^{t,s} = Flag_{C1}^{t,s} = 1 \text{ , if } Flag_{C3}^{t,s} = 1 \\ Flag_{C1}^{t,s} = 1 \text{ , if } Flag_{C2}^{t,s} = 1 \end{cases} \tag{3.41}$$

Constraint 1.2 The activation of each module represents a change in plant output capacity, as given by eqs. 3.42:

$$\begin{cases} Factor_{module} = 0.25 \text{ , if } Flag_{C1}^{t,s} = 1 \\ Factor_{module} = 0.5 \text{ , if } Flag_{C2}^{t,s} = 1 \\ Factor_{module} = 0.75 \text{ , if } Flag_{C3}^{t,s} = 1 \\ Factor_{module} = 1 \text{ , if } Flag_{C4}^{t,s} = 1 \end{cases} \tag{3.42}$$

where $Factor_{module}$ is a factor connecting the number of modules activated and the total output capacity of the plant (evenly split in 4 as per the assumptions in 3.4.1).

Constraint 1.3 To simulate the time constant in the operation of the plant, we set the rigidity constraints as given by eq. 3.43:

$$\left|Flag_{sum}^{t,s} - Flag_{sum}^{t-1,s}\right| \leq 1 \tag{3.43}$$

3.5.2.2 Total Costs

Objective function

The main objective function is the total energy cost in a year, as given by eq. 3.44:

$$EC_{total}^{y} = \sum_{s=1}^{4}(EC_{total}^{d,s} \times DaysPerSeason^{s}) \tag{3.44}$$

with $EC_{total}^{d,s}$ defined by eq. 3.45:

$$EC_{total}^{d,s} = \sum_{h=0}^{23}(Grid_{fixedcost}^{h} + Desalination_{exp.}^{h,s} + Pumping_{exp.}^{h,s}) \tag{3.45}$$

where $Grid_{fixedcost}^{h}$, the fixed portion of the grid tariff is set by the grid supplier, and the total desalination and pumping energy expenses for each hour are given by eq. 3.46:

$$\begin{cases} Desalination_{exp.}^{h,s} = OwnRES_{desal.exp.}^{h,s} + SurplusRES_{desal.exp.}^{h,s} + Grid_{desal.exp.}^{h,s} \\ \\ Pumping_{exp.}^{h,s} = OwnRES_{pump.exp.}^{h,s} + SurplusRES_{pump.exp.}^{h,s} + Grid_{pump.exp.}^{h,s} \end{cases} \tag{3.46}$$

Each of these terms is defined following the structure exemplified by $OwnRES_{desal.exp.}^{h,s}$ as given by eq. 3.47:

$$OwnRES_{desal.exp.}^{h,s} = OwnRES_{desal.cons.}^{h,s} \times OwnRES_{cost}^{h,s} \tag{3.47}$$

where $OwnRES_{desal.cons.}^{h,s}$ is the energy consumption (optimisation variable) in kWh and $OwnRES_{cost}^{h,s}$ the energy cost in EUR/kWh.

Electricity costs are the same whether used for pumping or desalination purposes, and they are given by eq. 3.48:

$$\begin{cases} OwnRES_{cost}^{h,s} = 0 \\ SurplusRES_{cost}^{h,s} = PriceFactor \times MarketPrice^{h,s} \\ Grid_{cost}^{h,s} = GridSupplier_{tariff}^{h,s} \end{cases} \tag{3.48}$$

Constraints

The first set of constraints, concerning total cost minimisation, is relative to how power consumption is organised, and the second one is relative to the usage of storage tanks.

Constraint 2.1 The first constraint imposed on energy consumption is that the total volume produced in a day must match the daily water demand. SEC_{desal} being constant, we convert this constraint from volume to energy units as shown in eq. 3.49 :

$$\sum_{h=0}^{23}(OwnRES_{desal.cons.}^{h,s} + SurplusRES_{desal.cons.}^{h,s} + Grid_{desal.cons.}^{h,s}) = SeasonDemand \times SEC_{desal} \tag{3.49}$$

i.e. the sum of the energy consumptions from all three sources in a day must be equal to the total energy needed to desalinate the volume imposed by the demand for that day.

Constraint 2.2 To ensure that all the produced water is pumped by the end of the day, we set eq. 3.50:

$$\sum_{h=0}^{23}(OwnRES_{pump.cons.}^{h,s} + SurplusRES_{pump.cons.}^{h,s} + Grid_{pump.cons.}^{h,s}) = SeasonDemand \times SEC_{pumping} \tag{3.50}$$

Constraint 2.3 The third constraint, on the total energy consumption for desalination, in one hour, is given by eq. 3.51:

$$OwnRES_{desal.cons.}^{h,s} + SurplusRES_{desal.cons.}^{h,s} + Grid_{desal.cons.}^{h,s} \leq Factor_{module} \times PlantOutput^{h} \times SEC_{desal} \tag{3.51}$$

where the hourly output is given by eq. 3.52:

$$PlantOutput^{h} = \frac{PlantOutput^{d}}{24} \tag{3.52}$$

i.e. the plant cannot produce more water in an hour than its maximum capacity, $PlantOutput^{h}$ in m^3

Constraint 2.4 In the same vein as Constraint 3 but applied to pumping and its hourly capacity limitation, we have eq. 3.53:

$$OwnRES_{pump.cons.}^{h,s} + SurplusRES_{pump.cons.}^{h,s} + Grid_{pump.cons.}^{h,s} \leq Q_{max}^{m^3/h} \times SEC_{pumping} \tag{3.53}$$

where $Q_{max}^{m^3/h}$ is the maximum pumping capacity converted to m^3/h

Constraints 2.5 and 2.6 Finally, and to ensure that the solutions are bounded and realistic, we set an upper and lower bound to the variables representing RES power consumption (relative to power availability) as shown in eq. 3.54:

$$\begin{cases} 0 \leq OwnRES_{desal.cons.}^{h,s} + OwnRES_{pump.cons.}^{h,s} \leq OwnRES_{prod.}^{h,s} \\ 0 \leq SurplusRES_{desal.cons.}^{h,s} + SurplusRES_{pump.cons.}^{h,s} \leq SurplusRES_{available} \end{cases} \tag{3.54}$$

with $SurplusRES_{available}$ given by eq. 3.55:

$$SurplusRES_{available} = RegionalRES_{prod.}^{h,s} - Factor_{RESpenetr.} \times ElectricityDemand_{region}^{h,s} \tag{3.55}$$

The operation constraints related to storage tank usage are the following:

Constraint 2.7 Storage tanks cannot be used overnight. Its level must be at zero at:

- the beginning of the first hour of each day;
- the end of the last hour of each day.

This guarantees that the last value of each day matches the first value of the following, for a clean cycle.

Constraint 2.8 At any given time, the difference between the volume of water produced and the volume pumped out to the water supply network cannot be larger than the storage tank capacity, as set by eq. 3.56.

$$Desalination^{h,s}_{volume} - Pumping^{h,s}_{volume} \leq StorageTank_{capacity} \tag{3.56}$$

where $Desalination^{h,s}_{volume}$ and $Pumping^{h,s}_{volume}$, both in m^3, are given by eq. 3.57:

$$Desalination^{h,s}_{volume} = \frac{1}{SEC_{desal}} \times (OwnRES^{h,s}_{desal.cons.} + SurplusRES^{h,s}_{desal.cons.} + Grid^{h,s}_{desal.cons.}) \tag{3.57}$$

and eq. 3.58:

$$Pumping^{h,s}_{volume} = \frac{1}{SEC_{pumping}} \times (OwnRES^{h,s}_{pump.cons.} + SurplusRES^{h,s}_{pump.cons.} + Grid^{h,s}_{pump.cons.}) \tag{3.58}$$

Optimisation package choice

The multi-objective MILP described in the previous sections is implemented in GUROBI through a Python interface. The choice of platform is justified by the vast documentation available for Python (amongst other options, Matlab, Java, C++ and R also have an interface available). GUROBI is an industry standard in multiple objective Linear Programming, chosen for its very simple academic licensing process. Other options would be CPLEX, GLPK, SCIP and FICO.

3.5.3 Sensitivity analysis

Once the results of the optimisation model are obtained, we run the same model while performing a sensitivity analysis on three input variables in order to understand how much of an impact they might have on the obtained LCOW. For each of the sensitivity analysis, the chosen variables are:

1. $Factor_{RESpenetr.}$, the share of electricity demand to be supplied by regional RES production;
2. $PriceFactor$, the price discount awarded to SWRO plants for buying electricity in bulk;
3. $StorageTank_{capacity}$, the volume available for water storage.

Table 3.3 summarises how each variable varies for its respective sensitivity analysis, while the other two are kept constant and equal to the values set in Section 3.3.

Sensitivity analysis #	$Factor_{RESpenetr.}$	$PriceFactor$	$StorageTank_{capacity}$
1	$\pm$10 p.p.	constant	constant
2	constant	$\pm$5 p.p.	constant
3	constant	constant	0 to 15,000 m^3

Table 3.3: Values taken for each sensitivity analysis

Chapter 4

Case study

In this section, the methods described in Chapter 3 are applied, in the exact same way, to three different scenarios: a Baseline (powered entirely by the grid), a Centralised and a Decentralised scenario. Both the Baseline and the Centralised scenario consider one large desalination plant with enough capacity to supply the water demand of the whole Algarve, while the Decentralised scenario breaks down the Algarve region into two independent sub-regions (Windward and Leeward, as shown by Figure 4.1). Each sub-region has its own desalination plant, its water demand as well as, for the latter two scenarios, its local RES production assessed separately. The main reason behind having two different geographical strategies is to assess the impact of economies of scale on the final water cost of production and to understand which strategy is the best suited to the characteristics of Algarve.

Figure 4.1: Algarve and its two sub-regions: Windward (1 to 8) and Leeward (9 to 16) [46]

The structure of the present chapter follows that of the LCOW definition i.e.:

- Total Water Production;
- CAPEX;
- Capital Recovery Factor;

- OPEX;
- Electricity costs.

4.1 Total Water Produced

To determine the total volume of water to be produced by the desalination plant, we must first determine the fresh water demand in the region considered.

4.1.1 Water Consumption

The water supply network in Algarve is managed by Aguas do Algarve (AdA), provider of drinking water to the local municipalities. It publishes every year the total monthly volume distributed (as shown by Figure 4.2), and each municipality's share of the total yearly volume consumed (as shown by Figure 4.3). Assuming that these values are discarding distribution losses, we take them as being the demand in volume of fresh water to be met by the desalination plants, and compute the peak seasonal demand highlighted in Table 4.1.

