UNIVERSIDADE DE LISBOA

INSTITUTO SUPERIOR TÉCNICO

Integrated Planning of Energy and Water Supply in Islands

Raquel Inês Segurado Correia Lopes da Silva

Supervisor: Doctor Maria da Graça Martins da Silva Carvalho
Co-Supervisor: Doctor Mário Manuel Gonçalves da Costa
Doctor Neven Duić

Thesis approved in public session to obtain the PhD Degree in Sustainable Energy Systems

Jury final classification: Pass With Distinction

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2015

Resumo

A penetração de Fontes de Energia Renovável (FER) intermitentes, como, por exemplo, energia eólica, nos sistemas de fornecimento de eletricidade de pequenas ilhas isoladas é geralmente limitada, mesmo quando há um grande potencial. Isto deve-se a constrangimentos técnicos das unidades de produção convencionais e ao limite dinâmico de penetração aplicado por questões de estabilidade da rede. Nestes casos, para minimizar a energia eólica desperdiçada, a potência eólica instalada é limitada. Uma solução para este problema pode ser o armazenamento de eletricidade, nomeadamente, bombagem hídrica, quando a topografia da região é adequada. Além disso, quando uma ilha não possui fontes naturais de água potável e necessita de usar a dessalinização da água do mar, a energia eólica produzida em excesso pode ser fornecida às unidades de dessalinização. A água dessalinizada produzida por estas unidades pode, por sua vez, ser usada numa central de bombagem hídrica e posteriormente ser fornecida à população. O presente estudo agrupa estas duas questões. A maior parte da investigação que integra o fornecimento de energia e água é focada no uso de FER na dessalinização (FER para produzir água) e no uso de água para produzir energia e não nestes dois assuntos simultaneamente. O aspeto inovador deste estudo é o uso de uma abordagem integrada ao planeamento de sistemas de fornecimento de eletricidade e água, com o objetivo de aumentar a integração de FER intermitentes e de minimizar os custos de produção de eletricidade e água. Esta abordagem integrada é aplicada à ilha de São Vicente, em Cabo Verde. O sistema de fornecimento de eletricidade atual é baseado em combustíveis fósseis e energia eólica. O recurso eólico desta ilha, apesar de ser abundante, não é totalmente aproveitado devido à sua natureza intermitente. A ilha de São Vicente apresenta uma topografia adequada ao uso de bombagem hídrica como forma de armazenamento de eletricidade. Esta ilha não possui fontes naturais de água potável, pelo que o seu sistema de fornecimento de água é baseado em unidades de dessalinização. O sistema proposto é modelado e a sua dimensão e estratégia operacional são otimizadas de modo a minimizar os custos totais anualizados e a maximizar a percentagem de FER na produção total de eletricidade. Pela análise dos resultados deste estudo conclui-se que o sistema proposto pode aumentar a penetração de FER numa ilha árida, enquanto minimiza os custos de produção. No caso da ilha de S. Vicente, este sistema permite o aumento de penetração de FER para 84% (58% energia eólica e 26% energia hídrica) e a diminuição de 27% nos custos de produção de eletricidade e água e 67% nas emissões de CO_2, em relação aos valores previstos para 2020.

Palavras-chave

Integração de fontes de energia renováveis intermitentes, Bombagem hídrica, Dessalinização, Nexo energia água, Fornecimento de eletricidade e água em ilhas.

Abstract

For small islands that are not interconnected with the mainland, the penetration of intermittent Renewable Energy Sources (RES), e.g., wind power, in the power supply system is limited, even when there is a large potential. This is due to technical constraints of the conventional generating units (namely their minimum loading level) and the dynamic penetration limit that is usually applied for grid stability. In these cases, in order to minimize the curtailed wind power, the installed wind power is limited. This problem can be tackled with energy storage, namely pumped hydro, when the topography is suitable. In addition, when an island has few or none fresh water resources and the desalination of seawater is a necessity, excess wind power can be provided to desalination units that can produce desalinated water to be used in the pumping and hydro station and later be supplied to the population. This study couples these two issues. Most previous research that combines energy and water supply focus on desalination with RES (RES to supply water) or on the use of water to produce energy and not both of these issues at the same time. The novel aspect of this study is the use of an integrated approach to power and water supply systems' planning, with the purpose of increasing the integration of intermittent RES and minimizing the electricity and water production costs. This integrated approach is applied to the Island of S. Vicente, in Cape Verde. The power supply system of this island is based on fossil fuel and wind power. Although the Island has important wind resources, they are not fully used due to its intermittent nature. S. Vicente presents a suitable topography for the use of pumped hydro as an energy storage system. The water supply system of this Island is entirely based on desalination units to provide drinkable water to the population, since there is no source of fresh water. The proposed integrated system is modelled and its size and operational strategy are optimized in order to minimize its total annualized costs and maximize the percentage of RES in the total power production. The results of this study show that the proposed system can indeed increase the penetration of RES in an arid island, while it minimizes the production costs. In the case of the Island of S. Vicente, this system allows the increase of the penetration of RES to 84% (58% from wind power and 26% from hydropower) and a decrease of 27% in the power and water production costs and 67% in the CO_2 emissions, in relation to the values foreseen for 2020.

Keywords

Intermittent renewable energy sources Integration, Pumped hydro, Desalination, Energy and water nexus, Power and water supply in islands

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Table of Contents

Nomenclature

Roman characters

a	Parameter used to determine the water produced from wind power	$(-)$
a_h	Parameter a in hour h, Eq. III.11	$(-)$
a_{h-1}	Parameter a in hour $h-1$, Eq. III.12	$(-)$
b	Parameter used to determine the water turbinated	$(-)$
b_h	Parameter b in hour h, Eq. III.16	$(-)$
b_{h-1}	Parameter b in hour $h-1$, Eq. III.17	$(-)$
CRF	Capital Recovery Factor; Eqs. III.5, III.6 and III.7	$(-)$
$desalcap$	Desalination capacity; Eqs. III.12 and III.19	(m^3/day)
E	Yearly electricity produced; Eqs. III.5 and III.8	(kWh)
EC	Yearly electricity cost, Eq. III.7	$(€)$
E_{FF}	Annual energy produced in the fossil fuel based units	(kWh)
E_{FF_h}	Energy produced in the fossil fuel based units in hour h, Eq. III.4	(kWh)
E_{FF_Water}	Annual electricity from fossil fuel used to produce water	(kWh)
$E_{FF\_Water\_h}$	Electricity from fossil fuel used to produce water in hour h, Eq. III.20	(kWh)
E_{Hydro}	Annual energy produced in the PHS	(kWh)
$E_{Hydro\ 1m^3}$	Energy produced for each m^3 of water turbinated; Eqs. III.10, III.17 and III.18	(kWh/m^3)
E_{Hydro_h}	Energy produced in the PHS in hour h; Eqs. III.4 and III.18	(kWh)
E_{Load}	Annual load	(kWh)
E_{Load_h}	Load in hour h; Eqs. III.2 and III.4	(kWh)
EPC	Electricity production cost; Eqs. III.5 and III.8	$(€/kWh)$
$E_{Pump\ 1m^3}$	Energy needed to pump each m^3 of water; Eqs. III.9, III.14 and III.15	(kWh/m^3)
etd	Energy needed to desalinate each m^3 of water; Eqs. III.12, III.13 and III.20	(kWh/m^3)
$E_{Und\_Load\_h}$	Undelivered load after the direct supply of wind power in hour h, Eq. III.17	(kWh)
E_{W_Curt}	Annual wind power curtailed	(kWh)
$E_{W\_Curt\_h}$	Wind power curtailed in hour h, Eq. III.3	(kWh)
E_{W_Desal}	Annual wind power used to desalinate	(kWh)
$E_{W\_Desal\_h}$	Wind power used to desalinate in hour h; Eqs. III.3, III.13 and III.14	(kWh)
E_{W_Pot}	Annual wind power production potential	(kWh)

$E_{W\_Pot\_h}$	Wind power production potential in hour h; Eqs. III.2, III.3, III.12 and III.14	(kWh)
E_{W_Pump}	Annual wind power used to pump water	(kWh)
$E_{W\_Pump\_h}$	Wind power used to pump water in hour h; Eq. III.3 and III.15	(kWh)
E_{W_Taken}	Annual wind power taken	(kWh)
$E_{W\_Taken\_h}$	Wind power taken in hour h; Eqs. III.2, III.3, III.4, III.12 and III.14	(kWh)
FC	Yearly fossil fuel cost, Eq. III.5	$(€)$
f_{FF}	Variable used to determine n_{FF}, Eq. III.27	$(-)$
f_H	Variable used to determine n_H, Eq. III.27	$(-)$
g	Acceleration of gravity; Eqs. III.9 and III.10	(m/s^2)
h	Hour of the year	$(-)$
H	Head of the PHS; Eqs. III.9 and III.10	(m)
h_{FF}	Number of hours of average water demand that must be available in the reservoir at all times	$(hours)$
$Hydro\ Power$	Power of the hydro turbines installed, Eq. III.17	(kW)
i	Discount rate, Eq. III.6	$(-)$
IC_E	Total investment cost of the electricity supply system, Eq. III.5	$(€)$
IC_W	Total investment cost of the water supply system, Eq. III.7	$(€)$
LR	Capacity of the lower reservoir; Eqs. III.11, III.16, III.17 and III.19	(m^3)
n	Lifetime of the equipment, Eq. III.6	$(years)$
n_0	Minimum level of the lower reservoir; Eqs. III.16, III.27 and III.28	(m^3)
n_{desal}	Maximum level of the reservoir to be filled with desalinated water	$(-)$
n_{FF}	Fossil fuel supply level of the lower reservoir; Eq. III.19 and III.27	$(-)$
n_H	Hydro stop level of the lower reservoir; Eqs. III.16 and III.27	$(-)$
n_{LR_h}	Level of the lower reservoir in hour h; Eqs. III.11, III.16, III.17 and III.21	(m^3)
n_{LR_h-1}	Level of the lower reservoir in hour $h-1$; Eqs. III.14, III.19 and III.21	(m^3)
n_T	Maximum level of the lower reservoir; Eqs. III.27 and III.28	(m^3)
n_{UR_h}	Level of the upper reservoir in hour h; Eqs. III.17 and III.22	(m^3)
n_{UR_h-1}	Level of the upper reservoir in hour $h-1$; Eqs. III.14 and III.22	(m^3)
n_{WB}	Wind balance level of the lower reservoir, Eq. III.11	$(-)$
OMC_E	Total yearly operation and management cost of the electricity supply system, Eq. III.5	$(€)$
OMC_W	Total yearly operation and management cost of the water supply	$(€)$

	system, Eq. III.7	
$P_{available}$	Available power after considering the security criteria, Eq. II.1	(kW)
PDC	Peak Demand Coverage index, Eq. II.1	$(-)$
$Peak$	Peak demand forecast, Eq. II.1	(kW)
$Pump\ Power$	Power of the pumps installed, Eq. III.14	(kW)
TC	Total cost, Eq. III.8	(€)
UR	Capacity of the upper reservoir, Eq. III.14	(m^3)
$v(10)$	Hourly wind speed obtained from the nearest meteorological station, Eq. III.1	(m/s)
$v(z)$	Hourly wind speed estimated for the hub height, Eq. III.1	(m/s)
W	Yearly water produced; Eqs. III.7 and III.8	(m^3)
W_{Cons_h}	Water consumed in hour h, Eq. III.21	(m^3)
W_{FF}	Annual water produced with fossil fuel	(m^3)
W_{FF_h}	Water produced with fossil fuel in hour h; Eqs. III.19, III.20 and III.21	(m^3)
WPC	Water production cost; Eqs. III.7 and III.8	(m^3/kWh)
W_{Pump}	Annual water pumped	(m^3)
W_{Pump_h}	Water pumped in hour h; Eqs. III.14, III.15, III.21 and III.22	(m^3)
W_{Turb}	Annual water turbinated	(m^3)
W_{Turb_h}	Water turbinated in hour h; Eqs. III.17, III.18, III.19, III.21 and III.22	(m^3)
W_{Wind}	Annual water produced with wind power	(m^3)
W_{Wind_h}	Water produced with wind power in hour h; Eq.III.12, III.13, III.19 and III.21	(m^3)
z	Hub height of the wind turbine, Eq. III.1	(m)

Greek characters

α	Wind shear, Eq. III.1	$(-)$
η_{Hydro}	Efficiency of the hydro turbines, Eq. III.10	$(-)$
η_{Pump}	Efficiency of the pumps; Eqs. III.9 and Eq. III.10	$(-)$
φ	Hourly intermittent limit, Eq. III.2	$(-)$
ρ	Water density; Eqs. III.9 and Eq. III.10	(kg/m^3)

Acronyms

BAU	Business As Usual
CER	Certified Emission Reduction
CO_2	Carbon dioxide
DMS	Direct MultiSearch
ED	Electro-Dialysis
MD	Membrane Distillation
MED	Multi-Effect Distillation
MSF	Multi-Stage Flash
MVC/TVC	Mechanical Vapour Compression/Thermal Vapour Compression
NEP	National Energy Plan for Cabo Verde
O&M	Operation and Management
OECD	Organisation for Economic Co-operation and Development
PHS	Pumped Hydro Storage
RES	Renewable Energy Sources
RO	Reverse Osmosis
SD	Solar Distillation
SIDS	Small Island Developing States

List of figures

List of tables

I. Introduction

I.1 Motivation

Currently, about 18% of the world's population still lacks access to electricity, while about 38% relies on wood, coal, charcoal or animal waste for cooking and heating [1]. This is a major barrier to eradicating poverty and building shared prosperity [2]. Moreover, where modern energy services are available, the problem is related to waste and pollution. Carbon dioxide (CO_2) and other greenhouse gases emissions from fossil fuels are contributing to climate change. The solution to both of these challenges is to provide sustainable energy for all, energy that is accessible, cleaner and more efficient [2]. In September 2011 the United Nations launched the Sustainable Energy for All initiative. This initiative is a partnership between governments, the private sector and the civil society with three interconnected objectives to be reached until 2030:

- Ensure universal access to modern energy services;
- Double the global rate of improvement in energy efficiency;
- Double the share of renewable energy in the global energy mix.

But more importantly, these objectives together must act as a catalyst for the creation of conditions for the development of income generation activities as a development motor and an instrument of poverty alleviation. Achieving the three objectives together will maximize development benefits and help stabilize climate change over the long run [2,3].

Small Island Developing States (SIDS) face a unique challenge in achieving sustainable development and fighting climate change. They are on the frontline of climate change and sustainable development. On one hand, they are more vulnerable to climate change and sea level rise. On the other hand, their small size, remoteness, vulnerability to external shock and fragile environments difficult the pursuit of sustainable development [4].

Most small islands that are not interconnected with the mainland depend mainly on the importation of fossil fuels for energy production but, at the same time, present a considerable potential in Renewable Energy Sources (RES). The use of this potential in the production of electricity and fresh water (in arid islands) could represent a large fraction of the total energy supply [5]. One of the major challenges of increasing the penetration of RES in a system is to integrate a high share of intermittent resources into the electricity supply system [6,7]. The intermittent nature of some RES, as well as the small energy systems of islands introduce barriers to their penetration, like the struggle to match the demand with the supply and the problems related with the integration in the network, namely the technical constraints of the conventional generating units (minimum load level of these units) and the dynamic penetration limit that is usually applied for grid stability [8]. The penetration of intermittent RES in the electricity supply system is therefore limited, even when there is a large RES potential.

The integration of RES in energy systems of small islands presents several advantages, namely at economic level, since their high investment cost is compensated by the high cost of the conventional energy sources. Indeed, the small dimension of the energy systems and the expensive importation of fossil fuels, whose transport costs make them even more expensive, cause a very expensive security of supply. Endogenous RES provide a clean and sustainable approach to energy production, help to ensure security of energy supply, decrease energy import dependence, and contribute to the achievement of the Kyoto Protocol's objectives. The integration of RES in the power system, along with appropriate policies and regulations on the rational use of energy, is very important for the achievement of sustainable development [9]. The conventional electricity production technologies are rarely adapted to the conditions of isolated regions and can seriously damage the vulnerable ecosystems and natural habitats [10].

The integration of intermittent RES in energy systems requires the development of energy storage technologies, energy management technologies and a greater sophistication of these systems. Furthermore, the several available RES, the increasing number of technologies for their use and the different options for energy storage, make the planning and modelling of energy systems complex and demanding [11].

In arid islands, in addition to the energy problem, there is the water scarcity problem, with the need to provide fresh water to the population in regions where there is no natural sources of fresh water. The installation of desalination units is a common solution throughout the world in areas with water scarcity [12], especially islands due to their proximity to the sea. However, desalination is a process that requires a significant amount of energy [13], thus, renewable energy driven desalination can play a vital role in the application of this technology.

The purpose of this study is to couple these two issues: the integration of RES in the electricity supply system and the water scarcity problem of islands. An integrated approach is used to energy and water supply systems' planning, with the aim of increasing the penetration of RES, taking into consideration the electricity and water production costs.

This study is applied to the island of S. Vicente, in Cabo Verde. This island has significant problems regarding the power and water supply systems, like other islands of Cabo Verde. Cabo Verde's power prices are among the highest in Africa due to its dependency on fossil fuel-based plants, which in turn rely on the importation of expensive fuel. In 2012, the electricity tariff reached 0.283 €/kWh

[14]. According to the Renewable Energies National Plan the electricity production cost in Cabo Verde is about 70% higher than the European average [15]. Cabo Verde has by far the most expensive water tariffs in Africa and among the most expensive in the world. In 2012 the water tariff reached 3.313 €/m^3, which is more than double the average water tariffs in the OECD major cities [16]. These high prices reflect the water scarcity problem that this country faces, where about 85% of its water production relies on desalination. Moreover, the cost of the energy-intensive desalination process is particularly high due to its dependence on power generation, whose high costs in turn reflect reliance on small-scale diesel generators and expensive imported oil [17].

The electricity supply system of S. Vicente is based on fossil fuel and wind power and, although this island has important wind resources, they are not fully used because of its intermittent nature. In addition, this island does not have any source of fresh water, being forced to desalinate seawater to produce water suitable for human consumption. On one hand, this puts more pressure on the power supply system but, on the other hand, this can be an opportunity to implement renewable energy driven desalination systems. Hence, this study proposes two scenarios to avoid the curtailment of this excess wind power, with two ways of storing excess wind power in S. Vicente. One way is to provide the excess wind power directly to the desalination units. The other way is to use both the desalination units and a pumped hydro energy storage system to store this excess wind power. S. Vicente has the suitable topography to install a pumped hydro storage system and the water produced in the desalination units can be used in this system.

I.2 Literature review

A number of studies have been carried out on the feasibility of integrating RES in islands, and all of them rely on energy storage and/or demand side management strategies. A number of analyses have been also carried out on the feasibility of using RES in desalination plants.

The use of excess wind power in the desalination units proposed in this study can be considered a demand side management strategy since the water cannot be turned back to electricity with a reasonable efficiency; water can, however, be stored.

Most of the studies undertaken so far have examined either the energy or the water supply system. When studies concentrate on the energy demand of the water supply systems, they usually do not analyse the overall power supply system of the region. However, there are some studies that begin to deal with this integrated approach.

In this section, a literature review is made concerning studies carried out on island energy systems with high penetration of intermittent RES and energy storage, namely, Pumped Hydro Storage (PHS); on the use of RES in desalination plants; on the energy water nexus, focusing on the integrated supply of power and water; and finally on the use of optimization methods in the design, planning and control of energy and water supply systems.

I.2.1 Intermittent RES in islands and energy storage

The intermittent nature of some RES and the small power systems of islands introduce barriers to their penetration. Wind power, for instance, has its largest disadvantage in its' strong weather dependence. Since wind speed can have sudden and large changes, the power output of a wind turbine can have large fluctuations, with significant impact on the operation of the power system and on the power quality. This impact increases with the increase of wind power penetration [18,19]. The impact on power quality is primarily on the level and fluctuations of voltage and frequency. The system must ensure the stability of voltage and frequency within required limits [19]. The variations in the wind power production can also cause disturbances between the power generation and power demand that can lead to dangerous operating conditions [20]. To avoid problems that can affect the safety and stability of the power supply system, wind power has to be limited to a specific percentage of the system's load [20]. This limit is the maximum instantaneous wind power directly supplied to the power grid and usually it is not higher than 30% [8,21]. In addition, the conventional generating units that are present in the power supply system have minimum loading levels, to avoid their operation in levels of lower efficiency. These two factors determine the maximum amount of wind power that can be injected in the power grid. For this reason, when there is large wind power potential, there can be a significant amount of wind power curtailed. The way to tackle this issue is to use energy storage. Research has shown that energy storage is crucial in the design of energy systems with high RES penetration. Energy storage allows the decoupling of production and demand, by transferring the energy surplus from one time to another where there is shortage, increasing the efficiency and the viability of such systems [22]. Energy storage is also advantageous for shorter duration applications, including grid stabilization, grid operational support, stable power quality and reliability, and load shifting [23]. Several solutions for wind energy storage are available, namely flywheels, capacitors, superconducting magnetic energy storages, batteries, compressed air energy storages, pumped hydro stations and hydrogen [18].

There is a significant amount of research carried out regarding the island energy systems with high penetration of intermittent RES.

Ntziachristos et al. [24] studied the coupling of a wind turbine with a fuel cell to improve the use of wind power in the non-interconnected Greek archipelago grid. Part of the wind power is stored in the form of hydrogen and then delivered to the consumption at constant power through a fuel cell. This decoupling between the wind power potential and the load is crucial to increase the contribution of RES to the small capacity grids of islands. The authors concluded that this type of installations can be used to complement or even replace conventional power stations, producing clean and renewable energy, without the limitations of the conventional wind power systems [24].

Papathanassiou and Boulaxis [8] evaluated the energy yield of wind farms operating in isolated power systems. The authors developed a methodology and applied it to a Greek island and state that wind farms installed on island systems are subject to significant restrictions, affecting their expected energy yield and, thus, the feasibility of investments. The authors concluded that a significantly higher wind power penetration requires fundamental changes in the structure and management of power supply systems, namely the application of advanced control centres and the introduction of energy storage, which for system sizes ranging from a few up to some hundreds MW, pumped storage seems to be the only viable alternative [8].

Kaldellis and Zafirakis [25] presented an integrated electricity production cost analysis for autonomous electrical networks based on RES and energy storage configurations and applied it to two Greek Aegean islands. The authors concluded that a properly sized RES-based power production system together with appropriate energy storage is a promising solution for this type of systems, providing clean energy and contributing to the decrease of the important environmental problems resulting from the electricity generation sector [25].

Zoulias and Lymberopoulos [26] examined the techno-economic aspects of replacing diesel generators of the Kythnos system by fuel cells, an electrolyser and a conventional hydrogen tank and also presented sizing optimization and simulation results of both conventional and hydrogen-based power systems. Kythnos is an island of the Cyclades region of Greece, located in the Aegean Sea. The authors concluded that the system proposed is technically feasible and increases RES penetration, decreasing the dumped excess energy, but in order to be economically viable the cost of the hydrogen based system must significantly decrease [26].

Bağcı [27] has shown that it is technically feasible to produce all of the required electricity of Peng Chau Island, Hong Kong, from RES, with almost no CO_2 emissions. The author concluded that solar, wind and wave energy are the most suitable alternative and that the model used can be applied to other outlaying islands of Hong Kong or any other small island in other part of the world with good RES potential [27].

Krajačić et al. [11] concluded that with an energy storage system based on hydrogen, the island of Mljet in Croatia could become a 100% renewable island concerning electricity and simulated transport needs and also could export additional power to the mainland power grid.

An autonomous wind/hydrogen energy demonstration system located at the island of Utsira in Norway was launched in July 2004 [28]. The system is composed of a wind turbine, water electrolyser, hydrogen gas storage, hydrogen engine, and a proton exchange membrane fuel cell. The system gives two to three days of full energy autonomy for ten households on the island, and was the first of its kind in the world. This autonomous wind/hydrogen system at Utsira has demonstrated that it is possible to supply remote area communities with wind power using hydrogen as energy storage. However, further technical improvements and cost reductions need to be made before wind/hydrogen systems can compete with existing commercial solutions, as, for example, wind/diesel hybrid power systems [28].

Parissis et al. [29] analysed the introduction of hydrogen as a storage means and wind energy as an electricity production source into the power supply system of the Portuguese Island of Corvo, in The Azores. A cost-benefit analysis was carried out in order to examine the proposed system from an economic, environmental and social perspective. The results indicate that a considerable RES penetration into the power system of Corvo Island is feasible and results in a significant reduction of the power generation costs (about 43%). The authors concluded that it is possible to reach an 80% penetration of wind power [29].

Table I.1 summarizes the characteristics of the major energy storage technologies available. The technologies that present the highest efficiency are flywheels, supercapacitors and superconducting magnetic energy storage, as well as the fastest response times. PHS has the highest capacity by a large margin [23]. The more mature technologies are PHS and lead-acid batteries.

Technology	Efficiency (%)	Capacity (MW)	Response time	Lifetime (years)	Maturity	Charge time
Compressed Air Energy Storage	70-89	5-400	Fast	20-40	Commercial	Hours
PHS	65-85	100-5,000	Fast	30-60	Mature	Hours
Flywheels	93-95	0.25	Very fast	~15	Demonstration	Minutes
Capacitor	60-65	0.05	Very fast	~5	Developed	Seconds
Supercapacitor	90-95	0.3	Very fast	20	Developed	Seconds
Superconducting magnetic energy storage	95-98	0.1-10	Very fast	20	Developed	Minutes
Lead-acid battery	70-90	0-40	Fast	5-15	Mature	Hours
Sodium–sulphur battery	80-90	0.05-8	Fast	10-15	Commercial	Hours
Nickel–cadmium battery	60-65	0-40	Fast	10-20	Commercial	Hours
Lithium-ion battery	85-90	0.1	Fast	5-10	Demonstration	Hours
Fuel cells	20-50	0-50	Good	5-15	Developing	Hours

Table I.1 – Main characteristics of the energy storage technologies [23,30]

The present study focuses on PHS because it is considered to be one of the most well suited storage systems to achieve high wind power penetrations in isolated systems [24] with a low maintenance cost. The main problem of this technology is the limited number of locations where it can be installed; however, the case study analysed in this work has the suitable topography to implement this technology. Batteries are not considered due to their high maintenance costs and short lifetime expectancy [25] that results in significant environmental problems, especially in islands.

Pumped hydro storage

As mentioned above, PHS is the most mature energy storage technology currently available [23]. Its operating principle is based on managing the gravitational potential energy of water. When the power demand is low and the intermittent RES production is high, this energy is used to pump water from a lower reservoir to an upper reservoir. When the power demand is high, and the RES production is low, this water is pumped back from the upper reservoir to the lower reservoir, activating hydroelectric turbines to produce electricity [30]. Generally the lifetime of these systems is around 30 to 60 years, with a round trip efficiency of 65-85% and a capital costs of 500-1,500 €/kW. It is an important instrument to control the electrical network frequency and as backup generation due to it fast response time (less than 1 minute) [23,30]. The fact that PHS can quickly respond to energy demands also implies that these facilities can provide peak shaving, valley-filling and spinning reserve capacity [31].

The use of PHS systems to increase the penetration of wind power has been widely analysed. The prospect of creating a combined wind hydro energy production station for Aegean Sea islands in Greece is analysed by Kaldellis and Kavadias [32]. The main factors that delay the economic development of these islands are energy shortage and clean water deficit, especially during the summer. However, these islands present an outstanding wind potential, but there is a significant disharmony between wind power production and electricity demand. Hence, the authors developed a methodology to estimate the most beneficial configuration of a wind-hydro energy production station and apply it to several Aegean Sea islands. The objective was to have maximum energy system autonomy from imported fuel and limited investment costs. All calculations were based on real data: long-term wind speed measurements, electricity load and the operational characteristics of the system's components. In order to understand the operational behaviour of the system proposed, the authors presented a detailed electricity balance for a typical 10 days period for all islands studied. The authors concluded that a significant part of the energy consumption is covered by wind power, while any energy deficit appearing is mainly covered by the hydro turbines, minimizing the necessity to use the conventional fuel based units. In all cases analysed, RES penetration may exceed 85%, decreasing the fuel imports and minimizing the negative environmental effects related to the operation of the conventional units [32].

The operation of a hybrid wind hydropower system aimed at producing low cost electricity for the island of Ikaria in Greece is discussed by Bakos [33]. Bakos presents the typical results of a hybrid wind power system already installed on the island and compares them to the results produced in a simulation. The simulation program is based on the stochastic behaviour of weather conditions, the monthly wind speed distribution and the rate of rainwater that is stored in the reservoir of the hydro system. A good compliance was observed between the experimental and the simulation results. A considerable reduction of electricity production cost is found, when the autonomous power stations' are replaced by a hybrid wind hydro system. The variation of electricity cost is given as a function of the installed wind power and hybrid system autonomy days. Bakos concluded that the analysis carried out emphasizes once more the necessity for the exploitation of RES in Greece. The rainwater collection in large reservoirs also guarantees the availability of adequate water quantities for consumption by the population. The stored water could also be used for the protection against fire and for agricultural purposes [33].

The concept of the combined use of wind power production and hydro storage/production is exploited in [34], through the development of an operation optimization approach applied to a wind park with small availability for water storage. The optimization model defines the operational strategy to be followed for the hours ahead by a pump station and a hydro turbine within a wind/hydro facility, using the Portuguese energy remuneration regulation. The objective was to identify the best strategy for the operation of a combined wind hydro pumping storage power plant in Portugal in order to fulfil the ambitious targets for RES production defined for the power sector in Europe. From the solution of the optimization problem it is possible to determine the hourly operation of the system that increases the profit. The proposed model also determines the optimal equipment specifications. Two different strategies to obtain gains were considered: through energy transferred between periods with different prices, and through storage of the available wind power production when it is greater than the transmission power acceptance limit imposed by the network. Near real operation conditions were considered and a yearly simulation was carried out considering wind speed data from a site in North of Portugal. Interesting gains are obtained when comparing the wind hydro strategy versus the wind operation alone.

Bueno and Carta [35] presented a model for the technical and economic sizing of a medium sized wind-powered PHS system that can be implemented in topographically suitable sites with enough wind resources. The objective of this model is to optimize the operation of this system and allow for several operational strategies that are based on the hypothesis that there is a centralised operator to control all the system components, except for the load systems. The characteristics and unit energy cost of each technically feasible combination of components are determined by applying the model. This enables the selection of the most viable composition for the system from an economic point of view given certain technical restrictions. The model simulates the operation of each feasible combination by making energy balance calculations for all the hours of the year. The authors [36] applied this model to the island of El Hierro, Canarian Archipelago. Real data was used regarding electricity demand, wind speed gathered over four years, investment costs (installed commercial equipment, civil engineering infrastructure, electrical and control infrastructure) and estimated operating and maintenance costs. The results indicate that an annual renewable energy penetration of 68% can be achieved. This results in a significant amount of saving of diesel oil and reduction of CO_2 emissions. The authors also concluded that the proposed system is currently not able to compete economically with the conventional units, although that would change with an increase of the price of diesel oil. In June 2014, the installation of this wind powered PHS system was completed and is currently operating in the island of El Hierro. The system is composed by a wind park with 11.5 MW, an upper and lower reservoir with 380,000 m^3 and 150,000 m^3 of capacity respectively; a pumping station with 6 MW, a hydro power station with 11.32 MW and three desalination plants. The upper reservoir was built on an existing crater. The total cost of the installation of this system rose to 64.7 M€. It is expected that this system will allow the island to cover 80% of its energy needs [37].

Bueno and Carta [20] also presented a proposal to mitigate the problem of the restriction of wind power penetration in the island grid of Gran Canaria, Canary Islands, through the installation of a wind powered PHS system [20]. The authors state that the restrictions imposed on the direct penetration of wind sourced power in the conventional grids of the Canary Islands are an obstacle to meeting the renewable energy objectives set out by the European Union. The authors proposed a partial solution to this problem with the installation of a wind powered PHS system in Gran Canaria Island. The system consists of a 20.4 MW wind farm, a 17.8 MW pump station (operated so that the variation in the energy demand for pumping is in line with the wind power production), a 60 MW hydro power plant and two reservoirs of 5,000,000 m^3 each with a 281 m height difference (already present on the island). Investment, operating and maintenance costs are taken into account, as well as costs involving health and environmental damage associated with energy production and use (externalities). The results obtained from the application of an optimum-sized economic model of this system indicate that penetration of RES can be increased at a competitive cost for the unit energy supplied. Furthermore, the proposed system has no negative effect on either the reliability of the power system or on power quality and would mean fossil fuel savings and CO_2 emissions reductions. The authors concluded that this system successfully combines a maximum exploitation of this RES with the maintenance of a power quality service. Therefore, for regions that have topographically suitable sites and which suffer energy problems similar to those of the Canary Islands it is proposed that an analysis be made of the technical and economic feasibility of the installation of such power systems. Within the general guiding framework of a policy promoting clean and renewable energy, these systems represent an enormous and as yet barely explored potential.

Caralis et al. [38] state that the combined use of wind power with pumped storage systems is a mean to exploit abundant wind potential, increase wind power installed and substitute conventional peak supply, in autonomous islands where the wind penetration is restricted due to technical reasons related with the safe operation of the electrical systems. The authors proposed a simulation of autonomous electrical systems and applied it in three Greek Islands. The simulation is based on the non-dynamic analysis of the electrical system, in order to calculate the energy contribution of the different power units. The aim was to analyse the prospects of wind powered PHS systems to decrease the production cost of the power system. The results show that with the introduction of this storage system, the wind power penetration increases, decreasing the system's electricity production cost. The authors concluded that another important advantage of the proposed system is that the production cost is to a large extent known in advance, contrary to the current cost that depends strongly on the fossil fuel price, providing both financial and environmental benefits [38].

Duić et al. [39] proposed a wind powered PHS system for the island of Corvo, in The Azores. This island is already mentioned above regarding the study carried out on the introduction of hydrogen as a mean to store wind power. This island is the smallest of the nine islands of The Azores Archipelago. It has only one population centre with about 380 inhabitants. The electricity supply of the island is based on fossil fuel and its cost is nearly five times higher than the average in The Azores. In addition, due to bad weather conditions it is common to have fuel shortages in the island during the winter months; hence the security of energy supply is a critical issue. Duić et al. state that there are many places where there is already an excellent storage potential in the local water supply system, and that by merging the energy and water supply system, where there is sufficient elevation difference, it is possible to use pumped hydro to increase the penetration of wind power, even in cases where there is not much hydro potential. The authors proposed a model of such a system applied to the island of Corvo and concluded that only by adding storage to energy and water resource systems is it possible to significantly increase the penetration of locally available renewable energy resources, and thus increase the security of supply and decrease the fossil fuels' import dependence.

Brown et al. [40] carried out an economic analysis of the inclusion of a PHS system in a small island with abundant RES available that cannot be integrated completely due to security criteria. The authors devised an optimization problem in order to determine both power capacity and best reservoir capacity for the PHS in this island. The dynamic security criteria were included in this optimization problem and the stochastic nature of the load and of the RES production were dealt with and scenarios were produced for the optimization problem. Results showed that the inclusion of this technology can be an effective means of allowing larger penetration of intermittent RES, improving both the dynamic security and the economic operation of a test system.

Connolly et al. [41] investigated how PHS can support the integration of wind power in the Irish energy system. The authors focused on three key aspects of this technology: operation, size and cost. The authors concluded that PHS can increase the wind penetration on this energy system and reduce operating costs. These savings are, however, sensitive to changes in PHS capacities used, fuel prices, interest rates and total wind power produced. In relation to the sizing of the PHS system this study identified a divergence between the pump and turbine capacities required for PHS when it is used to integrate increasing amounts of wind power. As wind power penetrations increase, the pumping capacity required also increases so the PHS can integrate more wind power production, but the turbine capacity does not increase as quickly because the power plant production, which it is replacing, remains the same. The slight increase in turbine capacity required is primarily related to the additional energy available in the PHS due to the increased pumping capacity. A single penstock and double penstock operating strategy have been also analysed to assess if the additional capacity required for a double penstock system is offset by the additional wind power penetrations feasible. The results suggest that as wind power penetrations increase, the double penstock system is a more economical alternative and it enables Ireland to utilise more indigenous wind power. However, it is also more sensitive to changes in fuel prices, interest rates, and total annual wind power production. The double penstock operating strategy also illustrated how ancillary services can be provided when integrating wind power onto modern electric grids. Although PHS is used in this study to create a flexible supply and demand portfolio in Ireland for the integration of wind power, other alternatives could be used in a similar way such as electric vehicles, the electrification of heat, thermal storage, and many more. The proposed solution for Ireland in 2020 was compared with two alternatives that require the same investment: domestic heat pumps and district heating with combined heat and power. These alternatives offer similar savings to PHS, but are not as sensitive to changes in fuel prices, interest rates, and wind power production. This outlines the importance of considering all sectors of an energy system when assessing future alternatives, as significant savings are feasible using existing technologies, especially by integrating the electricity and heat sectors. This study highlights that the ultimate necessity for the future is the demand for more detailed analyses of a wide range of alternatives for an energy system, as significant savings can be realised using existing technologies especially by integrating the electricity, heat, and transport sectors.

I.2.2 RES desalination

The increasing scarcity of water is driving a growing implementation of desalination technologies. However, the energy needed to run the desalination plants is a disadvantage. Hence, many studies have been made for the use of RES in desalination [42].