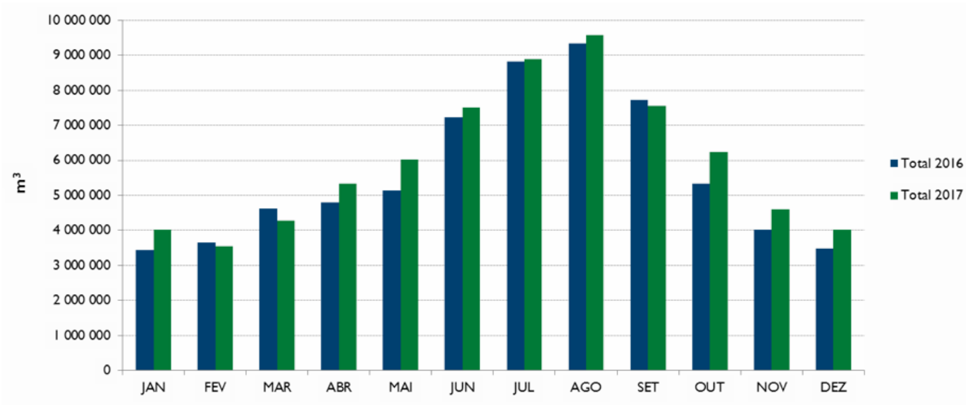


Figure 4.2: Monthly water consumption in Algarve for 2016 and 2017[47]

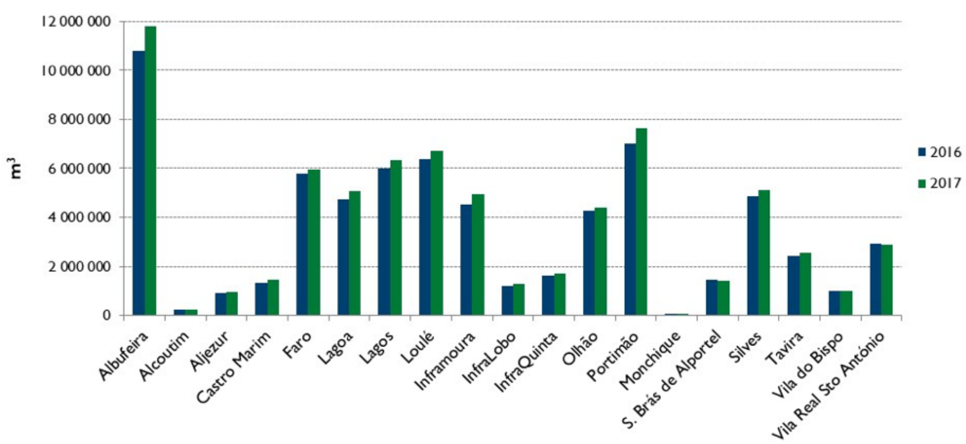


Figure 4.3: Total yearly water consumption in each municipality of Algarve for 2016 and 2017 [47]

Season	Centralised scenario	Decentralised scenario	
	Algarve (m^3/day)	Windward (m^3/day)	Leeward (m^3/day)
Winter	126 251	66 926	59 325
Spring	168 548	89 348	79 200
Summer	**279 570**	**148 200**	**131 370**
Autumn	200 538	106 305	94 233

Table 4.1: $SeasonDemand$ values for each region considered, based on 2017 values[47]

4.2 Capital Expenditures

4.2.1 Desalination plant capacity

Having estimated the maximum water demand, the following step is to determine the desalination plant's capacity needed in order to meet that demand. Each region's maximum daily demand is selected as per eq. 3.6, and a plant factor of 85%[37] is applied to determine the nominal plant capacity needed for each scenario as shown in table 4.2:

Region	Centralised scenario	Decentralised scenario	
	Algarve	Windward	Leeward
$PlantOutput^d$ (m^3)	280,000	148,500	131,500
$NominalPlantCapacity^d$ (m^3)	330,000	175,000	155,000
$DesalPlant_{CAPEX}$ (M EUR)	268.6	142.4	126.2

Table 4.2: Desalination plant capacities and respective CAPEX (in millions of EUR)

As suggested by Caldera et al. in [41], the $ReferenceCost$ used to compute the desalination plant's CAPEX is:

$$ReferenceCost = 2.23\,\text{EUR}/m^3/\text{year}$$

Over the last 10 years, the trend in Algarve's fresh water consumption has not been clear: although demand has risen since 2014, there was a significant consumption reduction between 2011 and 2013[48]. It is assumed that water demand will remain relatively unchanged over the project's lifetime.

The coast of Algarve is a difficult terrain when it comes to placing a large industrial plant close to the ocean: it is restricted by two national parks (Costa Vicentina and Ria Formosa) and by its many tourist beaches. Figures 4.4 and 4.5 show the suggested locations for the plants, taking the geographical constraints previously mentioned into consideration, and placing the plants as close to the ocean and to both the water supply and power networks as possible.

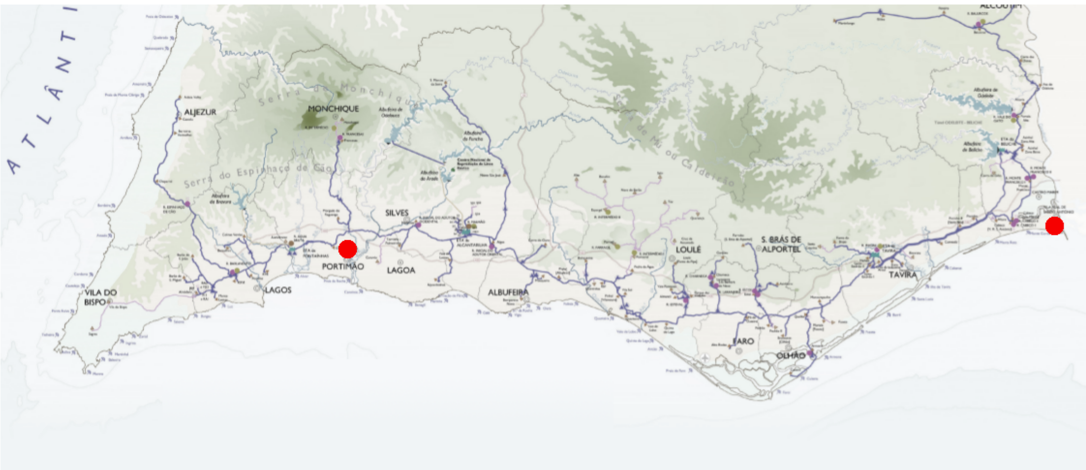


Figure 4.4: Locations suggested for the desalination plants at regional scale [49]

Figure 4.5: Left: Windward location (Portimão), Right: Leeward location (Monte Gordo) (adapted from Figure 4.4)

4.2.2 Water supply

The pipeline connecting the desalination plants to the water supply network must be capable of extracting the plant's daily water output in order to avoid creating a bottleneck. Assuming the recommended maximum flow velocity of $V_{max} = 1.5$m/s [40], we set the pipeline diameter D needed to ensure the desired flow rate. The $Pipeline_{length}$ and the pumping head H needed are measured thanks to Google Maps (represented by the pink line on Figure 4.5). Table 4.3 shows the values taken for the water supply dimensioning and resulting CAPEX.

Region	Centralised scenario	Decentralised scenario	
	Algarve	Windward	Leeward
D (m)	1.7	1.3	1.2
Q_{max} (l/s)	3403	1990	1696
H (m)	15	24	15
$CostPerMetre_D$ (EUR/m) [50]	1148	866	715
$Pipeline_{length}$ (km)	5	3.2	5
$Pipeline_{CAPEX}$ (M EUR)	5.74	2.79	3.57
$PumpConstr_{CAPEX}$ (M EUR)	1.32	0.79	0.68
$PumpEquip_{CAPEX}$ (M EUR)	1.45	1.13	0.90

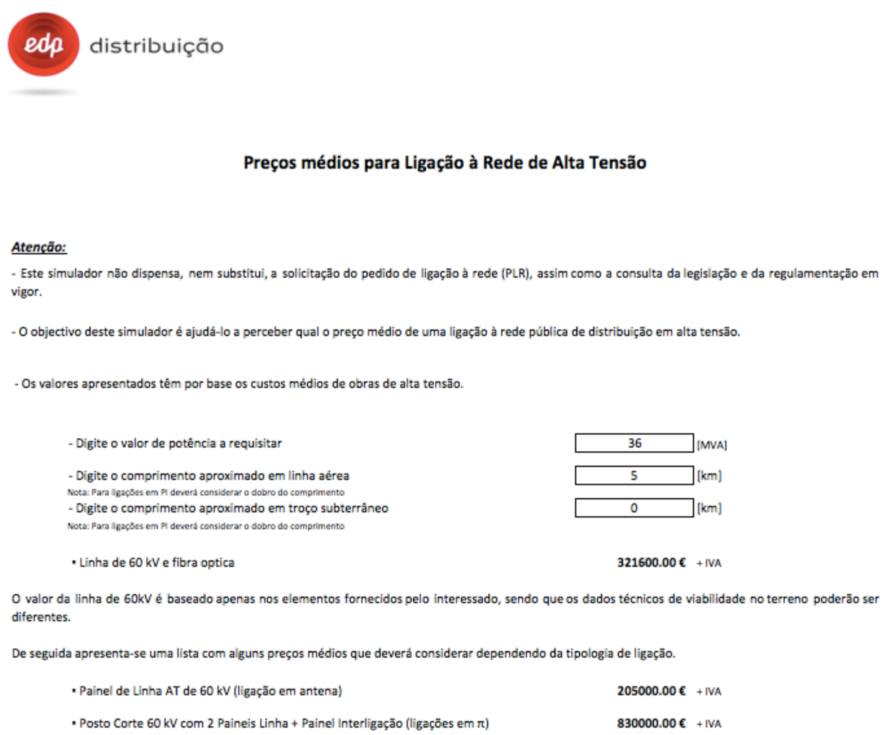
Table 4.3: Water supply dimensioning and resulting CAPEX (in millions of EUR)

4.2.3 Power line

The local grid supplier publishes a simulation spreadsheet (as shown in Figure 4.6) that computes the estimated cost of a high tension power line according to the power rating and the length of the connection. The Specific Energy Consumption for desalination is (within the range suggested in [41]) :

$$SEC_{desal} = 3\,\text{kWh}/m^3$$

Using the volume produced at peak $PlantOutput$ during one hour, we set the power rating needed for each desalination plant. The length of the power line connection is measured using Google Maps (represented by the green line on Figure 4.5). The resulting CAPEX are shown in Table 4.4 .



edp distribuição

Preços médios para Ligação à Rede de Alta Tensão

Atenção:

- Este simulador não dispensa, nem substitui, a solicitação do pedido de ligação à rede (PLR), assim como a consulta da legislação e da regulamentação em vigor.

- O objectivo deste simulador é ajudá-lo a perceber qual o preço médio de uma ligação à rede pública de distribuição em alta tensão.

- Os valores apresentados têm por base os custos médios de obras de alta tensão.

- Digite o valor de potência a requisitar: 36 [MVA]

- Digite o comprimento aproximado em linha aérea: 5 [km]

Nota: Para ligações em PI deverá considerar o dobro do comprimento

- Digite o comprimento aproximado em troço subterrâneo: 0 [km]

Nota: Para ligações em PI deverá considerar o dobro do comprimento

• Linha de 60 kV e fibra optica — **321600.00 €** + IVA

O valor da linha de 60kV é baseado apenas nos elementos fornecidos pelo interessado, sendo que os dados técnicos de viabilidade no terreno poderão ser diferentes.

De seguida apresenta-se uma lista com alguns preços médios que deverá considerar dependendo da tipologia de ligação.

• Painel de Linha AT de 60 kV (ligação em antena) — **205000.00 €** + IVA

• Posto Corte 60 kV com 2 Paineis Linha + Painel Interligação (ligações em π) — **830000.00 €** + IVA

Figure 4.6: Power line cost simulation spreadsheet [51]

Region	Centralised scenario	Decentralised scenario	
	Algarve	Windward	Leeward
$PowerConsumption$ (MVA)	36	25	25
Power line length (km)	5	3	5
$PowerLine_{CAPEX}$ (M EUR)	0.6	0.5	0.6

Table 4.4: Characteristics of connection to the grid and resulting CAPEX (in millions of EUR)

4.2.4 Own production of RES

To try and reduce electricity costs, the rooftops of the plants are covered with 1.3 MW of non-tracking PV panels following the example of the Barcelona Llobregat SWRO plant, a recent project with similar capacity [52]. The rooftop installation is coupled with a 5 MW plant of also non-tracking PV panels and a 5 MW wind turbine farm (equivalent to 10 Vestas V39). Applying the costs of Table 3.2, the resulting expenses (which are the same for the three plants) are:

$$PV_{CAPEX} = 3.5 \text{ M EUR}$$

$$Wind_{CAPEX} = 5.0 \text{ M EUR}$$

4.2.5 CAPEX summary

To compute the total CAPEX of each scenario, we apply eq. 3.5 using the various CAPEX contributions, summarised in Table 4.5.

	Centralised scenario		Decentralised scenario			
	Algarve		Windward		Leeward	
	Characteristics	Cost (M EUR)	Characteristics	Cost (M EUR)	Characteristics	Cost (M EUR)
Desal. plant (nominal)	330,000 m^3/day	268.6	175,000 m^3/day	142.4	155,000 m^3/day	126.2
Water supply	d= 5 km H= 15m	8.5	d= 3.2 km H= 24m	4.7	d= 5 km H= 15m	5.2
Power line	d= 3 km P= 36 MVA	0.6	d= 3 km P= 25 MVA	0.5	d= 5 km P= 25 MVA	0.6
PV panels	6.3 MW	3.5	6.3 MW	3.5	6.3 MW	3.5
Wind turbines	5 MW	5.0	5 MW	5.0	5 MW	5.0

Table 4.5: Capital expenditures summary (costs are in millions of EUR)

4.3 Capital Recovery Factor

The Capital Recovery Factor is a function of i, the Weighted Average Cost of Capital (WACC) and n, the lifetime of the project in years. It is the same for both scenarios: we consider a WACC of 7%, as suggested by Caldera et al.[41] , and an average lifetime of 30 years (for the desalination plant, water pumping and piping, PV panels and wind turbines). We have then:

$$CRF = 0.0806$$

4.4 Operational Expenditures

4.4.1 Desalination plant

The operational expenditures of running a SWRO plant are proportional to the plant capacity; Gao et al.[53] state them in 2015 USD. They were computed at an exchange ratio of:

$$1\,\text{USD} = 0.87\,\text{EUR}$$

and considering an inflation of +5.94% between 2015 and 2018 [54]. Labor costs suggested in the literature are considered to be proportional to local average salaries. To adapt labor costs to the Portuguese standard of living, we apply a ratio between the Portuguese average salary of 943 EUR [55] and the US average salary of 3498 EUR [56](both for 2017). The resulting OPEX are summarised in Table 4.6:

	Centralised scenario	Decentralised scenario	
Region	Algarve	Windward	Leeward
$DesalPlant_{OPEX}$ (M EUR)	13.6	7.2	6.4

Table 4.6: Desalination plant yearly OPEX (costs in millions of EUR)

4.4.2 Water supply

Water supply OPEX are straightforward computations, yielding Table 4.7:

	Centralised scenario	Decentralised scenario	
Region	Algarve	Windward	Leeward
$WaterSupply_{OPEX}$ (k EUR)	92.6	57.1	56.0

Table 4.7: Water supply yearly OPEX (costs in thousands of EUR)

4.4.3 Own production of RES

The three plants considered having the same capacity of RES installed, the resulting yearly OPEX is (in thousands of EUR):

$$RES_{OPEX} = 152.0\,\text{k EUR}$$

4.5 Electricity costs

4.5.1 Pumping power consumption

The Specific Energy Consumption for pumping is a function of the pump characteristics (pump efficiency considered = 90%), the needed head (H) and maximum flow rate. The obtained values are given by Table 4.8.

Region	Centralised scenario	Decentralised scenario	
	Algarve	Windward	Leeward
$SEC_{pumping}$ (kWh/m^3)	0.045	0.073	0.045

Table 4.8: Pumping Specific Energy Consumption

4.5.2 Desalination power consumption

4.5.2.1 RES power consumption

RES penetration

The local RES producers' top priority is to supply the region's regular power demand (i.e. excluding desalination power consumption). RES power output is injected in the power grid as much as possible, but because of RES intermittent nature, some of that power is curtailed. On average RES represented 52% of the total electricity consumption in Portugal for 2018 [57].

As RES mature and Power Grids get better adapted to their specificities, the RES penetration in the electrical mix is expected to increase in the near future. We set the factor of RES penetration for the next three decades (the project's lifetime) in Algarve to be:

$$Factor_{RESpenetr.} = 80\%$$

Electricity consumption estimation

To estimate the available surplus of RES power in the region (as defined in eq. 3.36) we first estimate the region's electricity demand, $ElectricityDemand^{h,s}_{region}$.

Neither the national electricity provider, Electricidade de Portugal (EDP), nor the company managing the power grid, Redes Energéticas Nacionais (REN), supply power consumption data for the region of Algarve alone, only nationwide consumption profiles.

To scale down the national power consumption values to the Algarve and obtain regional values, a two step approach was considered:

1. assume that the water consumption rate is indicative of the population variation throughout the year;
2. assume that energy consumption of each season is proportional to the number of inhabitants at that time.

We start by estimating the seasonal population in Algarve. The residential population of Algarve is around 450,000 habitants as per the 2011 census. Although there are several references (in the media) to the tripling of Algarve's population in summertime (reaching around 1.5M habitants), there are no solid references for that estimation, and it is unknown wether this value is relative to an absolute peak or an average taken over the season. An estimation of population fluctuation throughout the year is therefore needed.

The alternative approach found is to consider that the water consumption variation is indicative of the population fluctuation. Using data presented in section 4.1.3, and normalising the water consumption in winter over the residential population, we compute an estimation of the population for each season as shown in Table 4.9.

	Winter	Spring	Summer	Autumn
Water consumption (m^3)	126,251	168,548	279,570	200,538
Ratio to winter water consumption	1	1.335	2.214	1.588
Population estimation (M hab)	0.450	0.601	0.996	0.715

Table 4.9: Seasonal population estimation for Algarve

Since the model applied considers one representative day per season, we base our estimation on the hourly power consumption of continental Portugal made available by REN as exemplified for a day in winter by Figure 4.7.

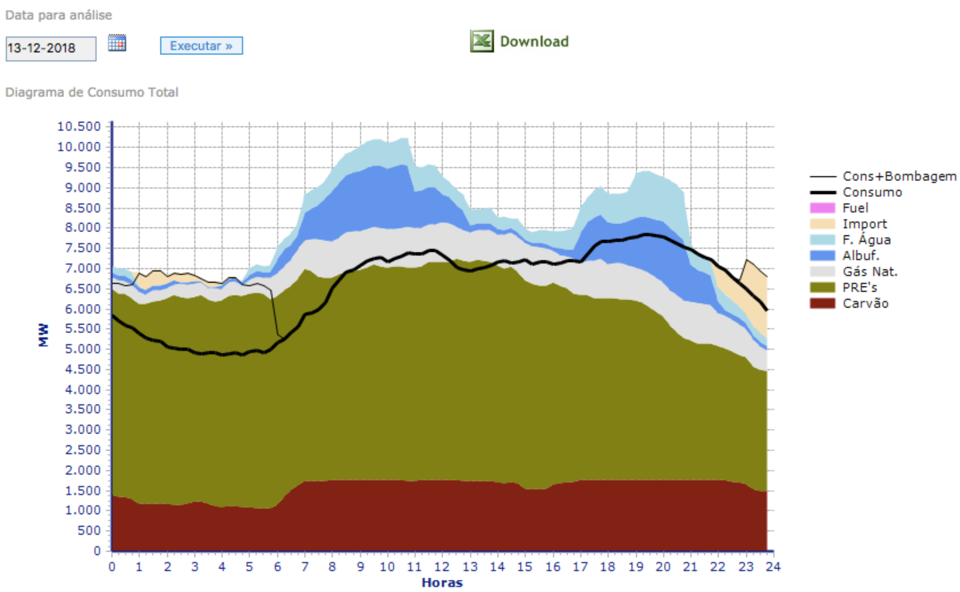


Figure 4.7: Hourly power consumption for continental Portugal, for the 13/12/2018[58]

The representative days chosen for each season were mid-week to ensure a consumption profile that is as close to the average profile as possible. Considering a population of 10.1M habitants for continental Portugal, the hourly power consumption values given by the database were converted to per capita values and brought to the population estimated in Table 4.9. For the Decentralised scenario, the same process was applied while considering the population of the municipalities within each of the two regions.

Regional RES power production

The two main types of RES production plants in the region of Algarve are Wind (224.5 MW) and solar PV (45.1 MW)[59], and several large PV projects have been licensed and are due between 2019 and 2021 [60](totalling 472 MW, mostly Leeward). Figure 4.8 indicates the locations of the existing plants, while Figure 4.9 shows the average hourly power production estimation of all the active plants plus those due until 2021.

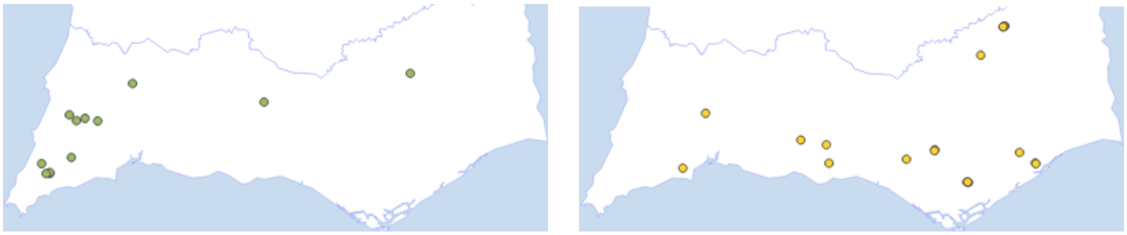


Figure 4.8: Wind (left) and solar PV (right) plant locations in Algarve as of 2018 [59]

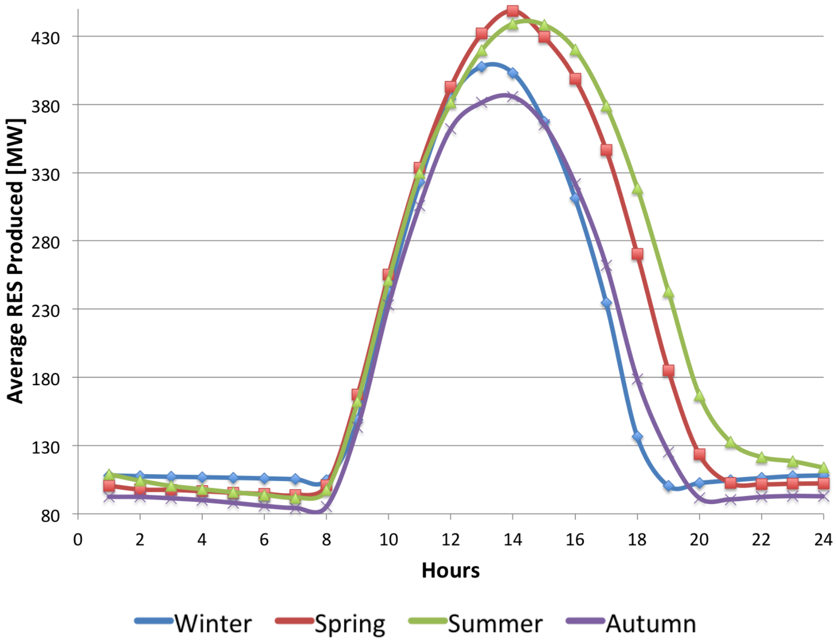


Figure 4.9: Average RES power produced in the region of Algarve

Solar PV is responsible for the majority of RES production in the region (evidenced by the Gaussian curve centred around 1-2 pm shown in Figure 4.9) because of the large increase (x10) in PV installed capacity by 2021 and of the abundance of solar irradiation in Algarve.

Once regional electricity consumption and RES power production are estimated, Surplus RES is computed based on eq. 3.36. The resulting power profiles are given by Figure 4.10. For the chosen penetration factor, we note that there is no available Surplus in the summer for the Centralised scenario and that the Windward region has no available Surplus whatsoever, explained in part by the uneven geographical distribution of RES plants in Algarve.