Desalination is a process that clears sea or brackish water from the minerals that cause salinity in order to provide water within acceptable standards for drinking [43]. Currently available desalination technologies can be mainly categorized as thermal and as membrane desalination, according to if there is a phase change process or not. The thermal desalination involves the heating of the feed water to its boiling point at the operating pressure to produce steam, and condensing the steam in a condenser unit that will produce fresh water. The thermal desalination processes include Multi-Stage Flash (MSF), Multi-Effect Distillation (MED), Mechanical/Thermal Vapour Compression (MVC/TVC), Membrane Distillation (MD) and Solar Distillation (SD). The membrane desalination involves the separation of dissolved salts from the feed waters by mechanical or chemical/electrical means using a membrane barrier between the feed water and the product (fresh water). The membrane desalination processes include Reverse Osmosis (RO) and Electro-Dialysis (ED). The dominant desalination processes are MSF and RO, with 44% and 42% of worldwide capacity, respectively. The MSF represents more than 93% of the thermal process production, while RO process more than 88% of membrane process production [44].

This study will focus only on RO desalination since it is the current technology installed in S. Vicente. In addition this is the most efficient desalination technology, requiring about 3-10 kWh of electricity to produce 1 m^3 of fresh water from seawater. RO is a membrane separation process in which the water from a pressurized saline solution is separated from the dissolved material by flowing through a membrane. The major energy required is for pressurizing the feed seawater [45]. RO is well developed and has been in commercial use for decades. Moreover, this method provides significant flexibility in adding capacity and can be provided in various sizes of power consumption and amount of water produced. The modular nature of this technology and its flexibility makes this technology an ideal candidate for the combination of RES and desalination systems.

Wind powered RO plants appear to be one of the most promising alternatives of RES desalination. This is because RO is the desalination process with lowest energy requirements and desalination plants are mostly located in coastal areas, where there is usually a high availability of wind resources [44].

There are several studies that analysed renewable energy powered desalination systems.

Carta et al. [46] analysed a prototype of an innovative fully autonomous wind powered desalination system, installed on the island of Gran Canaria in the Canarian Archipelago. This technology has a vital importance for regions like the Canary Islands, which suffer from potable water scarcity, lack conventional energy sources, but present high wind power potential. In this study, the design and operational strategies of a prototype for a desalination system powered exclusively with wind power are analysed. This system was designed to determine experimentally the feasibility of a stand-alone desalination unit powered by wind power, to verify the operational feasibility of several desalination techniques when the energy source driving the system is intermittent, and to analyse the influence that various operational strategies have on the volume and quality of the desalinated water produced and on the effect on the main components of the desalination unit. The feasibility of such stand-alone systems was clearly demonstrated. The results obtained have not revealed any significant variation in the level of quality or average volume of the product water, nor any physical deterioration to the main components of the system as a result of the start-ups and shut-downs due to the variations in the wind power supply or to the oscillations of the electrical parameters of voltage and frequency. The authors concluded that the system can be applied to seawater desalination, both on a small and large scale, in coastal regions with a scarcity of water and with wind power resource. The authors also concluded that RO technology seems to be the most suitable for coupling to a wind farm isolated from a conventional power grid, if it is operated with variation in capacity (number of desalination plants), but maintaining practically constant the operating parameters (pressure and flow) [46].

Later on, Carta et al. [47] redesigned this small-scale prototype seawater RO desalination plant to continuously adapt its energy consumption to the variable power supplied by a wind turbine, dispensing the use of batteries and proposing the use of a supercapacitor bank as a dynamic regulation system. The authors concluded that it is feasible to adapt the consumption of the prototype of the seawater RO desalination plant to widely varying wind power production.

Paulsen and Hensel [48] analysed how to combine a desalination plant with a fluctuating energy source like wind. The authors state that the main problem for the combination of desalination processes and wind power is the fluctuation of power supply generated through renewable energies. To address this issue an innovative RO desalination unit was designed and installed in the Island of Utsira, Norway. The ENERCON Energy Recovery System was designed for very low energy consumption, high flexibility and efficient combination with fluctuating energy sources. This system is supplied only by wind power eliminating the need to use fossil fuels. The system was designed to maximize daily water production, while minimizing the costs [48].

Fadigas and Dias [13] proposed an alternative configuration to conventional RO desalination systems by incorporating the use of both gravitational potential energy and wind power. In general, RO plants use a high-pressure pump powered by electricity. The pump is used to send a flux of saline water to a group of semi-permeable membrane modules, capable of filtering the dissolved salts. In this alternative configuration proposed it is intended to achieve a flux at the inlet of the membrane modules with a pressure high enough for the desalination process, without using either electricity or fossil fuels. For this, a hybrid system that uses both gravitational potential energy and wind power is devised. This configuration was modelled and the authors concluded that it is technically and economically viable. The economic viability of the proposed system is supported by the fact that only RES is used, due to low specific energy consumption and because of the low maintenance cost due to the simplicity of the system. The disadvantage of this system arises when there is the need to produce large quantities of fresh water. After this theoretical analysis, a prototype of this system was constructed and proved that this mechanism is technically viable.

Spyrou and Anagnostopoulos [12] investigated the optimum design and operation strategy of a stand-alone hybrid desalination scheme, capable of fulfilling the fresh water demand of a Greek island. The scheme consists of a RO desalination unit powered by wind and solar electricity production systems and by a PHS unit. An algorithm was developed to simulate in detail these system's operation and to carry out an economic evaluation of the investment. A sensitivity analysis was also carried out to analyse the effects of several critical parameters (population, water pricing, water demand satisfaction rate and investment cost). An optimally designed scheme is found to be economically viable investment, although power curtailment is significant and there is a clear need for better exploitation of RES excess production. The authors concluded that a PHS system is necessary to guarantee the desired fresh water production throughout the year. Its contribution to the desalination power feed varies between 13% and 23%, and its optimum installed power becomes greater for larger islands or higher water demand satisfaction requirements. This storage system is necessary to improve the capacity factor of the wind and solar electricity production systems, reduce the amount of curtailed power and improve the economic results of the entire desalination plant. The proposed scheme is capable of producing water at a competitive water production cost (about 1.5-3.0 €/m^3), in comparison with the current water supply in the Greek islands (5-8 €/m^3) [12].

The use of wind turbines for desalination has been proven to be economically feasible as wind technology is well advanced and coastal sites in particular often have a good wind resource [49]. The main challenges associated with the use of wind turbines are the intermittency and fluctuations of the wind resource which occur due to turbulence and gusts over short periods of time (seconds to a few minutes) and mass air movements over long periods of time (tens to hundreds of hours) [49]. The direct connection of a wind turbine to a RO system with no form of energy storage will inevitably result in large fluctuations in pressure and flow rate. This presents a considerable challenge for wind-powered membrane (wind-membrane) systems as membranes are designed to operate at constant operating conditions with no abrupt pressure or cross-flow variations in order to minimize damage [49]. In Park et al. [49] a wind-powered RO membrane system without energy storage was tested using synthetic brackish water over a range of simulated wind speeds under both steady-state and fluctuating conditions. The parameters varied were: average wind speed; wind turbulence intensity (from steady-state conditions to extreme fluctuations); and period of oscillation. This system produced good quality fresh water over the full range of wind speeds and fluctuations. The authors concluded that this wind-membrane system can be operated within a safe operating window with large power fluctuations, but further control strategies are required to deal with intermittent operation, especially with higher salinity feed waters. Park et al. [49] studied the effect of wind speed fluctuations on the performance of a wind-powered membrane system for brackish water desalination and demonstrated that membrane systems can be directly connected to RES (wind power presents the most extreme fluctuations) and operate effectively within a safe operating window. The authors state that the main challenge associated to this operation is not the size of the fluctuations but the effect of the power switching off which causes reduced flux and permeate quality of the membrane. They concluded this must be controlled with energy buffering, careful control of the water treatment load or disposal of the poor quality permeate [49].

The most suitable design for seawater RO desalination driven by off-grid wind energy systems is presented by Peñate et al. [50]. The authors address the design of two possible combinations useful for RES powered seawater RO desalination plant: with gradual capacity and with fixed capacity. The gradual capacity plant is more versatile because it can operate units independently or jointly, depending on the amount of power available. In the second case, the plant can operate within a more restrictive range of power consumption, when the wind resource is enough to supply all required power by the plant. The fixed capacity plant allows the production of a greater amount of water per year in comparison with gradual capacity design, but the desalination unit does not work more hours during the year. The gradual capacity design produces 2 to 8% less water than the fixed capacity design. However, the annual operation rates are higher with the gradual capacity plant and the excess energy is lower. Both designs reach rates above 95% production hours in months of high wind power production. In months with low wind power production, the fixed capacity design produces more water than the gradual capacity. In the case of an off-grid system, the power control component becomes a priority on producing the maximum volume of water. The power control technology of the RES production systems still requires the contribution of demand control systems for good tuning between variable RES production and the power demand. Consequently, gradual capacity is a major recommendation for the design and optimization of wind powered RO desalination plants. In general, the designs proposed require a study of the annual local water needs and the wind availability to ensure the optimized operation and stability in the functioning of the system. The use of wind power to supply such a system, adapted to medium or large water demands, compels to take into account the water storage as the key energy storage system. This solution guarantees to meet the water demand in periods of lack of wind resource or serious breakdowns of the system [50].

I.2.3 Energy water nexus

Energy and water are inextricably linked. Water is needed to produce energy and energy is needed to extract, treat and distribute water and to clean the used and polluted water [51]. This is called the energy water nexus, and it is important to understand due to the increasing energy demands and decreasing fresh water supplies in many regions [52]. Because of this close interrelationship, the design and operation of water and wastewater systems should take the energy aspect into consideration. Similarly, energy production should not be planned without taking water resources and water quality into consideration [51].

Siddiqi et al. [52] identified the water use in the energy sector and the energy use in the water sector in Jordan and concluded that integrated policy and planning is needed to meet the challenges of growing water and energy inter-dependencies in many regions. Joint consideration of both water and energy domains can identify new options for increasing overall resource use efficiencies. However, in order to identify such opportunities, a detailed knowledge of current and emerging water-energy couplings is needed along with an understanding of key actors and institutions engaged in decision-making [52]. The authors developed a framework in which the assessment of the physical systems is integrated with that of the social and political stakeholders. The aim of such an approach was to identify new and strategic opportunities for linking decision-making and ultimately increasing the efficiency of the resources [52]. The authors' analytical approach was based on three interconnected components: an assessment of the key sub-sectors within each of the two domains that currently (or in the future may) have high inter-dependencies by analysing quantitatively the water and energy physical inter-linkages; a stakeholder analysis for the main energy and water policy agencies to identify key actors and organizations; and an identification of the common definitive or dominant stakeholders that can potentially serve as intermediaries for bridging water and energy decision-making [52]. This framework offers approaches for instituting and implementing integrated resource management and policy for meeting societal economic development needs as well as ensuring long-term environmental sustainability [52]. Jordan is on the verge of developing new infrastructure that will merge its water and energy future. The authors state that one of the strategies of the Government, the intention to develop oil-shale, will create additional water requirements and for that they identified a new source that will help fulfil its demand (desalination of seawater and increase the reuse of wastewater). They also identified opportunities for using wastewater from the municipal sector for partially fulfilling water needs in the energy sector. However, these arrangements require joint cooperation across different national institutions related with water management, natural resources, local authorities, etc. [52]. The focus of this study was on Jordan, however, the overall approach used is generally applicable. It is important that each region and country develop its own knowledge base relevant to its specific conditions (geographic, environmental, socio-economic), because water has a high local variability. In addition, the water and the energy sectors both include sub-sectors, regarding the source of production (oil, gas, coal, hydro, etc.) and the point in the supply chain (production, distribution, etc.). For this reason, each region has its own set of specific inter-linkages that need to be characterized at the sub-sector and place in the chain basis in order to identify practical options for improving decision-making [52].

Integrated power and water supply

Power and water supply are two types of systems modelled and analysed frequently, but often in a separate way. Most studies focus either on the power or the water supply system. Some studies, as seen in section I.2.1 consider water as a means of storing energy in a power supply system (PHS). Moreover, some analyse the energy demand of the water supply system, as seen in section I.2.2, with the use of RES in desalination units. More rarely these two supply systems are analysed together in an integrated way.

There is a significant difference between the issues concerning the power supply and the water supply. Power production must meet demand at all times, while water can be easily stored. Hence the studies that analyse the integrated water and power supply in some cases do not consider the water demand curve explicitly, but only determine the amount of water that can be supplied with the system proposed.

Corsini et al. [53] compared a hydrogen based system and a desalinated water production system as two effective alternatives for renewable energy seasonal buffering in an island context (stand-alone system). The hourly behaviour of the proposed system is analysed in terms of fuel consumption and hydrogen system energy storage or desalination capacity. The proposed model included RES integrated with a hydrogen based production-storage-use cycle for seasonal energy buffering or a desalination water production for reducing the impacts related to clean water supply. The scenarios are applied in the Ventotene Island in Italy. This island features high renewable energy penetration onto the load demand (up to 55% of peak power capacity). The island's demographic, meteorological and load data were used. A model was developed to simulate the storage process of winter RES surplus and the time-dependent matching between the demand of electricity and the RES production combined with energy surplus conversion systems for the period of one year [53]. The study demonstrates the suitability of both scenarios for the winter renewable energy buffer, in order to improve to the matching of peak energy and water demands. The simulation model showed the advantages of two storage concepts for RES buffering in stand-alone power system, recovering energy as hydrogen or water [53]. From the energy buffering point of view, the two scenarios considered have a similar behaviour during fall period as a consequence of the combination of two factors: the decreasing number of inhabitants and the draining of the storage capacities during summer period [53]. Although the studied buffering systems have different purposes, both scenarios lead to fuel oil savings greater than 60% in relation to the current situation [53]. The available RES energy is nearly completely converted, especially in the hydrogen-based scenario. Moreover, the curtailed energy is related to the selected size for the hydrogen system components and reverse osmosis modules [53]. The higher fuel oil saving values in the hydrogen-based scenario, compared to the water-based one, result from the fuel cell energy contribution, which allows a further reduction of fossil fuel based units operating hours [53].

Henderson et al. [54] studied the feasibility of a wind diesel hybrid system that also includes a desalination system component, on Star Island, in New Hampshire, in the United States. The proposed system aimed to supply electricity during the peak demand summer months and to balance the seasonal mismatch between wind resource and electricity demand load via the production and storage of potable water during winter months. Using specific data obtained from the site, the proposed system was modelled for a number of small commercially available wind turbines. This work showed that is economical to install two or three 7.5 kW wind turbines on Star Island without desalination, even considering that much of the energy would be wasted in the winter. This installed wind power would substantially reduce the island's diesel fuel use. Although the addition of a desalination system is not economically viable, the authors concluded that from a technical point of view, seawater desalination offers an interesting solution to energy storage or long-term load management for wind diesel hybrid systems. This conclusion assumed that there is a reasonable close match between the wind resource and the need for water to make a system economically viable [54].

Setiawan et al. [55] analysed a scenario for supplying electricity and fulfilling demand for clean water in remote areas using RES and a diesel generator with RO desalination plant as deferrable load. Economic and environmental analyses were also carried out. The economic issues analysed are the initial capital cost needed, the fuel consumption and its annual cost, the total net present cost, the cost of electricity produced by the system and the simple payback time for the project. The authors simulate the performance of the proposed system in a remote area in the Maldives with about 300 inhabitants and concluded that the proposed system is economically and environmentally viable. The authors also set up a laboratory experiment to demonstrate the feasibility of providing reliable power and water supply to remote areas [55].

Currently, Jordan is one of the most water deprived countries in the world [56]. On the other hand, Jordan is also a country with high RES potential that is not used [56]. Novosel et al. [56] proposed a combination of desalination, pump storage that use the produced brine and RES to tackle this issue. These authors analysed the impact of RO desalination units on the potential for the penetration of intermittent RES in the energy system of Jordan [56]. The effect of the flexibility of the RO desalination units as well as the storage capacity of the brine operated PHS system was evaluated. It was found that the desalination plants could produce enough water to ensure the supply for Jordan's ever growing population while the use of wind and solar power could provide the much needed electricity and reduce the need for imported fossil fuels as well as the CO_2 emissions. The results demonstrate that an increase of the flexibility of the desalination units and the use of the brine operated PHS system greatly benefit the reduction of excess RES, increasing the penetration of wind power to about 32% and the penetration of solar power (photovoltaic power) to about 37% of the annual electricity demand. The case study also demonstrated that it is possible to greatly increase the water availability in Jordan, providing additional 95 m^3 of fresh water per capita annually, that corresponds to about 60% of the current annual per capita consumption. The authors concluded that the integration of water and energy systems can provide a real benefit to the country of Jordan regarding its water supply and energy security [56].

The effects of large-scale desalination on the Jordanian energy system were analysed by Østergaard et al. [57], with a particular focus on the large-scale introduction of wind power into the energy system. The authors used desalination to decrease excess electricity production and concluded that water storage has some implication on the system's ability to integrate wind power [57]. Contrary to the previous studies mentioned, this one considers the hourly fresh water demand in Jordan. Two different desalination technologies were investigated: RO driven by electricity and MSF driven by cogeneration of heat and power. The authors concluded that the two systems impact the energy systems in different ways due to the technologies' particular characteristics. The Jordanian primary energy supply with MSF is similar to the one with RO. The difference between the two technologies arises when considering the ability to integrate wind power in the power system. In this case RO is more appropriate, especially if water storage is considered [57].

Traditionally, the infrastructure systems that deliver energy and water, the water distribution and power transmission networks are thought of as separate, uncoupled systems. However, in reality, they are very much coupled in what is commonly known as the energy water nexus. Although the energy water nexus has recently caught the attention of several policy and regulatory agencies, it is rarely addressed in terms of an integrated engineering system for its management, planning and regulation as an interdisciplinary concern [58]. Santhosh et al. [58] addressed this issue by focusing on the supply side of this integrated engineering system, developing a multi-plant real-time simultaneous economic dispatch of power and water. In this analysis, the production costs are minimized subjected to capacity, demand and process constraints. A hypothetical system composed of four power plants, one water plant and three cogeneration plants was considered. The results of the optimization include: the dispatch levels of power and water, the power to water ratio for the coproduction plants relative to the power and water demand ratio and the total costs incurred over a 24 hour period. The authors demonstrate that the coproduction minimum capacity limits and process constraints can lead to scenarios where the dispatch can chose the multi-plant instead of the cheaper single product plants. Such results suggest that water and/or power storage can have an important role in reducing process constraints and reducing costs [58].

The alternative of using seawater desalination as a flexible load whenever excess RES power is present was analysed by Bognar et al. [59]. The authors carried out numerical simulations of combined energy and water supply systems for the island of Petite Martinique, Grenada, located in the Caribbean. Four scenarios were simulated considering RES (wind and solar power), energy storage technologies and different desalination processes. The first scenario considered only the electricity production using RES. The second scenario considered the use of the excess RES power to produce water in a desalination unit. This scenario resulted in less power production than the one needed to produce enough water to cover the demand. The third scenario considered the addition of a further load that needs to be served. This load can be deferred as long as it meets the constraints of a given period. In this case, if there is not enough excess RES power available, diesel generators need to operate in order to serve this deferrable load. The deferrable load is the energy consumption of a flexible operating desalination plant with a specific daily water production, and the water storage is acting as temporary buffer storage. In the second and third scenarios the desalination process is considered to operate discontinuously and with a flexible load depending on the available power. On the contrary, in the fourth scenario, the energy consumption of the desalination plant is integrated into the system as a secondary load that is a constant load all year round. This implies that this load is not adjusting to the RES production conditions and that the diesel generators need to operate whenever RES power cannot meet the demand. This is more close to the operation of conventional desalination units that are designed to operate at an optimal level and continuously at a constant rate. The optimal energy supply system found in the first scenario was composed of wind turbines, diesel generator units (already installed in the island) and batteries. The second scenario shows that the energy supply system of the first scenario was able to cover a significant part of the desalination plant's energy demand with excess wind power. In the third scenario, when no excess wind power is available, the existent diesel generators function as a backup. In the fourth scenario, the need of constant energy supply for the desalination plant requires additional energy storage capacities and more fossil fuel is consumed. In this sense, there is a clear benefit of scenario three over scenario four regarding the production costs of electricity and water. The authors concluded that, for an optimal energy and water supply system on the island, the desalination plant's energy demand should be integrated as deferrable load [59].

Bognar et al. [60] analysed the effects of integrating desalination into an island grid with a high share of renewable energies. The authors present options to include a RO desalination unit into an optimized wind diesel energy supply system for the Island of Brava, in Cabo Verde. Three different scenarios were analysed and simulated using hourly data. The first scenario only considered electricity production, the second scenario considered electricity and water production with a constantly operating desalination plant, and the third scenario considered the electricity and water production with a discontinuously operating desalination plant. Comparing these three scenarios the authors showed that the third scenario could provide the lowest and most stable electricity and water costs considering increasing oil prices. These results show that energy supply systems with a high wind power share can benefit from deferrable loads like a variable desalination plant. These processes are very attractive to implement as dynamic load in intermittent RES supply systems due to their flexibility. The authors concluded that the main benefits of using desalination as deferrable load in a micro-grid are: better capacity use of the fossil fuel based units, less fuel consumption and therefore less dependency on fuel imports, less unused excess electricity generated by RES technologies, saving of energy storages within the micro grid, and lower production costs of electricity and water. The authors determined the requirements of a flexible operating desalination plant based on the analysis of the hourly data of this island. Interruptions of the energy supply as well as some degree of pressure changes need to be tolerated by the seawater RO unit without damaging the modules and increasing operational costs. It was shown that such an operational mode is technologically feasible and profitable under given circumstances. Since the results of this study are based on simulations, it is envisage setting up a variable operating RES pilot plant in order to assess these results, especially regarding the energy consumption and costs of operation and maintenance of the desalination units [60].

From the examples mentioned, it is clear that the integrated planning of energy and water supply is crucial to tackle some of the problems arid islands face in the providing quality power and water to their population.

I.2.4 Optimization methods

Optimization methods play a crucial role in the design, planning and control of renewable energy systems. Baños et al. [61] presents a review of the current state of the art in computational optimization methods applied to renewable and sustainable energy. It concludes that the research that uses optimization methods to solve renewable energy problems has increased dramatically in recent years, especially for wind and solar energy systems [61].

According to Østergaard [62], many different optimisation criteria might be applied to the design of environmentally benign energy systems and no clear answer can be found to the question of how to design an optimal energy system. At a general level, renewable energy systems may be designed from an economic perspective or from a techno-operational perspective. Economic optimisations criteria include total energy systems costs, capacity costs and societal costs. From a techno-operational perspective, optimisation criteria include fuel savings, greenhouse gases emissions, minimisation of import/export, elimination of excess power generation, among others. All of these criteria can be applied to assess how well the system integrates renewable energy [62].

Petruschke et al. [63] distinguish between two types of approaches widely followed in designing RES systems: heuristic approaches and optimization-based approaches. Heuristic approaches typically rely on specific expert knowledge or physical insights to define possible energy systems and analyse them in simulation studies. On one hand, this type of approach is usually robust and generates solutions with manageable effort, but, on the other hand, only a limited number of alternatives can be studied in simulation studies and the risk to overlook better solutions is high. In contrast, optimization-based approaches allow the investigation of a practically unlimited number of alternatives and thus generally enable to find the optimal solution among all possible alternatives. However, for large problems the modelling effort and solution times can become prohibitively large. Petruschke proposes a combination of these two approaches [63].

For each approach, there are three levels in designing RES energy systems: configuration level, where technology and equipment choices are made, the sizing level where the equipment capacities are estimated, and the operational level where the operational strategies of the system are specified [63].

Optimization is the mathematical discipline concerned with finding inputs of a function that minimizes or maximizes its value, which may be subjected to constraints [61].

One of the problems that can arise in the implementation of an optimization algorithm is the difficulty of computing the derivatives of the objective function. In many applications these derivatives are unavailable, for example, if they are a result of an actual simulation [64]. These functions can be discontinuous, non-smooth and not defined in certain points. In these cases, the method used to optimize these functions must be a derivative free method, i.e. methods that do not explicitly use derivatives of the function being optimized [65]. One group of derivative free methods is the direct search methods, which are methods that only require ordinal information about function values. These methods are suitable for problems involving simulation-based optimization as well as problems involving non-smooth or discontinuous functions [65]. Minimization with these methods is achieved thorough an iterative process of function evaluation at finite set of points, using the results to determine the new points and decide which point presents a better value for the objective function [66].

Additionally, there are a large number of applications that require the simultaneous optimization of several objectives, which are often in conflict, and, for this, multiobjective algorithms are proposed. These algorithms can be divided between aggregate weight functions and Pareto-based optimization methods. In aggregate weight functions the combination of all the objectives to optimize in a single mathematical function is carried out, where the relative importance of each objective is adjusted according to relative weights. The difficulty of this approach relates mainly with the adjustment of the weights of the objectives to optimize. Furthermore, this approach only returns a single solution as a result of the search process, which becomes an important limitation in the decision-making process, where the decision maker must select one solution from several alternatives. The drawbacks of aggregating functions have been solved using Pareto-based multiobjective optimization, which establishes relationships among solutions according to the Pareto-dominance concept. Given a multiobjective optimization problem with two or more objectives to optimize, it is said that one solution dominates another when the first is better than second in at least one objective, and not worse in the others. It is said that two solutions are indifferent if neither dominates the other one. The set of non-dominated solutions constitutes the Pareto optimal set, which usually contains not one, but several solutions [61]. Selecting one solution of the Pareto optimal set instead of another will always sacrifice the quality of at least one of the objectives, while improving, at least, another [66].

Custódio et al. [67] proposed a multiobjective derivative free methodology: the Direct MultiSearch (DMS). This method directly extends, from single to multiobjective optimization, the direct search methods. Each iteration of these methods can be organized around a search step and a poll step. Given a current iterate (a poll centre), the poll step in single objective optimization evaluates the objective function at some neighbour points defined by a positive spanning set and a step size parameter. For DMS the same is done but changing the acceptance criterion of new iterates using Pareto dominance, which then requires the updating of a list of (feasible) non-dominated points. At each iteration, polling is performed at a point selected from this list and its success is dictated by changes in the list. This framework encompasses a search step too, whose main purpose is to further disseminate the search process of the entire Pareto front [67]. This method was compared with eight other solvers commonly used in derivative free multiobjective optimization, for

100 multiobjective optimization problems reported in literature. The method was assessed regarding the ability to obtain points that are Pareto optimal and to compute a highly diversified subset of the whole Pareto front [67]. For the metrics considered, DMS has proved to be highly competitive with the remaining solvers [67].

I.3 Objectives

This work studies the way to increase the penetration of RES in islands by coupling the power and water supply systems. For this, an integrated supply system is proposed, where excess wind power is provided to desalination units that can produce fresh water that can be used in a PHS system and later be supplied to the population. The excess wind power can also be stored in that PHS system. The electricity and water production costs of the scenarios modelled are estimated in order to find the solution that minimizes the cost, while keeping RES penetration as high as possible. As mentioned before, the installation of a large amount of wind power implies the increase of the intermittent curtailed, and this has a negative impact on the financial analysis of the system. In order to decrease the intermittent curtailed there is the need to increase the desalination capacity of the system. However, it is very important to assure that the load of the desalination units is enough to guarantee the financial viability of the system. The main purpose of this study is to understand how the electricity and water production costs vary with the intermittent curtailed and with the load of the desalination units in order to find an optimum solution.

The research questions that will be answered with this work are:

1. Which integrated power and water supply system can increase the penetration of RES, while minimizing the production cost, in an island?

2. How do electricity and water production costs of this integrated system vary with the wind power curtailed?

3. How do electricity and water production costs of this integrated system vary with the load of the desalination units?

4. What is the optimal operational strategy of this integrated system?

I.4 Present contribution

This study addresses a very important issue on the economic, technical and environmental sustainability of the electricity and water supply systems of dry islands.

Most previous research on the energy and water nexus focused on desalination with RES (RES to supply water) or the use of water to produce energy (water to supply energy) and not both of these issues at the same time. The novel aspect of this study is the coupling of these two supply systems in order to increase the integration of intermittent RES and minimize the electricity and water production costs, increasing their efficiency.

The proposed integrated system is modelled firstly with the H2RES model, which simulates the integration of RES and hydrogen in the energy systems of islands or other isolated locations. It is based on hourly time series analysis of demand (water, electricity, hydrogen, heat); storage (pumped hydro, batteries, hydrogen, heat) and resources (wind speed, solar radiation, precipitation) [11]. The wind power produced is used firstly to cover the load, according to the dynamic (hourly) penetration limit allowed. The wind power that surpasses this limit (excess) is used in the desalination units. The desalination units use this wind power to fill the reservoir used to supply water to the population (lower reservoir). After that, if there is still wind power available it is stored as pumped water into an upper reservoir. The energy that is stored can be retrieved later, and supplied to the system as electricity. The remaining energy needs are covered by fossil fuel-based systems. The desalination module is developed for the purpose of this study. This module uses excess wind power to supply the desalination units, that produce drinkable water and put it on the lower reservoir, this reservoir is then used to supply the population. This module takes into account the desalination capacity of these units and their electricity consumption. This module also allows the use of fossil fuel based units to supply electricity to the desalination units.

In order to optimize the sizing and the operational strategies of this integrated system and facilitate the use of optimization methods, the system is modelled separately from H2RES. The integrated electricity and water supply system proposed for S. Vicente is modelled for the year 2020, taking into account the electricity and water demand forecasted for that year. The size and the operational strategy of this system are translated into the variables of the optimization problem. The proposed integrated system is modelled based on the hourly wind power production potential (provided by the H2RES Model). Based on these hourly values and on the hourly load and hourly water load, it is possible to calculate the hourly wind power excess, the hourly wind power used to produce water and to pump water, as well as the water produced and pumped. In each hour, the wind power excess that is not used to produce or pump water is the wind power curtailed. The water turbinated is also calculated and the corresponding hydro production. The water produced from fossil fuel based units is also calculated. These calculations allow the estimation in each hour of the level of the upper and lower reservoir. Based on these hourly values it is possible to determine the annual load that is covered by the fossil fuel based units and the total annual costs of the system.

To solve the optimization problem a derivative-free method is used: the multiobjective optimization method DMS [67]. The Pareto optimal set is obtained, from this set several solutions are chosen and analysed in more detail.

I.5 Thesis outline

The remainder of the thesis is divided into four chapters. Chapter II presents the case study analysed, the Island of S. Vicente in Cabo Verde, as well as the scenarios proposed. Chapter III describes the methods used to model and optimize the system proposed. Chapter IV presents and discusses the results of the scenarios modelled and of the optimization. Finally, Chapter V summarizes the main conclusions of the present work and provides some suggestions for future research.

II. Case study

Cabo Verde is an insular country, with about half a million inhabitants and a reduced and disperse territory (about 4,000 km^2) [3]. It is composed of 9 inhabited islands situated at about 450 km of the West African coast, in the Atlantic Ocean (Figure II.1).

Figure II.1 - Map of Cabo Verde [68].

Cabo Verde has a semi-arid climate, hot and dry, with scarce rainfall. The islands have a volcanic origin, mostly are mountainous and with almost no vegetation and natural resources. The country is extremely dependant on importation; imports about 80% of all it consumes [3].

II.1 Power and water supply in Cabo Verde

Power in Cabo Verde is supplied by the multi-utility company ELECTRA, which is also responsible for the water supply in some of the islands. Cabo Verde has achieved a relatively high electrification rate. According to the National Census of 2010, 81% of the total population has access to electricity [69].

This value is above the average for African countries (43%), and also above the average for developing countries (76%), but below the average for transition economies and OECD countries that reach 99.8% [1]. However, the increase in the electrification rate over the years in Cabo Verde was not accompanied by a proportional increase in the electricity production, with the power installed decreasing. Between 2002 and 2006, the power installed decreased about 4%, while connections rose by 40% and production by 10%. Hence, blackouts became more frequent and longer due to a tight demand-supply balance [14].

In Cabo Verde energy production is largely dependent on fossil fuel-based plants, which in turn rely on expensive fuel imports. Fuel costs represent more than 70% of the power production costs [14]. A single power price is applied across all islands despite differences in costs due to a geographical cross-subsidization justified on the grounds of social equity. Cabo Verde’s power prices are among the highest in Africa due to its dependency on the importation of expensive fuel [14]. According to ELECTRA, the average electricity tariff in Cabo Verde in 2012 was 0.283 €/kWh [14], about 45% higher than the average European electricity tariff for households [70]. The power production costs are about 70% higher than the European average [15].

In 2012, the water tariff of Cabo Verde was 3.313 €/m^3 [14] by far the most expensive water tariff in Africa, and among the most expensive in the world [17]. This value is more than double the average water tariffs in the OECD major cities [16]. These high prices reflect the scarcity of the water resources that has forced the country to rely on desalination for approximately 85% of the production. Moreover, the cost of the energy-intensive desalination process is particularly high due to its dependence on power generation, whose high costs in turn reflect reliance on small-scale diesel generators and expensive imported oil [17].

Government vision and policy for the energy sector

Cabo Verde National Energy Policy was approved in June 2008. The policy sets out the Government objectives’ for the energy sector. The vision of the Government of Cabo Verde for the energy sector is to construct a secure, efficient, sustainable and independent energy sector [15]. This vision is based in four main pillars:

- Energy security of supply and reduction of energy imports dependency;
- Invest and adopt renewable energy technologies;
- Ensure the environmental, economic and socio-political sustainability of the energy sector;
- Ensure an efficient energy supply, distribution and consumption.

To accomplish this vision, the Government of Cabo Verde adopted a strategy with the following objectives: increase RES penetration; promote energy conservation and efficiency in the energy sector; increase the installed electricity production capacity; increase the electricity supply coverage and guarantee energy access; strengthen the legal and institutional framework; create an energy security fund; and to promote research and adoption of new technologies [15,71]. Within this policy, the main target is to reach 50% RES penetration in the electricity supply system until 2020 and at least one island with 100% of electricity supplied from RES. Another target is the reduction of the electricity cost to a maximum of 25% higher than the European average [15,71].

Although these objectives are already very ambitious, the recent significant increase in investment in RES has led to an even more ambitious target of the Government of Cabo Verde: to reach 100% of RES electricity by 2020 [15].

In a first phase the electricity mix will be dominated by wind and solar power, but biodiesel, geothermal energy and the use of urban solid waste to produce energy will be explored by one or two islands in a demonstration regime. Energy storage systems will also be integrated in the power supply system [15].

The Government of Cabo Verde launched recently the National Plan for Renewable Energy and the National Plan for Energy Efficiency, as well as the Action Agenda in the scope of Sustainable Energy for All of the Economic Community of West African States [3]. In Cabo Verde, the objectives of the Sustainable Energy for All initiative are perfectly aligned with the developed strategies for the national energy sector and with its role in the development of the country. The focus on renewable energies is considered structuring for Cabo Verde and a way to ensure the sustainability of the target of universal access to energy. In the context of Cabo Verde, the use of endogenous energy sources allows higher energy independence and the access to energy at competitive prices for families and companies [3].

The foreseen strong penetration of RES in the power supply should be accompanied of measures to reduce losses in the power distribution system, that is currently quite high (about 30%), to about 8% until 2020 [15].

Regarding RES integration in Cabo Verde, one of the main barriers is the technical limitation of integrating variable wind resources in the grid. The existing grid is quite weak, which does not ensure that the power is in fact delivered to the consumers due to structural problems. The existing grid also restricts the addition of capacity, and thus the development of small to medium scale renewable energy projects [71].

II.2 The Island of S. Vicente, Cabo Verde

S. Vicente is the second most crowed Island in the Archipelago of Cabo Verde, with about 76 thousand inhabitants in 2010 [69], mostly concentrated in its main city, Mindelo. Figure II.2 presents a map of S. Vicente. The island has about 227 km^2 of area.

Figure II.2 - Map of S. Vicente [72].

The electricity supply system of S. Vicente is based on fossil fuel and wind and, although this island has important wind resources, they are not fully used because of its intermittent nature. In addition, this island does not have any source of fresh water, being forced to desalinate seawater to produce water suitable for human consumption. This puts more pressure to the electricity supply system, since desalination requires a significant amount of energy. This can be an opportunity to implement renewable energy driven desalination. However, it is always necessary to have energy storage. The topography of this Island is relatively uniform, with the exception of Mont Verde, a 774 m high mountain (Figure II.2), which could be suitable for PHS.

This island is a suitable case study to test the use of desalinated water in a pumping and hydro station before being supplied to the population – a wind powered desalination and PHS.

II.2.1 Electricity supply system of S. Vicente

The electrification rate of S. Vicente reached 90% in 2010 [69], a value above the national average. The technologies used for the production of electricity on the island are based on fossil fuel-fired plants and wind turbines. Furthermore, this island is not interconnected with any of its neighbouring islands. Figure II.3 shows the evolution, from 2001 to 2012, of the power installed and the peak power in S. Vicente. The power installed increased about 90% from 2001 to 2012, while the peak power increased 52%.