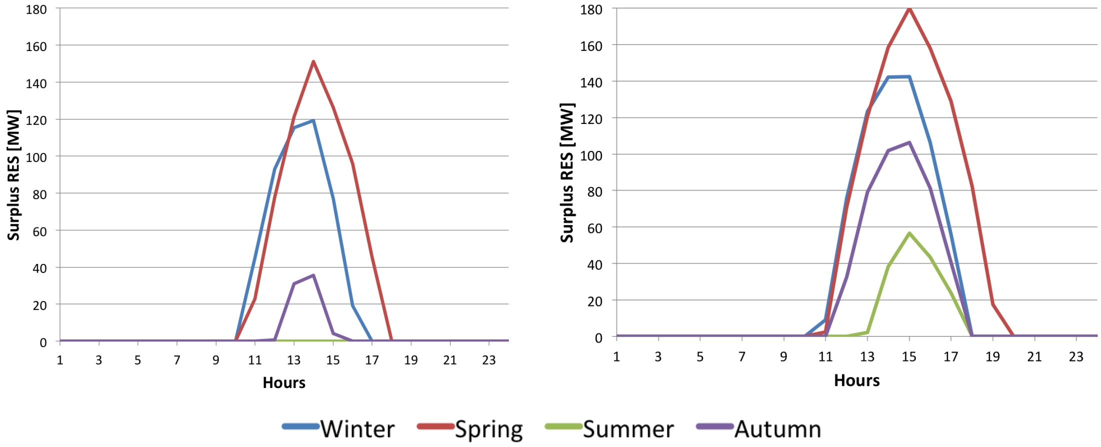


Figure 4.10: Surplus RES for the whole Algarve (left) and for Leeward (right)

4.5.3 RES power costs

The Mercado Iberico de Eletricidade (MIBEL) sets the hourly market price of the kWh applicable to Algarve. Because it is complex and unpredictable, the estimation of $MarketPrice^{h,s}$ for each season is based on monthly historical values of the MIBEL over the last decade (shown in Figure 4.11).

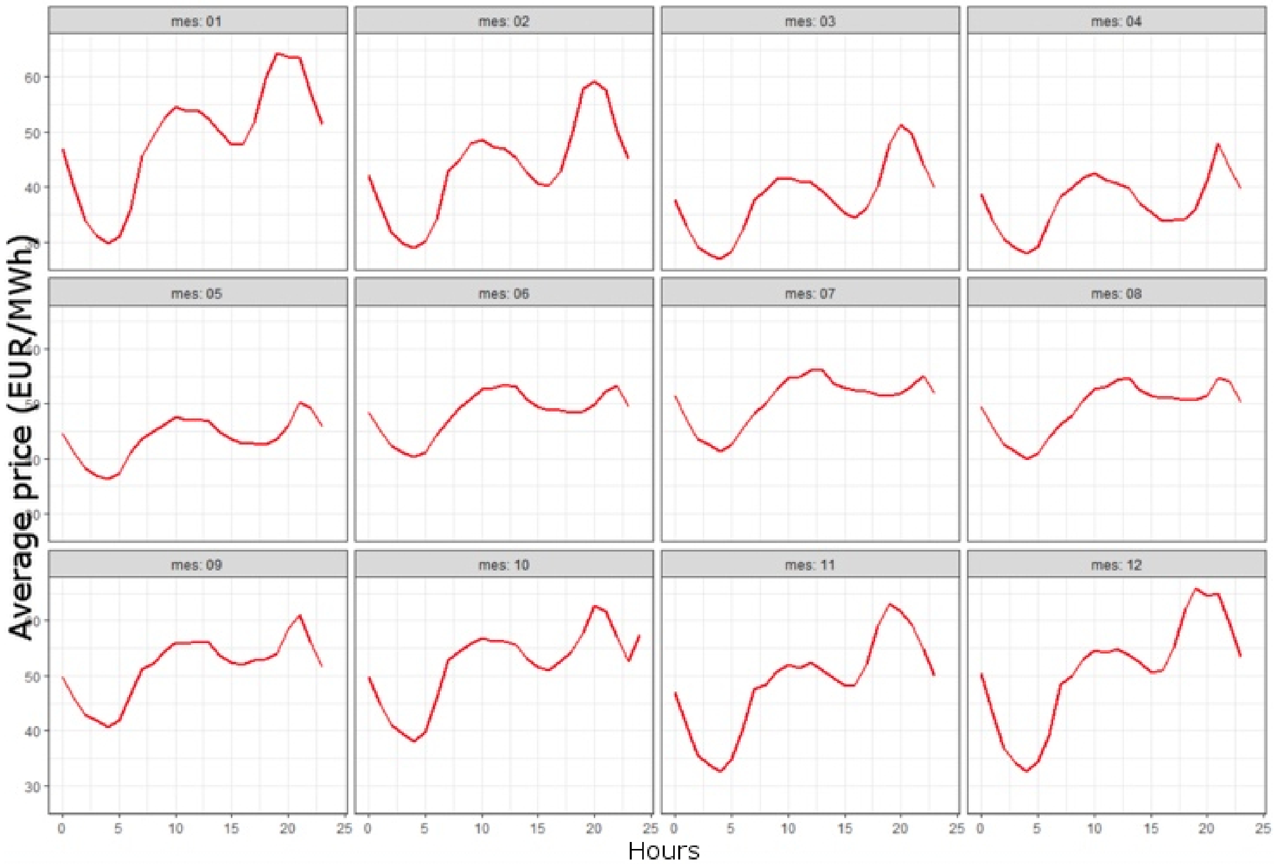


Figure 4.11: Average hourly price (EUR/MWh) on MIBEL for each of the 12 months of the year (from 2008 to 2018)[61]

As stated in the assumptions in Section 3.3, the cost factor on the market price is:

$$PriceFactor = 75\%$$

Chapter 5

Results and Discussion

As stated in Section 3.1, the main evaluation parameter of this project is its resulting LCOW. To assess the solution's competitiveness, the LCOW is compared to the estimated cost of production of the conventional water supplier of the region. In this section, we first compute the cost of production of the conventional water supplier and then compare it to the resulting LCOW of the various scenarios studied.

Aguas do Algarve water production cost estimation

Although being a private company, the profit of Algarve water supplier is regulated by law because it is a public service [62], hence in their Annual Report of 2017 it is stated:

"The concession contracts determine that the profitability of equities to be recovered through tariff mechanisms should be equal to the yield of 10-year Treasury bonds plus 3%".

As of 09/03/2019, the yield of 10-year Treasury bonds is at 1.376%, leading to a fixed margin of 4.376%. Knowing that the average tariff charged by the AdA is of 0.4710 EUR/m^3 [14], we can estimate the total cost of production $LCOW_{Ref}$ by deducting the fixed margin from the average tariff:

$$LCOW_{Ref} = 0.4504 \, \text{EUR/m}^3$$

5.1 Baseline Scenario

Each scenario yields a LCOW that is compared to $LCOW_{Ref}$ (as defined before), but the various scenarios are also compared with each other. The standard to which each solution will be compared against is a scenario where all the power consumed by one centralised SWRO plant comes from the electrical grid, using the spreadsheet model. Taking the input data of the Centralised scenario, the methods of Section 3.4 are applied while forcing the RES power consumption (from both Surplus and Own Production) to be null. The resulting LCOW is:

$$LCOW_{Baseline} = 0.9055 \, \text{EUR/m}^3$$

where $LCOW_{Baseline}$ represents a 101% higher cost than the estimated $LCOW_{Ref}$.

The various contributions to the $LCOW_{Baseline}$ are summarised in Table 5.1:

Component	Cost (k EUR / year)
Electricity	28,000
Desal. plant CAPEX	21,646
Desal. plant OPEX	13,661
Water Supp. CAPEX	686
Water Supp. OPEX	93
Power Line CAPEX	52
Total	64,138

Table 5.1: Cost breakdown of $LCOW_{Baseline}$ (in thousands of EUR per year)

The share of each component of the total cost is illustrated in Figure 5.1:

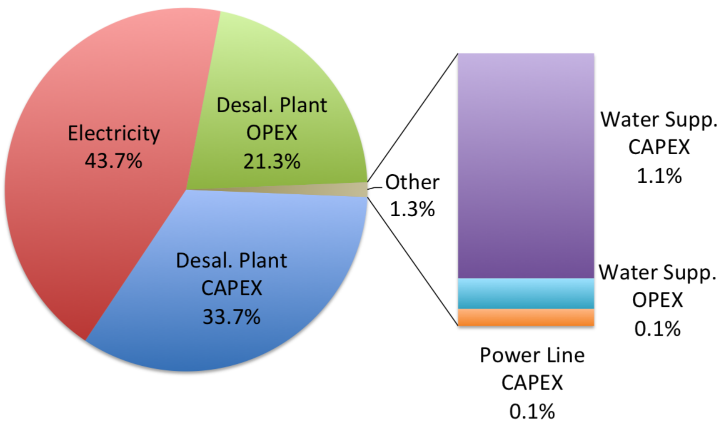


Figure 5.1: Components' share of total $LCOW_{Baseline}$

We notice that the main contribution to the LCOW, electricity costs at 43.7%, represent a slightly larger share than the 25 to 40% estimation given by Voutchkov [16]. Because labor costs are corrected for the local standard of living, operating a plant in Portugal leads to smaller labor costs (-73%) than for a project in the USA, whereas the remaining costs are considered to be proportionally equal in both countries. The share of every other cost increases as a consequence, which could explain why electricity costs represent a larger share than expected.

5.2 Centralised Scenario

The Centralised scenario considers a single large SWRO plant at Monte Gordo with a real capacity of 280,000 m^3/day. The desalination output being constant throughout the day, the spreadsheet model does not consider a storage tank, while the optimisation model includes a 10,000 m^3 storage tank. The storage tank capacity choice is developed in the sensitivity analysis presented in Subsection 5.2.4.3.

5.2.1 Spreadsheet model

The resulting LCOW of the Centralised scenario through Excel is:

$$LCOW^{Excel}_{Centr} = 0.8409 \text{ EUR/m}^3$$

where $LCOW_{Centr}^{Excel}$ represents a 86.7% higher cost than $LCOW_{Ref}$, but a 7.1% reduction when compared to $LCOW_{Baseline}$. The cost difference to the 100% Grid reference is a result of a much lower (19.3%) electricity expenditure for the solution that utilises RES (as evidenced in Table 5.2), even though it adds RES CAPEX and OPEX to the total cost. The reason behind the electricity cost difference is that the tariff of grid power is systematically higher than the MIBEL $MarketPrice^{h,s}$ used in the computation of surplus RES power, as illustrated by Figure 5.2.

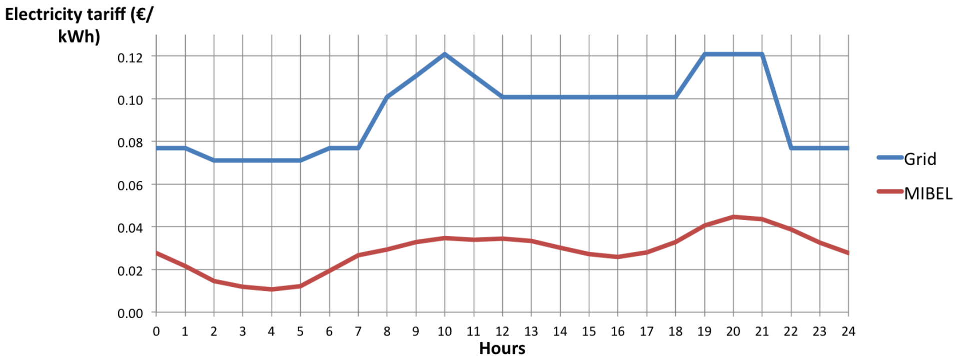


Figure 5.2: Grid and MIBEL tariff for a representative day in Spring[61]

5.2.2 Optimisation

The resulting LCOW of the Centralised scenario while optimising the power consumption is:

$$LCOW_{Centr}^{Optim.} = 0.7420\,\text{EUR/m}^3$$

where $LCOW_{Centr}^{Optim.}$ represents a 64.7% higher cost than $LCOW_{Ref}$, but a 18.1% reduction when compared to $LCOW_{Baseline}$.