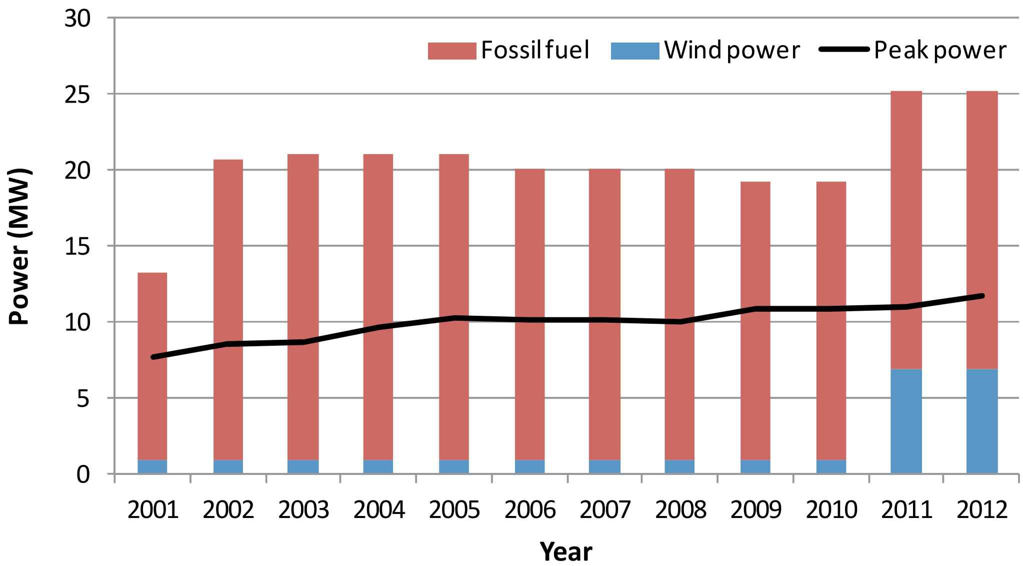

Figure II.3 - Power installed by technology and peak power in S. Vicente from 2001 to 2012 [14,73-83].

The 900 kW of installed wind power observed in the first years are related to the Selada Flamengo wind park inaugurated in 1994, with three Nordtank wind turbines of 300 kW each [82].

In 2006 and 2009 there was a decrease of the power installed in S. Vicente due to the decommissioning of fossil fuel units that were not replaced. The increase of the power installed in 2011 is entirely due to wind power. In early 2011, the company Cabeólica installed seven Vestas V52 wind turbines of 850 kW each, increasing the fraction of installed wind power from 5% to 27% of the total installed power. In September 2011 only four of these wind turbines started to operate and to provide electricity to the central grid. The remaining three wind turbines were firstly not in operation. Hence, the installed wind power in the island was about 6.85 MW, despite only 4.3 MW in operation. Currently, all wind turbines are in operation [84]. Figure II.4 presents the wind power curve of each type of wind turbine installed in S. Vicente.

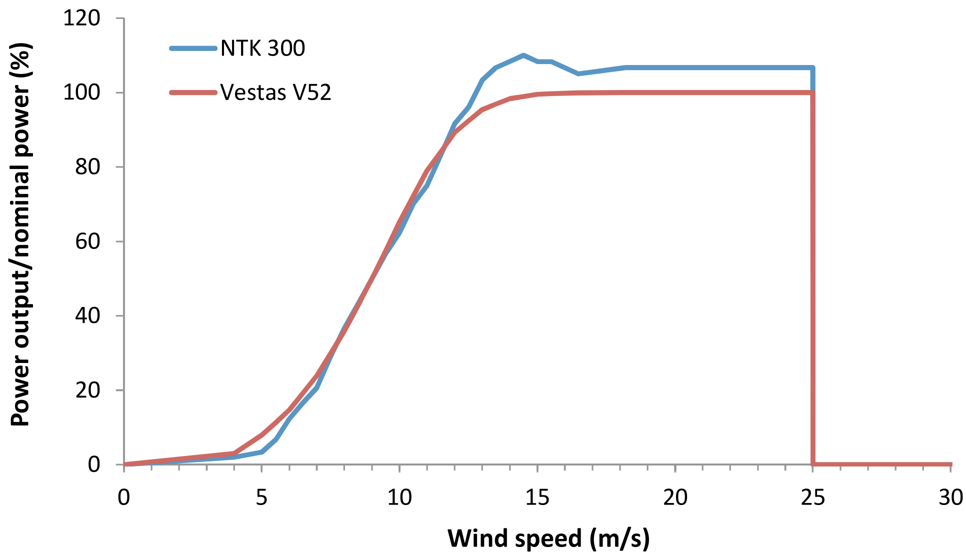

Figure II.4 – Wind power curve of the wind turbines installed in S. Vicente [85,86].

Table II.1 shows the power units installed in S. Vicente in 2012. There are two conventional thermal fossil fuel-based plants, the Matiota and the Lazareto plants. In 2012, the Matiota plant had four fuel oil and diesel generators, with an installed capacity of 10,900 kW. The Lazareto plant had two fuel oil generators, with an installed capacity of 7,440 kW.

Location	Name	Installed capacity (kW)	Commissioning date
Matiota power plant	Group III (Deutz)	2,100	1977
	Group IV (Deutz)	2,200	1982
	Group V (MAK)	3,300	1994
	Group VI (MAK)	3,300	1994
Lazareto power plant	Group VII (Caterpillar)	3,720	2002
	Group VIII (Caterpillar)	3,720	2002
Selada Flamengo wind park	3 NTK 300	3 x 300	1994
Cabeólica wind park	7 Vestas V52	7 x 850	2011

Table II.1 - Power units installed in S. Vicente in 2012 [14].

According to the Renewable Energy Plan of Cabo Verde [87], Group III and IV (Deutz generators) were decommissioned in the end of 2012 (after about 30 years of operation), and groups V and VI

(MAK generators) will also be decommissioned in 2015 (after about 20 years of operation), taking out a total of 10.9 MW capacity from S. Vicente.

Figure II.5 presents the evolution of the electricity production in S. Vicente by technology used. The power production in 2012 was about 66 GWh, a 44% increase in relation to 2001.

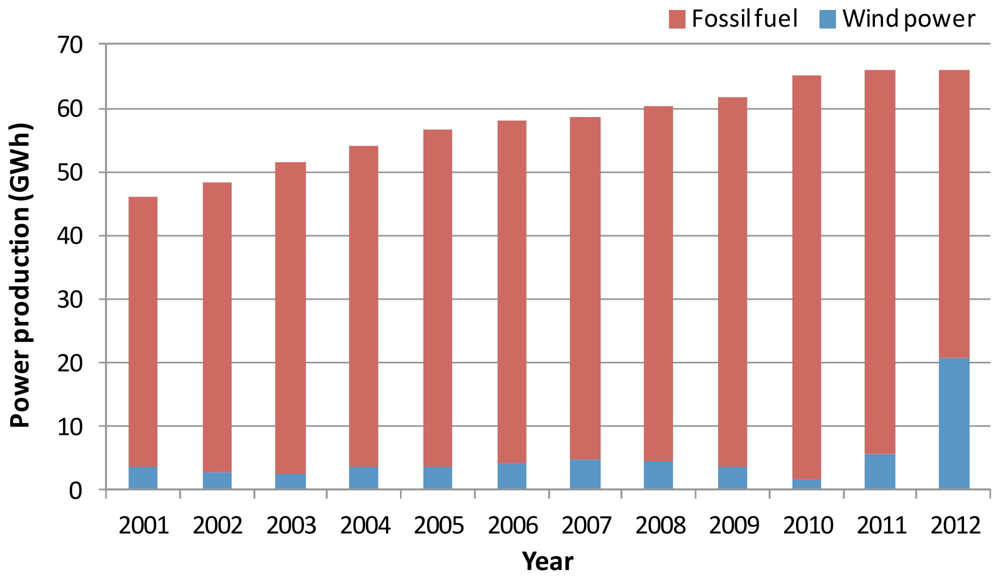

Figure II.5 - Power production in S. Vicente from 2001 to 2012 [14,73-83].

The installation of the Cabeólica Wind Park increased the wind power penetration in the power system from 8% in 2011 to 31% in 2012. However, this great increase came with the increase of the wind power curtailed. Due to the hourly dynamic penetration limit, not all wind power produced can be used to cover the load, hence wind power is curtailed. This wind power curtailed is wasted power, since it had no additional production cost, it is free power. Not using this wind power will increase the specific power production cost of S. Vicente, which is already quite high, as it is pointed out in section IV.1.1. Data regarding the current wind power curtailed in S. Vicente is not available; however, with the modelling of the power system carried out in this study it is possible to determine this value for the baseline scenario (section IV.1.1).

The hourly electricity production of each power production unit installed in S. Vicente for the year 2005 and 2006 has been provided by ELECTRA. An example of the daily report of the Production Direction of ELECTRA can be seen in Annex 1. This study is based on the data from 2006. This data presents several gaps, due to blackouts (the production of all units is zero) and due to the units' disconnection from the power system. This occurred about 0.2% of the time in 2006. These gaps are filled by averages of adjacent values. The sum of the hourly values (the yearly power production of

2006) results in a value about 0.3% higher than the one stated in the corresponding ELECTRA report [78].

The electricity production is relatively stable throughout the year, as there are not large climate variations, as can be seen in Figure II.6, which represents the hourly electricity load of S. Vicente in a weekday in the summer and the winter of 2006.

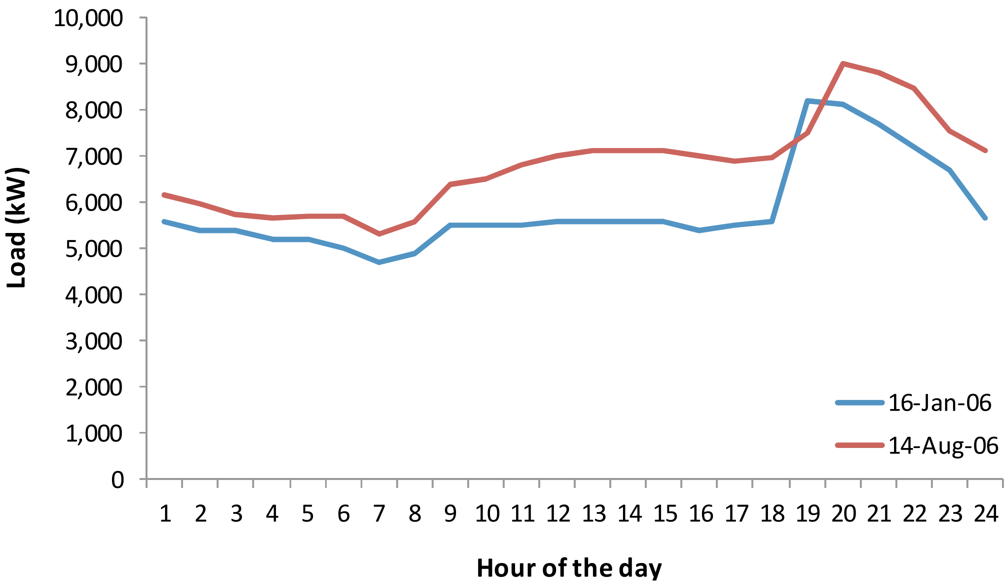

Figure II.6 - Hourly electricity load of S. Vicente in a summer day and in a winter day in 2006.

II.2.2 Wind resources in S. Vicente

Wind power represents the greater contribution within the RES in the Cabo Verde Islands. This is due to good wind conditions in the islands where the trade winds prevail (winds of north-east direction) which are characterized by being constant and with medium-high speeds. Indeed, wind parks in Cabo Verde are the ones with greatest productivity in the world, with capacity factors higher than 40% [88]. The wind resources in Cabo Verde present a clear seasonal asymmetry with two distinct periods: from January to June with high average wind speeds, and from July to December with a significant decrease of the average wind speeds.

S. Vicente is the island of Cabo Verde that has the highest wind resource potential. Although it presents a rugged terrain, its structure presents favourable conditions to the acceleration of the wind resource, increasing the average wind speeds. This island presents vast areas with average wind speed higher that 8.5 m/s [87]. For this study, the hourly wind speed values are collected from the meteorological station of S. Pedro in 2005 [89]. The average wind speed registered in 2005 is 7.9 m/s, the monthly averages range from 7.1 m/s in September to 10.3 m/s in May. Although the meteorological station is very close to the wind parks (Figure II.2), a wind speed adjustment is applied using monthly correction factors defined to match monthly wind power production in 2005. Figure II.7 presents the monthly average wind speed with and without this adjustment, as well as the annual average. The seasonal asymmetry mentioned above is clearly stated.

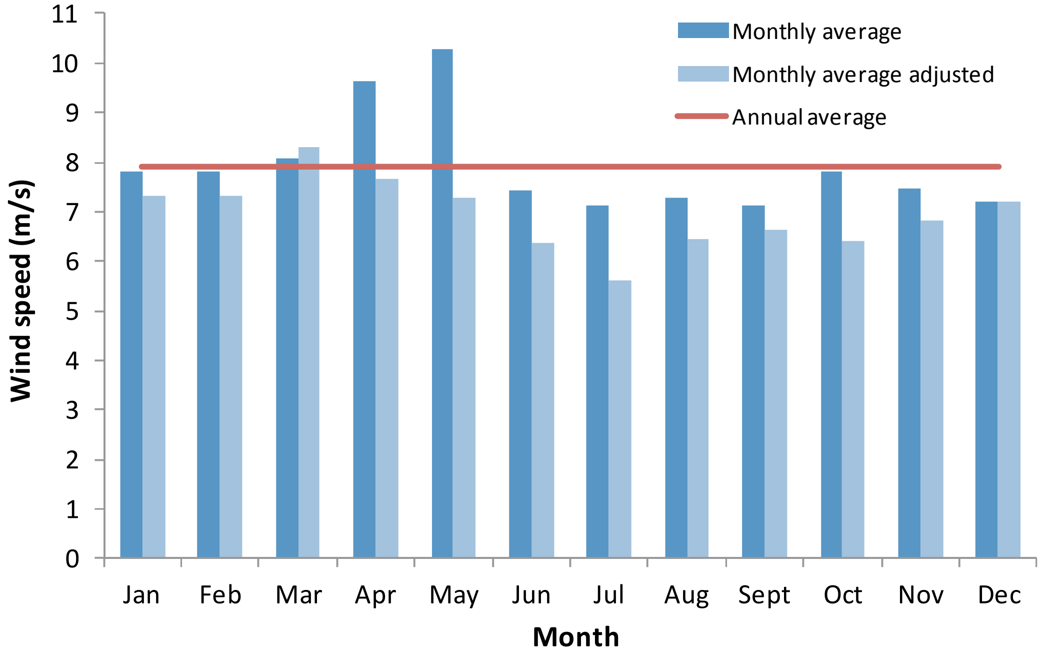

Figure II.7 - Annual and monthly average wind speed in 2005.

The wind speed adjustment causes a decrease in the monthly and annual averages. The monthly adjusted averages range from 5.6 m/s in July and 8.3 m/s in March. The annual adjusted average is 6.9 m/s.

Figure II.8 presents the frequency of occurrence, in hours per year, of each class of wind speed in S. Vicente, for the measured data and for the adjusted data of 2005.

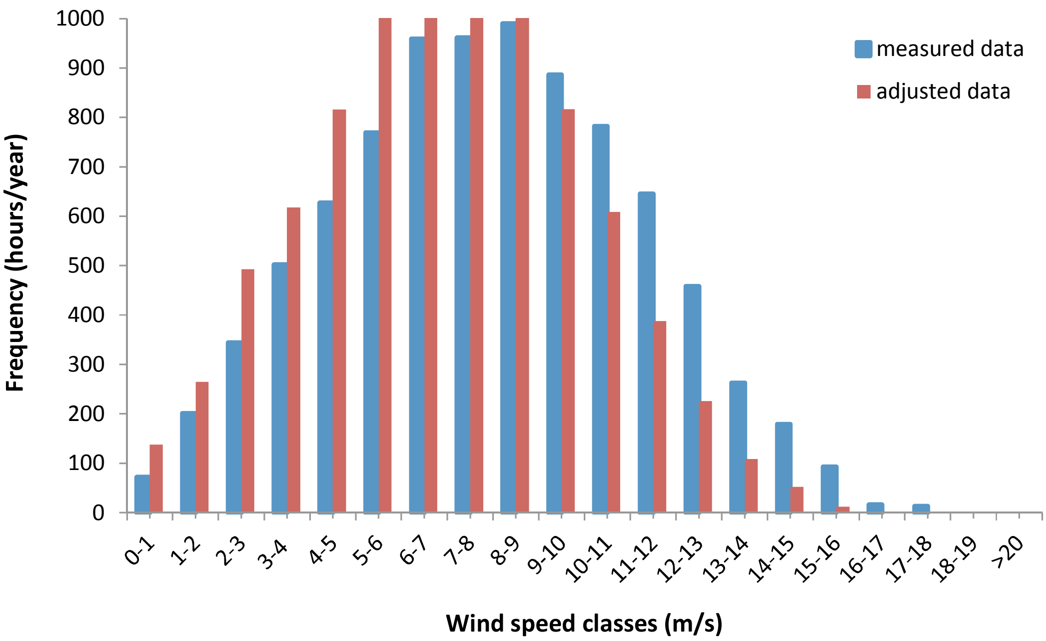

Figure II.8 – Frequency of occurrence of measured and adjusted wind speed in 2005.

II.2.3 Water supply system of S. Vicente

All fresh water supplied to the population in S. Vicente is desalinated water [14,82]. Figure II.9 shows the evolution, from 2001 to 2012, of the desalination capacity installed and of the water production. The desalination capacity increased about 50% from 2001 to 2012, although it decreased in 2011. The evolution of the water produced has been variable.

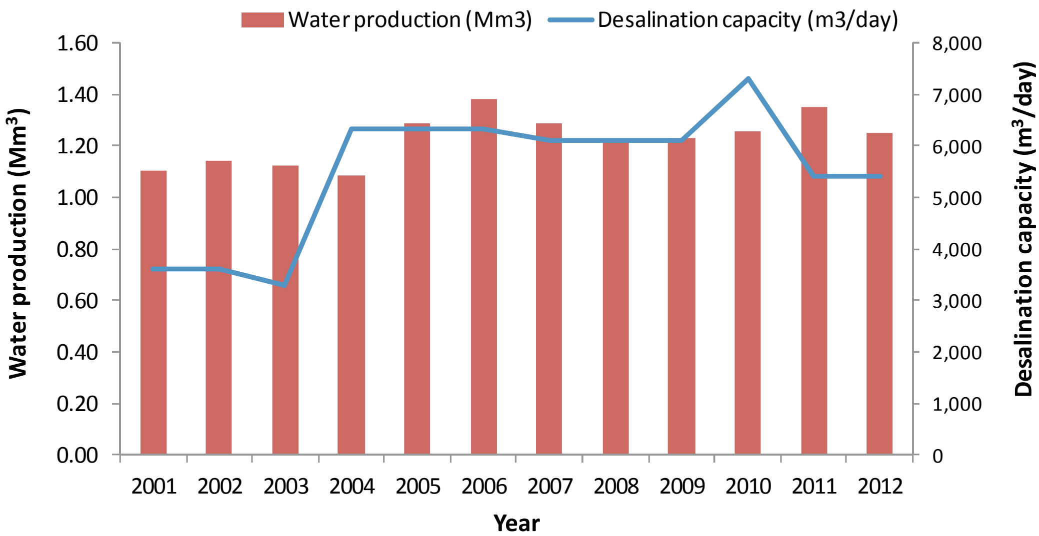

Figure II.9 - Water production and desalination capacity installed in S. Vicente from 2001 to 2012 [14,73-83].

In 2012, all the desalination units used RO technology, three with a production capacity of 1,000 m^3/day and two with a production capacity of 1,200 m^3/day. According to the ELECTRA 2012 report, to produce and pump 1 m^3 of water to be supplied to the population, about 5 kWh of electricity is needed [14]. The water reservoirs available in S. Vicente are distributed throughout the island, close to the population clusters. The total capacity of these reservoirs is about 14,680 m^3.

The ELECTRA's daily report mentioned above also presents the daily water production by desalination units installed. This study is based on the daily water production of 2006. This data presented several days with lower water production without an apparent reason to have a lower water demand. It is thought that these lower production days can result from malfunction of the desalination units. This occurred in 30 days of the year, i.e. about 9% of the time. These days are filled by averages of adjacent days. The sum of the daily values (the yearly water production of 2006) results in a value about 4% higher than the one stated in the corresponding ELECTRA report [78]. Figure II.10 shows the daily water production in S. Vicente in 2006.

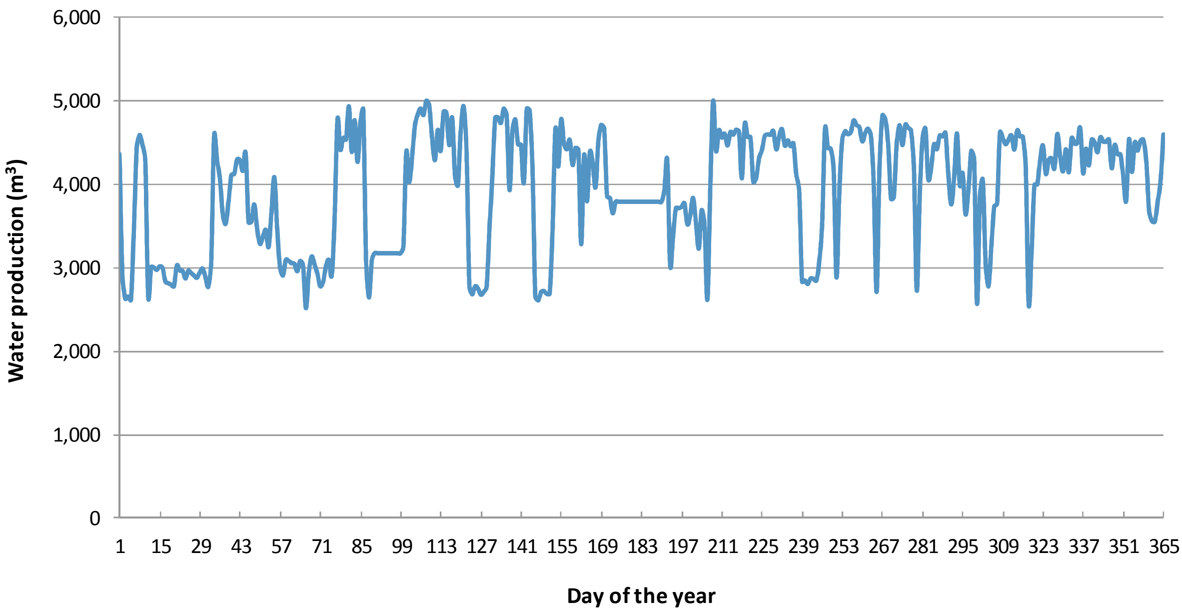

Figure II.10 - Daily water production in S. Vicente in 2006.

Since the analysis is done in an hourly basis, the daily water production is turned to hourly by dividing the water production of each day by 24 hours.

II.2.4 Future electricity and water demand

The evolution of the electricity and water demand considered in this study is the one estimated in the National Energy Plan for Cabo Verde (NEP) [90]. This plan was developed in 2002 and considers the forecast of the evolution of the Gross Domestic Product and of the resident population in order to estimate the growth in the consumption of electricity in the different islands of Cabo Verde. A comparison is done between the three scenarios developed in this plan (slow, Business As Usual (BAU) and accelerated) and the actual data from the ELECTRA reports regarding power production in S. Vicente. It is noticed that this forecast is greater than the actual production. Against this background, the data for the yearly production of electricity considered in this study is the actual data for 2010, 2011 and 2012 and for the remaining years, the growth considered is the one estimated in the slow scenario of the NEP. Figure II.11 presents the forecasted evolution of power production for S. Vicente in the three scenarios developed in the NEP for Cabo Verde, the actual power production verified and the forecast considered in this study (Slow from 2012).

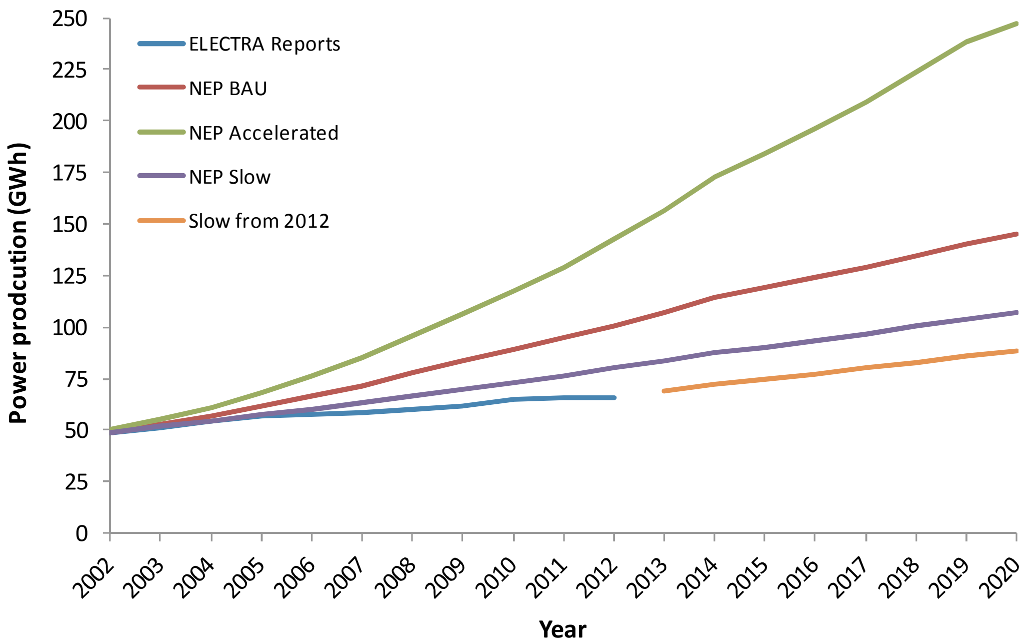

Figure II.11 - Evolution of power production in S. Vicente forecasted in the three scenarios of NEP, actual power production and forecasted for this study.

The forecast of the water production is determined in the same way as the electricity production. Table II.2 shows the electricity and water production in 2010 [82] and the forecast for 2015 and 2020 along with the peak power production for each year.

Year	2010	2015	2020
Electricity production (MWh)	65,029	74,922	88,518
Peak production (MW)	10.9	13.8	16.3
Water production (m^3)	1,252,665	1,469,404	1,736,061

Table II.2 - Electricity and water production in 2010 [82] and the forecast for 2015 and 2020.

Several other studies present values for the forecasted power production in S. Vicente for the year 2020. For instances, in the Renewable Energy Plan of Cabo Verde the baseline scenario considers a power production of 107,659 MWh in 2020 for S. Vicente [87]. With this in mind, a sensitivity analysis is done, analysing the results obtained considering an increase of 21.6% of the power production for 2020.

The forecasted peak production is used to determine the installed fossil fuel-based generators in each year (for all scenarios), according to the security criteria currently used by ELECTRA. These criteria include the consideration of the unavailability of the biggest thermal unit (N-1 situation), the failure of all intermittent renewable energy sources, and a 3% reduction of the production in relation to the power installed, corresponding to a temperature factor. This temperature factor is introduced to account for the reduction in nominal production capacity of the power generating units due to the increase of the ambient temperature. In this way, the peak demand coverage index (PDC) can be calculated as follows:

$$PDC = \frac{P_{available} - Peak}{Peak} \tag{II.1}$$

where $P_{available}$ is the available power after considering all the three security criteria and $Peak$ is the peak demand forecasted for the period in analysis [87].

For 2015, and after considering the decommissioning of the two smaller groups of the Matiota power station, there is a need to install more fossil fuel power in order to keep this index positive. The Renewable Energy Plan of Cabo Verde [87] foresees the installation of two fossil fuel-based generators, one of 3.5 MW and another of 5.5 MW, and hence this solution is considered in this study. The power of the fossil fuel-based plants considered for this year is 23.04 MW. For 2020, the remaining groups of the Matiota power station will be decommissioned and the need to install more fossil fuel power in order to keep the peak demand coverage index positive occurs again, hence the installation of one more generator of 3.5 MW and another of 5.5 MW is considered. The total installed fossil fuel power considered for this year is 25.44 MW.

II.2.5 Economic data

The discount rate used to annualize the investment costs of the system is 10% [11,87], which is the value usually used in the region for the analyses of the financial viability of this type of projects.

Table II.3 shows the costs and lifetime of the installed equipment. The fixed operation and maintenance (O&M) costs are different according to the technology and are a given percentage of the total investment cost that should be paid each year during the lifetime.

Technology		Investment cost	Fixed O&M cost (%)	Variable O&M cost (€/MWh)	Lifetime (years)
Wind turbines [87]		2,000 €/kW	3	-	20
Fossil fuel-based units [87]		1,200 €/kW	1.5	-	20
Desalination [91]		1,000 €/(m^3/day)	10	-	20
PHS [41]	Hydro	500 €/kW	1.5	1.5	40
	Pump	500 €/kW			
	Storage	7.5 €/kWh			

Table II.3 - Costs and lifetime of the installed equipment [41,87,91].

The investment and O&M costs of the wind parks and of the fossil fuel-fired units are based on the costs for projects foreseen for Cabo Verde stated in the Renewable Energy Plan of Cabo Verde published in 2011 [87].

The fuel cost per kWh of electricity produced by the fossil fuel technologies is estimated for the years from 2007 to 2012 based on the information on the fuel specific consumption (g/kWh) of the existing fossil fuel-fired units, percentage of use of each fuel to produce electricity [14,82], and the current prices of each fuel (€/kg) in Cabo Verde, according to the National Economic Regulatory Agency [92]. In 2010, fuel costs reached 0.129 €/kWh. Based on these values, the estimations for 2015 and 2020 are made by linear regression, which lead to 0.195 €/kWh in 2015 and 0.268 €/kWh in 2020. It is important to refer that the volatile nature of the fuel costs requests for a sensitivity analysis that is done in this study.

The estimation of the investment costs of PHS is very difficult to accomplish because it is very site specific, it largely depends on the geography of the location, on the workers costs, etc. [18]. Hence a sensitivity analysis is done, analysing the results obtained with a higher investment cost of the PHS system.

II.3 Energy scenarios for S. Vicente

Five different scenarios are considered in this study, all having 2010 as the base year. The first is the Baseline Scenario, as it only considers the projects that are already foreseen for the island, and it is established in order to allow the comparison between the results of the proposed solutions and the current energy and water supply systems, including electricity and water production costs and total yearly costs.

The second Scenario considers the supply of wind power to the desalination plants already installed on the island. Although S. Vicente has several reservoirs spread through the island, this Scenario considers that there is only one reservoir in the island with the capacity of all of them, about 14,680 m^3, where the water that comes out of the desalination plant is stored before being supplied to the population. When the excess wind power is not enough to desalinate all the water needed, the fossil fuel-based generators are used to supply the remaining required electricity.

The third Scenario is established by finding which installed wind power and desalination capacity minimizes the total annual costs of the electricity and water supply systems for 2020, while keeping the wind power penetration the highest possible.

The fourth Scenario considers the storage of the excess wind power production through pumping of the desalinated water. This Scenario contemplates the construction of two water reservoirs, one at low altitude and another at 500 m of altitude. The wind park would supply electricity to a desalination plant and to a pumping station that pumps desalinated water from the lower reservoir into the upper reservoir. When it is necessary to supply water and electricity to the population, the water retrieved from the upper to the lower reservoir, passing through the hydro turbine, as shown schematically in Figure II.12. The cycle efficiency of the PHS is about 69%.

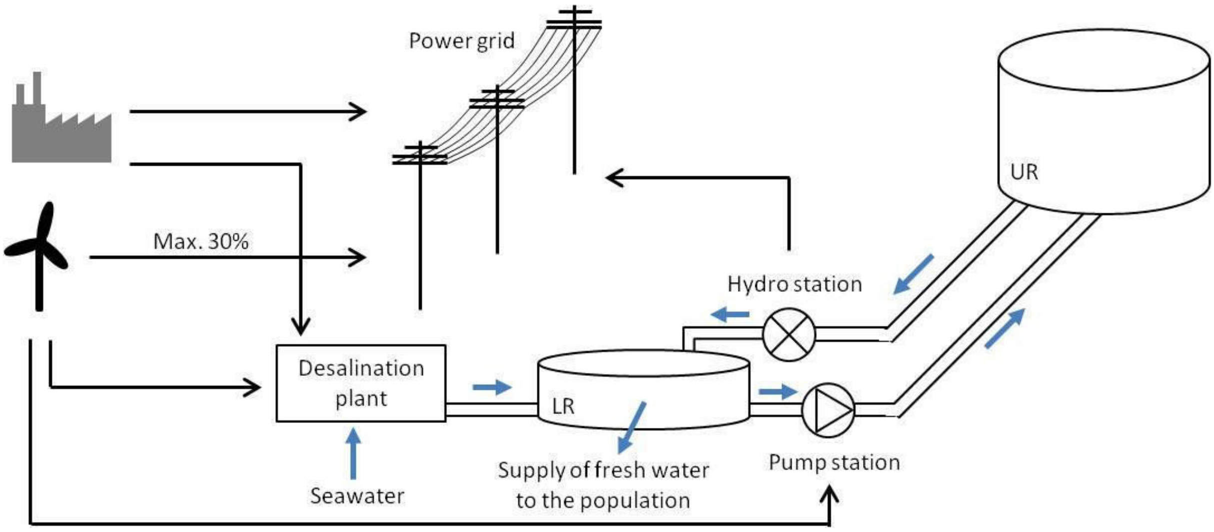

Figure II.12 - Schematic diagram the wind powered desalination and PHS system.

The fifth Scenario is established by finding which installed wind power, desalination capacity, hydro power and pump power minimizes the total annual costs of the electricity and water supply systems for 2020, while keeping the wind power penetration the highest possible.

These five scenarios are modelled limiting to 30% the hourly intermittent energy penetration, which means that only 30% of the load of one hour can be covered by wind power [8,21].

For Scenarios 1, 3 and 5, alternative scenarios are made taking into consideration an hourly intermittent energy penetration of 100% (Scenarios 1a, 3a and 5a), in order to compare the results with the remaining scenarios. It is important to notice that these scenarios present great risk of power instability on the grid, hence, it is necessary to consider that the wind turbines installed possess some degree of frequency and voltage control. There is no need to simulate Scenario 2 and 4 with an hourly intermittent energy penetration of 100% because, with this limit, the wind power curtailed is not enough to supply the desalination units and the pumps. For the other three scenarios, it is interesting to examine the consequences of an increase in the installed wind power.

In Scenarios 1, 1a, 2 and 4 the current installed wind power and desalination capacity in S. Vicente is considered. In Scenarios 3, 3a, 5 and 5a, the installed wind power and desalination capacity are those that minimized the total costs, while keeping the RES penetration the highest possible. Table II.4 summarizes all scenarios considered in this analysis.

Scenario	Description	Hourly wind power penetration
1	Baseline	30%
2	Only wind powered desalination	
3	Only wind powered desalination with minimum costs	
4	Wind powered desalination and PHS	
5	Wind powered desalination and PHS with minimum costs	
1a	Baseline	100%
3a	Only wind powered desalination with minimum costs	
5a	Wind powered desalination and PHS with minimum costs	

Table II.4 - Scenarios considered.

For the first part of this study, the tool used to model these scenarios (H2RES model – cf. section III.1.1) does not allow performing optimization, hence it is necessary to run all potential configurations and verify their technical feasibility (i.e. if they are able to supply the required electricity and water demand at all hours) and identify the one with lower total annual costs. The optimization performed in this study is an investment and operational optimization. On one hand each iteration has a specific potential configuration (capacity of the installed equipment) and, on the other hand, certain operational conditions could be changed in order to avoid the overflow of the reservoirs, namely the maximum amount of wind powered desalinated water in each hour. For the second part of this study, a mathematical optimization is performed where the sizing and operational strategy of the proposed system is optimized.

The power technologies considered are the ones already installed in S. Vicente (fossil fuel based units and wind turbines) and a system for energy storage that is pumped hydro. The technology considered for the production of water is the only one that is used in S. Vicente, i.e. desalination of seawater using reverse osmosis.

III. Methods

In this study, different scenarios for increasing the penetration of RES in the power and water supply systems of arid islands are analysed. The system proposed is modelled using H2RES, a model designed to simulate the integration of RES and hydrogen in islands or other isolated locations. The total annual costs for each scenario are estimated using the simplified levelised cost of energy method. Subsequently, an optimization problem is formulated to analyse one of the solutions proposed. The objective is to determine the optimal sizing and operational strategy of the proposed system.

III.1 Integrated power and water supply systems' modelling

The modelling of the integrated power and water supply system is done using the H2RES and considers two types of scenarios. Scenarios with 30% hourly intermittent RES penetration and scenarios without this limit, where it is assumed that the conversion technologies provide output control and auxiliary services, enabling the penetration of 100% of intermittent RES in the power grid [93].

III.1.1 H2RES model

Connolly et al. [94] reviewed the different tools than can be used to analyse the integration of RES. H2RES is classified as a simulation tool, since it simulates the operation of a given energy system to supply a given energy demand; and a bottom-up tool, because it analyses the specific energy technologies and thereby identifies investment options and alternatives [94].

The H2RES model (Figure III.1) simulates the integration of RES and hydrogen in the energy systems of islands or other isolated locations. It is based on hourly time series analysis of demand (water, electricity, hydrogen, heat); storage (pumped hydro, batteries, hydrogen, heat) and resources (wind speed, solar radiation, precipitation). The main purpose of this model is energy planning of islands and isolated regions, which operate as stand-alone systems, but it can also serve as a planning tool for single wind, hydro or solar power producer connected to a central power system [9]. Throughout time, H2RES has been evolving and several new modules have been developed according to the needs of the case studies analysed. The grid module was added to consider the import and export of electricity in the Island of Mljet, Croatia. The geothermal module was used in Terceira Island, The Azores, Portugal [11,93]. The biomass module was developed and applied to a Croatian wood processing factory [95]. The wave module was developed for the Portugal case study, where the possibility for a 100% RES electricity production for Portugal was assessed [96]. This model has also been applied to Porto Santo, Madeira, Portugal [5,93,97,98], Corvo, The Azores, Portugal [5,32,39,93] and Malta [93]. For the purpose of this study, a desalination module has been developed.

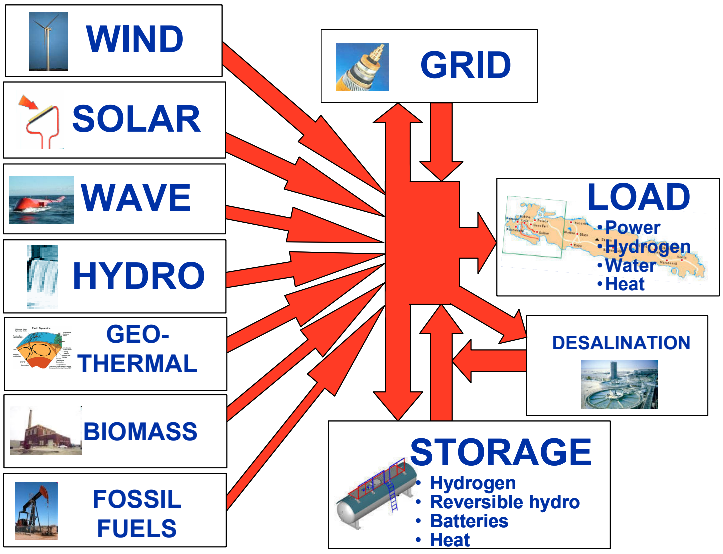

Figure III.1 - H2RES computer model v2.8 [99].

The main characteristic of the H2RES model is that it uses hourly meteorological data for intermittent RES and technical data of equipment. Energy balancing is regulated by equations [11].

Wind speed, solar radiation and precipitation data obtained from the nearest meteorological station are used in the H2RES model. The load module, based on a given criteria for the maximum acceptable RES electricity in the power system, puts a part or all of RES output into the system and discards the rest. The hourly load of the power system is obtained from the local utility. The excess renewable electricity is then stored either as hydrogen, pumped water or electricity in batteries. The energy stored can be retrieved later, and supplied to the system as electricity. The rest is covered by fossil fuel based units.

The outputs of the H2RES model are the total power generation and supplying demand (energy used to cover the demand) of each technology considered, and also the intermittent RES potential, the intermittent RES taken directly by the power system, the intermittent RES stored and the intermittent RES curtailed, i.e. that is not possible to integrate in the power system. The CO_2 emissions of the system are estimated by multiplying the total electricity produced from fossil fuel based units by an emission factor of these units.

In this study, the main modules used are: wind, fossil fuel, load, pumped hydro and desalination modules.

The wind module uses the hourly wind speed data at 10 m height obtained from the nearest meteorological station ($v(10)$), and adjusts it to the wind turbines hub level ($v(z)$) using the power law [97]:

$$v(z) = v(10)\left(\frac{z}{10}\right)^{\alpha} \quad \text{(III.1)}$$

where z is the hub height of the wind turbine and α is the wind shear. Usually, the wind shear is equal to 0.15 that corresponds to a more smooth terrain. For each type of wind turbine installed, the wind module converts the hourly wind speeds at hub height level to hourly power output according to its wind power curve. When data is available regarding the power production of a specific wind park, a wind speed adjustment is made using monthly correction factors defined to match monthly wind power production. The result is the hourly wind power production potential - $E_{W\_Pot\_h}$, where h refers to the hour of the year.

The fossil fuel module considers the fossil fuel based units installed, their rated power, their minimum load and their efficiency (in order to estimate the fossil fuel consumption).

The load module balances the hourly load (E_{Load_h}) obtained from the local utility with the hourly energy production available with the technologies considered. The intermittent potential taken, in this case the wind power taken ($E_{W\_Taken\_h}$), is determined based on the maximum allowed intermittent RES in the power grid, i.e. the intermittent limit (φ) in relation to the hourly demand [98]:

$$E_{W\_Taken\_h} = Min(\varphi E_{Load\_h}, E_{W\_Pot\_h}) \quad \text{(III.2)}$$

The total wind power potential is either taken by the system, stored as pumped water ($E_{W\_Pump\_h}$), used to desalinate water ($E_{W\_Desal\_h}$) or curtailed ($E_{W\_Curt\_h}$), according to the following energy balance equation:

$$E_{W\_Pot\_h} = E_{W\_Taken\_h} + E_{W\_Pump\_h} + E_{W\_Desal\_h} + E_{W\_Curt\_h} \quad \text{(III.3)}$$

The hourly load is supplied as follows:

$$E_{Load\_h} = E_{W\_Taken\_h} + E_{Hydro\_h} + E_{FF\_h} \quad \text{(III.4)}$$

where E_{Hydro_h} is the energy produced in the PHS system (that is stored and can be retrieved later), and E_{FF_h} is the energy produced by the fossil fuel based units. In order to avoid the operation of the fossil fuel based units below their minimum load, if the load that is necessary to be supplied by this units is less than their technical minimum, the energy supplied is equal to their minimum load and the energy from the other sources will be reduced accordingly [98].

The pumped hydro module estimates the wind power that can be stored in the PHS ($E_{W\_Pump\_h}$). This power depends on the installed power of the pumps, their efficiency, the amount of water available in the lower reservoir and the space available in the upper reservoir. This module also determines the power that can be provided by the PHS (E_{Hydro_h}). It depends on the power of the hydro turbines installed, their efficiency, the amount of water available in the upper reservoir and the space available in the lower reservoir. Another limitation of the power produced by the PHS is the load of the power system.

Desalination module

The desalination module uses the electricity produced from excess wind power to supply the desalination units that produce drinkable water and put it in a reservoir, which is then used to supply the population. The inputs of the desalination module are: the desalination capacity ($Desalcap - m^3/h$), the energy needed to desalinate 1 m^3 of water ($etd - kWh/m^3$), the capacity of the reservoir used to store the fresh water, and the maximum level of the reservoir to be filled with desalinated water (n_{desal}). This module also needs the inputs regarding the use of fossil fuel based units to supply the desalination units: if it is or not possible to consider this situation and the condition for this to occur. This condition is determined by h_{FF}, the number of hours of average water demand that must be available in the reservoir at all times. If the amount of water in the reservoir is less than the amount of water of h_{FF} the desalination units can be supplied by the fossil fuel based units. This module is integrated with the pumped hydro module, hence, the reservoir used to store the desalinated water is the lower reservoir of the PHS system. However, it is possible to simulate a system with desalination, but without PHS installed, and the opposite is also true.

In each hour of the year, the desalination module verifies the level of the reservoir used to store fresh water. If this level is below n_{desal}, the desalination module is activated. The amount of water desalinated is the minimum of three values: the water needed to reach n_{desal}, the water possible to desalinate according to the wind power excess verified in that hour and the water possible to desalinate with the desalination capacity installed. After, it is verified if the amount of water in the reservoir is enough to supply h_{FF} hours of water demand, if not, and if the user allows this options, the desalination units are supplied with electricity from the fossil fuel based units. This production takes into account the desalination capacity and the part of this capacity that is already used with wind power in this hour.

The output of this module is information about the total desalinated water, with wind power and with fossil fuel based units, and if it is enough to cover the water demand.

III.1.2 Financial analysis

The total annual costs are estimated using the simplified levelised cost of energy method. The term levelised cost of energy emphasizes the fact that this cost is determined over a certain time (time of life of a specific technology). In practise, the objective is to find the price of energy that sets the sum of all future discounted cash flows to zero [57]. This method is adapted to calculate also the water production cost. Each production cost includes the cost of the components used to produce the specific output (electricity and water).

Electricity production cost

The electricity production cost of each scenario is estimated as follows:

$$EPC = \frac{IC_E \times CRF + OMC_E + FC}{E} \ (€/kWh) \quad \text{(III.5)}$$

where IC_E is the total investment cost of the system. This value includes the investment costs of all necessary equipment in the energy supply system. The investment costs of the equipment already installed on the island, but within lifetime, are considered. CRF is the capital recovery factor (annuity factor) that is used to annualize the investment cost and depends on the lifetime of the equipment (n) and on the discount rate considered (i) as follows:

$$CRF = \frac{i\,(1+i)^n}{(1+i)^n - 1} \quad \text{(III.6)}$$

In Eq. III.5, OMC_E is the total yearly operation and management cost of the system that usually is, according to the technology, a given percentage of the investment cost. FC is the yearly fossil fuel cost, and E is the total yearly electricity produced. The total annual costs are divided by this value to estimate the electricity production cost in $€/kWh$.

Water production cost

The water production cost is calculated as follows:

$$WPC = \frac{IC_W \times CRF + OMC_W + EC}{W} \ (€/m^3) \qquad \text{(III.7)}$$

where IC_W is the total investment cost of the water supply system. In this case, it is also considered the investment cost of the equipment already installed in the island, but still in lifetime. In Eq. III.7, OMC_W is the total yearly operation and management cost of the system that usually is a given percentage of the investment cost. EC is the yearly electricity cost, i.e. the cost of the electricity used to desalinate, and W is the total yearly water produced. The electricity costs consider the electricity production costs calculated with the method described above. In this way, the electricity production cost has obviously a strong influence on the water production costs.

Total costs

The total annual costs (TC) can be divided in electricity production costs and water production costs, and depend on the total yearly electricity and water produced. It can be calculated as follows:

$$TC = EPC \times E + WPC \times W \ (€) \qquad \text{(III.8)}$$

III.1.3 Internalizing the CO_2 emissions' cost

In order to internalize environmental problems related with CO_2 emissions, namely climate change, the cost of the tonne of CO_2 emitted is included in the total production costs. The cost of CO_2 considered in this study is the cost of the Certified Emission Reduction (CER). CER are emissions certificates issued by the United Nations Framework Convention on Climate Change and the Kyoto

Protocol for the successful completion of Clean Development Mechanism climate protection projects. This mechanism allows countries or companies to acquire CER that can be used to meet their own commitments by investing in projects in developing and newly industrializing countries (without themselves having to reduce emissions) [100].

The assumption is that if in the future CO_2 emissions are to be charged, i.e. if a carbon price would be charged to a company or country that has systems that emit CO_2, one starting value for this price can be the current value of CER. The CER value is extremely volatile, hence, the proposed system is analysed with two different values of CER: the average value of CER since this market was created until February 2015 - 6.96 €/tCO_2, and the maximum value of CER ever reached - 22.60 €/tCO_2 [100].

III.2 Sensitivity analysis

In order to analyse the influence of the inputs on the results of the modelling, a sensitivity analysis is accomplished. The inputs varied are the ones considered more volatile and/or more unpredictable, i.e. electricity and water demand, fuel costs and investment costs of the PHS.

The modelling of the integrated system uses the wind speed data collected from the local meteorological station adjusted to the wind power production of an existing wind park. However, the wind power production can depend on other issues than the instant wind speed, like the possibility of wind power injection in the grid and the fact that a wind turbine can be in maintenance. Hence, in order to assess the influence of this fact on results, the system is modelled once again but without this adjustment.

III.3 Optimization

The wind powered desalination and PHS system proposed (Figure II.12) is modelled outside H2RES in order to optimize it. A tool has been designed to model this particular system for one year, estimating its hourly operation. The sizing and the operational strategy of this system are translated into the variables of the optimization problem.

III.3.1 Integrated power and water supply systems' modelling

The first step to model this system is to calculate the wind power production potential in each hour of the year, according to the installed wind power considered. This calculation is made using the

H2RES model. Having the wind power production potential ($E_{W\_Pot\_h}$), the load and the water demand for each hour of the year, it is possible to calculate the hourly values of:

- Wind power directly injected in the power grid ($E_{W\_Taken\_h} - kWh$),
- Undelivered load after the direct supply of wind power ($E_{Und\_Load\_h} - kWh$),
- Water produced with wind power ($W_{Wind\_h} - m^3$),
- Wind power used to produce water ($E_{W\_Desal\_h} - kWh$),
- Wind power used to pump water ($E_{W\_Pump\_h} - kWh$),
- Water pumped ($W_{Pump\_h} - m^3$),
- Wind power curtailed ($E_{Curt\_h} - kWh$),
- Water turbinated - water retrieved from the upper to the lower reservoir, passing through a hydro turbine ($W_{Turb\_h} - m^3$),
- Hydro power production ($E_{Hydro\_h} - kWh$),
- Water produced with electricity from the fossil fuel based units ($W_{FF\_h} - m^3$),
- Level of the lower reservoir ($n_{LR\_h} - m^3$),
- Level of the upper reservoir ($n_{UR\_h} - m^3$).

Based on these hourly values it is possible to determine the annual load that is covered by the fossil fuel based units (kWh) and the total annual costs of the system ($TC - €$).

In order to model this system it is necessary to estimate the energy needed to pump 1 m^3 of water from the lower reservoir to the upper reservoir, with a height difference of $H\ (m)$, as follows:

$$E_{Pump\ 1m^3} = \frac{\rho \times g \times H}{3600 \times 1000 \times \eta_{Pump}} (kWh/m^3) \qquad \text{(III.9)}$$

where ρ is the density of water and is considered $1000\, kg/m^3$, g is the acceleration of gravity and is considered $9.81\, m/s^2$, and η_{Pump} is the efficiency of the installed pumps. The inverse of this value is used to determine the volume of water possible to pump per unit of energy.

It is also necessary to determine the energy that is possible to produce for each m^3 of water that goes from the upper reservoir to the lower reservoir, passing through the hydro turbine (water turbinated), as follows:

$$E_{Hydro\ 1m^3} = \frac{\rho \times g \times H \times \eta_{Hydro}}{3600 \times 1000} (kWh/m^3) \qquad \text{(III.10)}$$

where η_{Hydro} is the efficiency of the installed hydro turbines.

Figure III.2 presents the scheme of the lower reservoir (LR in Figure II.12), as well as the definition of the three variables related with the operational levels of the wind powered desalination and PHS system (n_{WB}, n_H and n_{FF}). The variable n_{WB} is the level of the lower reservoir that determines the balance between the excess wind power that is used to desalinate and to pump water to the upper reservoir. This variable ranges from zero to the maximum level of the reservoir (n_T). The variable n_H is the level of the lower reservoir in which the hydro production stops. This variable ranges from n_0, the minimum level of the reservoir, to n_T. When the level of the lower reservoir is less than n_0, and it is not possible to turbinate water from the upper reservoir, the fossil fuel based units supply the desalination units to produce water until the level of the lower reservoir reaches n_{FF}. This variable also ranges between n_0 and n_T. Figure III.2 also presents a typical value of n_{FF}.

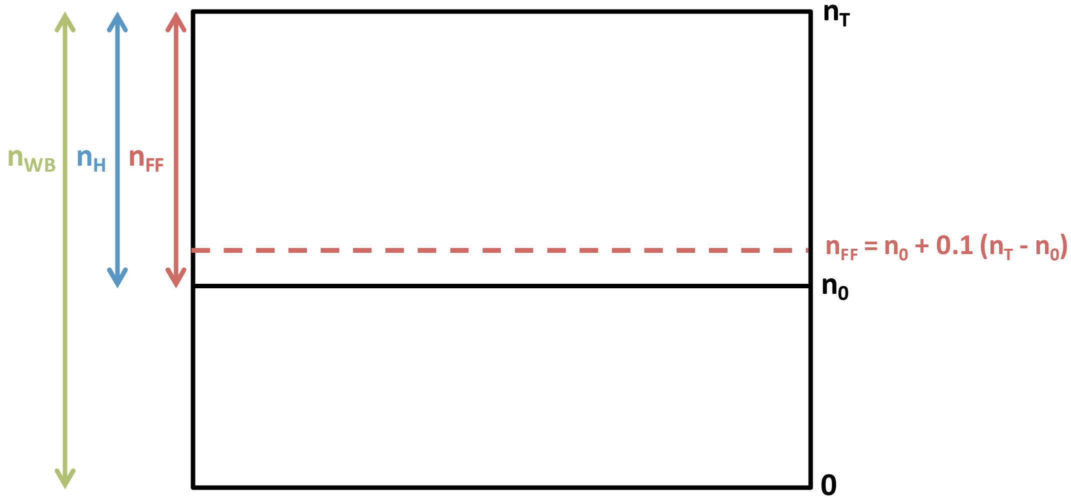

Figure III.2 - Definition of variables n_{WB}, n_H, n_{FF} and a typical value of n_{FF}.

The level n_0 is the minimum level of the lower reservoir and it is fixed at 21,400 m^3 of water, equivalent of about seven days of minimum water demand forecasted for 2020. Figure III.3 and Figure III.4 show typical values of n_{WB} and n_H, and the definition of the parameters a and b.

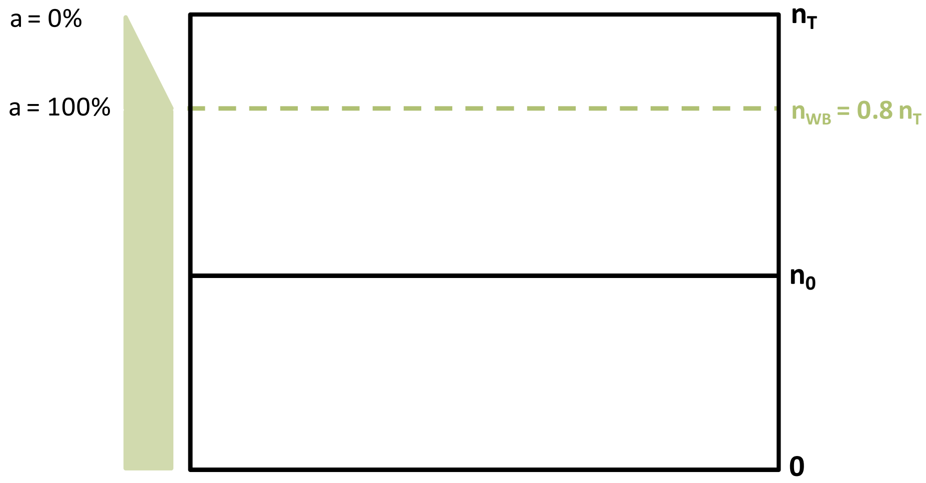

Figure III.3 - Typical values of n_{WB} and definition of parameter a.

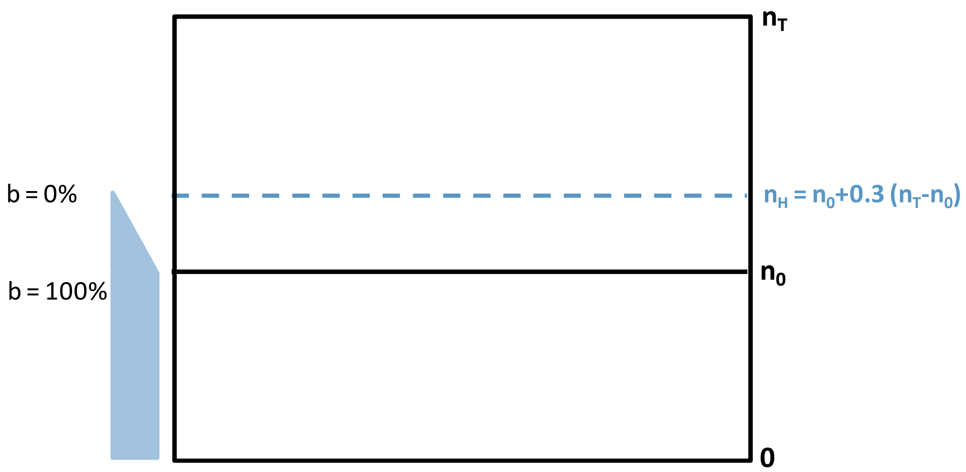

Figure III.4 - Typical values of n_H and definition of parameter b.

Water produced from wind power

The water produced in the desalination units is placed in the lower reservoir, with a capacity of LR. The amount of water produced is limited by the desalination capacity installed. When the level of the lower reservoir is between 0 and n_{WB} (wind balance level), all wind power excess is used in the desalination units to produce fresh water. Only if after the desalination there is still some wind power left, it is used to pump water from the lower reservoir to the upper reservoir. When the level of the lower reservoir surpasses n_{WB}, a balance starts with the use of the wind power excess: a% of the wind power excess is used in the desalination units and $(1-a)$% is used to pump water (Figure III.3). Hence, when a is equal to 100% (the level of the reservoir is equal or inferior to n_{WB}), 100% of the wind power excess is used in the desalination units, and only what is left is used in the pumps.

When a is equal to 0, all wind power excess is used in the pumps and none is used to desalinate. From $a = 100\%$ to $a = 0$, the amount of wind power used to desalinate decreases and the amount of wind power used to pump increases. The equation used to determine a in each hour and for each level of the lower reservoir is the following:

$$a_h(n_{LR\_h}) = \begin{cases} 1, & n_{LR\_h} \leq n_{WB} \times LR \\ \dfrac{LR - n_{LR\_h}}{LR - n_{WB} \times LR}, & n_{LR\_h} > n_{WB} \times LR \end{cases} \quad \text{(III.11)}$$

The estimation of the hourly water produced from wind power, and the hourly wind power used to produce water is done using the following equations:

$$W_{Wind\_h} = Min\left(a_{h-1}\,\frac{E_{W\_Pot\_h} - E_{W\_Taken\_h}}{etd}; desalcap\right)\ (m^3) \quad \text{(III.12)}$$

$$E_{W\_Desal\_h} = W_{Wind\_h} \times etd\ (kWh) \quad \text{(III.13)}$$

Water pumped

The pumps send the water from the lower reservoir to the upper reservoir. The pumps are always in operation provided that: there is enough wind power, there is water in the lower reservoir in the previous hour, and there is space in the upper reservoir in the previous hour (Eq. III.14). As mentioned above, the wind power available to pump depends on parameter a (Figure III.3). Other limitation of the water pumped is, naturally, the installed pump power (Eq. III.14). It is considered that the energy the pumps can provide in one hour is equal to their nominal power. Eqs. III.14 and III.15 are used to estimate the hourly water pumped and hourly wind power used to pump:

$$W_{Pump\_h} = Min\left(\frac{E_{W\_Pot\_h} - E_{W\_Taken\_h} - E_{W\_Desal\_h}}{E_{Pump\ 1m^3}}; \frac{Pump\ Power}{E_{Pump\ 1m^3}}; n_{LR\_h-1}; UR - n_{UR\_h-1}\right)\ (m^3) \quad \text{(III.14)}$$

$$E_{W\_Pump\_h} = W_{Pump\_h} \times E_{Pump\ 1m^3}\ (kWh) \quad \text{(III.15)}$$

where $Pump\ Power$ is the power of the pumps and UR is the capacity of the upper reservoir.

Water turbinated

When the level of the lower reservoir in less or equal to n_0, the water is always being retrieved from the upper to the lower reservoir through a hydro turbine (turbinated), as long as there is water in the upper reservoir, with the limitation of the hydro turbine capacity installed. The hydro turbine operates at $b\%$ of its capacity (Figure III.4, Eq. III.16), hence it works at 100% when the level of the lower reservoir is n_0 or lower, and at 0 when the level of the lower reservoir reaches n_H (level at which the hydro production stops). Other limitation of the water turbinated is the available space for water in the lower reservoir (Eq. III.17). Finally, the water turbinated must not produce more electricity than the one needed to supply the undelivered hourly load after the direct supply of wind power (Eq. III.17), in order to match the supply with the demand.

$$b_h(n_{LR\_h}) = \begin{cases} 1, & 0 \le n_{LR\_h} \le n_0 \\ \dfrac{n_{LR\_h} - n_0 \times LR}{n_H \times LR - n_0 \times LR}, & n_0 < n_{LR\_h} < n_H \times LR \\ 0, & n_{LR\_h} \ge n_H \times LR \end{cases} \qquad \text{(III.16)}$$

Equations III.17 and III.18 are used to calculate the hourly water turbinated and the corresponding hydro production:

$$W_{Turb\_h} = Min\left((1 - b_{h-1}) \frac{Hydro\ Power}{E_{Hydro\ 1m^3}}; n_{UR\_h}; LR - n_{LR\_h}; \frac{E_{Und\_Load\_h}}{E_{Hydro\ 1m^3}} \right) (m^3) \qquad \text{(III.17)}$$

$$E_{Hydro\_h} = W_{Turb\_h} \times E_{Hydro\ 1m^3}\ (kWh) \qquad \text{(III.18)}$$

where $Hydro\ Power$ is the power of the hydro turbines of the PHS system. It is considered that the energy the hydro turbines can produce in one hour is equal to their nominal power.

Water produced from fossil fuel

The fossil fuel based units are used to feed the desalination units only if the level of the lower reservoir is less than n_0 and if it is not possible to retrieve water from the upper to the lower reservoir. In this case, fossil fuel supplies the desalination units that produce water in order to increase the level of the lower reservoir until n_{FF}. Obviously, the desalination capacity limits this operation. It is considered that the desalination units can provide in one hour the amount of water equal to their nominal production capacity. The hourly water produced with fossil fuel and the corresponding electricity needed are calculated using the following equations:

$$W_{FF\_h} = Min\left(n_{FF} \times LR - n_{LR\_h-1} - W_{Turb\_h}; desalcap - W_{Wind\_h}\right)\ (m^3) \quad \text{(III.19)}$$

$$E_{FF\_Water\_h} = W_{FF\_h} \times etd\ (kWh) \quad \text{(III.20)}$$

Upper and lower reservoir levels

The level of the lower reservoir in each hour of the year (Eq. III.21) is the sum of the water stored in the previous hour with the water produced (from wind power and from fossil fuel) and with the water turbinated, minus the water consumed (supplied to the population) and the water pumped:

$$n_{LR\_h} = n_{LR\_h-1} + W_{Wind\_h} + W_{FF\_h} + W_{Turb\_h} - W_{Cons\_h} - W_{Pump\_h}\ (m^3) \quad \text{(III.21)}$$

The level of the upper reservoir in each hour of the year (Eq. III.22) is the sum of the water stored in the previous hour with water pumped minus the water turbinated:

$$n_{UR\_h} = n_{UR\_h-1} + W_{Pump\_h} - W_{Turb\_h}\ (m^3) \quad \text{(III.22)}$$

Yearly values

After the hourly calculations, the following results are summed into yearly values: wind power used to desalinate, wind power used to pump, wind power curtailed, fossil fuel used to desalinate and electricity produced in the PHS system. It is assumed that the remaining load that is not covered by wind power and by PHS production is covered by the fossil fuel based units. In this case, the minimum load of these units is not considered, since its production is not estimated in an hourly basis. With these results it is possible to calculate the total annualized costs of the integrated electricity and water supply system.

III.3.2 Optimization problem

A constrained non-linear optimization problem can be written in the following form [67]. Find n design variables:

$$\boldsymbol{x} = (x_1, x_2, \dots, x_n)^T \tag{III.23}$$

which minimizes:

$$\min_{s.t. x \in \Omega} F(\boldsymbol{x}) = [f_1(\boldsymbol{x}), f_2(\boldsymbol{x}), \dots, f_m(\boldsymbol{x})]^T \tag{III.24}$$

involving m objective functions $f_j: \Omega \subseteq \mathbb{R}^n \rightarrow \mathbb{R} \cup \{+\infty\}, j = 1, \dots, m$ to minimize. If $m = 1$ one has a single objective optimization problem, and if $m > 1$ one has a multiobjective optimization problem. In the presence of $m > 1$ objective functions, the minimizer of one function is not necessarily the minimizer of another. In this case, one does not have a single point that yields the "optimum point for all objectives". Instead, one has a set of points, called Pareto optimal or non-dominated set. Given two points x, $y \in \Omega$, x is said to dominate y, in Pareto sense, if and only if solution x is strictly better than y in at least one of the objectives and x is not worse than y in any of the objectives. A set of points in Ω is non-dominated when no point in the set is dominated by another one in the set [67]. Maximizing f_j is equivalent to minimizing $-f_j$. Ω represents the feasible region.

A multiobjective derivative free method is used: DMS. DMS [67] does not aggregate any components of the objective function. It is inspired by the search/poll paradigm of direct-search methods of directional type from single to multiobjective optimization and uses the concept of Pareto dominance to maintain a list of feasible non-dominated points. At each iteration, the new feasible evaluated points are added to this list and the dominated ones are removed. Successful iterations correspond then to changes in the iterate list, meaning that a new feasible non-dominated point was found. Otherwise, the iteration is declared as unsuccessful.

The multiobjective optimization problem of this study is to find nine design variables, presented in Table III.1.

$$\boldsymbol{x} = (x_1, \dots, x_9)^T \qquad \text{(III. 25)}$$

that simultaneously minimize the total annualized production costs of the integrated energy and water supply system (f_1), maximize the percentage of RES production of this system (f_2) and minimize the wind power curtailed (f_3), which is equivalent to:

$$\min_{s.t.\boldsymbol{x}\in\Omega} F(\boldsymbol{x}) = [f_1(\boldsymbol{x}), -f_2(\boldsymbol{x}), f_3(\boldsymbol{x})\ ]^T \qquad \text{(III. 26)}$$

In this case, the Ω is defined by the bound constraints of each design variable, defined in the range column of Table III.1.

Variable		Range	Iteration step
x_1	$Wind\ power$ (MW)	6.85 - 28.10	0.85
x_2	$Desalcap\ (m^3/day)$	5,400 - 16,400	1,000
x_3	$Pump\ power$ (MW)	0.5 - 20	0.5
x_4	$Hydro\ power$ (MW)	0.5 - 20	0.5
x_5	LR (m^3)	30,000 - 100,000	5,000
x_6	UR (m^3)	30,000 - 500,000	5,000
x_7	n_{WB}	0.00 - 1.00	0.01
x_8	f_{FF}	0.00 - 1.00	0.01
x_9	f_H	0.00 - 1.00	0.01

Table III.1 - Variables of the optimization problem.

The first six variables are related to the sizing of the integrated power and water supply system. The installed wind power ($Wind\ power$) ranges from the current wind power installed to the addition of 25 Vestas V52 turbines (with 850 kW of capacity); hence the iteration step of this variable is 0.85 MW. The desalination capacity installed ($Desalcap$) ranges from the current capacity installed to the addition of 11 desalination units of 1,000 m^3/day units. The installed pump and hydro power range between 0.5 MW and 20 MW, their iteration step is 0.5 MW, corresponding to one unit installed of each technology. LR and UR are the capacity of the lower and upper reservoirs of the PHS proposed, respectively. The remaining three variables are the ones that translate the operational strategy of the proposed system.

Since n_H and n_{FF} can range from n_0 to n_T, f_H and f_{FF} are used to determine n_H and n_{FF}, respectively, as follows:

$$n_{FF} = n_0 + f_{FF}(n_T - n_0) \tag{III.27}$$

$$n_H = n_0 + f_H\,(n_T - n_0) \tag{III.28}$$

The total annual costs are estimated using the simplified levelised cost of energy described in section III.1.2. The CO_2 emissions cost is also considered. Three penalties are added to this objective function in order to avoid solutions that would result in undelivered water to the population and overflow of the upper and lower reservoirs.

IV. Results and discussion

In this chapter the results of the modelling of the scenarios proposed for the island of S. Vicente, the results of the sensitivity analysis carried out and the results of the sizing and operational strategy optimization of the integrated power and water supply system are presented and discussed.

Most of the results included in this chapter are already available in open literature; see Segurado et al. [101,102] (Annex II and III).

IV.1 Integrated power and water supply systems' modelling

The integrated power and water supply system proposed for S. Vicente is modelled with the H2RES model for all scenarios mentioned in section II.3. The base year is the year 2010, and the system is modelled for the years 2015 and 2020, according to the forecasted electricity and water demand (cf. section II.2.4). The optimization scenarios consider only the electricity and water demand for 2020.

IV.1.1 Scenario 1 - Baseline

This scenario considers the currently installed wind power and fossil fuel based generators in S. Vicente. For 2015 and 2020, the installed wind power is similar to that of 2012, with all the installed wind turbines in operation, but the fossil fuel power is increased in order to keep the *PDC* index positive, as described in section II.2.4. Table IV.1 summarizes the results obtained for this scenario. It is clear that with the new wind generators installed in 2011, the percentage of wind power generation increases significantly; specifically, from 5.3% in 2010 to 22.3% in 2015, and 21.4% in 2020. Wind power will have a strong presence in the power generation of S. Vicente in the upcoming years, but the fossil fuel will remain very important, promoting a considerable increase in the electricity production cost, and, consequently, in the water production cost. The results also reveal that the wind power curtailed will be significant; specifically, in 2015 it will reach 44.1% of all potential wind power, and in 2020 about 36.5%. Scenario 2 is built to use this wasted wind power.

Year	2010		2015		2020	
Power generation (MWh)						
Wind power	3,455	5.3%	16,706	22.3%	18,966	21.4%
Fossil fuel	61,760	94.7%	58,215	77.7%	69,552	78.6%
Total	65,215	100%	74,922	100%	88,518	100%
Wind power curtailed (MWh)	-	-	13,158	44.1%	10,898	36.5%
Production costs						
$EPC\ (€/kWh)$	0.161		0.212		0.276	
$WPC\ (€/m^3)$	1.772		1.861		2.059	
$TC\ (€)$	12,747,010		18,638,284		28,045,624	

Table IV.1 - Results obtained for Scenario 1.

IV.1.2 Scenario 2 - Wind desalination

A good way to decrease the wind power curtailed is to supply directly the desalination units with this excess wind power. However, when modelling this scenario, the first conclusion reached is that this excess wind power is not enough to desalinate all the water needed. Hence, the supply of electricity produced by the fossil fuel based units to the desalination units is considered.

Scenario 2 considers the construction of a medium voltage (MV) power line from the wind parks (located in Selada Flamengo) to the desalination units (located in the Matiota power station). This would enable the supply of wind power directly to the desalination units. The distance between these two locations is about 12 km, and the cost per km of the construction of a MV power line is considered to be 20,000 €/km [103]. This cost is annualized considering the discount rate and the lifetime of 20 years and is added to the total yearly costs of the water supply system. Besides the power line, this scenario considers the equipment already installed in the island: 6.85 MW of wind power, 5,400 m^3/day of desalination capacity and a 14,680 m^3 reservoir. As mentioned before, S. Vicente has several reservoirs spread through the island; however this scenario considers that there is only one reservoir in the island with the capacity of all of them.

The hourly load considered in the first scenario includes the electricity needed to desalinate water to supply the population, thus, there is the need to subtract this electricity. According to ELECTRA Report for 2012, 9.4% of the electricity produced in S. Vicente in 2012 was to supply the desalination units [14]. Hence, this percentage was deducted from the hourly load.

Table IV.2 summarizes the results obtained for this scenario. In 2020, the electricity production costs are about 4% lower than those in the Baseline Scenario. This is because there is more wind power used, lowering the electricity needed from fossil fuel. The wind power curtailed decreases from 44.1% to 31.2% in 2015 and from 36.5% to 24.7% in 2020. The water production costs, which include the investment in the new power line mentioned before, are slightly lower, and the electricity used to desalinate water is mostly wind power. This percentage of wind powered desalination can increase if the capacity of the reservoir increases. This, however, would involve the construction of additional reservoirs, which is not considered in this scenario.

Year	2015		2020	
Power generation (MWh)				
Wind power	20,545	27.3%	22,475	25.3%
Fossil fuel	54,722	72.7%	66,434	74.7%
Total	75,267	100%	88,909	100%
Wind power curtailed (MWh)	9,319	31.2%	7,389	24.7%
Water production (m^3)				
Wind power	1,019,002	69.0%	973,076	55.8%
Fossil fuel	458,586	31.0%	769,381	44.2%
Total	1,477,588	100%	1,742,458	100%
Production costs				
EPC (€/kWh)	0.202		0.266	
WPC (€/m^3)	1.825		2.019	
TC (€)	17,918,962		27,155,385	

Table IV.2 - Results obtained for Scenario 2.

IV.1.3 Scenario 3 - Wind desalination with minimum total costs

Since the H2RES model does not allow performing optimization, it is necessary to run all proposed solutions and verify their technical feasibility (i.e. if they are able to supply the required electricity and water demand at all hours) and identify the one with lower total annual costs for the year 2020. The optimal configuration found has 6.85 MW of wind power installed and 5,400 m^3/day of desalination capacity, which are the capacities currently installed on the island.

During the optimization process it is possible to conclude that the addition of more desalination capacity only increased the costs. Even if the desalination capacity increases dramatically, the wind power curtailed does not decrease much. This is due to the limited capacity of the reservoirs in which the desalinated water is stored, and the relatively low water consumption. If the reservoirs are full, the desalination stops and wind power is curtailed. Hence, from economic point of view, it is possible to conclude that it is better to keep the load of the desalination units higher than to minimize the wind power curtailed by adding more desalination units. This optimal configuration leads to the results stated in Table IV.2 and a load of the desalination units of 88.4%. The total annual costs are about 3.2% lower than those in the Baseline Scenario for 2020.