This improvement is made possible by the operational flexibility of the optimisation model: because the plant is over dimensioned for the seasons where water demand is smaller than peak demand, the plant can work at an hourly output below or above the hourly average output of the season. There are two main consequences:

- a better usage of available Surplus RES, leading to less Grid power consumption;

- the hours with the largest output (and therefore power consumption) coincide with the hours where tariffs are cheapest.

The first point is illustrated by Figure 5.3 in which we can see that the optimisation model has a larger share of Surplus RES usage than the spreadsheet model, bringing down the total electricity costs.

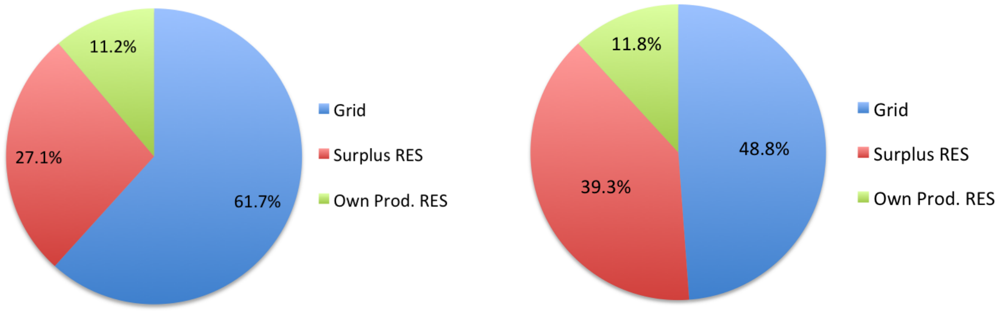


Figure 5.3: Breakdown of power consumption of a day in Spring, for the spreadsheet model(left) and the optimisation model (right)

The second point is illustrated by Figure 5.4: the two peaks of power consumption (for both desalination and pumping) between 2 to 5 am and between 11 am to 17 pm match the intervals with the lowest tariffs seen in Figure 5.2. Figure 5.4 shows the hourly operation of the Centralised scenario for a representative day in Spring. The same point is repeated for both 0h and 24h in order to represent the daily cycle closure, and because it illustrates the storage tank constraints imposed by constraint 2.7 in section 3.5.2.2.

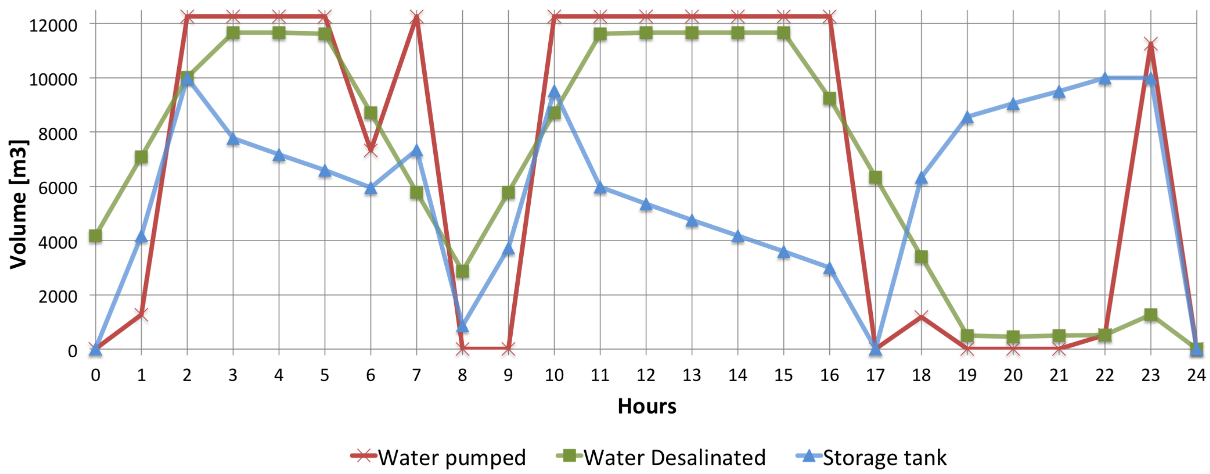


Figure 5.4: Hourly operation of the Centralised scenario, on a representative day in Spring, with smoothened water output and pumping profile (Storage Tank capacity of 10,000 m^3)

Rigidity constraint and its impact on operations

Figure 5.5 shows that the water pumped closely follows the water desalination output (matching the cheapest tariffs as mentioned before), but with larger capacity variations. In general, water pumping functions in an almost binary fashion: either at maximum capacity, or totally off. The reason why water desalination output increases in steps is because of rigidity constraints (as defined in eq. 3.43): each step represents the activation of a module, one by one, as per eqs. 3.41 and 3.42. If the rigidity constraints on output capacity variation were to be relaxed, the desalination curve would have abrupt variations, nearly matching the pumping curve. This would result in a LCOW reduction, but large and sudden variations in flow rate come at the cost of increasing the probability of membrane fouling, a common and costly maintenance issue of SWRO plants. Because the impact of membrane fouling on the LCOW is out of the scope of this work, we settle for a system with rigidity.

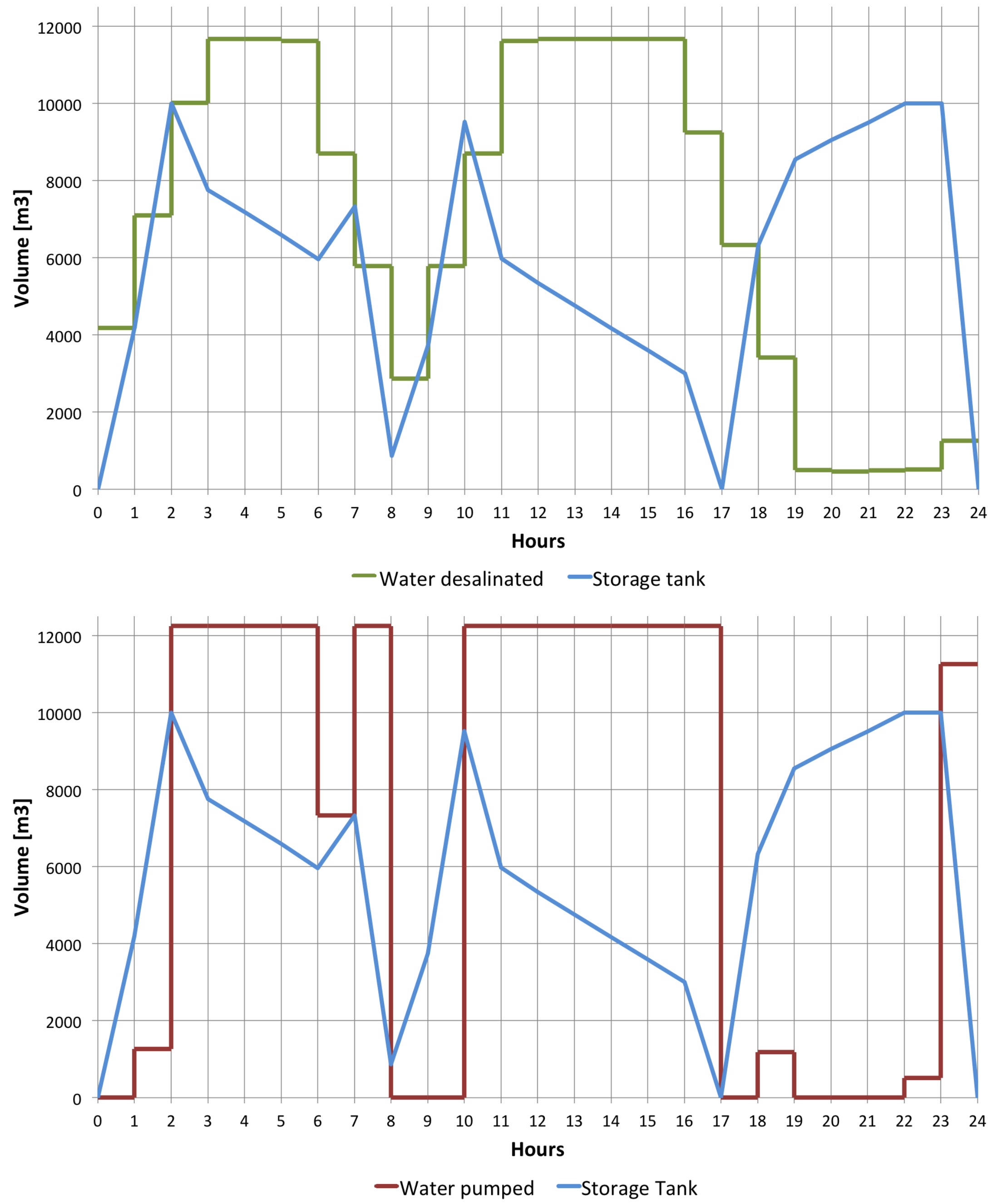


Figure 5.5: Hourly operation with real, quantised water output (top) and pumping (bottom) profile (same data as Figure 5.4)

Storage tank usage

The storage tank acts as a buffer, allowing for a looser management of water pumping and, consequently, a smaller expense in pumping power costs. The optimisation model makes it so that the storage tank reaches its maximum capacity around the time where it is cheapest to pump the desalinated water to the water supply network, while ensuring that the storage tank is empty at the start of each new day (as per constraint 2.7 in section 3.5.2.2). Storage tank usage has no direct impact on water desalination output because of the assumption that the water supply network is capable of absorbing any volume of water, at any time.

5.2.3 Centralised scenario costs summary

Figure 5.6 shows the contribution of each cost to the best (i.e. lowest) LCOW obtained for the Centralised scenario.

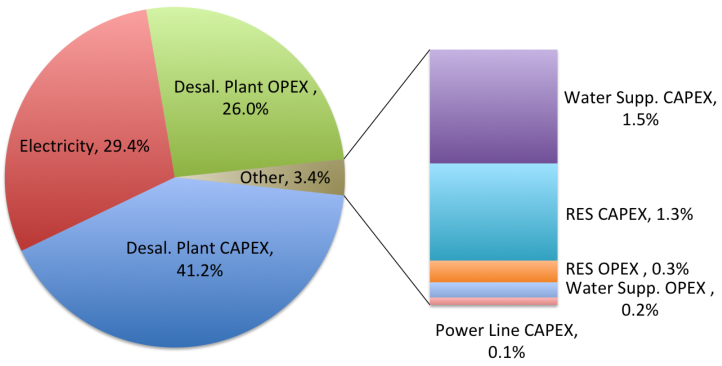


Figure 5.6: Components' share of total $LCOW^{Optim.}_{Centr}$

Table 5.2 summarises the costs of each model's solution for a Centralised scenario: although this scenario implies an added cost for the RES installation (+1.3% of total Reference Cost), it is largely compensated by savings in Electricity costs (-19.3% for the Excel model, when compared to the Reference Cost). The Optimisation model adds further expenses (16.5% and 15.1% in, respectively, Water Supply CAPEX and OPEX), for the storage tank absent in the Excel model, but these costs are once again compensated by the savings in Electricity costs (-44.8% when compared to the Reference Cost).

Component	Baseline Scenario Cost (100% GRID)	Centralised Cost (Excel model)	Centralised Cost (Optimisation model)
Electricity	28,000	22,594	15,460
Desal. plant CAPEX	21,646	21,646	21,646
Desal. plant OPEX	13,661	13,661	13,661
Water Supp. CAPEX	686	686	799
Water Supp. OPEX	93	93	107
Power Line CAPEX	52	52	52
RES CAPEX	-	682	682
RES OPEX	-	152	152
Total	64,138	59,566 **(-7.1%)**	52,559 **(-18.1%)**

Table 5.2: Cost breakdown of $LCOW_{Centr}$ (in thousands of EUR per year, variations are relative to $LCOW_{Baseline}$)

5.2.4 Sensitivity analysis

The assumptions made in Section 3.3 have an impact on the way power is consumed, and therefore on electricity costs and on the resulting LCOWs. In this section, a sensitivity analysis is performed by running the optimisation model for the Centralised scenario while varying the three variables mentioned in Subsection 3.5.3: $Factor_{RESpenetr.}$, $PriceFactor$ and $StorageTank_{capacity}$.

As it will be shown by the following Subsections, the results of the sensitivity analysis are either fairly predictable or not prone to strong conclusions, and can be qualitatively extrapolated to other scenarios: it was deemed unnecessary to repeat the analysis for the Decentralised scenario.

5.2.4.1 RES penetration

The assumption that RES represent 80% of total electricity consumption (Subsection 4.5.2.1) is a conservative approach, and it overshoots the actual consumption of regional PV and wind RES because it does not take into account hydro power's contribution to the RES mix. Taking values from 50% (the average share of RES in total electricity consumption in 2018) to 100%, the resulting LCOWs for the Centralised scenario are given in Table 5.3:

$Factor_{RESpenetr.}$	$LCOW_{Centr}^{Optim.}$	Diff. to $Factor_{RESpenetr.}$ =80%
50%	0.6859	-7.55%
60%	0.6984	-5.88%
70%	0.7286	-1.80%
80%	0.7420	-
90%	0.7528	+1.46%
100%	0.7596	+2.37%

Table 5.3: RES penetration sensitivity analysis for the Centralised scenario

The large decrease in LCOW that results from lowering $Factor_{RESpenetr.}$ to 50% is the result of two factors. The first is straightforward: for the hour blocks where Surplus RES was being consumed, a larger portion of this cheaper alternative to Grid power is now available. The second is a consequence of the profile of RES production shown in Figure 4.9: for high values of $Factor_{RESpenetr.}$, the only moment when Surplus RES is available is around the peak of production of PV panels at 13h/14h, limiting the possibilities of optimisation (the installed capacity of PV panels is much larger than that of Wind turbines, which explains the Gaussian shape of the curve). The number of hour blocks where Surplus RES is available increases as the factor is brought down, leading to not only more Surplus RES power available but also more flexibility as for when to use it.

5.2.4.2 RES market price factor

Surplus RES (around 40% of total power consumption in spring) is bought at the average MIBEL market price, with a discount factor that might be negotiated with local RES producers. Being a subjective variable, performing a sensitivity analysis on $PriceFactor$ helps us see how important the negotiation of this discount might be, while also giving us an idea of the impact of market price volatility on the economical viability of the project (if different values of $PriceFactor$ are interpreted as price fluctuations). The resulting LCOWs are shown in Table 5.4.

$PriceFactor$	$LCOW_{Centr}^{Optim.}$	Diff. to $PriceFactor$ =75%
60%	0.7394	-0.34%
65%	0.7403	-0.23%
70%	0.7411	-0.11%
75%	0.7420	-
80%	0.7428	0.11%
85%	0.7437	0.23%
90%	0.7445	0.34%

Table 5.4: RES market cost factor sensitivity analysis for the Centralised scenario

The LCOW is not particularly sensitive to $PriceFactor$ variations, yielding small differences when compared to the assumed 75% value. The most important factor in determining the LCOW is Surplus RES availability: the price difference between the MIBEL and the Grid tariff (Figure 5.2) is significant and has therefore a bigger impact than the discount negotiated.

5.2.4.3 Storage tank capacity

Storage tanks serve as a buffer between desalinating water and pumping it into the water supply network: they help avoid bottleneck situations that might occur because of pumping constraints (eq. 3.53). The construction of a storage tank adds a CAPEX and OPEX to Water Supply expenditures, as given by eqs. 5.1 and 5.2[40]:

$$StorageTank_{CAPEX} = 1400 \times (StorageTank_{capacity})^{0.75} \tag{5.1}$$

$$StorageTank_{OPEX} = 1\% \times StorageTank_{CAPEX} \tag{5.2}$$

Table 5.5 shows the LCOWs obtained for the Centralised scenario with the optimisation model for various storage tank capacities. Having a storage tank slightly loosens the constraints on the pumping operation and allows for a different optimum (as shown by Figure 5.7), resulting in lower electricity costs. Table 5.5 also shows, however, that the savings in Electricity costs are outbalanced by the added annualised $StorageTank$ CAPEX and OPEX for every capacity chosen. The relatively small impact on Electricity costs of having a storage tank can be explained in part by it only influencing the pumping operation, while the desalination operation (which has a SEC two orders of magnitude larger) remains unchanged. The lowest LCOW possible is therefore for a solution where there is no storage tank installed, at 0.7404 EUR/m^3.

$StorageTank_{capacity}$	Electricity costs (k EUR per year)	$StorageTank$ CAPEX + OPEX (k EUR per year)	$LCOW^{Optim.}_{Centr}$
0	15,476	0	0.7404
1000	15,472	20	0.7407
5000	15,464	68	0.7413
10,000	15,460	114	0.7420
15,000	15,460	154	0.7426

Table 5.5: Storage tank installed capacity, respective costs and resulting LCOW (costs in thousands of EUR)

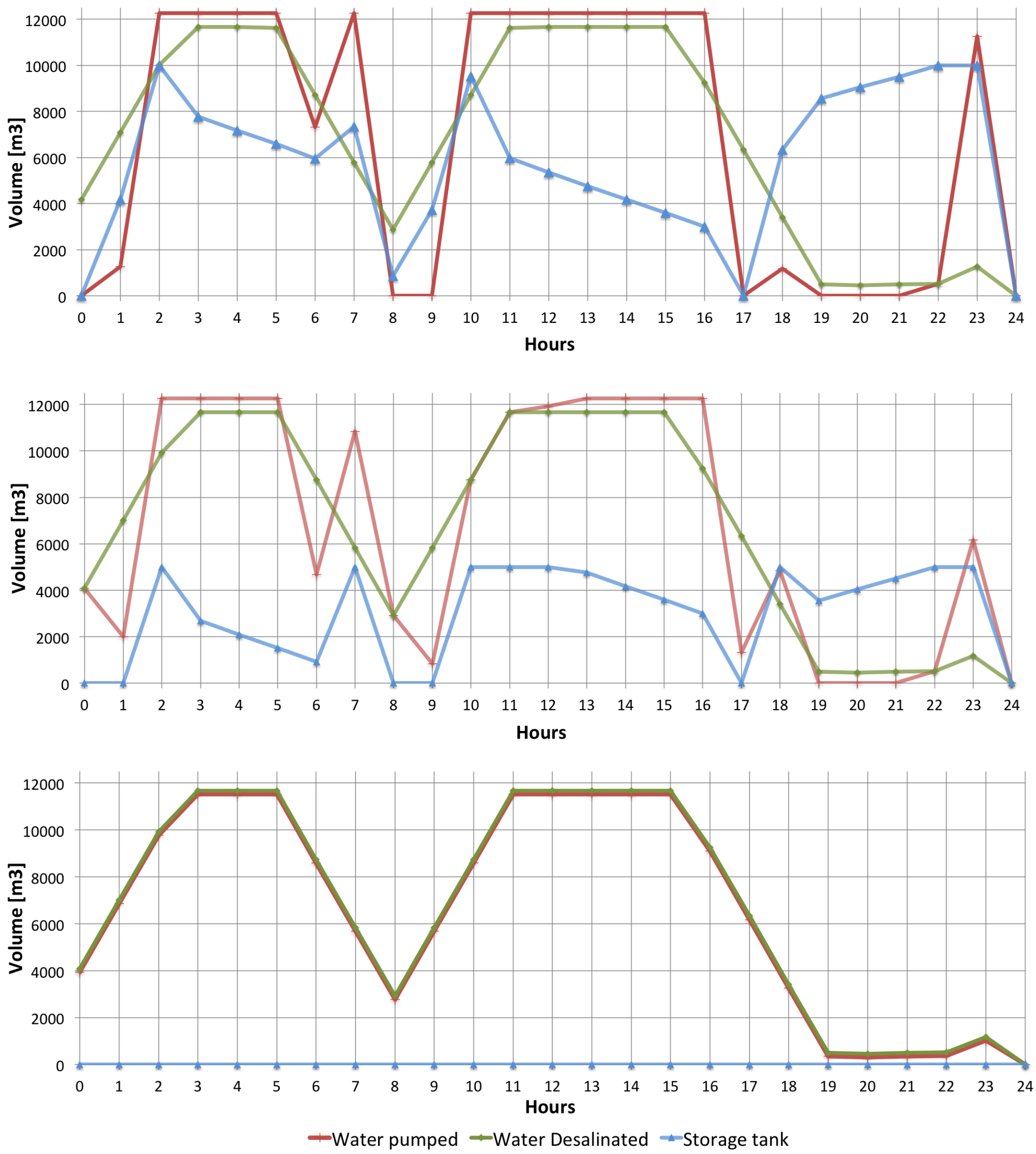


Figure 5.7: Hourly operation of the Centralised scenario, on a representative day in Spring with a storage tank capacity of 10,000 m^3(top), 5000 m^3(middle) and no storage tank(bottom)

Although the lowest LCOW is obtained without a storage tank, the recommended solution is one where a storage tank with a capacity of 10,000m^3 is considered (for the Centralised scenario). Table 5.5 also shows that capacities larger than 10,000m^3do not help further reduce electricity costs. At around 3% of the nominal plant capacity (Table 4.2) this volume represents a safety measure for when maintenance work must be done and for when unexpected occurrences might temporarily disturb the plant's capacity to supply demand.

5.3 Decentralised Scenario

The Decentralised scenario considers two SWRO plants, at Portimão (Windward) and Monte Gordo (Leeward) with real capacities of, respectively, 148,500 m^3/day and 131,500 m^3/day. As for the Centralised scenario, the spreadsheet model does not consider a storage tank, while the optimisation model includes two 5000 m^3 storage tanks.

5.3.1 Spreadsheet model

The resulting LCOW for each plant is:

$$LCOW_{Windward}^{Excel} = 0.8402 \text{ EUR/m}^3$$

$$LCOW_{Leeward}^{Excel} = 0.7986 \text{ EUR/m}^3$$

To obtain the total LCOW we take:

$$LCOW_{Decentr}^{Excel} = 0.53 \times LCOW_{Windward}^{Excel} + 0.47 \times LCOW_{Leeward}^{Excel}$$

i.e. each LCOW weighted by the fraction of total Algarve water demand the respective plant will supply, yielding:

$$LCOW_{Decentr}^{Excel} = 0.8182 \text{ EUR/m}^3$$

which represents a 81.7% higher cost than $LCOW_{Ref}$, but a 9.6% lower cost than $LCOW_{Baseline}$. We note that the LCOW of the Windward plant is higher (5.2%) than for the Leeward plant: this is a consequence of the geographical distribution of RES plants across Algarve. Because the RES plants with the largest capacities are installed near the Spanish border around the region of Alcoutim, and electricity demand is relatively even across the region, the available Surplus is much larger Leeward than Windward. For a penetration factor of 80%, Windward's available Surplus RES is null: the plant exclusively consumes power from its own production and from the grid, which drives its electricity costs up, and therefore its LCOW. Because of the Own production RES available to both scenarios and of Leeward's Surplus RES, the overall Decentralised electricity costs are nonetheless lower than for the Baseline scenario, showing a 28% reduction.

5.3.2 Optimisation model

The resulting LCOW while optimising the power consumption for each plant is:

$$LCOW_{Windward}^{Optim.} = 0.7505 \text{ EUR/m}^3$$

$$LCOW_{Leeward}^{Optim.} = 0.6996 \text{ EUR/m}^3$$

The total LCOW of the Decentralised scenario is then:

$$LCOW_{Decentr}^{Optim.} = 0.7266 \text{ EUR/m}^3$$

which represents a 61.3% higher cost than $LCOW_{Ref}$, but a 19.7% lower than $LCOW_{Baseline}$. This solution turns out being the one with the lowest LCOW (2.1% lower than $LCOW_{Centr}^{Optim.}$), benefitting from a 52.3% reduction in electricity costs, and is therefore the optimal solution. Comparing the LCOW of each plant, before and after optimisation, we note that the Windward plant has a smaller margin for optimisation (10.7% LCOW reduction) than the Leeward plant (12.4% reduction). The reason is the same as the one stated in the previous sub-section: having no Surplus RES available, the Windward plant is forced to use a larger share of Grid power than the Leeward plant.