For the current desalination capacity installed, it is not possible to have 100% wind powered desalination. Only if the installed desalination capacity doubles would be possible to achieve such goal, and even then, a reservoir of about 300,000 m^3 would be needed, which corresponds to about 60 days of water demand in 2020. These values are disproportionate to the water consumption of this island. This is the first difficulty of coupling the electricity and water supply systems. The construction of new reservoirs is not accounted for in this scenario, as it is considered that the existing ones are suitable for the current and forecasted water consumption of the island.

IV.1.4 Scenario 4 - Wind desalination and PHS

The previous scenario still resulted in a certain amount of wind power curtailed. In order to use this curtailed wind power, a PHS is included in Scenario 4. Apart from the PHS, the existing equipment on the island is also considered (wind power and desalination capacity). It is also considered the construction of an upper reservoir with a capacity of 50,000 m^3, and a lower one with a capacity of 35,000 m^3 (about one week of average water demand in 2020).

In order to implement this system there is the need to transport the desalinated water from the Matiota Plant, where the desalination units are installed, to the lower reservoir located at the bottom of Mont Verde. It is considered that the current water distribution system can be used in this case, however it is necessary to confirm if that is the case and if it is not necessary to install a new dedicated penstock to transport the desalinated water. This would increase the total costs and the electricity consumption (due to pumping). Because of the difficulty in assessing the costs of constructing a penstock, this case is not considered. Only the total costs of the installation and maintenance of the PHS system are considered, although with some degree of unpredictability.

The value considered for the electricity needed to produce each m^3 of potable water, already considers its pumping to the reservoirs spread throughout the island, as it is based on real data provided by ELECTRA and based on the water supply system present in S. Vicente. Hence, it is considered that this value already includes the extra energy needed to pump the desalinated water through this penstock.

It is also considered that the electricity produced in the PHS system is injected in the existent power grid. Since the exact location of the PHS station is not determined, it is not possible to estimate the distance between this facility and the power grid. This also can have some impact on the investment cost of the PHS system. Due to this and the fact that the investment cost of a PHS is very difficult to estimate since it depends greatly on the location, a sensibility analysis is carried out, where the investment cost of the PHS is doubled.

According to Kaldellis and Kavadias [32], the most theoretically disturbed energy management scenario is based on the hypothesis that there is a complete disharmony between electricity demand and wind power harnessing. Hence, the rated power of the hydro station is determined in order to cover the peak production, which is about 12.5 MW for 2015. The pump station should have capacity to absorb the rated wind power minus the minimum consumption of the grid. Thus, the pump power should be around 4.5 MW. With these hydro and pump power, the production of RES reached 43% in 2015, but the load of the hydro turbines is very low. To face this issue, the rated power of the pumps and the hydro turbine is decreased step by step, always checking if the percentage of RES did not decrease. In this way, 2.5 MW for hydro power and 3.5 MW for pump power are reached.

It is noticed that the capacity of the upper reservoir does not influence the results, since all that is pumped is immediately retrieved back through the hydro turbine. Hence the capacity of this reservoir is kept as low as possible (10,000 m^3) to decrease the costs. Figure IV.1 shows the power demand (load, desalination and PHS charging) of one day in January 2020 in this scenario, and Figure IV.2 shows the power production (wind, fossil fuel and PHS) of the same day.

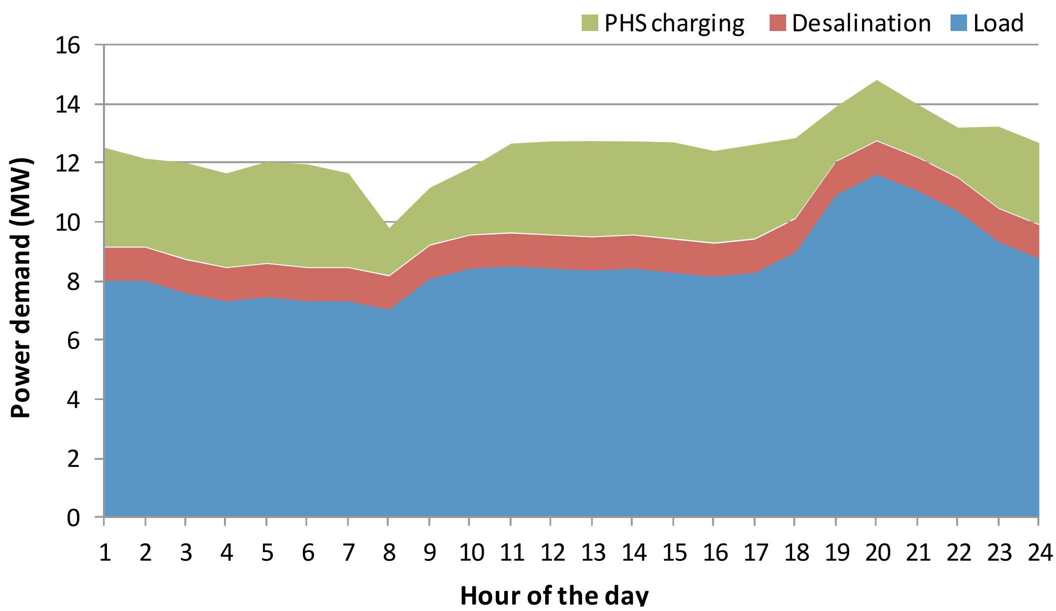

Figure IV.1 - Power demand of one day in 2020 for Scenario 4.

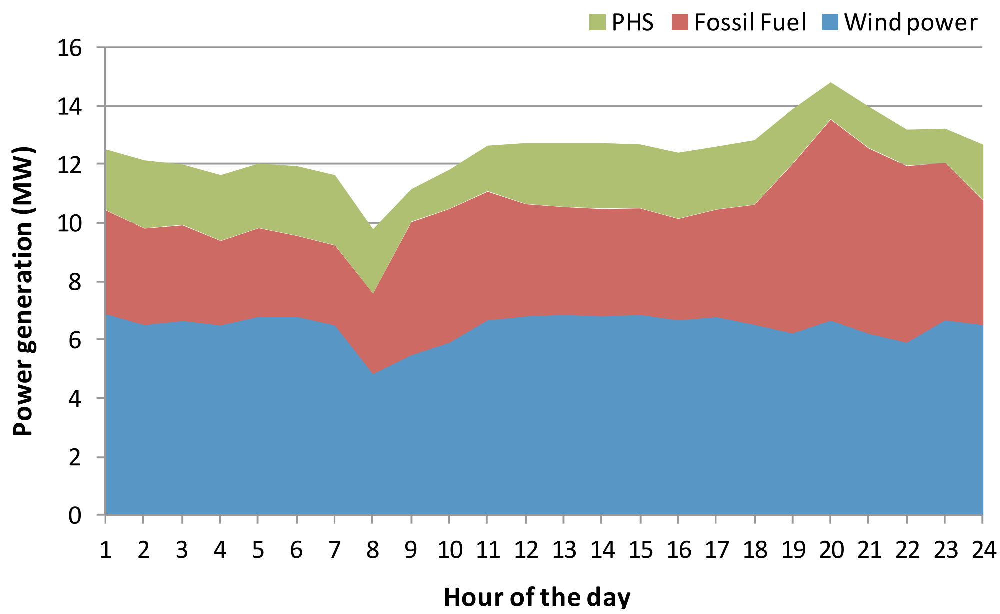

Figure IV.2 - Power generation of one day in 2020 for Scenario 4.

Table IV.3 shows the results obtained for Scenario 4. The total annual costs are lower than those for Scenario 2 because there is more wind power used, lowering the electricity needed from fossil fuel based units. The wind power curtailed decreases from 31.2% to 0.6% in 2015, and from 24.7% to 1.0% in 2020, which means that almost all wind power potential is used. In comparison with the Baseline Scenario, the costs decrease about 9.6% in 2015 and 7.3% in 2020. In 2015 about 31.8% of the electricity used to supply demand is RES based (22.7% wind power and 9.1% PHS). In 2020 this value decreases to 28.0% (22.0% wind power and 6.1% PHS).

Year	2015		2020	
Power generation (MWh)				
Wind power	29,679	35.3%	29,573	30.8%
PHS	6,144	7.3%	4,876	5.1%
Fossil fuel	48,347	57.4%	61,526	64.1%
Total	84,169	100%	95,974	100%
Wind power curtailed (MWh)	184	0.6%	291	1.0%
Water production (m^3)				
Wind power	1,068,465	72.3%	980,233	56.3%
Fossil fuel	408,841	27.7%	761,942	43.7%
Total	1,477,306	100%	1,742,176	100%
Production costs				
EPC (€/kWh)	0.171		0.237	
WPC (€/m^3)	1.669		1.875	
TC (€)	16,858,269		26,001,803	

Table IV.3 - Results obtained for Scenario 4.

IV.1.5 Scenario 5 - Wind desalination and PHS with minimum total costs

In order to establish Scenario 5, and having Scenario 4 as a starting point, several values for the wind, hydro, pump power and desalination capacity are evaluated with the H2RES model.

The configuration that minimizes the total yearly costs is 18.75 MW of installed wind power, 7,400 m^3/day of desalination capacity, 8 MW of hydro power and 10.5 MW of pump power. This results in a load of the desalination units of 64.8%, a load of the hydro turbine of 42.3% and a load of the pumps of 46.7%. The RES production reached 75.8% (53.3% wind power and 22.5% PHS) and the wind power curtailed is about 15.0%. Regarding the electricity used to supply demand, about 61.4% is RES based (24.4% wind power and 36.9% PHS).

Again it is noticed that the capacity of the upper reservoir has a small influence in the results, since all water that is pumped is immediately retrieved back through the hydro turbine. Hence, the capacity of this reservoir is kept as low as possible, in this case 35,000 m^3, to decrease costs.

Table IV.4 shows the results obtained for Scenario 5. The higher penetration of wind power with the wind powered desalination and the PHS results in a reduction of the total yearly costs of about 21.4% in relation to the Baseline Scenario.

Power generation (MWh)		
Wind power	70,258	53.3%
PHS	29,615	22.5%
Fossil fuel	32,004	24.3%
Total	131,876	100%
Wind power curtailed	12,424	15.0%
Water production (m^3)		
Wind power	1,549,828	88.5%
Fossil fuel	201,653	11.5%
Total	1,751,481	100%
Production costs		
$EPC\ (€/kWh)$	0.145	
$WPC\ (€/m^3)$	1.660	
$TC\ (€)$	22,050,753	

Table IV.4 - Results obtained for Scenario 5.

Considering an emission factor of 0.66 kgCO_2/kWh for the fuel oil power plants [87], this configuration avoids the emission of 24,782 tCO_2 in comparison with the Baseline Scenario, which represents about 54.0% of the total CO_2 emissions foreseen for 2020.

Figure IV.3 shows the power demand (load, desalination and PHS charging) of each month of 2020 in this scenario, and Figure IV.4 shows the same for the power production (wind, fossil fuel and PHS). These figures show that there are not significant changes in the electricity and water demand throughout the year (cf. section II.2.1). It also shows that the PHS charging follows the wind power production, but the PHS discharging also, because what is pumped is immediately retrieved back through the hydro turbine, as mentioned before. Since the system that minimizes the costs is not large enough to store electricity in a longer term, the month that has the lower wind power production is the month with higher fossil fuel production (July).

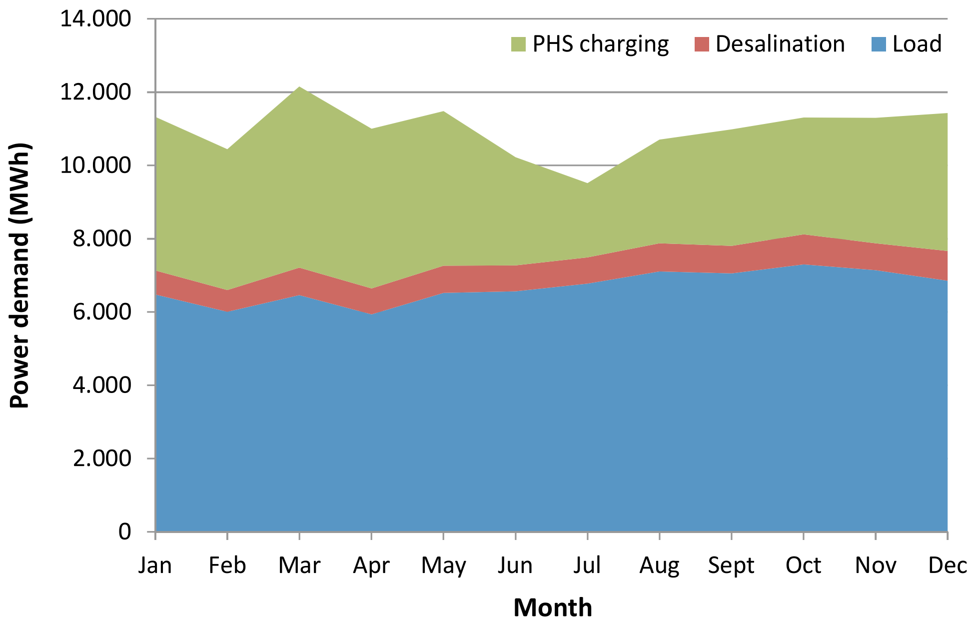

Figure IV.3 - Power demand in each month of 2020 for Scenario 5.

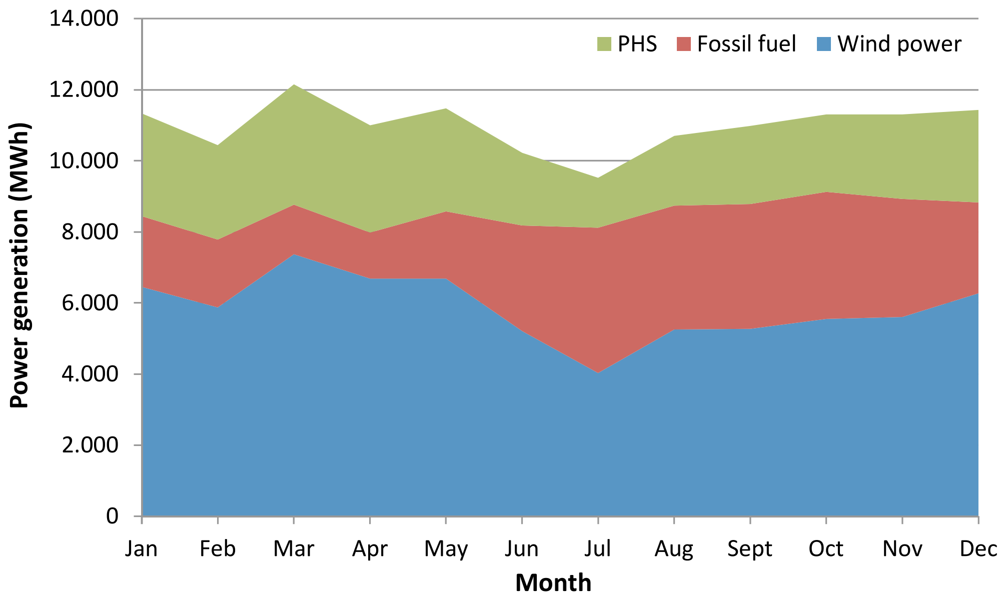

Figure IV.4 - Power generation in each month of 2020 for Scenario 5.

IV.1.6 100% hourly intermittent energy penetration scenarios

As referred to earlier, Scenarios 1, 3 and 5 are modelled one more time, but now allowing the hourly intermittent energy penetration rate to reach 100% (see Table II.4). For this, it is necessary to consider that the wind turbines installed possess some degree of frequency and voltage control, with a correspondent investment cost rise of 15% [88].

The Baseline Scenario with this condition (Scenario 1a, Table II.4) decreases dramatically the wind power curtailed; specifically, 2.3% in 2015 and 0.5% in 2020. The percentage of wind power in the production of energy reaches 38.9% in 2015 and 33.6% in 2020, which means that the current installed wind power is not sufficient to cover the load at all hours of the year.

To establish Scenario 3a, the method described earlier to set up Scenario 3 is repeated for 2020. The configuration that minimizes the annual costs is 17.05 MW of wind power and 5,400 m^3/day of desalination capacity, which results in 65.7% of total electricity produced from wind power, 49.9% of wind powered desalination, 22.3% of wind power curtailed, and a load of the desalination units of 88.4%. Again, it is noticed that from an economic point of view, it is better to keep the load of the desalination units higher than to minimize the wind power curtailed by adding more desalination units. Table IV.5 shows the costs obtained for Scenario 3a. In this scenario the electricity production cost is 24.9% lower than in Scenario 3, the water production cost is 16.4% lower and the total costs decrease 23.8%. In this case, although these wind turbines are more expensive, the extra amount of wind power produced compensates the higher costs. Moreover, increasing significantly the desalination capacity does not reduce much the wind power curtailed due, again, to the capacity of the reservoirs and the low water demand.

Year	2020
EPC (€/kWh)	0.200
WPC (€/m^3)	1.689
TC (€)	20,695,702

Table IV.5 - Results obtained for Scenario 3a.

To establish Scenario 5a, the method described earlier to establish Scenario 5 is repeated for 2020. The configuration that minimizes the total yearly costs is 17.9 MW of installed wind power, 6,400 m^3/day of desalination capacity, 1 MW of hydro power, and 1.5 MW of pump power. This resulted in a load of the desalination units of 74.7%, a load of the hydro turbine of 15.3% and a load of the pumps of 14.9%. The RES production reached 69.8% (68.3% wind power and 1.5% PHS), the wind power curtailed is about 21.4%, and the wind powered desalination is 61.1%. Table IV.6 shows the costs obtained for Scenario 5a. This configuration resulted in total annual costs about 6.7% lower than those of Scenario 5, but with a slightly lower RES production. It seems that Scenario 5a does not take advantage of the PHS system as much as Scenario 5 and this is expected since there is less need for storage when it is possible to deliver 100% of wind power directly to the grid. The fact that the configuration that minimizes the total yearly costs in this case has a lower installed wind power than in Scenario 5 is related with the higher cost of the wind turbines.

Year	2020
EPC (€/kWh)	0.192
WPC (€/m^3)	1.775
TC (€)	20,576,920

Table IV.6 - Results obtained for Scenario 5a.

IV.1.7 Comparison between scenarios

Figure IV.5 shows the power generation in 2020 for five different scenarios. It is clear that Scenario 3 (only desalination) does not differ much from the Baseline Scenario, although the costs are lower. In Scenario 5 (desalination and PHS) there is a significant increase in the penetration of RES. Comparing the scenarios that only consider desalination but have different intermittent limits, a 100% intermittent limit allows a significantly higher penetration of wind power. However, for the scenarios that consider desalination and PHS, the penetration of RES is almost the same.

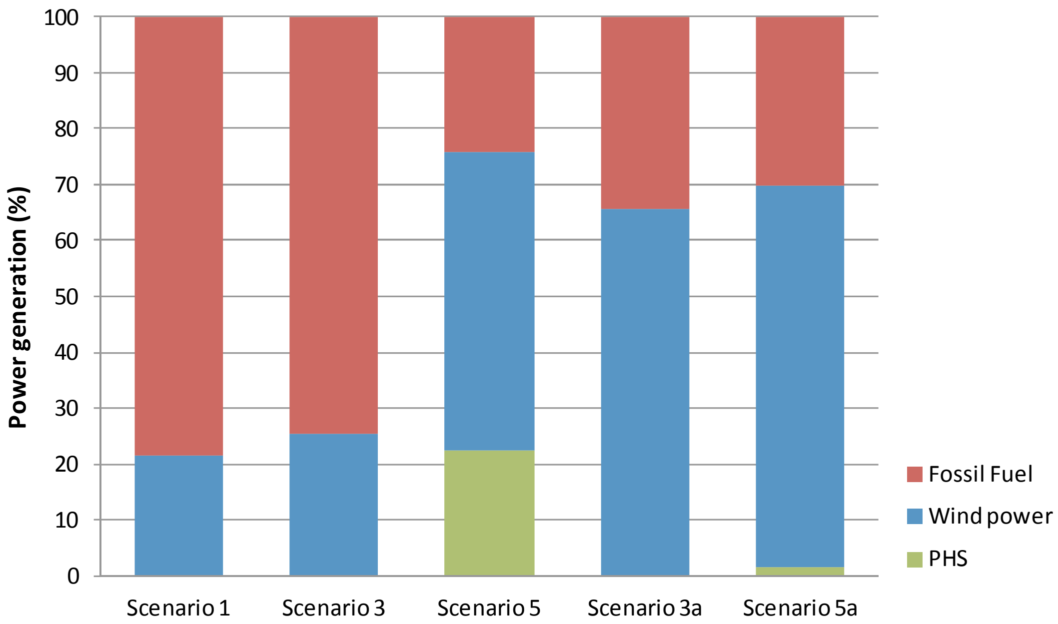

Figure IV.5 - Power generation in S. Vicente in 2020 for different scenarios.

Figure IV.6 shows the desalinated water production in 2020 for four different scenarios. The desalination and PHS scenarios allowed for a higher percentage of water desalinated from wind power than the scenarios with only desalination, for both intermittent limits. This is due to two factors. On one hand the reservoirs used to store the desalinated water in Scenarios 3 and 3a are smaller than the ones used on Scenario 5 and 5a. On the other hand, since Scenarios 5 and 5a consider PHS, the water stored in the lower reservoir can be pumped to the upper reservoir, resulting in more space to put wind powered desalinated water in the lower reservoir.

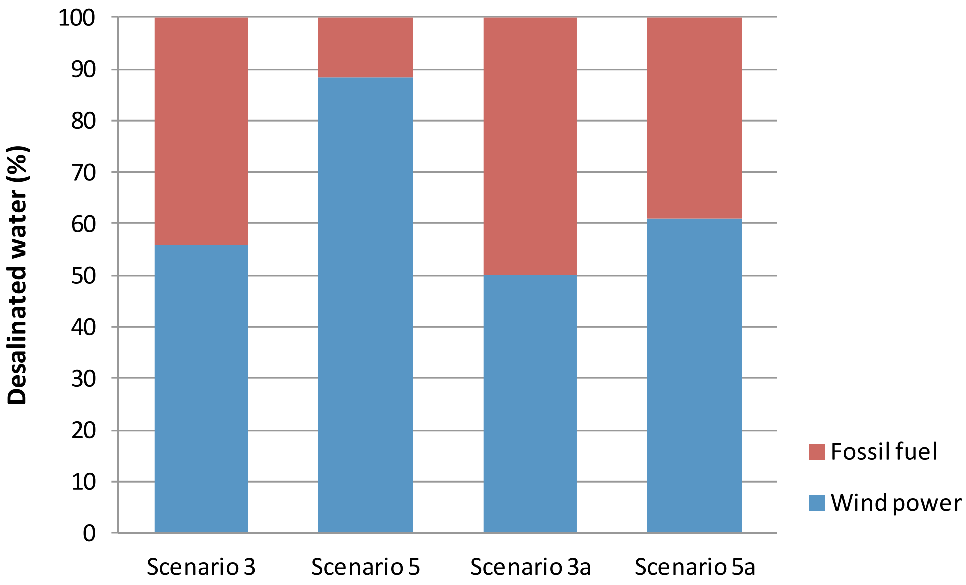

Figure IV.6 - Production of desalinated water in S. Vicente in 2020 for different scenarios.

IV.1.8 Internalizing the cost of the CO_2 emissions

In order to internalize environmental problems related with CO_2 emissions, the scenarios are modelled again considering the cost of CO_2. It is assumed that if in the future CO_2 emissions are to be charged, the value could be the current CER cost. Since the CER cost is extremely volatile, two different values are considered: the average value of CER since this market was created until today - 6.96 €/tCO_2, and the maximum value of CER ever reached - 22.60 €/tCO_2 [100]. The minimum value ever reached was 0.01 €/tCO_2, which is not much different than the reference scenarios of this study, where this cost is not considered. For example, considering the Baseline Scenario for 2020, the CO_2 emissions reach 45,904 tCO_2, which would result in a yearly cost of 459.04 €, about 0.002% of the total costs estimated for that year.

In regard to the Baseline Scenario, Scenario 2 and Scenario 4, the only difference with the reference case is the costs. The results of these scenarios are stated in Table IV.7. A cost of 6.96€/tCO_2 for the CO_2 emissions increases the total costs of these three scenarios about 1% in relation to the costs of the reference scenarios. The cost of 22.60 €/tCO_2 increases the total cost of these scenarios in about 4% in relation to the cost of the reference scenarios.

Scenario		Reference	6.96€/tCO_2	22.6€/tCO_2
Baseline	$EPC\ (€/kWh)$	0.276	0.280	0.288
	$WPC\ (€/m^3)$	2.059	2.077	2.117
	$TC\ (M€)$	28.05	28.40	29.18
2	$EPC\ (€/kWh)$	0.266	0.269	0.277
	$WPC\ (€/m^3)$	2.019	2.036	2.075
	$TC\ (M€)$	27.16	27.49	28.24
4	$EPC\ (€/kWh)$	0.237	0.240	0.246
	$WPC\ (€/m^3)$	1.875	1.889	1.922
	$TC\ (M€)$	26.00	26.31	27.00

Table IV.7 - Power and water production costs of Baseline Scenario, Scenario 2 and 4 for the reference case and considering two different CO_2 emissions' cost.

Table IV.8 presents the results of Scenario 5 for the reference case and considering CO_2 emissions cost. The lower cost of CO_2 does not change the optimal integrated system; however, the higher cost of CO_2 results in a higher installed wind power and a slightly higher installed hydro power and RES production. In this case of high CO_2 emissions cost, the total costs of the proposed systems decrease about 23% and the CO_2 emissions about 56% in relation to the Baseline Scenario with the same CO_2 emissions' cost.

Scenario		Reference	6.96€/tCO_2	22.60€/tCO_2
Installed equipment	Wind power (MW)	18.75	18.75	20.45
	Desalination capacity (m^3/day)	7,400	7,400	7,400
	Pump power (MW)	10.5	10.5	10.5
	Hydro power (MW)	8.0	8.0	8.5
RES production	Wind power	53.3%	53.3%	54.1%
	PHS	22.5%	22.5%	23.3%
	Total RES	75.8%	75.8%	77.4%
Wind powered desalination		88.5%	88.5%	89.5%
$EPC\ (€/kWh)$		0.145	0.146	0.147
$WPC\ (€/m^3)$		1.660	1.666	1.669
$TC\ (M€)$		22.05	22.21	22.60

Table IV.8 - Comparison between Scenario 5 in the reference case and considering CO_2 emissions' cost.

IV.1.9 Discussion

Considering only the direct supply of wind power to the desalination units, the optimal configuration found is the current one installed in S. Vicente. This is because the simple installation of more desalination units does not decrease the wind power curtailed, because of the influence of the reservoir capacity installed and the relatively low water consumption verified in S. Vicente. In 2020 this configuration still causes about 25% of the wind power to be curtailed.

In order to decrease significantly the wind power curtailed a PHS system is necessary, resulting in a less expensive system since more wind power is used. The optimal configuration found has an installed wind power of 18.75 MW, 7,400 m^3/day of desalination capacity, 10.5 MW of pumps, 8.0 MW of hydro turbines and lower and upper reservoirs with 35,000 m^3 of capacity. With this system's configuration, it is possible to have 75.8% of RES (53.3% wind power and 22.5% PHS) in the total electricity production. This higher penetration of wind power results in savings of 21.4% of the total costs and a reduction of 54% of CO_2 emissions in relation to the Baseline Scenario.

The lower cost considered for the CO_2 emissions (6.96 €/tCO_2) increases the total cost about 1% in all scenarios considered and does not change the optimal configuration found for the integrated electricity and water supply system. The higher CO_2 cost considered (22.60 €/tCO_2) has a higher, but still small impact. Scenarios 1 to 3 increase their total costs in 4%, and the optimal configurations found differ slightly from the reference scenarios. With a CO_2 emissions cost of 22.60 €/tCO_2 the costs are minimized with more wind and hydro power.

IV.2 Sensitivity analysis

The variables assessed in the sensitivity analysis are the ones considered more volatile and/or more unpredictable, i.e. electricity and water demand, fuel costs and investment cost of the PHS. Additionally, the modelling of the integrated system is also done for the hourly wind speed registered in the S. Pedro meteorological station, i.e. not adjusted to the wind power production of the Selada Flamengo Wind Park (as referred on section II.2.2). The sensitivity analysis is done only for the year 2020.

IV.2.1 Increased electricity and water demand

As mentioned in section II.2.4, there are several studies that forecast a greater increase of the electricity demand in S. Vicente than the one foreseen in this study. Hence, all scenarios are modelled once again considering a 21.6% higher electricity and water demand for 2020. Table IV.9 presents the results obtained. For Scenario 1, the Baseline Scenario, the increase of electricity and water demand results in a decrease of the wind power curtailed from 37% to 27% of the total wind power potential. However, the wind power penetration is slightly lower. For the wind desalination scenarios it is necessary to consider the installation of at least one more desalination unit, in order to cover the water demand. Contrary to the reference case, here Scenarios 2 and 3 differ, as there is more desalination capacity installed, and the optimal wind power installed also increases; however the RES penetration does not change much. Naturally, the total costs are higher since more electricity and water is needed to cover the demand.

Scenario	1	2	3	4	5	3a	5a
Power generation							
Wind power	20.2%	23.4%	25.4%	26.3%	51.9%	65.4%	67.6%
PHS	-	-	-	2.6%	21.4%	-	1.3%
Fossil fuel	79.8%	76.6%	74.6%	71.1%	26.7%	34.6%	31.1%
Wind power curtailed	27.0%	15.3%	26.6%	1.1%	22.8%	21.6%	20.7%
Water production							
Wind power	-	46.7%	55.5%	47.0%	81.5%	48.0%	56.5%
Fossil fuel	-	53.3%	44.5%	53.0%	18.5%	52.0%	43.5%
Production costs							
$EPC\ (€/kWh)$	0.273	0.264	0.264	0.251	0.154	0.197	0.191
$WPC\ (€/m^3)$	1.921	1.992	1.988	1.925	1.642	1.655	1.724
$TC\ (€)$	33.45	32.80	32.72	32.28	27.56	24.80	24.66

Table IV.9 - Results of the different scenarios with an increased electricity and water demand.

Table IV.10 presents the comparison between Scenario 5 in the reference case and in the case of higher demand. The increased electricity and water demand allows a larger integrated system to be installed. The capacities of all equipment are greater than in the reference case.

Scenario 5		Reference	Increased demand
Installed equipment	Wind power (MW)	18.75	23.85
	Desalination capacity (m^3/day)	7,400	8,400
	Pump power (MW)	10.5	14.0
	Hydro power (MW)	8.0	8.5
RES production	Wind power	53.3%	51.9%
	PHS	22.5%	21.4%
	Total RES	75.8%	73.3
Wind powered desalination		88.5%	81.5
$EPC\ (€/kWh)$		0.145	0.154
$WPC\ (€/m^3)$		1.660	1.642
$TC\ (M€)$		22.05	27.54

Table IV.10 - Comparison between the results of Scenario 5 in the reference case and with an increased demand.

Scenario 5 with increased demand allows a saving of 18% of the total costs and 51% of the CO_2 emissions, in comparison with the Baseline Scenario with increased demand.

IV.2.2 Fuel cost

The volatile nature of the fossil fuel cost makes it suitable for a sensitivity analysis. The fuel cost around the world has been decreasing. A new estimation for the fossil fuel costs is done based on the values for Cabo Verde in February 2015 [92], and the value reached is 0.126 €/kWh, about 53% lower than in the reference case.

In regard to the Baseline Scenario, Scenario 2 and Scenario 4, the only difference with the reference case is the costs. The results of these scenarios are showed in Table IV.11. The decrease of fossil fuel costs results in a decrease of total cost of about 39% in the Baseline Scenario, of 38% in Scenario 2 and of 37% in Scenario 4.

Scenario		Reference	Decreased fuel cost
Baseline	EPC (€$/kWh$)	0.276	0.165
	WPC (€$/m^3$)	2.059	1.501
	TC (M€)	28.05	17.21
2	EPC (€$/kWh$)	0.266	0.160
	WPC (€$/m^3$)	2.019	1.489
	TC (M€)	27.16	16.81
4	EPC (€$/kWh$)	0.237	0.146
	WPC (€$/m^3$)	1.875	1.420
	TC (M€)	26.00	16.48

Table IV.11 - Comparison between the results for Scenario 1, 2 and 4 in the reference case and with decreased fuel cost.

Although the decrease in fuel cost decreases the total costs of the Baseline Scenario significantly in relation to the reference case, the proposed integrated system is still able to decrease the total costs of the power and water supply in S. Vicente, i.e. in the case of decreased fuel cost, Scenario 4 results in a 4% decrease in costs in relation to the Baseline Scenario.

Table IV.12 presents the comparison between the results of Scenario 5 in the reference case and in this case. The decreased fuel costs results in a smaller optimal integrated system to be installed.

Scenario 5		Reference	Decreased fuel cost
Installed equipment	Wind power (MW)	18.75	12.8
	Desalination capacity (m^3/day)	7,400	6,400
	Pump power (MW)	10.5	8.5
	Hydro power (MW)	8.0	5.5
RES production	Wind power	53.3%	46.2%
	PHS	22.5%	16.5%
	Total RES	75.8%	62.7%
Wind powered desalination		88.5%	84.1%
$EPC\ (€/kWh)$		0.145	0.120
$WPC\ (€/m^3)$		1.660	1.411
$TC\ (M€)$		22.05	16.51

Table IV.12 - Comparison between the results of Scenario 5 in the reference case and with decreased fuel cost.

Scenario 5 with a decreased fuel cost allows a saving of 4% of the total costs and 37% of the CO_2 emissions, in comparison with the Baseline Scenario with decreased fuel cost.

IV.2.3 PHS investment cost

As mentioned before, the investment cost of the PHS system is very difficult to estimate because it is very site specific. Scenarios 4 and 5 are modelled with an increased PHS investment cost, about twice as much as the investment cost considered in the reference case, for the installation of the hydro turbines, the pumps and the construction of the two reservoirs.

For Scenario 4, this increase in the investment cost of the PHS system results in a 1.3% increase in the total costs. This small influence is due to the annualization of the investment costs done in the lifetime of the equipment, in this case, 40 years.

In Scenario 5, the optimal sizing of the system in this case differs from the reference case only in the hydro power installed, that decreases from 8 MW to 7.5 MW. However the optimal pump power does not decrease. Table IV.13 presents the comparison between the results of Scenario 5 in the reference case and in this case.

Scenario 5		Reference	Increased PHS investment cost
Installed equipment	Wind power (MW)	18.75	18.75
	Desalination capacity (m^3/day)	7,400	7,400
	Pump power (MW)	10.5	10.5
	Hydro power (MW)	8.0	7.5
RES production	Wind power	53.3%	53.1%
	PHS	22.5%	22.4%
	Total RES	75.8%	75.5%
Wind powered desalination		88.5%	88.6%
EPC $(€/kWh)$		0.145	0.154
WPC $(€/m^3)$		1.660	1.704
TC $(M€)$		22.05	23.29

Table IV.13 - Comparison between the results of Scenario 5 in the reference case and with increased PHS investment cost.

As the optimal installed equipment does not vary much, the RES production behaves the same, with similar results than the reference scenario. This increase in the investment cost of the PHS system results in a 5.6% increase in the total costs in comparison with the reference case. However, there are still savings of 18% of the total costs when comparing with the Baseline Scenario.

IV.2.4 Wind speed not adjusted

As mentioned before, this study considers an adjustment of the hourly wind speed data of 2005 considering the wind power production of that year. If this adjustment is not carried out, the result is a 25% higher annual wind power production in comparison to the reference case. Table IV.14 presents the results of the scenarios modelled in this case. They are very similar to the results reached in the reference case. However, there is a slightly higher wind power production for each turbine installed; hence the production costs are lower. The total costs in this case are about 9% lower than in the reference case.

Scenario	1	2 and 3	4	5	3a	5a
Power generation						
Wind power	23.4%	28.1%	35.7%	56.0%	73.4%	73.9%
PHS	-	-	7.2%	24.6%	-	1.6%
Fossil fuel	76.6%	71.9%	57.1%	19.4%	26.6%	24.5%
Wind power curtailed	41.8%	29.8%	0.5%	13.2%	26.8%	20.6%
Water production						
Wind power	-	67.7%	68.7%	91.2%	62.3%	70.3%
Fossil fuel	-	32.3%	31.3%	8.8%	37.7%	29.7%
Production costs						
EPC $(€/kWh)$	0.271	0.258	0.216	0.125	0.179	0.171
WPC $(€/m^3)$	2.032	1.982	1.771	1.560	1.585	1.666
TC $(€)$	27.54	26.42	24.54	20.00	18.67	18.44

Table IV.14 - Results of the different scenarios with wind speed not adjusted to wind production.

Table IV.15 presents a comparison between the results of Scenario 5 in the reference case and in this case. The optimal wind power installed is lower in this case because each wind turbine is able to produce more wind power. The RES penetration is also higher. This results in a lower electricity and water production cost.