5.3.3 Decentralised scenario costs summary

For the Decentralised scenario, some costs were expected to increase since having two plants running in parallel eliminates the advantage of economies of scale associated with a centralised solution. Table 5.6 summarises the yearly costs of each model for the Decentralised scenario.

Component	Baseline Scenario Cost (100% GRID)	Decentralised Cost (Excel model)	Decentralised Cost (Optimisation model)
Electricity	28,000	20,172	13,354
Desal. plant CAPEX	21,646	21,646	21,646
Desal. plant OPEX	13,661	13,664	13,664
Water Supp. CAPEX	686	795	929
Water Supp. OPEX	93	113	130
Power Line CAPEX	52	93	93
RES CAPEX	-	1364	1364
RES OPEX	-	304	304
Total	64,138	58,150 **(-9.3%)**	51,483 **(-19,7%)**

Table 5.6: Cost breakdown of $LCOW_{Decentr}$ (in thousands of EUR per year, variations are relative to $LCOW_{Baseline}$)

The Desalination plant CAPEX being defined as a linear function of its capacity (eq. 3.7), there is no difference in this domain between the Centralised and the Decentralised solutions. On the other hand, because both plants must have their own power line and water supply system (category in which storage tanks are included), we note an increase of 35.4% and 39.8% in water supply CAPEX and OPEX respectively and of 78.8% in power line CAPEX for the optimisation model. The Decentralised scenario's main advantage is in being able to have twice as much RES capacity installed for own consumption: RES CAPEX and OPEX have doubled when compared to the Centralised scenario (as shown by comparing Table 5.2 and Table 5.6), but they are largely surpassed by the electricity cost savings they guarantee.

Figure 5.8 shows the contribution of each cost to the Optimisation LCOW for the Decentralised scenario. Electricity costs decreased 40.7% when compared to $LCOW_{Baseline}$ and have dropped to third in largest contributions, behind Desalination Plant CAPEX and OPEX.

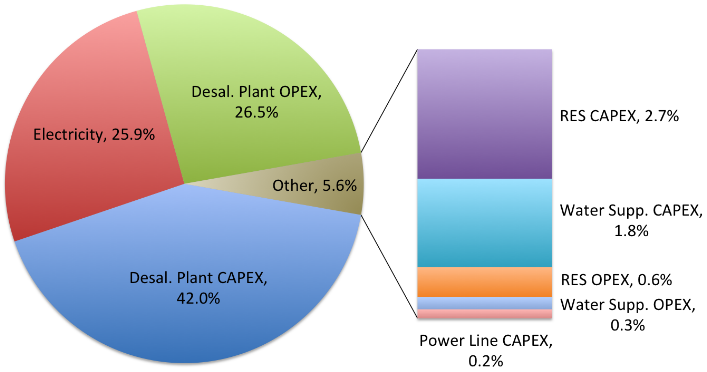


Figure 5.8: Components' share of total $LCOW^{Optim.}_{Decentr}$

5.4 Centralised versus Decentralised conclusions

Having obtained the results for both scenarios, we now proceed to a more in depth comparison of the two in order to substantiate a recommendation. The following will show that although the Decentralised scenario produces the lowest LCOW, its pricing edge over the Centralised scenario is relatively small, and that other important factors such as the produced water's carbon footprint or the index of Surplus RES exploitation can make or break one of the solutions in the eyes of decision makers.

Deciding between a Centralised or a Decentralised solution is not straightforward. It has been shown in the literature that economies of scale (associated with a Centralised solution) do not necessarily equate to lower levelised costs[33]. A comparison of the solutions obtained in this work (shown in Table 5.7) confirms this observation: the lowest LCOW obtained is for the Decentralised scenario, with a slight advantage over the Centralised scenario (-2.1%)

	Excel model	Optimisation model
$LCOW_{Ref}$	0.4504	-
$LCOW_{Baseline}$	0.9055	-
$LCOW_{Centr}$	0.8409	0.7420
$LCOW_{Decentr}$	0.8182	**0.7266**

Table 5.7: Resulting LCOWs summary (optimal solution in bold)

Electricity costs

An analysis of the absolute values of power consumption (shown in Table 5.8) helps us understand the difference in electricity costs between the two scenarios: although the Decentralised scenario leads to a slightly larger Total power consumption (+0.5%, explained by the higher pumping head needed for the Windward plant), Grid power consumption is 9.2% lower than for the Centralised scenario.

Power Consumptions (MWh)	Centralised scenario	Decentralised scenario
Grid	1717	1559
Surplus RES	426	324
Own Prod. RES	217	489
Total	2360	2372
CO_2 emission savings (tonnes)[63]	164.6	205.1

Table 5.8: Yearly power consumption and resulting CO_2 emissions of each strategy

Using less Grid power means not only smaller electricity costs but also less CO_2 emissions, as Grid power includes non renewable energy sources (52% in 2018[57]): opting for the Decentralised solution leads to a 24.6% increase in CO_2 emission savings when compared to the Centralised scenario, and a 51.4% increase when compared to the Baseline scenario.

Surplus RES exploitation

Figures 5.9 and 5.10 show that the Decentralised solution uses a smaller share (27.5%) of Surplus RES than the Centralised scenario (36.1%). Analysing Figure 4.10, which shows the hourly average Surplus RES available, we note that because of an uneven population (and therefore electricity demand) distribution between Windward and Leeward, there is more Surplus RES available in absolute terms for the Leeward plant alone than for the Centralised scenario. But because the two plants considered in the Decentralised scenario have smaller output capacities than in the Centralised one, the plant's maximum capacity limits the consumption of Surplus RES. Adding to that, Own Production RES competes with Surplus RES in the interval of time where most of Surplus RES is available. In terms of Surplus RES exploitation, the Centralised solution is therefore better adapted than the Decentralised scenario, which is quickly forced to curtail it.

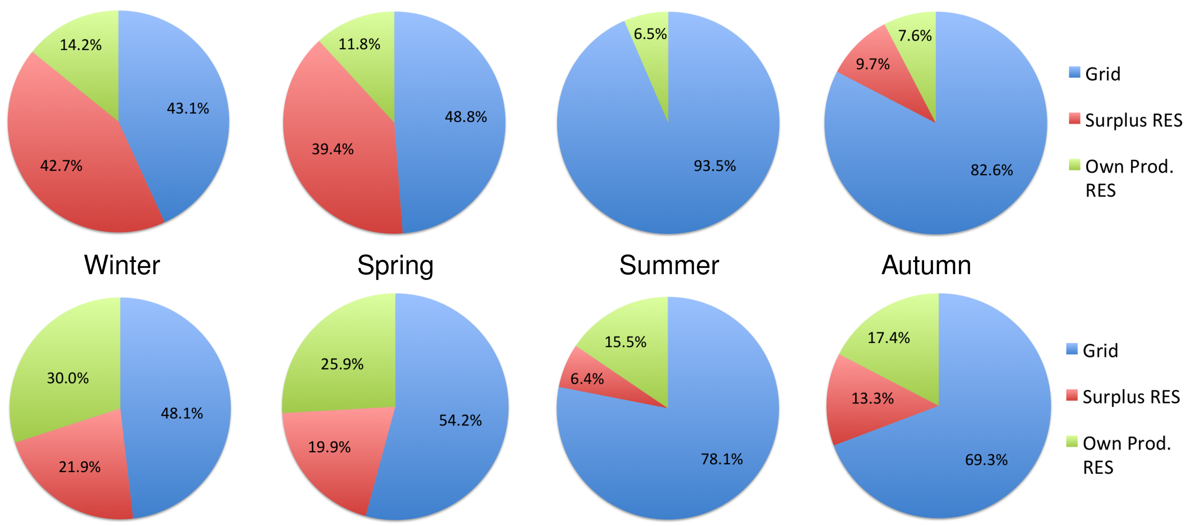


Figure 5.9: Breakdown of power consumption in Winter (far left), Spring (left), Summer (right) and Autumn (far right) for the optimised Centralised (top) and Decentralised (bottom) scenarios

Own Production RES capacity

As mentioned in the previous Subsection, the reduction in Grid power consumption is explained by having twice the installed capacity of RES for own production, when compared to the Centralised scenario. If we look at the total power shares over one year of operation (shown in Figure 5.10), we notice that, as expected, the total share of Own Production RES essentially doubles for the Decentralised scenario.

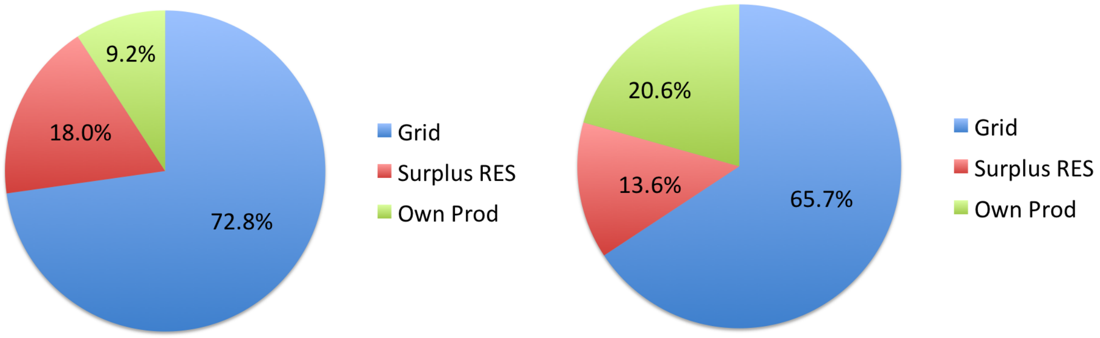


Figure 5.10: Average (whole year) power consumption shares for the Centralised (left) and Decentralised (right) scenarios

The reasoning behind limiting the total RES capacity installed in each desalination plant is two fold:

1. solar PV and wind turbine farms require large surface areas available (besides the area taken by the desalination plant itself) and coastal regions are in short supply of land;
2. wind turbines are visually polluting and noisy, which can be problematic for a region whose main industry is tourism.

If we compute the LCOW for the Centralised scenario using the same installed capacity of RES for own consumption as the total capacity of the Decentralised scenario, we obtain:

$$LCOW_{Centr.}^{2X\,Own\,Prod} = 0.7204\,\text{EUR/m}^3$$

which is 0.9% lower than $LCOW_{Decentr}$. From a purely economic standpoint, both the Centralised and Decentralised yield LCOWs too close to each other to confidently choose one as the optimal solution. The main deciding factor, and what set solutions apart, is how well the least expensive sources of energy are exploited by each solution.

5.5 Towards a new water supply paradigm

Although this work focuses on Algarve, the whole country of Portugal has been having increasingly regular problems with severe droughts. There is however a mismatch between the reassuring conclusions reached by governmental agencies regarding water scarcity and the sense of urgency caused by the extreme localised events occasionally experienced by the population. The water supply system seems globally adequate for the current consumption patterns, but any deviation from the mean on either the demand or the supply side has led to major shortcomings in meeting water demand. Because water scarcity problems are underestimated and deprioritised as soon as there is some precipitation, the contingency plans in place seem inadequate, and inefficient emergency solutions are the norm: the water crisis of the Viseu region, in late 2017, had 120,000 inhabitants depending on tanker trucks bringing 14,000 m^3 of water daily to fill the Fagilde dam and supply 82% of the normal water demand, at ten times the normal cost [64].

This chapter presents four guidelines that would help the Portuguese water supply network become more robust and drought-ready in the long run. As previously mentioned, solutions to fight water scarcity are usually divided into two categories: demand management and supply enhancement. With regard to demand management solutions, we suggest a refurbishment of the existing water distribution network, and an awareness campaign aimed at valuing water in the eyes of the consumers. As to supply enhancement strategies, we suggest the implementation of desalination technology in coastal regions when deemed feasible, and the introduction of an interregional water supply system to fill dams in drought-threatened regions.