Scenario 5		Reference	Wind speed not adjusted
Installed equipment	Wind power (MW)	18.75	17.05
	Desalination capacity (m^3/day)	7,400	7,400
	Pump power (MW)	10.5	10.5
	Hydro power (MW)	8.0	8.0
RES production	Wind power	53.3%	56.0%
	PHS	22.5%	24.6%
	Total RES	75.8%	80.6%
Wind powered desalination		88.5%	91.2%
EPC $(€/kWh)$		0.145	0.125
WPC $(€/m^3)$		1.660	1.560
TC $(M€)$		22.05	20.00

Table IV.15 - Comparison between the results of Scenario 5 in the reference case and with the wind speed not adjusted to wind power production.

IV.2.5 Discussion

The increased electricity and water demand results in an optimal integrated system larger than in the reference case. The increase of 21.6% of demand results in an increase of 19.3%, 20.8% and 24.2% of Scenarios 1, 2 and 4, respectively, in relation to the reference case.

In order to assess the influence of the fuel cost in the Baseline Scenario, it is seen that the decrease of 53% in the fuel cost results in a reduction of 38.6% of the total costs of the Baseline Scenario in comparison with the reference case. The scenarios that consider the proposed system also verify significant reductions in the total costs, due to the decrease of the fuel cost. The savings in the total cost verified for the proposed system in relation to the Baseline Scenario are due to the fuel cost; hence, with the decrease of fuel cost, it is natural that the proposed system allows for lower savings; nevertheless, these savings still exist. Even with a significant decrease of fuel cost, the proposed system is more economically viable than the current one installed in S. Vicente, with the advantage of being more environmentally friendly since its yields lower CO_2 emissions.

An increase of the PHS investment cost of 100% results in an increase of the total costs of 1.7% and 5.6% for Scenario 4 and 5 in relation to the reference case. The proposed system still allows for significant savings in relation to the Baseline Scenario.

If the data considered for the wind speed is not adjusted for the wind production of that year, the proposed integrated power and water supply system is even more attractive. It can decrease the total costs in 27.4% and the CO_2 emissions in 60.4% in relation to the Baseline Scenario.

IV.3 Optimization

In order to optimize the integrated electricity and water supply system proposed for S. Vicente, the same is modelled outside of the H2RES model. A tool has been designed to model this particular system for the year 2020, estimating its hourly operation. As before, the electricity and water demand forecasted for that year is taken into account.

The cost of CO_2 emissions considered in this optimization is 6.96 €/tCO_2, that is, as mentioned before, the average value of CER since the carbon market was created until today [100].

As mentioned in section III.3.2, the variables of this optimization problem are the wind power, the desalination capacity, the pump power, the hydro power, the capacity of the upper and lower reservoirs and the operational levels of the integrated electricity and water supply system. When the level of the lower reservoir is less than n_0, and it is not possible to turbinate water from the upper reservoir, the fossil fuel based units supply the desalination units to produce water until the level of the lower reservoir reaches n_{FF} (Figure III.2). The variable n_{WB} is the level of the lower reservoir that determines the balance between the excess wind power used to desalinate and to pump water to the upper reservoir (Figure III.3). The variable n_H is the level of the lower reservoir in which the hydro production stops (Figure III.4).

The proposed integrated system is optimized considering three objective functions: f_1 that is the minimization of the total annualized costs of the integrated energy and water supply system, f_2 that is the maximization of the percentage of RES in the total power production, and f_3 that is the minimization of the curtailed wind power. The method DMS, a derivative free multiobjective method, is used. Figure IV.7 presents the 5910 non-dominated solutions (Pareto optimal set) obtained with this optimization.

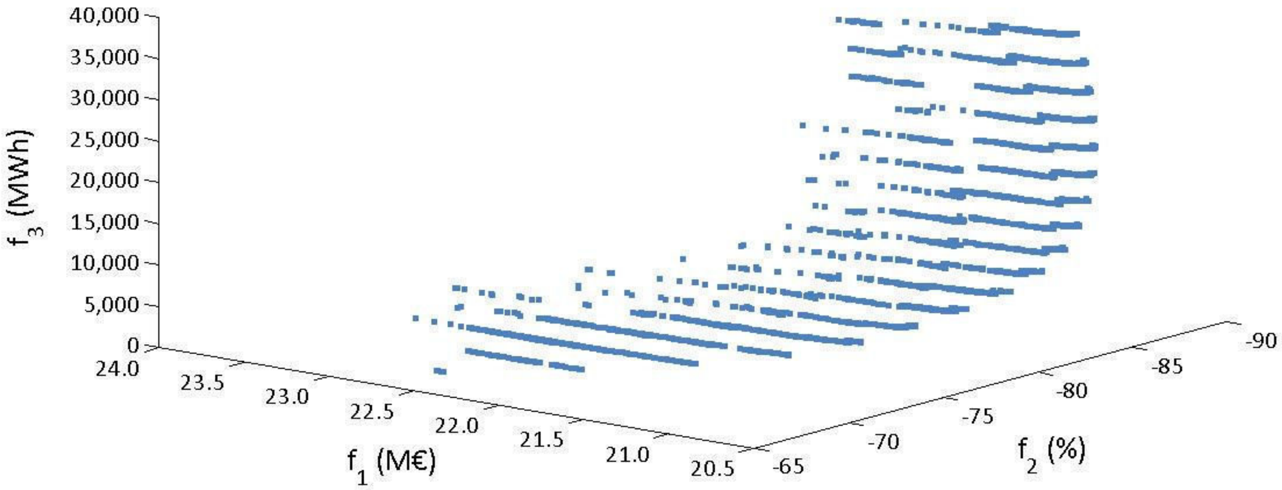

Figure IV.7 - Pareto optimal set of the optimization problem.

To analyse these solutions in more detail, three projections are carried out in planes f_1-f_2, f_2-f_3 and f_1-f_3.

Figure IV.8 presents the projection of the Pareto optimal set in the plane f_1-f_3. The best solution for f_1 in relation to f_3, i.e. the total annualized production costs in relation to the wind power curtailed, is 1501, which is the solution that minimizes the total costs. The best solution for f_3 in relation to f_1 is 4540, which is the solution that minimizes the wind power curtailed. These solutions are analysed in more detail, together with solutions 1259 and 5509, which are located in between.

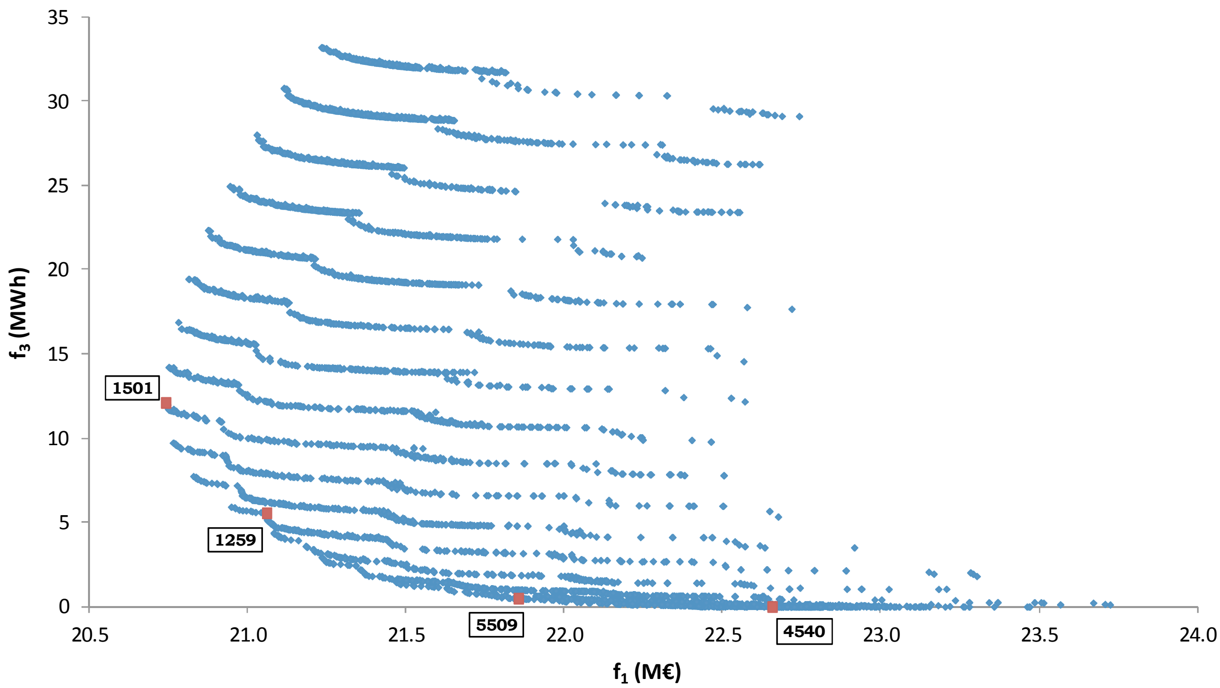

Figure IV.8 - Pareto optimal set in the plane f_1-f_3.

Table IV.16 presents the detailed results of these solutions regarding the sizing, the operational strategy and the results of the modelling for the year 2020. As the solutions go from the minimum total cost (1501) to the minimum wind power curtailed solution (4540), the installed wind power decreases, as well as the PHS systems' size. The exception is the hydro power that increases from solution 1501 to solution 1259, but then decreases from solution 1259 to 5509 and from solution 5509 to 4540. The evolution of n_{WB} is similar to the evolution of hydro power. The desalination capacity is constant, but the wind powered desalination decreases. The share of RES in the power production decreases, hence the CO_2 emissions increase. n_H and n_{FF} are similar in all solutions, being its maximum and minimum value, respectively.

Solution		1501	1259	5509	4540
Installed equipment	x_1 - Wind power (MW)	21.30	18.75	15.35	13.65
	x_2 - Desalcap (m^3/day)	6,400	6,400	6,400	6,400
	x_3 - Pump power (MW)	14.5	14.0	11.5	11.0
	x_4 - Hydro power (MW)	8.5	11.0	9.0	7.5
	x_5 - LR (m^3)	100,000	100,000	100,000	95,000
	x_6 - UR (m^3)	150,000	140,000	130,000	75,000
Operational strategy	x_7 - n_{WB}	77.0%	96.0%	95.0%	61.0%
	$x_8 - f_H$	99.0%	99.0%	98.0%	98.0%
	n_H	99.2%	99.2%	98.4%	98.5%
	$x_9 - f_{FF}$	0.0%	9.0%	5.0%	5.0%
	n_{FF}	21.4%	28.5%	25.3%	26.4%
RES production	Wind power	58.0%	56.4%	52.6%	49.5%
	PHS	25.5%	24.1%	20.9%	18.4%
	f_2 - Total RES	83.5%	80.5%	73.5%	67.9%
Wind powered desalination		99.6%	98.4%	93.9%	89.4%
f_3 - Wind power curtailed (MWh)		12,126	5,568	507	0
f_1- TC $(M€)$		20.74	21.59	21.85	22.66
CO_2 Emissions ($ktCO_2$)		15.4	17.6	22.3	25.7

Table IV.16 - Results of the solutions analysed in the plane f_1-f_3.

Figure IV.9 presents the projection of the Pareto optimal set in the plane f_2-f_3. The best solution for f_2 in relation to f_3, i.e. the share of RES in relation to the wind power curtailed, is 4429, which is the solution that maximizes the share of RES in the total power production. The best solution for f_3 in relation to f_2 is 2139, which is the solution that minimizes the wind power curtailed. These solutions are analysed in more detail, together with solutions 3277 and 3475, which are located in between.

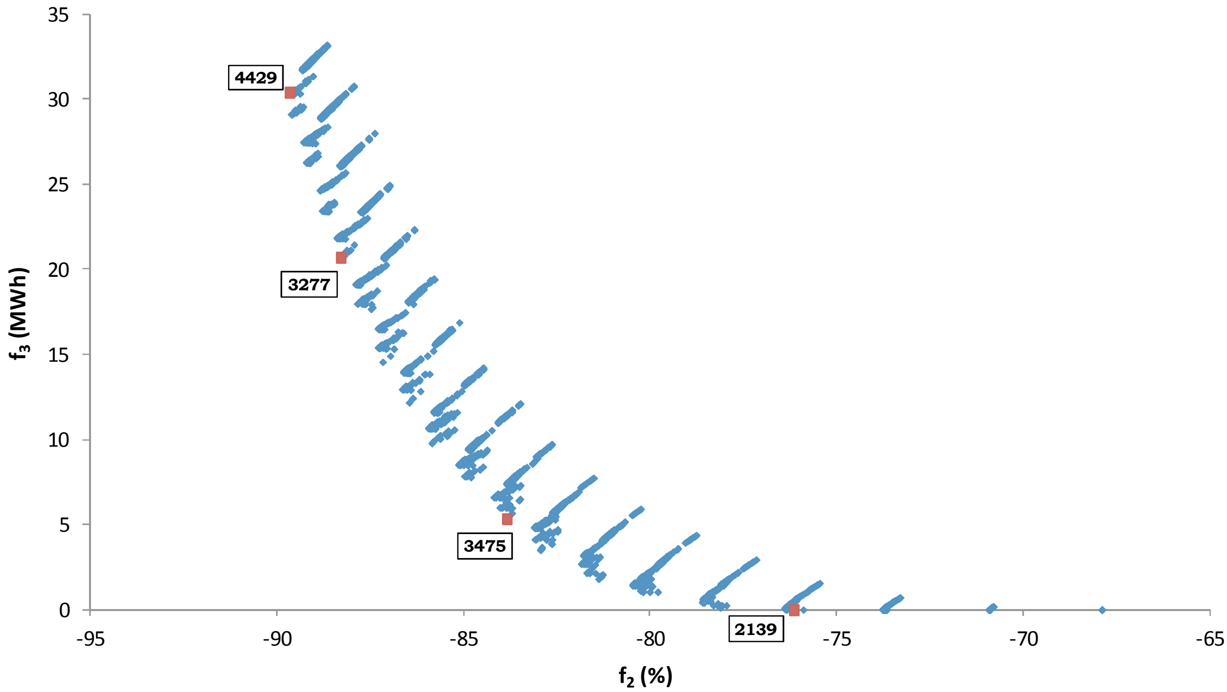

Figure IV.9 - Pareto optimal set in the plane f_2-f_3.

Table IV.17 presents the detailed results of these solutions regarding the sizing, the operational strategy and the results of the modelling for the year 2020. As the solutions go from the maximum percentage of RES solution (4429) to the minimum wind power curtailed solution (2139), the installed wind power decreases, as in the previous analysis. But in this case, the installed wind power reaches higher values; this is because the most important objective functions are the percentage of RES and the wind power curtailed and not the total costs, as in the previous analysis. The installed desalination capacity increases, as well as the percentage of wind powered desalination, although slightly. The total costs also increase. In this case, the operational strategy is similar for all solutions, with n_H and n_{FF} at its maximum and minimum value, respectively. n_{WB} is low due to lower installed wind power and higher installed desalination capacity.

Solution		4429	3277	3475	2139
Installed equipment	x_1 - Wind power (MW)	28.10	25.55	20.45	16.20
	x_2 - Desalcap (m^3/day)	7,400	8,400	10,400	11,400
	x_3 - Pump power (MW)	19.5	19.5	15.0	12.5
	x_4 - Hydro power (MW)	19.5	19.0	19.0	19.0
	x_5 - LR (m^3)	100,000	100,000	95,000	100,000
	x_6 - UR (m^3)	280,000	370,000	485,000	340,000
Operational strategy	x_7 - n_{WB}	5.0%	11.0%	11.0%	11.0%
	$x_8 - f_H$	100%	100%	100%	100%
	n_H	100%	100%	100%	100%
	$x_9 - f_{FF}$	5.0%	3.0%	3.0%	3.0%
	n_{FF}	25.3%	23.8%	24.9%	23.8%
RES production	Wind power	61.4%	61.0%	58.8%	54.4%
	PHS	28.2%	27.3%	25.0%	21.8%
	f_2 - Total RES	89.7%	88.3%	83.8%	76.2%
Wind powered desalination		99.3%	99.4%	99.7%	99.8%
f_3 - Wind power curtailed (MWh)		30,418	20,721	5,348	0
f_1- $TC\ (M€)$		22.08	22.24	22.67	23.47
CO_2 Emissions ($ktCO_2$)		10.4	11.7	15.4	20.7

Table IV.17 - Results of the solutions analysed in the plane f_2-f_3.

Figure IV.10 presents the projection of the Pareto optimal set in the plane f_1-f_2. The best solution for f_1 in relation to f_2, i.e. the total annualized production costs in relation to the share of RES, is 1501 – this is the solution that minimizes the total costs of the proposed system. The best solution for f_2 in relation to f_1 is 4429, which is the solution that maximizes the share of RES in the total power production. These two solutions are already analysed above since solution 1501 is also the best for f_1 in relation to f_3, i.e. the total annualized production costs in relation to the wind power curtailed, and solution 4429 is also the best for f_2 in relation to f_3, i.e. the share of RES in relation to the wind power curtailed. These solutions are compared with solutions 1301 and 5882 (Table IV.18), which are located in between.

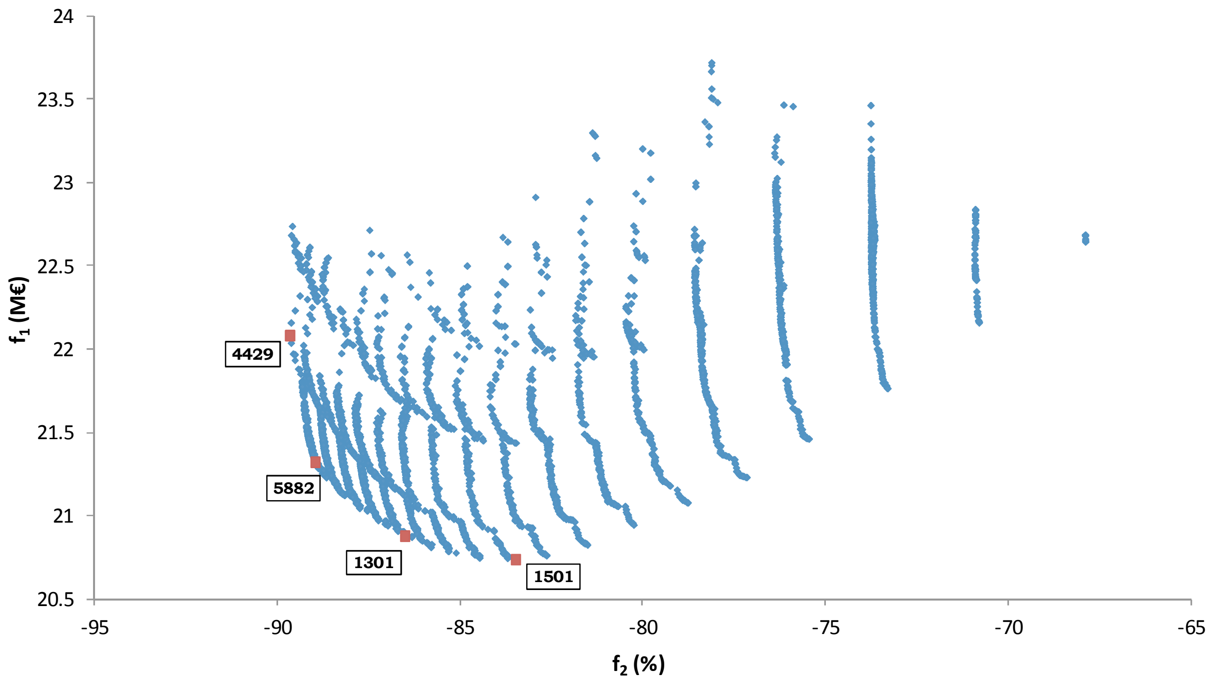

Figure IV.10 - Pareto optimal set in the plane f_1-f_2.

Solution		1501	1301	5882	4429
Installed equipment	x_1 - Wind power (MW)	21.30	24.70	28.10	28.10
	x_2 - Desalcap (m^3/day)	6,400	6,400	6,400	7,400
	x_3 - Pump power (MW)	14.5	15.5	18.5	19.5
	x_4 - Hydro power (MW)	8.5	9.5	11.0	19.5
	x_5 - LR (m^3)	100,000	100,000	100,000	100,000
	x_6 - UR (m^3)	150,000	170,000	180,000	280,000
Operational strategy	x_7 - n_{WB}	77.0%	46.0%	38.0%	5.0%
	$x_8 - f_H$	99.0%	99.0%	99.0%	100%
	n_H	99.2%	99.2%	99.2%	100%
	$x_9 - f_{FF}$	0.0%	3.0%	1.0%	5.0%
	n_{FF}	21.4%	23.8%	22.2%	25.3%
RES production	Wind power	58.0%	59.6%	60.9%	61.4%
	PHS	25.5%	26.9%	28.1%	28.2%
	f_2 - Total RES	83.5%	86.5%	89.0%	89.7%
Wind powered desalination		99.6%	99.5%	99.5%	99.3%
f_3 - Wind power curtailed (MWh)		12,126	22,017	32,553	30,418
f_1 - TC $(M€)$		20.74	20.88	21.33	22.08
CO_2 Emissions ($ktCO_2$)		15.4	13.0	10.9	10.4

Table IV.18 - Results of the solutions analysed in the plane f_1-f_2.

As the solutions go from the minimum total cost solution (1501) to the maximum percentage of RES solution (4429), the size of the proposed system increases in terms of installed power and size of the upper reservoir. The size of the lower reservoir (LR) does not increase because this is already the maximum capacity allowed. The installed wind power in solutions 5882 and 4429 is the maximum allowed. The share of RES production increases due to the increase of both wind power and PHS contribution to the total power production. The share of wind powered desalination decreases slightly, but is always almost 100%. Solution 4429 has less wind power curtailed that solution 5882 although they have the same wind power installed; this is due to a higher desalination capacity installed in solution 4429. Regarding the operational strategy, n_H and n_{FF} are practically the same, being at its maximum and minimum value, respectively. n_{WB} decreases significantly from solution 1501 to solution 4429, this together with the increase of the size of the PHS system allows more water to be pumped from the lower to the upper reservoir.

Figure IV.11 presents the total power generation for each solution analysed in plane f_1-f_2. Although the share of RES production increases, the total power generation also increases.

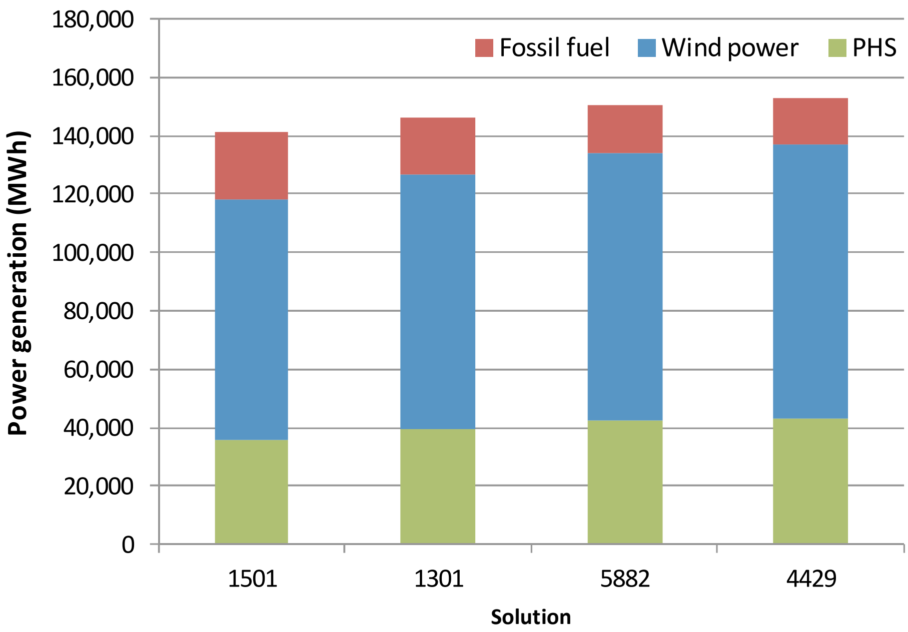

Figure IV.11 - Power generation for each solution analysed.

For decision makers, the plane f_1-f_2 is the most relevant, since it contains what is more important: the total costs and the percentage of RES in the total power production of the proposed system.

Considering all the non-dominated solutions of this optimization problem, the solution that minimizes the total cost (f_1) is solution 1501, that is the same that minimizes f_1 in relation to f_2 and in relation to f_3. The solution that maximizes the share of RES in total power production (f_2) is solution 4429, that is the same that minimizes f_2 in relation to f_1 and in relation to f_3. Regarding the minimization of the wind power curtailed, there are 26 solutions where this value is zero, one is solution 2137 that minimizes f_3 in relation to f_2, and another is solution 4540 that minimizes f_3 in relation to f_1.

As mentioned in section III.3.1, the method used to determine the contribution of the fossil fuel based units for the production of power and water in the modelling carried out for this optimization, does not take into account the minimum load of these units. However it is possible to determine the error resulting from this approximation. In each hour of the year, the electricity needed from the fossil fuel based units is determined, if it is less than its minimum load, than there is an error. The error is the amount of wind power and/or PHS production that would need to be subtracted to avoid the operation of the fossil fuel based units in levels below its minimum value. The values reached for this error are never above 6%.

IV.3.1 Discussion

The optimization carried out for the sizing and the operational strategy of the proposed integrated system for power and water supply resulted in several solutions. The more relevant solutions are the non-dominated solutions projected in the plane f_1-f_2. The overall solution that minimizes the total costs is solution 1501 and the overall solution that maximizes the share of RES in the total power production is solution 4429. Table IV.19 presents the results of these solutions together with the baseline scenario foreseen for 2020. The baseline scenario considers the system installed in S. Vicente and the forecasted electricity and water consumption for 2020. The total costs of this scenario also consider the CO_2 emissions cost of 6.96 €/tCO_2.

Solution		1501	4429	Baseline
Installed equipment	x_1 - Wind power (MW)	21.30	28.10	6.85
	x_2 - Desalcap (m^3/day)	6,400	7,400	5,400
	x_3 - Pump power (MW)	14.5	19.5	-
	x_4 - Hydro power (MW)	8.5	19.5	-
	x_5 - LR (m^3)	100,000	100,000	14,980
	x_6 - UR (m^3)	150,000	280,000	-
Operational strategy	x_7 - n_{WB}	77.0%	5.0%	-
	$x_8 - f_H$	99.0%	100%	-
	n_H	99.2%	100%	-
	$x_9 - f_{FF}$	0.0%	5.0%	-
	n_{FF}	21.4%	25.3%	-
f_2 - Total RES		83.5%	89.7%	21.4%
f_3 — Wind power curtailed (MWh)		12,126	30,418	10,898
Wind power curtailed		12.9%	24.5%	36.5%
f_2 - TC $(M€)$		20.74	22.08	28.40
CO_2 Emissions ($ktCO_2$)		15.4	10.4	45.9

Table IV.19 - Results of solutions 1501 and 4429 compared with the baseline scenario.

Both solutions of the optimization problem present significant reduction in total annualized costs, increase of the share of RES in total power production and decrease of CO_2 emissions in comparison with the baseline scenario. Naturally, solution 1501 presents the greatest savings regarding total costs and solution 4429 presents the greatest increase in the share of RES and decrease in CO_2 emissions. The adoption of the proposed integrated system can reduce the total annualized costs by 22% to 27% in 2020, can decrease the percentage of wind power curtailed in relation to the wind power potential between 33% and 65% (i.e. a decrease of 24pp and 12pp, respectively), increase the share of RES four times, and reduce the CO_2 emissions between 67% and 77%.

It is important to refer that the optimal capacity of the lower reservoir in these solutions is the maximum of the range considered for this variable. Despite this, this range is not increased because this capacity is considered the maximum suitable to construct in this island. Regarding the solution that maximizes the share of RES production, the same occurs for the wind power installed. A wind power of 28.10 MW is the equivalent of installing 25 more V52 wind turbines than the ones already installed on S. Vicente. Hence, the range of this variable is also not increased.

IV.4 Summary

From the results of the modelling of the system proposed for S. Vicente, it is possible to conclude that the direct supply of wind power to the desalination units is able to somewhat decrease the wind power curtailed, improving the electricity and water production costs and reducing the CO_2 emissions. However, only with the addition of a PHS system it is possible to cancel out all wind power curtailed. With this storage system, it is even possible to increase the installed wind power and desalination capacity in order to decrease the total costs, resulting in 75.8% of RES in the total electricity production and in a reduction of the total production costs of 21.4% in relation to the Baseline Scenario.

The optimal configuration found for the proposed system practically does not change with the addition of the CO_2 emission cost, and the total costs increase very slightly.

The sensitivity analysis revealed that even with a large decrease of the fossil fuel cost, the proposed system still brings economic savings in relation to the Baseline Scenario, and that a high increase of the PHS investment cost results in a small increase of the total production costs, i.e. the proposed system still allows for significant savings in relation to the Baseline Scenario.

The optimization carried out for the sizing and the operational strategy of the proposed integrated system for power and water supply revealed that, considering that the most important objective function is the minimization of the total costs, the optimized solution is the one listed in Table IV.20. This table also includes the results of Scenario 5 considering a CO_2 emission cost of 6.96 €/tCO_2 for comparison purposes. Since, in the optimization process, the capacities of the reservoirs of the PHS are allowed to vary, it is expected that the results from this optimization reach higher values for the installed wind, pump and hydro power than in Scenario 5. Nevertheless, the desalination capacity reached is smaller. The share of wind power and PHS is of the same order of magnitude, although it increases slightly for the optimized solution, for the same reasons. This implies a decrease of the CO_2 emissions by 27% in relation to scenario 5. Although the optimized solution presents a higher installed wind power, the percentage of wind power curtailed in relation to the total wind power production potential decreases slightly. Even though the desalination capacity installed is smaller in the optimized solution than in scenario 5, the wind powered desalination is higher. This is a result of the higher capacity of the lower reservoir.

<table>
<tr><th colspan="2"></th><th colspan="2">Scenario 5 with 6.96€/tCO_2</th><th colspan="2">Optimized solution</th></tr>
<tr><td rowspan="6">Installed equipment</td><td>Wind power (MW)</td><td colspan="2">18.75</td><td colspan="2">21.30</td></tr>
<tr><td>Desalcap (m^3/day)</td><td colspan="2">7,400</td><td colspan="2">6,400</td></tr>
<tr><td>Pump power (MW)</td><td colspan="2">10.5</td><td colspan="2">14.5</td></tr>
<tr><td>Hydro Power (MW)</td><td colspan="2">8.0</td><td colspan="2">8.5</td></tr>
<tr><td>LR (m^3)</td><td colspan="2">35,000</td><td colspan="2">100,000</td></tr>
<tr><td>UR (m^3)</td><td colspan="2">35,000</td><td colspan="2">150,000</td></tr>
<tr><td colspan="2" rowspan="3">Operational strategy</td><td rowspan="2">n_{desal}</td><td rowspan="2">30%</td><td>n_{WB}</td><td>77.0%</td></tr>
<tr><td>n_H</td><td>99.2%</td></tr>
<tr><td>h_{FF} (h)</td><td>36</td><td>n_{FF}</td><td>21.4%</td></tr>
<tr><td rowspan="3">RES production</td><td>Wind power</td><td colspan="2">53.3%</td><td colspan="2">58.0%</td></tr>
<tr><td>PHS</td><td colspan="2">22.5%</td><td colspan="2">25.5%</td></tr>
<tr><td>Total RES</td><td colspan="2">75.8%</td><td colspan="2">83.5%</td></tr>
<tr><td colspan="2">Wind powered desalination</td><td colspan="2">88.5%</td><td colspan="2">99.6%</td></tr>
<tr><td colspan="2">Wind power curtailed</td><td colspan="2">15.0%</td><td colspan="2">12.9%</td></tr>
<tr><td colspan="2">$TC\ (M€)$</td><td colspan="2">22.21</td><td colspan="2">20.74</td></tr>
<tr><td colspan="2">CO_2 Emissions ($ktCO_2$)</td><td colspan="2">21.1</td><td colspan="2">15.4</td></tr>
</table>

Table IV.20 – Comparison between the results of the modelling and of the optimization.

V. Closure

V.1 Conclusions

In this study, an integrated power and water supply system is proposed to tackle the issues of RES integration and water scarcity of the Island of S. Vicente in Cabo Verde.

Based on the existing load, water load and meteorological data, different scenarios are built and modelled using the H2RES model. The proposed wind powered desalination and PHS system is then optimized regarding its size and operational strategy.

The financial analysis is carried out using the simplified levelised cost of energy method that finds the price of energy that sets the sum of all future discounted cash flows to zero. This method is adapted to consider the power and water production costs. Each production cost includes the investment cost of the components used to produce the specific output (power and water). The costs are annualized considering the capital recovery factor that uses the discount rate and the lifetime of the equipment. The discount rate considered in this study is 10%.

The results reveal that, with the current installed wind power and desalination capacity on S. Vicente, it is possible to have, by 2020, more than 25% of wind power production, together with more than 56% of the water supplied to the population produced from wind power, with slightly lower costs than the ones foreseen for this year in the baseline scenario. With a PHS system, the RES production can reach 36% (31% wind power and 5% PHS), with 56% of wind powered desalinated water and with about 7% decrease of costs in relation to the ones foreseen for 2020 in the baseline scenario. If the installation of more wind power and desalination capacity is considered, RES production can reach 76% (53% wind power and 23% PHS), with 89% of wind powered desalinated water, with about 21% decrease of costs in relation to those predicted for 2020. This configuration avoids about 54% of CO_2 emissions forecasted for 2020.

The consideration of the CO_2 emissions cost in the production costs of the integrated system has a small influence on the results. This is due to the fact that fossil fuel is already quite expensive in S. Vicente.

In relation to the sensitivity analysis carried out, the increase in electricity and water demand results in an increase in the production costs of the same magnitude. It also results in a larger optimal wind powered desalination and PHS system, as expected. Also, as expected, the decrease of fuel costs results in a smaller optimal integrated system. However, even with a significant decrease of fuel cost, the proposed system is more economically viable than the current one installed in S. Vicente, with the advantages of being more environmentally friendly since it produces lower CO_2

emissions, using mostly endogenous resources and less subjected to fossil fuel cost oscillations that are difficult to predict. The large increase of the PHS system investment's cost results in a relatively low increase in the production costs and in an optimal integrated system very similar to the reference case. The use of the wind speed data from the nearest meteorological station without the adjustment of real wind power production allows for an even better performance of the integrated system, with greater savings in production costs and CO_2 emissions in relation to the Baseline Scenario.

An optimization analysis is carried out applying the Direct MultiSearch method for the sizing and operational strategy of the proposed integrated system. The solutions of the Pareto optimal set are presented and analysed, namely the projection of this set of solutions in the plane total costs versus share of RES in the total power production of the system. In this way, the decision maker has more information about the system and has the possibility to select a given solution depending on what he considers to be the most important objective function. The optimized solution, considering the minimization of the total costs of the integrated power and water supply system, indicates that the RES production can reach 84% (58% wind power and 26% PHS), with 99.6% of wind powered desalinated water, with about 27% decrease of costs in relation to those predicted for 2020. This configuration avoids about 67% of CO_2 emissions forecasted for 2020.

An integrated power and water supply system can indeed increase the penetration of RES in an arid island, while minimizing the production costs. In the case of S. Vicente, an island with important wind resources and the topography suitable for PHS, the proposed wind powered desalination and PHS system is able to significantly increase the RES penetration and decrease the electricity and water production costs in relation to the ones foreseen for 2020.

Generally, the total annualized costs increase with the wind power curtailed, however, the relation between these two values is not linear. The results reveal that in some situations it is economically viable to have a little more wind power curtailed.

The load of the desalination units does not have a significant influence on the results, being the capacity of the reservoirs of the PHS system more important to allow the desalination units to work with a higher load.

The optimal operational strategy of this integrated system depends greatly on the sizing of the system installed. Considering the results of the optimization analysis regarding the minimization of the total costs, the optimal operational strategy consists in only producing water from the fossil fuel based units when the lower reservoir has less water that it minimum allowed, producing electricity from the hydro plant as long as there is water in the upper reservoir and space for water in the lower reservoir and, finally, balancing the wind power that goes to the desalination units and to the pumps from about 77% of capacity of the lower reservoir.

V.2 Future work

To tackle the issue of integrating RES in the island of S. Vicente it is important to study in detail the impact of the integration of wind power in the power grid stability of this island, using power grid simulation software. It is also important to explore in more detailed the effects of the intermittent limit considered in the results of this analysis, and analyse if modernized wind turbines and power distribution grids can support the increase of the intermittent limit to values above 30% in S. Vicente.

In addition, this study is based on wind speed data of one year; hence it is important to consider the variability of this resource from year to year, as well as the impact of climate change on the wind resource of S. Vicente.

This study is based on data obtained for the production of electricity and water in the island of S. Vicente. It is important to perform a detailed demand side modelling of the consumption of electricity and water in the island. It is also essential to improve the forecast of the consumption of these commodities in the island, considering the forecasted population and economic growth.

Regarding the scenarios proposed, it is necessary to have an environmental impact assess of the installation of a PHS system in S. Vicente, as well as carry out a detailed examination of possible sites to construct the reservoirs of this system.

It would be interesting to integrate a new method of producing water in the proposed system. In the suggested location of the PHS there is the occurrence of fog that can be collected to the upper reservoir. In this way, it is possible to increase the amount of water stored and, at the same time, increase the amount of energy stored in the PHS system. To verify if this brings additional value to the proposed system, the occurrence of fog in Mont Verde needs to be modelled and integrated in the model developed.