The most pressing issue needing to be addressed is the inefficiency of water distribution systems. According to a survey made by the Water and Waste Services Regulation Authority (ERSAR in Portuguese), the average municipality wastes about 30% of the total water it distributes, and the worst performing municipalities waste over 70% of water through pipeline leakage [12]. This is freshwater that has been collected, treated and brought to high quality standards: it represents not only a loss in water but also a significant expense incurrence. Priority should therefore be given to overhauling the water distribution network by periodically doing maintenance work on distribution pipelines and by consistently monitoring its efficiency.

Water is still perceived as a low value commodity in European countries, which could explain why municipalities skip on water distribution maintenance, or why so much water is wasted in industrial, agricultural and residential use. Because conventional means of collecting water are relatively inexpensive, the economical incentive alone is not enough to change freshwater consumption behaviours. The price paid for water is not, however, a true reflection of its value as it does not account for the sustainability limitations of the water sources used. A public awareness campaign should be launched in order to promote a conscious use of water, reminding consumers that the perceived abundance of freshwater is misleading, while also calling for a global water consumption reduction.

Demand management solutions are usually the cheapest way to tackle water scarcity, but they might not be enough when considering the impact potential of unpredictable weather events. The first supply enhancement solution proposed here is to integrate seawater desalination plants in strategic coastal regions. The methods described in Chapter 3 were designed so that the regions they are applied to could vary significantly in size and characteristics: the approach can be used for municipalities, cities, large regions such as Algarve or even the whole country. With a coastline of around 943km, mainland Portugal has an abundance of coastal regions where seawater desalination could become an alternative water supplier. The most cost-effective setup for each desalination plant considered would have to be evaluated according to the chosen region's available RES, the feed-water salinity concentrations or even the desalination plant's surroundings. Desalination technologies such as electrodialysis might be more suitable for brackish water, whereas phase change technologies such as multi-stage flash or multi-effect distillation can use waste heat from neighbouring industries. Alternative RES for heat production could come from biomass or solar concentration, while promising technologies such as wave or tidal power could contribute to smoothing the power production profile of current RES solutions.

This approach is not directly applicable to inland Portugal however, which includes some of the country's most water stressed regions such as Viseu Dão-Lafões (previously mentioned) or Alto and Central Alentejo. These regions are isolated from the coast and exclusively relying on dams and subterranean resources (often over-exploited), which means that they have no alternatives in the case of severe drought and low water availability. The proposed solution for these challenging regions is to design an interregional water supply system where a desalination plant in a coastal region would provide freshwater to a neighbouring inland region in need (saline water corrodes metal and alloys, so pumping seawater over long distances is not viable). This system could pump water into a small number of key, geographically distributed dams across inland Portugal: a minimum water availability per region could be guaranteed, with every drought-threatened region having a dam serving as a drinking water reserve. Displacing water over long distances is very energy-intensive, so using a strategy that combines the use of surplus RES power and an operational scheduling that minimises pumping costs (in an similar approach to the one taken in this work to curb desalination's energy consumption) could play an important role in determining if such solution is feasible.

Chapter 6

Closure

6.1 Conclusions

Feasibility studies of desalination implementation are complex projects. A variety of factors have to be considered, such as the direction taken by local policy makers, existing water and electricity networks and environmental concerns. From an economic point of view, the main parameter to be gauged is the resulting LCOW of the project. It is the main focus of this work.

Following the state of the art in water desalination found in the literature, we set to project a SWRO plant driven by both grid electricity and RES power. Because water desalination is so energy-intensive, having desalination plants work solely on the RES power it produces would require the installation of unrealistically large capacities of solar PV and Wind turbines on site. It would lead to prohibitive costs, and finding the required terrain in an already disputed coastal area is difficult. A possible solution found for large scale sustainably powered desalination is to source power from neighbouring RES commercial producers. The present work proposes a novel approach: use RES power that cannot be injected into the grid locally as desalination's main energy source, in conjunction with some RES power produced on site and grid electricity (as a last resort).

Algarve's population, electricity consumption and fresh water demand fluctuation throughout the year make for a challenging case study. On the other hand, the flexibility requirements of this case present a good opportunity to test the impact of operational strategy optimisation on the viability of desalination projects.

Economic factors

Of the two scenarios considered, the Decentralised scenario turned out being the solution with the lowest resulting LCOW at **0.7266 EUR/m^3**, 2.1% lower than the Centralised LCOW and 19.7% lower than the Baseline scenario LCOW (100% Grid). This result shows that, under the assumptions set for this project, having two smaller plants comes at a slightly lower cost than having a single large one. Although the Centralised scenario benefits from economies of scale, with yearly savings of 853,000 EUR in total CAPEX (-3.5%), the increased installed capacity in RES for own consumption of the Decentralised scenario leads to 2.1 M EUR savings in electricity costs (-13.6%) every year. It must be noted, however, that if we relax the constraint on total RES capacity installed for the Centralised scenario and set it equal to the total capacity installed for the Decentralised scenario, the LCOW obtained for one large plant drops to 0.7204 EUR/m^3.

Sensitivity analysis were performed on three variables: RES market cost, storage tank capacity and RES penetration. RES market cost variations were found to have little impact on the obtained LCOW. Storage tank capacity variations show that, first, the lowest LCOW obtained is for a setup with no storage tank and secondly, increasing storage tank capacity has diminishing returns in terms of electricity cost savings (which are exclusively related to water pumping). The retained solution settles for a total storage tank capacity of 10,000 m^3, a compromise between added expenses and the need for an operational security margin. Lastly, a variation in RES penetration is shown to have a significant impact on the LCOW (-7.5% for a RES penetration of 50%). Surplus availability strongly influences the total electricity costs, which makes RES penetration a very important aspect of the feasibility study.

Under the conditions set for this project, the recommended solution considers a nominal plant capacity of 175,000 m^3/day at the Windward location (Portimão) and a 155,000 m^3/day plant Leeward (Monte Gordo). Each of them was equipped with 5000 m^3 of storage tank capacity (for a total of 10,000 m^3), with 1.3 MW of rooftop solar PV, 5 MW of fixed tilt solar PV panels and a 5 MW wind turbine farm (for a grand total installed capacity of 12.6 MW of solar PV and 10 MW of wind turbines).

The obtained LCOW of 0.7266 EUR/m^3 ranks among the lowest production costs mentioned by Gao et al. [53], at around 0.8 USD/m^3, but is still 61.3% higher than the estimated cost of the conventional water supplier. This means that from a purely economic point of view, and under the conditions set in this project, water desalination cannot compete with conventional water suppliers. We must note, however, that the comparison with the estimated cost of production of the conventional water supplier is merely indicative. As this is a preliminary study, the estimation of this production cost is simplified and underestimated; by instance network maintenance costs were not considered. The cost structure analysis presented in Subsection 5.3.3 shows that with the right operational strategy we can minimise electricity costs (33.8% reduction when compared to the Excel model), but further cost reductions are hampered by the total CAPEX (298 M EUR). To make this project economically viable, it is recommended to follow the example of Barcelona's LLobregat desalination plant project: built in 2008 with a capacity similar to the ones considered in this work (200,000 m^3/day) and a total investment of 230 M EUR, it financed its CAPEX thanks to contributions from the European Union's Cohesion Fund (150 M EUR) and from Spain's Ministry of Environment (52 M EUR). The company operating the water supply concession defrayed 28 M EUR, 12.2% of the total investment [65].

Political, Social and Environmental factors

The solution presented is capable of supplying 100% of Algarve's fresh water demand, making desalinated water a suitable alternative to water sourced from ground and surface resources. This would greatly reduce the stress on local aquifers, allowing them to slowly replenish themselves and avoid the risk of contamination. It would make Algarve's fresh water supply drought-proof, and it would free surface resources, which are subject to precipitation and to the effects of advancing desertification, for agricultural use.

With regard to CO_2 emissions, the Decentralised has an edge over the Centralised scenario by consuming less Grid power, resulting in a 24.6% increase in CO_2 emission savings compared to the Centralised solution (and a 51.4% increased savings compared to the Baseline scenario of 100% Grid power).

Model limitations

Although some of the assumptions set in Sections 3.3 and 3.5.1 help simplify the problem, they also impose limitations on the model. Forcing the storage tank level to be zero at the start and at the end of each day is one such case. In reality, monthly water demand variations are approximately continuous, but because each season is modelled by a representative average day that is repeated in a loop until the next season is reached, the model only considers one constant quantised level of seasonal water demand. The two days representing the passage from one season to the next must deal with a significant increase or decrease in water demand. This could be, for example, an opportunity to produce and store an extra amount of water the last day of a season with good Surplus RES availability and help reduce the costs of the first operating day of the following season. But because every day in each season is the same, the storage tank level at the end of the last day of the season would also be imposed on every day before it, disturbing the optimisation process.

Assuming that the water supply network is capable of absorbing any volume of water at any time of the day is also overly optimistic and represents another limitation to the model. In reality, the network pipeline capacity adds a hydraulic constraint to the optimisation model, slightly reducing its operational flexibility.

The combination of these two limitations explains why storage tank capacities only have an impact on pumping power consumption, and not on desalination power consumption in the obtained results.

Closing remarks

So could RES powered desalination become a viable solution for water stressed regions such as Algarve? From an energy policy standpoint, yes: albeit being very energy-intensive, this work shows that the SWRO plants would mainly rely on RES power (68.5% of total power consumption). It would also contribute to increasing the exploitation of the region's RES power production (27.5%), by offering a regular and foreseeable demand in RES power. From an economic point of view, the Centralised and Decentralised scenarios yield LCOWs from 0.73 to 0.74 EUR/m^3, both coming above the estimated production cost of the conventional water supply provider (+61.3%). For this project to be economically viable, national and european funding must be involved, following the example of the LLobregat plant in Barcelona, or much of the projects in California[66] and Australia[67].

6.2 Future Work

The present work shows that it is possible to have water desalination mainly powered by renewable energy sources. To achieve a 100% RES powered system, several hypothesis could be tested:

1. What is the impact of installing batteries in the desalination plants in order to store Surplus RES? What would be the resulting RES share of total power consumption? How would it affect the LCOW?
2. Is an over-dimensioned plant a better solution? By increasing the desalination output capacity, more Surplus power could be exploited around the hours of RES production peak before the capacity constraint forced curtailment. Do the electricity cost savings compensate for the increased CAPEX? How could larger storage tanks contribute?

With regard to energy systems modelling, the present work strictly considers solar PV and Wind power for the local RES production estimation: other sources such as hydro power and biomass could be included in a future model.

To fully integrate the desalination plants into the existing water supply network, assumptions related to water management can be further developed, and existing water pumping efficiency models found in the literature[68] could be considered. Strong assumptions are made, for instance, with regard to the way water is pumped into the water supply network. As mentioned in the previous section, under model limitations, the point of junction where the desalination plant's pipeline feeds the water supply network has to be sufficiently large so that the volume demand of the entire region can be injected. Taking the network's hydraulic constraints in consideration would contribute to a more realistic integration of the desalinated water. Fresh water demand could also be estimated for an hourly basis, instead of assuming that demand is an average taken over 24h.

Brine management and its impact on the environment are yet to be fully understood. For desalination to become a new standard in water supply systems, it is imperative to come up with innovative solutions to recycle or reuse the large volumes of brine produced by SWRO.

Desalination is an increasingly frequent option in water supply diversification policies, but it shouldn't be used in isolation. Although the plants in this work were dimensioned to supply 100% of the drinking water demand, mixing water coming from desalination, water reuse and rain harvesting technologies might lead to solutions that are both more cost-effective and sustainable. Policy makers should take a hollistic approach when rethinking water supply networks, and this work can be regarded as a preliminary study to help and make decisions.

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