The relatively short distance between S. Vicente and its neighbouring island Santo Antão, about 20 km, allows the possibility of interconnection of the power systems of these two islands with a submarine connection. The Renewable Energy Plan of Cabo Verde published in 2011 [87] refers this possibility and concludes that this interconnection would decrease the current production costs of both islands. It would be interesting to verify the impact of this interconnection on the scenarios proposed in this thesis.

Finally, the decreasing cost of solar photovoltaic technology and the apparent high solar resource of the region, make its integration in the proposed system worthwhile to analyse.

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Annex I

Daily report of October 7th, 2006, of the Production Direction of ELECTRA

ELECTRA, S.A.

DIRECÇÃO PRODUÇÃO

RELATÓRIO DIÁRIO - **Data: 07 de Outubro de 2006**

Legenda:

EF	Em funcionamento
AV	Avariado
ER	Em reparação
FS	Fora de serviço

1. PRODUÇÃO DE ELECTRICIDADE TÉRMICA DIESEL)

UP	MEIOS DE PRODUÇÃO					Horas Func.		Consumos					ESTADO				Ponta (kW)*	
	MEIOS	P. NOM. (KVA)	P. DISP. (kW)	(kWh)	Rend.	Horas*	Acum.	Gasóleo	FO 180cSt	FO 380cSt	g/kWh	Lub.	EF	AV	ER	FS	Mín.	Máx.
S.VICENTE	DEUTZ N.º 1	1,250	0	0	0%	0	47,672	0			-		X				5757(6h)	9368(20h)
	DEUTZ N.º 3	2,750	2,200	0	100%	0	76,873	0			-			AV				
	DEUTZ N.º 4	2,950	2,360	0	100%	0	98,161	0			-		X					
	MAK N.º 5	3,968	3,175	28,200	100%	15	76,138	431	6,588		232		X					
	MAK N.º 6	3,968	3,175	0	100%	0	70,943	0	0		-		X					
	TURBINA MED	919	735	8,644	100%	24	48,429						X					
	CAT N.º 1	4,650	3,720	66,872	100%	24	27,619	0	0	15,697	225	410	X					
	CAT N.º 2	4,650	3,720	66,436	100%	24	29,653	0	0	15,457	223	205	X					
	TOTAL	25,105	19,085	170,153				431	6588	31154		615						

2. PRODUÇÃO DE ELECTRICIDADE (EÓLICA)

UP	MEIOS DE PRODUÇÃO								ESTADO			
	MEIOS	P. NOM. (kVA)	P. DISP. (kW)	(kWh)	Dispon.	Explor. Diária	Horas Func.	Hrs. Acomul.	EFICAZ	AVAR.	EM REP.	F. SERV.
S.VICENTE	WTG n.º 1	438	350	**1,400**	100%	16.7	24		X			
	WTG n.º 2	438	350	**1,400**	100%	16.7	24		X			
	WTG n.º 3	438	350	**1,400**	100%	16.7	24		X			
	TOTAL	1314	1050	4,200								
	Média/hora			175								

3. PRODUÇÃO DE ÁGUA

460

UP	MEIOS DE PRODUÇÃO					Horas Func.		Consumos					Contr. Quali. Água		ESTADO			
	MEIOS	P.NOM.(m^3/dia)	P.DISP.(m^3/dia)	P. Dia. (m^3)	Rend.	Horas*	Acum.	COMB. (L)	kW Import.	kW Export.	l/m^3	kWh/m^3	pH	Cond.(mS/cm)	EF	AV	ER	FS
S.VICENTE	R O N.º 1	1000	1000	918	92	24	14,106		3,940			4.3	8.96	0.9	X			
	R O N.º 2	1000	1000	266	27	7	14,242		1,420			5.3	8.65	0.75	X			
	R O N.º 3	1000	1000	876	88	22	13,842		3,740			4.3	8.70	0.8	X			
	MVC	1200	1120	0	0	0	82,657		0			-						X
	MED	2400	2150	1782	74	24	55,409	17,100	8,700	0	9.6	9.7	0	0	X			
	TOTAL	6600	6270	3,842				17100	17,800	0								

»»»Ocorrências:(incidentes, indisponibilidades, cortes, paragens gerais etc.)

»»»Substituida a bomba de captação de água do mar dos Ros

»»»O separador de fuel Nº2 da central Mak foi aberto para inspeção

»»»O RO3 parou ás 18h30 por pressão baixa a entrada do P2

O Chefe de Turno
Gabriel Boaventura Gonçalves

O Chefe da UP-SV
Amilcar Moreira

ELECTRA - sarl - DELEGAÇÃO DE S. VICENTE
SERVIÇO DE PRODUÇÃO DE ENERGIA

RELATORIO DIÁRIO DE EXPLORACAO

	Diagrama de carga diária - Dia 07 de Outubro de 2006										
Horas	**DEUTZ 3**	**DEUTZ 4**	**MAK 1**	**MAK 2**	**CAT 1**	**CAT 2**	**PE I**	**PEII**	**T.MED**	**T.MSF**	**Total (kW)**
1					2900	2800		500	353		6,553
2					2800	2800		500	345		6,445
3					2700	2700		600	326		6,326
4					2500	2500		800	356		6,156
5					2600	2500		600	343		6,043
6					2400	2400		700	341		5,841
7					2300	2200		800	362		5,662
8				2200	2800			900	345		6,245
9					2900	2800		900	346		6,946
10					3100	3100		600	373		7,173
11					3000	3000		800	343		7,143
12					3000	3000		800	369		7,169
13					3000	2900		700	352		6,952
14					2800	2700		900	340		6,740
15					2800	2700		800	376		6,676
16					2800	2700		800	376		6,676
17					2900	2800		600	340		6,640
18					3000	2900		500	349		6,749
19			1700		3100	3100		600	354		8,854
20			1750		3000	3000		600	331		8,681
21			1800		3000	3000		500	351		8,651
22			1800		3000	2900		500	358		8,558
23			2200	210	2800			300	345		5,855
24					3200	3100		100	346		6,746
Total	0	0	9,250	2,410	68,400	61,600	0	15,400	8,420	0	165,480

P.max.	P.min.	P.med.
8,854	**5,662**	**6,895**

Annex II

Increasing the penetration of renewable energy resources in S. Vicente, Cape Verde. Applied Energy 2011.

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Increasing the penetration of renewable energy resources in S. Vicente, Cape Verde

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ABSTRACT

In this article different scenarios are analysed with the objective of increasing the penetration of renewable energies in the energy system of S. Vicente Island in Cape Verde. An integrated approach is used to analyse the electricity and water supply systems. The H_2RES model, a tool designed to simulate the integration of renewable sources and hydrogen in the energy systems of islands or other isolated locations, is applied.

There is no other source of fresh water available to supply the population of S. Vicente, apart from desalinated seawater. The electricity supply system of this Island is based on fossil fuel and wind. S. Vicente has important wind resources that are not fully used because of its intermittent nature. The topography of this Island is relatively uniform, with the exception of Mont Verde, a 774 m high mountain located in its centre, which could be suitable for pumped hydro storage.

The present analysis incorporates the possibility of using pumped hydro as a storage technique to increase the penetration of renewable energy sources, using desalinated seawater.

The results show that is possible to have more than 30% of yearly penetration of renewable energy sources in the electricity supply system, together with more than 50% of the water supplied to the population produced from wind electricity.

1. Introduction

Most islands depend mainly on the importation of fossil fuels for energy production and, at the same time, present a considerable potential in renewable energies. The use of this potential in the production of electricity and fresh water (usually very scarce in islands) could represent a large fraction of the total energy distribution [1].

One of the major challenges of increasing the penetration of renewable energy in a system is to integrate a high share of intermittent resources into the electricity supply system [2,3].

The intermittent nature of some renewable energy sources as well as the small energy systems of islands introduce barriers to their penetration, like the struggle to match the demand with the supply and the problems related with the integration in the network. Hence, the integration of intermittent renewable energy sources in energy systems requires the development of energy storage technologies, energy management technologies and a greater sophistication of these systems.

The integration of renewable energy sources in energy systems of small islands presents several advantages, namely at economical level, their high technological cost is compensated by the high cost of the conventional sources of energy due to the small dimension of the energy systems and because of a very expensive security of supply. In order to achieve sustainable development, the integration of renewable energy sources for the production of electricity, together with suitable policies and regulations regarding rational use of energy, are very important. The conventional electricity production technologies are rarely adapted to the conditions of isolated areas and can seriously damage the vulnerable ecosystems and natural habitats. There is the need to develop an energy supply infrastructure that takes into consideration the seasonal variations caused by the tourist activity, without destroying the local environment or producing avoidable emissions.

Due to the several available renewable energy sources, the increasing number of technologies for their use and the different options for energy storage, the planning and modelling of energy systems are complex and demanding. Specialized models were developed to help in solving that problem [4].

To date, a number of analyses have been carried out on the feasibility of integrating renewable energy resources in islands. Many of them consider the possibility of using hydrogen as energy storage, in order to increase the penetration of intermittent renewable energy sources in the energy systems of islands [4–9].

In many places there is already an excellent storage potential in the local water supply system. By merging the energy and water supply systems, where there is sufficient elevation difference, it

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is possible to use pumped hydro storage in order to increase the penetration of intermittent renewable energy sources, as for example wind, even in case where there is not much hydro potential.

In Duić et al. [10], the possibility of using pumped hydro storage in the Island of Corvo, in Azores, is analysed. In this case, with the integration of the water supply system with pumped hydro, adding storage to energy and resources systems, it is possible to significantly increase the penetration of locally available resources and thus increase the security of supply and decrease the import dependence.

A wind-powered pumped hydro system is proposed in Bueno and Carta [11] for the Island of El Hierro, Canary Islands, in order to increase the renewable sourced energy penetration of the Island grid. The results indicate that an annual renewable energy penetration of 68% can be achieved.

S. Vicente has very important and stable wind resources. The Island also has Mont Verde, a 774 m high mountain located in its centre. These features make S. Vicente suitable for the use of pumped hydro as a storage technique. As there is no fresh water available in the Island, the proposed solution considers the use of desalinated water in the pumping and hydro station to later be supplied to the population.

The installation of desalination units is a common solution throughout the world in areas with water scarcity [12]. However, desalination is a process that requires a significant amount of energy [13], thus, renewable energy driven desalination plays a vital role in the application of this technology.

There are several studies that analyse renewable energy powered desalination systems [12–21].

The purpose of this study is to couple these two issues: the integration of renewable energy sources in the electricity supply system and the water scarcity problems of S. Vicente, using the intermittent excess to supply the desalination and the pumping units.

The innovation of this study lies on the analysis of the combination of these two supply systems (energy and water) in order to increase their efficiency.

In this article different scenarios are analysed for increasing the penetration of renewable energy in the energy system of S. Vicente Island. The tool used is H_2RES, a model designed to simulate the integration of renewable energy sources and hydrogen in islands or other isolated locations.

There are two types of scenarios. Scenarios with 30% hourly intermittent energy penetration, that is considered the limit of the current conversion technology that is installed on the Island, and scenarios without this limit, where it is assumed that the conversion technologies can also provide output control and auxiliary services [8].

It is shown that is possible to have more than 30% of yearly penetration of renewable energy sources in the electricity supply system, together with more than 50% of the water supplied to the population produced from wind electricity. The penetration of renewable energy sources can reach 70%, when 100% hourly intermittent energy penetration is considered.

2. Methodology

2.1. H_2RES model

In Connolly et al. [22], a review is made of the different tools than can be used to analyse the integration of renewable energy. H_2RES is classified as a simulation tool, as it simulates the operation of a given energy system to supply a given set of energy demands; a scenario tool, as it combines a series of years into a long term scenario; a bottom-up and an operation optimisation tool.

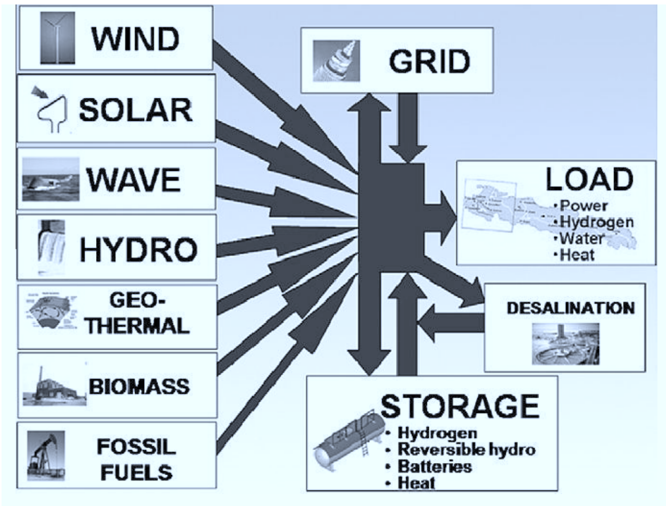

Fig. 1. H_2RES computer model v2.8.

The H_2RES model (Fig. 1) simulates the integration of renewable sources and hydrogen in the energy systems of islands or other isolated locations. It is based on hourly time series analysis of demand (water, electricity, hydrogen, heat); storage (pumped hydro, batteries, hydrogen, heat) and resources (wind speed, solar radiation, precipitation). The main purpose of this model is energy planning of islands and isolated regions which operate as stand-alone systems, but it can also serve as a planning tool for single wind, hydro or solar power producer connected to a central power system. Throughout time, the model is evolving and several new modules have been developed such as wave, biomass, solar heat and desalination.

Several articles describe H_2RES model with details of its operation [1,4–8,10]. The version that has been used for calculating Portugal case study has been updated with a wave module. The main characteristic of H_2RES model is that it uses technical data of equipment, hourly meteorological data for intermittent sources and, according to description in [6,7], energy balancing is regulated by equations.

Wind velocity, solar radiation and precipitation data obtained from the nearest meteorological station are used in the H_2RES model. The wind module uses the wind velocity data at 10 m height, adjusts them to the wind turbines hub level and, for a given choice of wind turbines and converts the velocities into the output.

The load module, based on a given criteria for the maximum acceptable renewable electricity in the power system, puts a part or all of wind and solar output into the system and discards the rest of the renewable output. The hourly load of the power system is obtained from the local utility.

The excess renewable electricity is then stored either as hydrogen, pumped water or electricity in batteries. The energy that is stored can be retrieved later, and supplied to the system as electricity. The rest is covered by diesel blocks.

A comparative study between H_2RES and EnergyPLAN, a model designed for the analysis of different regulation strategies of complex energy systems, is made in Lund et al. [23].

2.2. Desalination module

The desalination module uses the electricity produced from excess wind to supply the desalination units, that produce drinkable water and put it on the lower reservoir, this reservoir is then used to supply the population. This module takes into account the total capacity of these units (m^3 of water produced per hour) and their electricity consumption per unit of water produced. At each hour, the desalination module verifies if the lower reservoir has at least 1 day of water demand, if it does not, and if the user allows this option, the desalination units are supplied with electricity from the fossil fuel blocks.

2.3. Optimisation criteria

According to Østergaard [24], many different optimisation criteria might be applied to the design of environmentally benign energy systems and no unequivocal answer can be found to the question of how to design an optimal energy system.

The optimisation criteria used in this study is the maximization of the penetration of renewable energy sources in the electricity system of S. Vicente, keeping the rejected intermittent electricity close to 10% in the scenarios with 30% hourly intermittent energy penetration. In scenarios with 100% hourly intermittent energy penetration, the rejected intermittent electricity is kept under 30% [1].

3. Results

3.1. The Island of S. Vicente

S. Vicente is the second most crowed Island in the Archipelago of Cape Verde, which is composed of 10 Islands and is situated at about 450 km of the West African coast, in the Atlantic Ocean (Fig. 2). This Island had about 74,031 inhabitants in 2005 [25], mostly concentrated in its capital, Mindelo.

S. Vicente has about 228 km^2 of area and its topography is relatively uniform, having just one high point – Mont Verde – located at 774 m of altitude.

The Island is extremely dry; all of the fresh water provided to the population is obtained by seawater desalination. The desalination units installed in S. Vicente are showed in Table 1.

The reverse osmosis unit of 1200 m^3 per day is the most recent unit, installed in 2007.

In 2005 the total fresh water production was about 17 m^3 per capita.

The electricity production in the Island is based in fossil fuel and wind technologies. There are two conventional thermal fossil fuel power plants, the Matiota and the Lazareto plants. The total fossil fuel power installed in 2005 was about 20,170 kW. There are also three Nordtank wind turbines of 350 kW each [27].

Table 1
Desalination installed capacity in S. Vicente [27,28].

Technology	Number of units	Nominal capacity (m^3/day)
Reverse osmosis	3	1000
Mechanical vapour compression	1	1200
Multiple effect distillation	1	2400
Reverse osmosis	1	1200
Total	6	7800

The electricity production in this year was about 57 GWh and the peak power was 10,200 kW.

The electricity demand is relatively stable throughout the year, as there are not large climate variations, as can be seen in Fig. 3, with the hourly load of January 15th and August 15th 2005.

The Island has important wind resources. The hourly wind speed of 2005 was collected from the local meteorological station. In this year, the average wind speed was about 8 m/s.

3.2. Energy scenarios for S. Vicente

In order to apply the H_2RES model to the Island of S. Vicente, five scenarios were elaborated, having all 2005 as base year.

The first scenario is the Business As Usual, as it only considers the projects that are already foreseen for the Island.

Regarding the evolution of the electricity and water demand, study made by the Research Group on Energy and Sustainable Development in the scope of the National Energy Plan for Cape Verde [29], was considered. This study considered the forecast of the evolution of the Gross Domestic Product and of the resident population in order to forecast the growth in the consumption of electricity in the different Islands of Cape Verde (Table 2), the growth in the consumption of water was considered the same.

Currently, wind energy can be considered economic viable in islands, as long as it does not surpasses a certain limit of penetra-

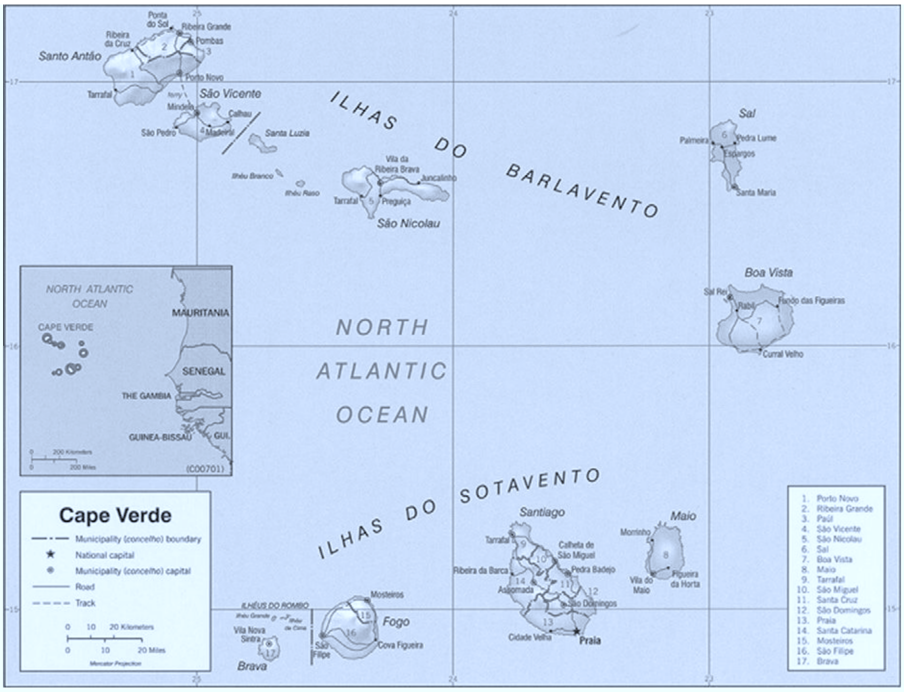

Fig. 2. Map of Cape Verde [26].

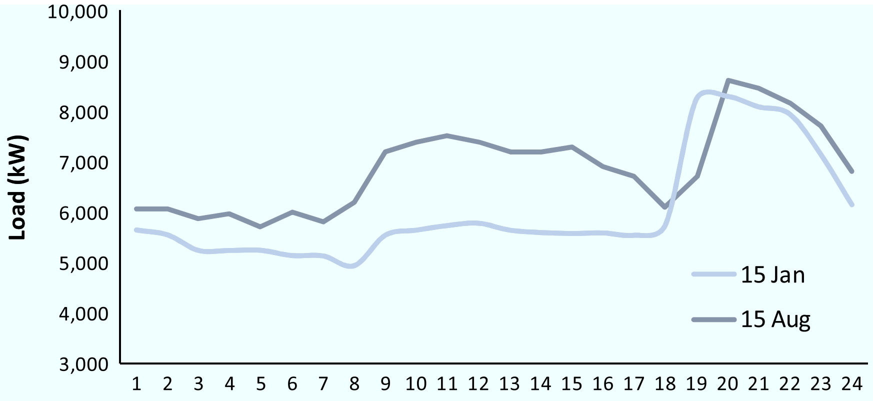

Fig. 3. Hourly electricity load of 1 day in the summer and 1 day in the winter in 2005, in S. Vicente.

Table 2
Forecast of the annual demand growth of electricity in the Island of S. Vicente [29].

Period	Annual growth (%)
2006–2009	7.92
2010–2014	6.40
2015–2019	4.20
2020–2024	3.36
2025–2030	3.08

tion. The base scenario is then defined delimiting 30% of the hourly renewable energy penetration, which means that only 30% of the load of 1 h can be covered by electricity generated from wind.

According to ELECTRA, the local utility, it is foreseen the installation of more 6800 kW of wind-power in the Island, in this study it is considered that it will be 8 turbines V52 of 850 kW each, from Vestas.

The second scenario considers the supply of electricity produced from wind to the desalination plants already installed on the Island. This scenario considers the construction of a 30,000 m^3 reservoir, at low altitude, where the water that comes out of the desalination plant will be stored before being supplied to the population. It is believed that S. Vicente has several reservoirs of smaller dimension spread through the Island. When the excess electricity from wind is not enough to desalinate all the water needed the diesel blocks are used to supply the remaining required electricity.

The succeeding scenario maximizes the desalination from wind electricity.

Scenario four considers the storage of the excess wind production through pumping of the desalinated water. This scenario contemplates the construction of a dam or water reservoir with about 50,000 m^3 at 500 m of altitude. Thus, the wind park would supply electricity to a desalination plant and to a pumping station that puts desalinated water in the upper reservoir. When it is necessary to supply water and electricity to the population, the water is turbinated from the upper to the lower reservoir (Fig. 4).

The fifth scenario is similar to the previous one, but aims to maximize the renewable energy sources (RES) penetration in this energy supply system.

All of these scenarios were modelled once more, but allowing an hourly intermittent energy penetration of 100% (scenarios 6–9).

3.3. Results of the modelled scenarios

3.3.1. Scenario 1 – BAU

Regarding the first scenario, the electricity production in S. Vicente from 2005 to 2030 is stated in Fig. 5. It was considered the above mentioned installation of 6800 kW of wind energy by 2010 and the addition of diesel blocks to satisfy the growth of the demand.

It is clear that the penetration of the wind electricity production increases from 2005 to 2010, due to the installation of the new wind turbines, it increases from 6% to 22%. However, from then on, it decreases, as no more wind turbines are added to satisfy the demand growth, only diesel blocks.

In this scenario, the electricity produced from wind has a large amount that is rejected, especially in 2010, with 45% of wind electricity rejected. As the years go by, this rejection decreases due to the growth of demand and the non installation of more wind turbines, in 2030 it reaches about 9% (Fig. 6).

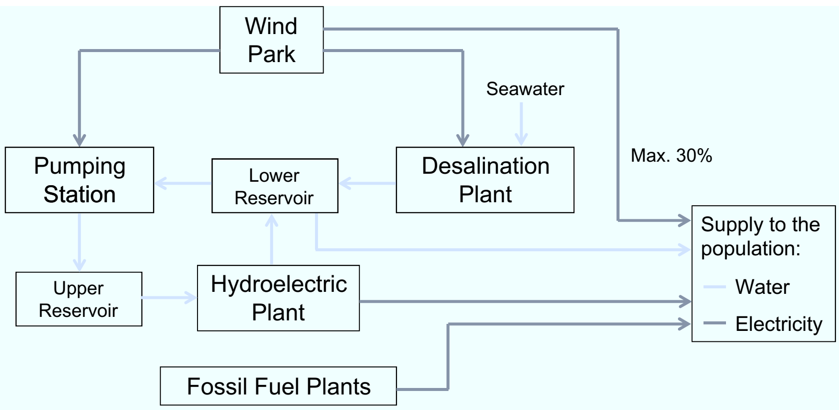

Fig. 4. Scheme of scenario 4.

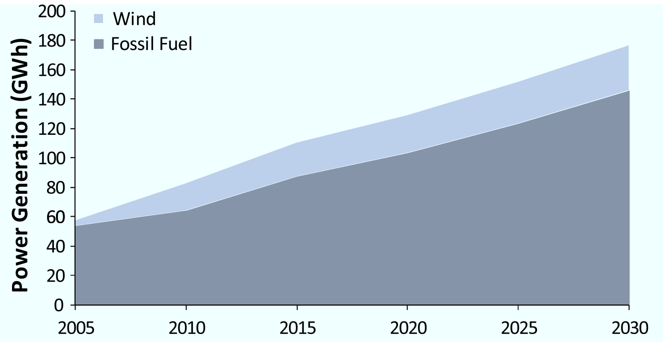

Fig. 5. Power production in S. Vicente for the BAU scenario.

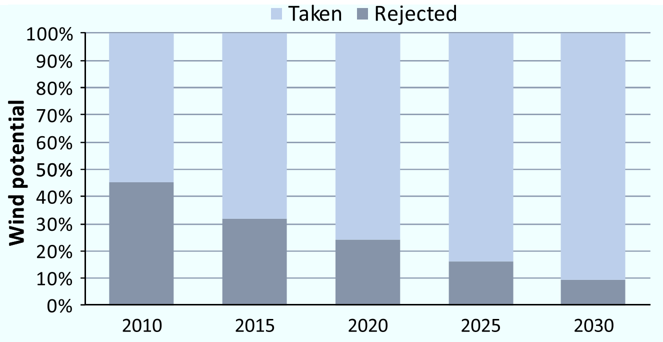

Fig. 6. Wind potential taken and rejected in S. Vicente for the BAU scenario.

3.3.2. Scenarios 2 and 3 – desalination from wind

An excellent way to decrease the wind electricity rejected is to supply the desalination plant with this excess electricity. However, when modelling this scenario, the first conclusion reached was that the wind produced was not enough to desalinate all the water needed. Hence, it was considered the supply of electricity from the diesel blocks, when the electricity from wind was not enough.

The evolution of the water demand was considered to be the same as the electricity demand.

These calculations considered desalination units already installed in the Island, and the addition of desalination units to satisfy the growth of the demand over the years.

The load considered in the first scenario included the electricity needed to desalinate water to be supplied to the population, thus, there was the need to subtract the electricity used for desalination. According to [27], 14% of the electricity produced in S. Vicente in 2005 was to supply the desalination units. Hence, and because hourly consumption of water does not vary very much, as there are not large water storages, this percentage was deducted from the hourly load.

Regarding the supply of electricity from wind, although there is a 30% hourly limit for the supply of the population, there is no limit for the supply to the desalination units.

A reservoir of 30,000 m^3 was considered, in order to have water storage with a capacity of about 5 days of the demand of 2010.

In this scenario, the penetration of wind electricity reaches higher levels than in the previous one. The proportion of wind electricity rejected in this scenario is much lower, reaching its higher value, about 23%, in 2010.

In order to maximize the desalination from wind (scenario 3), the influence of the wind turbines installed, of the capacity of the desalination units and of the capacity of the lower reservoir was studied. Although the most important factor was the power of the wind turbines installed, the increase of this value leads to an increase of the wind electricity rejected. To avoid this, the capacity of the desalination units needs also to increase. Hence, as mentioned above, the number of wind turbines and desalination units was optimised so that yearly wind desalination was maximized while keeping the rejected wind electricity close to 10% [1].

With the installation of wind turbines throughout the year, it is possible to increase the penetration of wind electricity and keep it more or less constant along the years.

The production of desalinated water, by electricity from wind and from the fossil fuel blocks is stated in Fig. 7.

The fraction of desalinated water produced from wind reaches 57% in 2020, and although it decreases slightly in the following years, it never goes below 47%.

3.3.3. Scenarios 4 and 5 – desalination and pumped hydro

Scenario 4 considers the pumping of desalinated water to an upper reservoir with 500,000 m^3 of capacity, at 500 m of altitude, and its later supply to the population producing also electricity from the hydroelectric plant. It was considered that the hydroelectric plant is used for peak shaving, about 80% of the weekly peak. The load factor of the hydraulic turbines was kept above 20%.

In scenario 5, the RES penetration in the energy supply system of the Island of S. Vicente was maximized with the installation of more wind turbines. When modelling this scenario, there was the need to verify, when testing all the possibilities, if none of the reservoirs overflowed. This is a very important issue, especially in an island as arid as S. Vicente. Thus, the two restrictive factors in maximizing RES penetration were the prevention of overflow of the reservoirs and the control of the intermittent rejected.

The electricity production along the years for this scenario is indicated in Fig. 8.

In 2020, the hydroelectric plant produces about 3% of the total electricity produced in the Island, 30% is produced from wind, totalizing 33% of RES electricity.

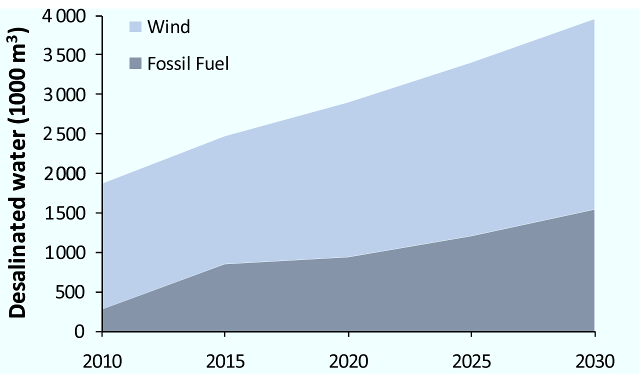

Fig. 7. Production of desalinated water in S. Vicente for scenario 3.

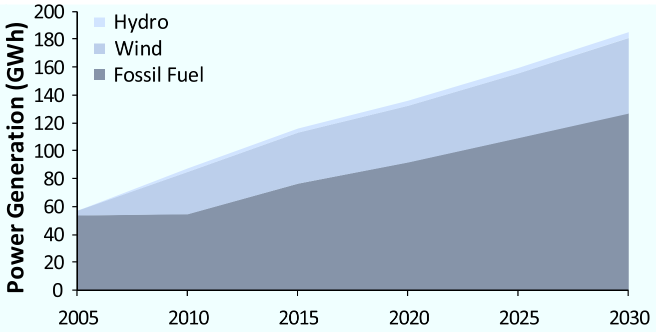

Fig. 8. Power production in S. Vicente for scenario 5.

3.3.4. 100% hourly intermittent energy penetration scenarios

These scenarios allow the hourly intermittent energy penetration rate to reach 100%. The number of wind turbines was optimised so that yearly wind penetration was maximized while keeping the rejected wind electricity close to 30% [1].

Unsurprisingly, in these scenarios the penetration of wind electricity is much higher. In scenario 7, where the desalination from wind is maximized, this value reaches 75% in 2020. The electricity produced from wind is about 70%.

In scenario 9, where the RES penetration is maximized, the hydroelectric plant produces about 6% of the total electricity produced in the Island in 2020, 65% is produced from wind, totalizing 71% of RES electricity.

3.3.5. Comparison between scenarios

In Fig. 9 the power generated to supply the Island of S. Vicente in the year 2020 in stated for four different scenarios.

It is clear that in scenario 9 the renewable energy sources have a higher fraction. In this scenario, the avoided electricity production from fossil fuel reaches 62.2 GWh. Using an overall electricity emission factor of diesel generators of 0.75 kg CO_2 per converted kWh [17], the avoided greenhouse gas emissions are 46,671 ton CO_2.

Considering the 30% of hourly penetration limit (scenario 5), the avoided electricity production from fossil fuel reaches 11.8 GWh which corresponds to 8860 ton CO_2 of avoided greenhouse gas emissions.

Fig. 10 illustrates the amount of desalinated water produced from wind and from fossil fuel in the different scenarios.

In scenarios 3 and 4, the desalination from wind is always balanced with the desalination from fossil fuel. In 2020, these scenarios present a fraction of desalinated water produced from wind of 53% and 56% respectively. Scenarios 7 and 9 have a higher fraction of desalinated water produced from wind, 75% and 59% respectively.

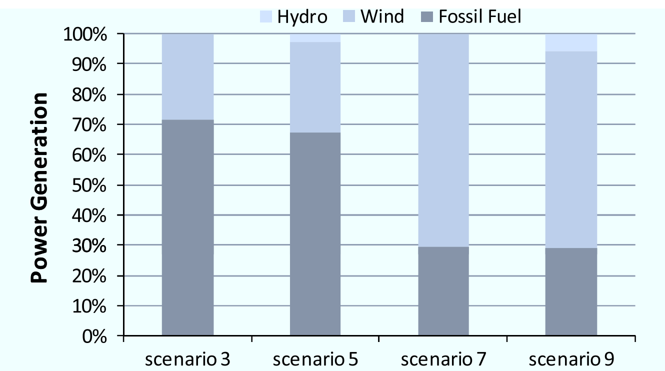

Fig. 9. Power production in S. Vicente in 2020, for four different scenarios.

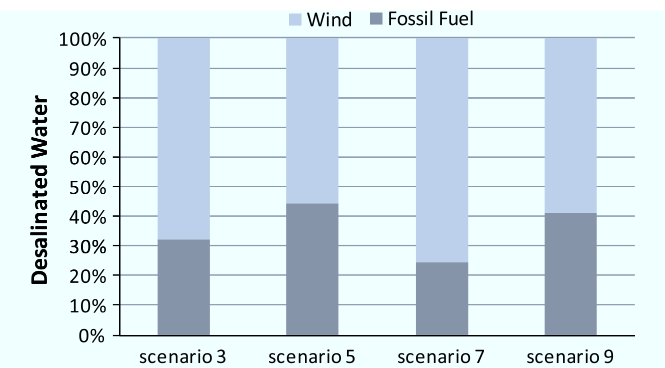

Fig. 10. Production of desalinated water in S. Vicente in 2020, for four different scenarios.

4. Conclusions and future developments

This article analyses the way to increase the penetration of renewable energy sources in the Island of S. Vicente, in Cape Verde, coupling the energy and water supply systems. Based on existing load data and meteorological data, several scenarios were built and modelled using the H_2RES model. The scenarios considered wind, pumped hydro storage and desalination technologies.

The maximization of desalination from wind resulted in fractions of desalinated water produced from wind of about 57% in 2020, but from the following years, this value decreased to around 50%.

The maximization of renewable energy sources in this supply system resulted in a penetration of about 33% of these technologies, with a major fraction from wind and a much lower contribution from hydroelectricity.

If an hourly intermittent energy penetration rate of 100% is allowed, the percentage of desalinated water produced from wind can reach 75% and 59% in 2020 for the scenarios 7 and 9, respectively, but for the following years, this value decreases. Regarding the maximization of renewable energy sources, the penetration of these technologies in this supply system reached 71%, with 65% of wind and 6% of hydroelectricity.

These scenarios need to be analysed in environmental and financial terms. There is also the need to examine the sites were the reservoirs can be built and the wind turbines installed, for instance to determine if it is possible to install reservoirs with this dimension, and what is the impact on the local environment.

In order to improve the input data of the first scenario and the baseline year, an update of the forecast of the demand growth will be carried out, together with an assessment of the demand in water and energy of the tourist projects foreseen for the Island.

Later work will be done on modelling the occurrence of fog in Mont Verde, and consider its collection to the upper reservoir, having this way more water stored in the upper reservoir, increasing the amount of water that can be turbinated to generate electricity and supplied to the population.

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Annex III

Integrated analysis of energy and water supply in islands. Case study of S. Vicente, Cape Verde. Energy 2015.

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Integrated analysis of energy and water supply in islands. Case study of S. Vicente, Cape Verde

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A B S T R A C T

The electricity production in S. Vicente is based on fossil fuel and wind power and, although there are significant wind resources, they are not fully used because of its intermittent nature. In a previous work, we proposed solutions to tackle this issue. Since this island does not have fresh water available, excess wind power can be provided to desalination units to produce desalinated water to supply the population. Other solution studied previously was the use of desalinated water in a pumped hydro system to store the remaining excess wind power. In this article, the scenarios modelled previously are updated with more recent data on energy and water consumption and the respective annual costs are estimated. The results show that with the current installed wind power and desalination capacity, and with the installation of a pumped hydro system, it is possible to have, by 2020, 36% of electricity production from renewable energy sources, with costs 7% lower than those forecasted for that year. If the installation of more wind power and desalination capacity is considered, renewable energy sources production can reach 72% (51% wind power, 21% pumped hydro), with about 19% decrease of costs in relation to those predicted for 2020.

1. Introduction

For small islands that are not interconnected with the mainland, the penetration of intermittent energy sources, e.g., wind power, in the electricity supply system is limited, even when there is a large renewable energy potential. This is due to technical constraints of the conventional generating units (namely their minimum loading level) and the dynamic penetration limit that is usually applied for grid stability [1]. In these cases, in order to minimize the curtailed wind power, the installed wind power is limited.

The electricity supply system of S. Vicente, Cape Verde, is based on fossil fuel and wind power (cf. Section 3.1) and, although this island has important wind resources (cf. Section 3.1), they are not fully used because of its intermittent nature. In addition, this island does not have any source of fresh water, being forced to desalinate seawater to produce water suitable for human consumption (cf. Section 3.2). This puts more pressure to the electricity supply system, since desalination requires a significant amount of energy. This can be an opportunity to implement renewable energy driven desalination.

To date, a number of studies have been carried out on the feasibility of integrating renewable energy sources (RES) in islands, and all of them rely on energy storage and/or demand side management strategies. Duić et al. [2] proposed a wind powered pumped hydro system (PHS) for the island of Corvo in The Azores. This study showed that only by adding storage to energy and water resource systems is it possible to significantly increase the penetration of locally available renewable energy resources, and thus increase the security of supply and decrease the import dependence. Krajačić et al. [3] concluded that with an energy storage system based on hydrogen, the island of Mljet in Croatia could become 100% renewable island concerning electricity and simulated transport needs and also could export additional power to the mainland power grid. The prospect of creating a combined wind-hydro energy production station for Aegean Sea islands in Greece has been analyzed by Kaldellis and Kavadias [4]. Bakos [5] discussed the operation of a hybrid wind/hydro power system aimed at producing low cost electricity for the island of Ikaria in Greece.

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0360-5442/

A number of analyses have been also carried out on the feasibility of using RES in desalination plants. Spyrou and Anagnostopoulos [6] investigated the optimum design and operation strategy of a stand-alone hybrid desalination scheme, capable of fulfilling the fresh water demand of an island. The scheme consisted of a reverse osmosis desalination unit powered by wind and solar electricity production systems and by a pumped storage unit. Fadigas and Dias [7] proposed an alternative configuration to conventional reverse osmosis desalination systems by incorporating the use of both gravitational potential energy and wind energy.

All of the cited studies have examined either the energy or the water supply system. The studies in Refs. [2–5] focus on the energy supply systems and the studies in Refs. [6,7] concentrate on the water supply systems, although they deal with the energy demand of such systems. Novosel et al. [8] stated that an important concept for a wide scale implementation of desalination units is the integration of energy and water resources. Siddiqi et al. [9] conclude that joint consideration of both water and energy domains can identify new options for increasing overall resource use efficiencies. Østergaard et al. [10] investigated a Jordanian energy scenario with different desalination technologies; they use desalination to decrease excess electricity production and conclude that water storage has some implication for the system's ability to integrate wind power.

This article discusses ways to increase the penetration of RES in the island of S. Vicente, Cape Verde, by coupling the energy and water supply systems. The scenarios established propose two ways of storing excess wind power in this island. One way is to provide the excess wind power to the desalination units and the other is to use this excess in a pumped hydro system, which is possible in S. Vicente, since it has the suitable topography.

The use of excess wind power in the desalination units can be considered a demand side management strategy since the water cannot be turned back to electricity with a reasonable efficiency. However water can be stored. In our previous work [11], these solutions have already been proposed and modelled. The results showed that it is possible to have more than 30% of yearly power production from RES (33% wind power and 3% PHS) and 50% of the water supplied to the population from wind power. It was concluded that there was the need to calculate the cost of the scenarios developed, in order to assess their economic viability and compare the solutions proposed to the current systems [11]. It was also previously demonstrated that to decrease the wind power curtailed, the capacity of the desalination units need to increase; however, it is very important to ensure that the load of the desalination units is high enough to guarantee the financial viability of the system [11].

The main objective of this study is to find a solution that minimizes the costs, while keeping the penetration of wind power the highest possible. The scenarios modelled previously are updated with more recent data on energy and water consumption of the island, and the electricity and water production costs are estimated. This study intends also to understand how the electricity and water production costs vary with the wind power curtailed and with the load of the desalination units in order to find an optimum configuration.

2. Methodology

As in our previous work [11], the simulation tool used is the H2RES model, which simulates the integration of renewable sources and hydrogen in the energy systems of islands or other isolated locations. It is based on hourly time series analysis of demand (water, electricity, hydrogen, heat); storage (pumped hydro, batteries, hydrogen, heat) and resources (wind speed, solar radiation, precipitation) [3]. More information on the H2RES model can be found in Ref. [3] and, more specifically, on the desalination module in Ref. [11].

The wind power produced is used firstly to cover the load, according to the dynamic (hourly) penetration limit allowed. The wind power that surpasses this limit (excess) is used in the desalination units. The desalination units use this wind power to fill the reservoir used to supply water to the population (lower reservoir). After that, if there is still wind power available it is stored as pumped water into an upper reservoir. The energy that is stored can be retrieved later, and supplied to the system as electricity. The remaining energy needs are covered by fossil fuel-based systems.

Østergaard [12] investigated how energy systems can be designed to achieve the optimal integration of fluctuating energy sources. Such systems can be designed from an economic perspective or from a technical-operational perspective, which render different results. The optimization criteria used in this study is the minimization of the costs, while keeping the wind power integration in the water and energy supply systems the highest possible.

Since the H2RES model does not allow performing optimization, it is necessary to run all potential configurations and verify their technical feasibility (i.e., if they are able to supply the required electricity and water demand at all hours) and identify the one with lower total annual costs. The optimization performed in this study is an investment and operational optimization. On one hand each iteration has a specific potential configuration (capacity of the equipments installed), and, on the other hand, certain operational conditions could be changed in order to avoid the overflow of the reservoirs, namely the maximum amount of wind powered desalinated water in each hour.

The total annual costs are estimated using the simplified levelised cost of energy method. The term levelised cost of energy emphasizes the fact that this cost is determined over a certain time (technical lifetime of a specific technology). In practise, the objective is to find the price of energy that sets the sum of all future discounted cash flows to zero [12]. Each production cost includes the investment cost of the components used to produce the specific output (electricity and water).

2.1. Electricity production cost

The electricity production cost of each scenario is estimated as follows:

$$\mathrm{EPC} = \frac{\mathrm{IC}_e \times \mathrm{CRF} + \mathrm{OMC}_e + \mathrm{FC}}{E} \quad (€/\mathrm{kWh}) \tag{1}$$

where IC_e is the total investment cost of the system. This value includes the investment costs of all necessary equipment in the energy supply system. The investment costs of equipments already installed on the island, but within lifetime, are considered. *CRF* is the capital recovery factor (annuity factor) that is used to annualize the investment cost and depends on the lifetime of the equipments (n) and on the discount rate considered (i) as follows:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{2}$$

In Eq. (1), OMC_e is the total yearly operation and maintenance cost of the system that usually is, according to the technology, a given percentage of the investment cost, *FC* is the yearly fossil fuel costs, and *E* is the total yearly electricity production. The total annual costs are divided by this value to assess the electricity production cost in €/kWh.

The technologies considered are the ones already installed in S. Vicente: fossil fuel-based generators, wind turbines and a system for energy storage that is pumped hydro.

2.2. Water production cost

The water production cost is calculated as follows:

$$\mathrm{WPC} = \frac{\mathrm{IC}_W \times \mathrm{CRF} + \mathrm{OMC}_W + \mathrm{EC}}{W} \quad \left(€/\mathrm{m}^3\right) \tag{3}$$

where IC_W is the total investment cost of the water supply system. It also considers the investment cost of existing equipment on the island. In Eq. (3), OMC_W is the total yearly operation and maintenance cost of the system that usually is a given percentage of the investment cost, EC is the yearly electricity costs, and W is the total yearly water produced.

The technology considered for the production of water is the only one that is used in S. Vicente, i.e., desalination of seawater using reverse osmosis. The electricity costs consider the electricity production costs calculated with the method described above. In this way, the electricity production cost has obviously a strong influence on the water production costs.

2.3. Total costs

The total annual costs (TC) can be divided in electricity production costs and water production costs, and depend on the total yearly electricity and water produced. It can be calculated as follows:

$$\mathrm{TC} = EPC \times E + \mathrm{WPC} \times W \quad (€) \tag{4}$$

3. Case study

S. Vicente is a 227 km^2 island of the Arquipelago of Cape Verde, located about 450 km of the West African coast. It is the second most crowed island of the country, it had ~76,000 inhabitants in 2010, mostly concentrated in Mindelo, its main city [13]. Fig. 1 shows a map of S. Vicente [14]. This island is not interconnected with any other island.

Power in Cape Verde is supplied by the multi-utility ELECTRA, which is also responsible for the water supply in some of the islands, like in S. Vicente. Cape Verde has achieved a relatively high electrification rate. According to the National Census of 2010, 81% of the total population has access to electricity [13]. This value is above the average for African countries (43%), and also above the average for developing countries (76.1%), but below the average for transition economies and OECD countries that reach 99.8% [15]. However, the increase in the electrification rate over the years in Cape Verde was not accompanied by a proportional increase in the electricity production, with the power installed decreasing. Between 2002 and 2006, the power installed decreased about 4%, while connections rose by 40% and production by 10%. Hence, blackouts became more frequent and longer in duration due to a tight demand-supply balance [16].

In Cape Verde energy production is largely dependent on fossil fuel-based plants, which in turn rely on expensive fuel imports. Fuel costs represent more than 70% of the power production costs [16].

A single power price is applied across all islands despite differences in costs – a geographical cross-subsidization justified on the grounds of social equity. Cape Verde's power prices are among the highest in Africa due to its dependency on the importation of expensive fuel [16]. According to ELECTRA, the electricity price in Cape Verde in 2012 was 0.283 €/kWh [17].

The local authorities are planning to replace diesel-fired generating plants by fuel oil-fired plants, which would immediately halve the fuel costs. The government also plans to invest in renewable energy to reduce oil dependency [16].

Cape Verde has by far the most expensive water tariffs in Africa, and among the most expensive in the world [16]; specifically, 3.313 €/m^3 in 2012 [17]. This value is more than double the average water tariffs in the OECD major cities [18]. These high prices reflect the scarcity of the water resources that has forced the country to rely on desalination for approximately 85% of the production. Moreover, the cost of the energy-intensive desalination process is particularly high due to its dependence on power generation, whose high costs in turn reflect reliance on small-scale diesel generators and expensive imported oil [16].

3.1. Electricity supply system of S. Vicente

The electrification rate of S. Vicente reached 90% in 2010 [13], a value above the national average. The technologies used for the production of electricity on the island are based on fossil fuel-fired plants and wind turbines. Fig. 2 shows the power generation in S. Vicente by source in 2010. There are two conventional thermal fossil fuel-based plants, the Matiota and the Lazareto plants. In 2010, the Matiota plant had four fuel oil and diesel generators, with an installed capacity of 10,900 kW. The Lazareto plant had two fuel oil generators, with an installed capacity of 7440 kW. There is also a wind park in Selada Flamengo with three Nordtank wind turbines of 300 kW each. The electricity production in 2010 was about 65 GWh, with a peak power of 10.9 MW [19]. The electricity demand is relatively stable throughout the year, as there are not large climate variations, as can be seen in Fig. 3, which represents the hourly electricity load of S. Vicente in a summer day and in a winter day in 2010.

Early in 2011, the company Cabeólica installed seven Vestas V52 wind turbines of 850 kW each, and in September 2011 four of these wind turbines started operation and supplying electricity to the central grid. The remaining three wind turbines were not in operation. Hence, the installed wind power in the island was about 6.85 MW, although only with 4.3 MW in operation.

In 2012, the installed fossil fuel-based generators were the same as in 2010, and the electricity production was about 66 GWh with a peak power of 11.7 MW. Table 1 shows the power installed in S. Vicente in 2012.

According to the Renewable Energy Plan of Cape Verde [20], Group III and IV (Deutz generators) were decommissioned in the end of 2012 (after about 30 years of operation), and groups V and VI (MAK generators) will also be decommissioned in 2015 (after about 20 years of operation), taking out a total of 10.9 MW capacity from S Vicente.

The island has important wind resources. The hourly wind speed values used in this study were collected from the meteorological station of S. Pedro in 2005 [21]. Although the meteorological station is very close to the wind parks (Fig. 1), a wind speed adjustment was applied using monthly correction factors defined to match wind power production in 2005. In this year, the average wind speed was about 8 m/s.

3.2. Water supply system of S. Vicente

All fresh water supplied to the population in S. Vicente is desalinated water [17,19]. The desalination units are installed in the

Fig. 1. Map of S. Vicente.

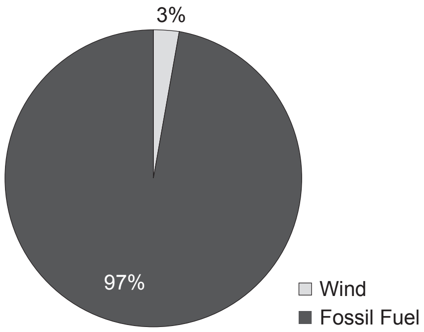

Fig. 2. Power production in S. Vicente in 2010.

Matiota plant and, in 2010, the desalination capacity was about 7300 m^3/day. The total water production in 2010 was 1,252,665 m^3. In August 2010, the oldest desalination unit, MED 2400, was deactivated [19]. Fig. 4 shows the daily water production in S. Vicente in 2010.

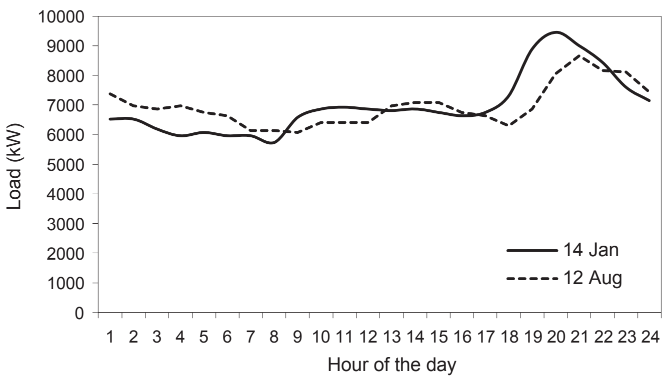

Fig. 3. Hourly electricity load of S. Vicente in a summer day and in a winter day in 2010.

In 2012, all the desalination units used reverse osmosis technology, three with a production of 1000 m^3/day and two with a production of 1200 m^3/day. According to the ELECTRA 2012 report, about 5 kWh/m^3 of water produced was necessary to desalinate and pump the water supplied to the population, that reached 1,250,804 m^3 [17].

The water reservoirs available in S. Vicente are distributed throughout the island, close to the population clusters. The total capacity of these reservoirs is about 14,680 m^3.

3.3. Future electricity and water demand

In our previous work [11], the evolution of the electricity and water demand considered was the one estimated in the National Energy Plan for Cape Verde [22]. This plan considered the forecast of the evolution of the Gross Domestic Product and of the resident population in order to estimate the growth in the consumption of electricity in the different islands of Cape Verde.

The forecast for the electricity production in S. Vicente considered in this article was compared with the actual data from the ELECTRA reports, and it was noticed that this forecast is greater than the actual production. Against this background, the data for the yearly production of electricity was updated and, in this study, actual data for 2010, 2011 and 2012 are considered. For the remaining years, the growth considered is the one estimated in the slow scenario of the National Energy Plan. The forecast of the water production was determined in the same way as the electricity

Table 1
Installed capacity in S. Vicente in 2012 [17].

Location	Name	Installed capacity (kW)
Matiota power plant	Group III (Deutz)	2100
	Group IV (Deutz)	2200
	Group V (MAK)	3300
	Group VI (MAK)	3300
Lazareto power plant	Group VII (Caterpillar)	3720
	Group VIII (Caterpillar)	3720
Selada Flamengo wind park	3 NTK 300	3 × 300
Cabeólica wind park	7 Vestas V52	7 × 850

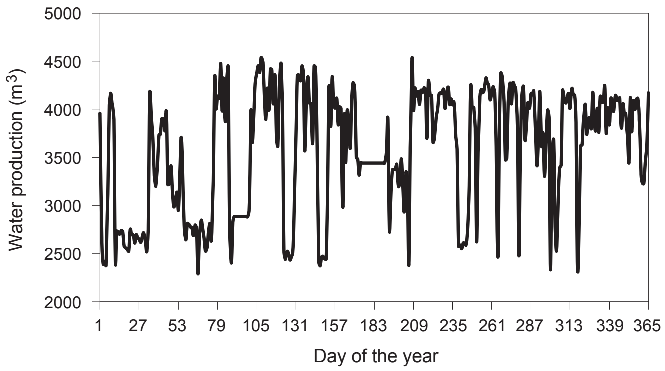

Fig. 4. Daily water production in S. Vicente in 2010.

production. Table 2 shows the electricity and water production in 2010 [19] and the forecast for 2015 and 2020 [22] along with the peak power production for each year.

The forecasted peak production was used to determine the installed fossil fuel-based generators in each year (for all scenarios), according to the security criteria currently used by ELECTRA. These criteria include the consideration of the unavailability of the biggest thermal unit (N − 1 situation), the failure of all intermittent renewable energy sources, and a 3% reduction of the production in relation to the power installed, corresponding to a temperature factor. This factor is introduced to account for the reduction in nominal production capacity of the power generating units due to the increase of the ambient temperature. In this way, the peak demand coverage (*PDC*) index can be calculated as follows:

$$PDC = \frac{P_{available} - Peak}{Peak} \quad (5)$$

where $P_{avaliable}$ is the available power after considering all the three security criteria and *Peak* is the peak demand forecasted for the period in analysis [20].

For 2015, and after considering the decommissioning of the two smaller groups of the Matiota power station, there is a need to install more fossil fuel power in order to keep this index positive. The Renewable Energy Plan of Cape Verde [20] foresees the installation of two fossil fuel-based generators, one of 3.5 MW and another of 5.5 MW in the Lazareto power station, and hence this solution was considered in this study. The power of the fossil fuel-based plants considered for this year is 23.04 MW.

For 2020, the remaining groups of the Matiota power station will be decommissioned and the need to install more fossil fuel power in order to keep the peak demand coverage index positive occurs again, hence the installation of one more generator of 3.5 MW and another of 5.5 MW is considered. The total installed fossil fuel power considered for this year is 25.44 MW.

3.4. Economic data

The discount rate used to annualize the investment costs of the system is 10% [3], which is the value usually used in the region for the analyses of the financial viability of this type of projects.

Table 3 shows the costs and lifetime of the installed equipment. The fixed operation and maintenance (O&M) costs are different according to the technology and are a given percentage of the total investment cost that should be paid each year during the lifetime.

The investment and O&M costs of the wind parks and of the fossil fuel-fired units are based on the costs for projects foreseen for Cape Verde stated in the Renewable Energy Plan of Cape Verde published in 2011 [20].

The fuel cost per kWh of electricity produced by the fossil fuel technologies is estimated for the years from 2007 to 2012 based on the information on the fuel specific consumption (g/kWh) of the existing fossil fuel-fired units, percentage of use of each fuel to produce electricity [17,19], and the current prices of each fuel (€/kg) in Cape Verde, according to the National Economic Regulatory Agency [25]. In 2010, fuel costs reached 0.129 €/kWh. Based on these values, the estimations for 2015 and 2020 are made by linear regression, which lead to 0.195 €/kWh in 2015 and 0.268 €/kWh in 2020. It is important to refer that the volatile nature of the fuel costs requests for a sensitivity analysis that will be made in the future.

3.5. Scenarios considered

Five different scenarios are considered in this study, all having 2010 as the base year. The first scenario is the Business As Usual (BAU), as it only considers the projects that are already foreseen for the island, and it was established in order to allow the comparison between the results of the proposed solutions and the current energy and water supply systems, including electricity and water production costs and total yearly costs.

The second scenario considers the supply of wind power to the desalination plants already installed on the island. Although S. Vicente has several reservoirs spread through the island, this scenario considers that there is only one reservoir in the island with the capacity of all of them, about 14,680 m^3, where the water that comes out of the desalination plant is stored before being supplied to the population. When the excess wind power is not enough to desalinate all the water needed the fossil fuel-based generators are used to supply the remaining required electricity.

The third scenario was established by finding which installed wind power and desalination capacity minimizes the total annual costs of the electricity and water supply systems for 2020, while keeping the wind power penetration the highest possible.

The fourth scenario considers the storage of the excess wind power production through pumping of the desalinated water. This scenario contemplates the construction of two water reservoirs, one at low altitude and another at 500 m of altitude. The wind park would supply electricity to a desalination plant and to a pumping

Table 2
Electricity and water production in 2010 [19] and the forecast for 2015 and 2020 [22].

	2010	2015	2020
Electricity production (MWh)	65,029	74,922	88,518
Peak production (MW)	10.9	13.8	16.3
Water production (m^3)	1,252,665	1,469,404	1,736,061

Table 3
Costs and lifetime of the installed equipment [20,23,24].

Technology		Investment cost	Fixed O&M cost (%)	Variable O&M cost (€/MWh)	Lifetime (years)
Wind turbines		2000 €/kW	3	–	20
Fossil fuel-based units		1200 €/kW	1.5	–	20
Desalination [23].		1000 €/(m^3/day)	10	–	20
Pumped hydro storage [24].	Hydro	500 €/kW	1.5	1.5	40
	Pump	500 €/kW			
	Storage	7.5 €/kWh			

station that pumps desalinated water from the lower reservoir into the upper reservoir. When it is necessary to supply water and electricity to the population, the water retrieved from the upper to the lower reservoir, passing through the hydro turbine, as shown schematically in Fig. 5. The cycle efficiency of the pumped hydro storage is about 69%.

The fifth scenario was established by finding which installed wind power, desalination capacity, hydro power and pump power minimizes the total annual costs of the electricity and water supply systems for 2020, while keeping the wind power penetration the highest possible.

These five scenarios were modelled limiting to 30% the hourly intermittent energy penetration, which means that only 30% of the load of 1 h can be covered by wind power [1,26].

For Scenarios 1, 3 and 5, alternative scenarios were made taking into consideration an hourly intermittent energy penetration of 100% (Scenarios 1a, 3a and 5a), in order to compare the results with the remaining scenarios. It is important to notice that these scenarios present great risk of power instability on the grid, hence, it is necessary to consider that the wind turbines installed possess some degree of frequency and voltage control. There is no need to simulate Scenario 2 and 4 with an hourly intermittent energy penetration of 100% because, with this limit, the wind power curtailed is not enough to supply the desalination units and the pumps. For the other three scenarios, it is interesting to examine the consequences of an increase in the installed wind power.

In Scenarios 1, 1a, 2 and 4 the current installed wind power and desalination capacity in S. Vicente is considered. In Scenarios 3, 3a, 5 and 5a, the installed wind power and desalination capacity are those that minimized the total costs, while keeping the RES penetration the highest possible. Table 4 summarizes all scenarios considered in this study.

4. Results

4.1. Scenario 1 — BAU

This scenario considers the installed wind power and the fossil fuel-based generators currently in S. Vicente. For 2015 and 2020, the installed wind power is similar to that in 2012, with all the installed wind turbines in operation, but the fossil fuel power is increased in order to keep the peak demand coverage index positive, as described in Section 3.3. Table 5 summarizes the results obtained for this scenario. It is clear that with the new wind generators installed in 2011, the percentage of wind power generation increases significantly; specifically, from 5% in 2010 to 22% in 2015, and 21% in 2020. The wind power will have a strong presence in the power generation of S. Vicente in the upcoming years, but the fossil fuel will remain very important, promoting a considerable increase

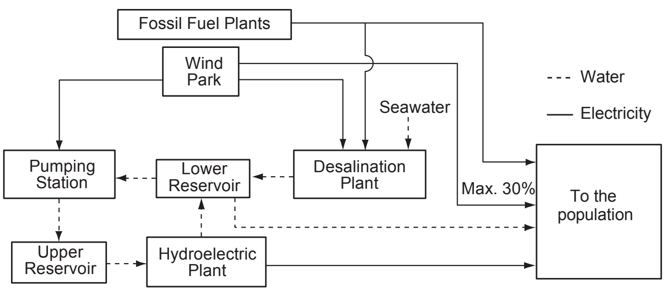

Fig. 5. Schematic diagram of Scenario 4.

Table 4
Scenarios considered.

Scenario	Description	Hourly wind power penetration
1	BAU	30%
2	Wind powered desalination	
3	Wind powered desalination with minimum costs	
4	Wind powered desalination and PHS	
5	Wind powered desalination and PHS with minimum costs	
1a	BAU	100%
3a	Wind powered desalination with minimum costs	
5a	Wind powered desalination and PHS with minimum costs	

Table 5
Results obtained for Scenario 1.

Year	2010		2015		2020	
Power generation (MWh)						
Wind power	3455	5%	16,706	22%	18,966	21%
Fossil fuel	61,760	95%	58,215	78%	69,552	79%
Total	65,215	100%	74,922	100%	88,518	100%
Wind power curtailed (MWh)	–	–	13,158	44%	10,898	37%
Production costs						
EPC (€/kWh)	0.161		0.212		0.276	
WPC (€/m^3)	1.772		1.893		2.086	
Total costs (€)	12,747,010		18,577,899		27,952,711	

in the electricity production cost, and, consequently, in the water production cost.

The results also reveal that there will be a significant wind power curtailed; specifically, in 2015 it will reach 44% of all potential wind power, and in 2020 about 37%. Scenario 2 is built to use this wasted wind power.

4.2. Scenario 2 — wind powered desalination

Scenario 2 considers the construction of a medium voltage (MV) power line from the wind parks (located in Selada Flamengo) to the desalination units (located in the Matiota power station). This would enable the supply of wind power directly to the desalination units. The distance between these two locations is about 12 km, and the cost per km of the construction of an MV power line was considered to be 20,000 €/km [27]. This cost was annualized considering the discount rate and the lifetime of 20 years and was added to the total yearly costs of the water supply system. Besides the power line, this scenario considers equipments already installed in the island: 6.85 MW of wind power and 5400 m^3/day of desalination capacity.

Table 6 summarizes the results obtained for this scenario. In 2020, the electricity production costs are about 3% lower than those in the BAU Scenario. This is because there is more wind power used, lowering the electricity needed from fossil fuel. The wind power curtailed decreases from 44% to 31% in 2015 and from 37% to 25% in 2020.

The water production costs, which include the investment in the new power line mentioned above, are slightly lower, and the electricity used to desalinate water is mostly wind power. This percentage of wind powered desalination can increase if the capacity of the reservoir increases. This, however, would involve the construction of additional reservoirs, which was not considered in this scenario.

Table 6
Results obtained for Scenario 2.

Year	2015		2020	
Power generation (MWh)				
Wind power	20,545	27%	22,475	25%
Fossil fuel	54,722	73%	66,434	75%
Total	75,267	100%	88,909	100%
Wind power curtailed (MWh)	9319	31%	7389	25%
Water production (m^3)				
Wind power	1,019,002	69%	973,076	56%
Fossil fuel	458,586	31%	769,381	44%
Total	1,477,588	100%	1,742,458	100%
Production costs				
EPC (€/kWh)	0.202		0.266	
WPC (€/m^3)	1.825		2.019	
Total costs (€)	17,918,962		27,155,385	

4.3. Scenario 3 — wind powered desalination with minimum total costs in 2020

The optimal configuration found has 6.85 MW of installed wind power and 5400 m^3/day of desalination capacity, which is currently installed on the island.

During the optimization process it was possible to conclude that the addition of more desalination capacity only increased the costs. Even if the desalination capacity increases dramatically, the wind power curtailed does not decrease much. This is because of the limited capacity of the reservoirs in which the desalinated water is stored, and the relatively low water consumption. If the reservoirs are full, the desalination stops and wind power is curtailed.

For the current desalination capacity installed, it is not possible to have 100% wind powered desalination. Only if the installed desalination capacity doubles would be possible to achieve such goal, and even then, a reservoir of about 300,000 m^3 would be needed, which corresponds to about 60 days of water demand in 2020. These values are disproportionate to the water consumption of this island. This is the first difficulty of coupling the energy and water supply systems. The construction of new reservoirs was not accounted for in this scenario, as it is considered that the existing ones are suitable for the current water consumption of the island.

This optimal configuration leads to 25% of total electricity production from wind power, 56% of wind powered desalination, about 25% of wind power curtailed and a load of the desalination units of 88%. The total annual costs are about 3% lower than those in the BAU Scenario for 2020.

From an economic point of view, it is possible to conclude that it is better to keep the load of the desalination units higher than to minimize the wind power curtailed by adding more desalination units.

4.4. Scenario 4 — wind powered desalination and pumped hydro

The previous scenario still resulted in a certain amount of wind power curtailed. In order to use this curtailed wind power, a pumped hydro storage is included in Scenario 4. Apart from the pumped storage, the existing equipments on the island are also considered (wind power and desalination capacity). The upper reservoir has a capacity of 50,000 m^3, and the lower one a capacity of 35,000 m^3 (about one week of average water demand in 2020).

According to Kaldellis and Kavadias [4], the most theoretically disturbed energy management scenario is based on the hypothesis that there is a complete disharmony between electricity demand and wind power harnessing. Hence, the rated power of the hydro station is determined in order to cover the peak production, which is about 12.5 MW. The pump station should have capacity to absorb the rated wind power minus the minimum consumption of the grid. Hence, the pump power should be around 4 MW.

With these hydro and pump power, the production of RES reached 43% in 2015, but the load of the hydro turbines was very low. Hence, their rated power was decreased step by step, always checking if the percentage of RES did not decrease. The same was done with the power of the pumps. In this way, 2.5 MW for hydro power and 3.5 MW for pump power were reached.

It was noticed that the capacity of the upper reservoir does not influence the results, since all that is pumped is immediately retrieved back through the hydro turbine. Hence the capacity of this reservoir was kept as low as possible (10,000 m^3) to decrease costs. Fig. 6 shows the power demand (load, desalination and PHS charging) for one day in January 2020 in this scenario, and Fig. 7 shows the power production (wind, fossil fuel and PHS) for the same day.

Table 7 shows the results obtained for Scenario 4. The total annual costs are lower than those for Scenario 2 because there is more wind power used, lowering the electricity needed from fossil fuel. The wind power curtailed decreases from 31% to 0.6% in 2015, and from 25% to 1% in 2020, which means that almost all wind power potential is used. In comparison with the BAU Scenario, the costs decrease about 9% in 2015 and 7% in 2020. In 2015 about 32% of the electricity used to supply demand is RES (23% wind power and 9% PHS). In 2020 this value decreases to 28% (22% wind power and 6% PHS).

4.5. Scenario 5 — wind powered desalination and pumped hydro with minimum total costs

In order to establish Scenario 5, and having Scenario 4 as a starting point, several values for the wind, hydro, pump power and desalination capacity were evaluated with the H2RES model.

The configuration that minimized the total yearly costs was 17.9 MW of installed wind power, 7400 m^3/day of desalination capacity, 6.5 MW of hydro power and 8.5 MW of pump power. This resulted in a load of the desalination units of 65%, a load of the hydro turbine of 47% and a load of the pumps of 52%. The RES production reached 72% and the wind power curtailed was about 17%. As for the electricity used to supply demand, about 57% is RES (23% wind power and 33% PHS).

Again it was noticed that the capacity of the upper reservoir has a small influence in the results, since all water that is pumped is immediately retrieved back through the hydro turbine. Hence, the

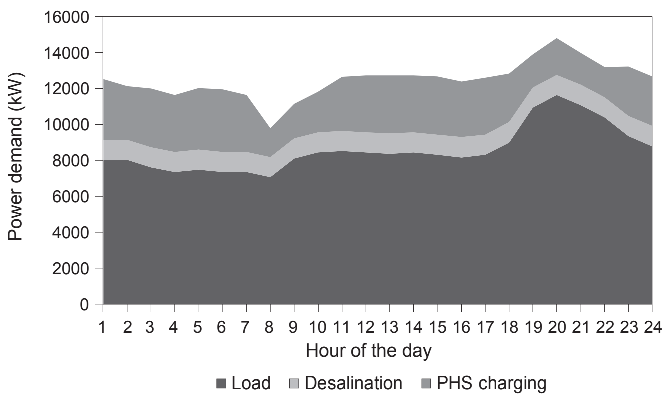

Fig. 6. Demand in 2020 for Scenario 4.

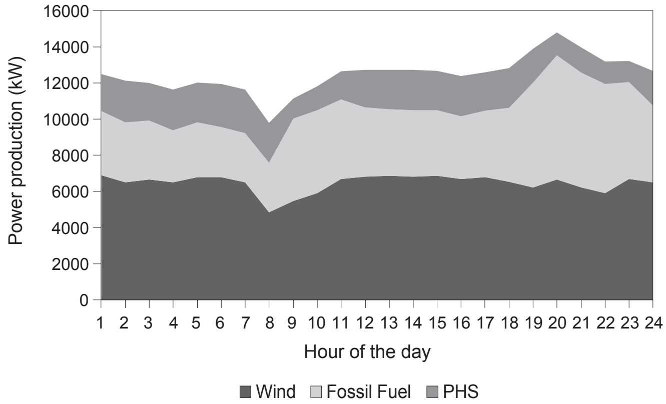

Fig. 7. Production in 2020 for Scenario 4.

Table 7
Results obtained for Scenario 4.

Year	2015		2020	
Power generation (MWh)				
Wind power	29,679	35%	29,573	31%
PHS	6144	7%	4876	5%
Fossil fuel	48,347	57%	61,526	64%
Total	84,169	100%	95,974	100%
Wind power curtailed (MWh)	184	0.6%	291	1%
Water production (m^3)				
Wind power	1,068,465	72%	980,233	56%
Fossil fuel	408,841	28%	761,942	44%
Total	1,477,306	100%	1,742,176	100%
Production costs				
EPC (€/kWh)	0.171		0.237	
WPC (€/m^3)	1.669		1.875	
Total costs (€)	16,858,219		26,001,803	

capacity of this reservoir was kept as low as possible, in this case 35,000 m^3, to decrease costs.

Table 8 shows the results obtained for Scenario 5. The higher penetration of wind power with the wind powered desalination and the pumped hydro storage results in a reduction of the total yearly costs of about 19% in relation to the BAU Scenario.

Considering an emission factor of 0.66 $kgCO_2$/kWh for the fuel oil power plants [20], this configuration avoids the emission of 22,423 tCO_2 in comparison with the BAU Scenario, which represents about 49% of the total CO_2 emissions foreseen for 2020.

Table 8
Results obtained for Scenario 5.

Power generation (MWh)		
Wind power	65,348	51%
PHS	26,632	21%
Fossil fuel	35,578	28%
Total	127,558	100%
Wind power curtailed	13,555	17%
Water production (m^3)		
Wind power	1,613,387	92%
Fossil fuel	140,503	8%
Total	1,753,890	100%
Production costs		
EPC (€/kWh)	0.154	
WPC (€/m^3)	1.703	
Total costs (€)	22,626,074	

4.6. 100% Hourly intermittent energy penetration scenarios

As referred to earlier, Scenarios 1, 3 and 5 were modelled one more time, but now allowing the hourly intermittent energy penetration rate to reach 100% (see Table 4). For this, it is necessary to consider that the wind turbines installed possess some degree of frequency and voltage control, with a correspondent cost rise of 15% [28].

The BAU Scenario with this condition (Scenario 1a, Table 4) decreases dramatically the wind power curtailed; specifically, 2.3% in 2015 and 0.5% in 2020. The percentage of wind power in the production of energy reaches 39% in 2015 and 34% in 2020, which means that the current installed wind power is not sufficient to cover the load at all hours of the year.

To establish Scenario 3a, the method described earlier to set up Scenario 3 was repeated for 2020. The configuration that minimizes the annual costs is 17.05 MW of wind power and 5400 m^3/day of desalination capacity, which results in 66% of total electricity produced from wind power, 50% of wind powered desalination, 22% of wind power curtailed, and a load of the desalination units of 88%. From an economic point of view, it is better to keep the load of the desalination units higher than to minimize the wind power curtailed by adding more desalination units. Table 9 shows the costs obtained for Scenario 3a. In this scenario the electricity production costs are 25% lower than those in Scenario 3, the water production costs are 16% lower and the total costs decrease 24%. In this case, although these wind turbines are more expensive, the extra amount of wind power produced compensates the higher costs.

Moreover, increasing significantly the desalination capacity does not reduce much the wind power curtailed due, again, to the capacity of the reservoirs and the low water demand.

To establish Scenario 5a, the method described earlier to establish Scenario 5 was repeated for 2020. The configuration that minimized the total yearly costs was 17.9 MW of installed wind power, 6400 m^3/day of desalination capacity, 1 MW of hydro power, and 1.5 MW of pump power. This resulted in a load of the desalination units of 75% and a load of the hydro turbine and of the pumps of 15%. The RES production reached 70% (68% wind power and 2% PHS), the wind power curtailed was about 22%, and the wind powered desalination was 61%. This configuration resulted in total annual costs about 9% lower than those of Scenario 5, but with a very slightly lower RES production. It seems that Scenario 5a does not take advantage of the pumped hydro system as much as Scenario 5 and this is expected since there is less need for storage when it is possible to deliver 100% of wind power directly into the grid.

4.7. Comparison between scenarios

Fig. 8 shows the power production in 2020 for five different scenarios. It is clear that Scenario 3 (only desalination) does not differ much from the BAU Scenario, although the costs are lower. In Scenario 5 (desalination and pumped hydro) there is a significant increase in the penetration of RES.

Table 9
Results obtained for Scenario 3a.

	2020
Electricity production cost (€/kWh)	0.200
Water production cost (€/m^3)	1.689
Total yearly costs (€)	20,144,822

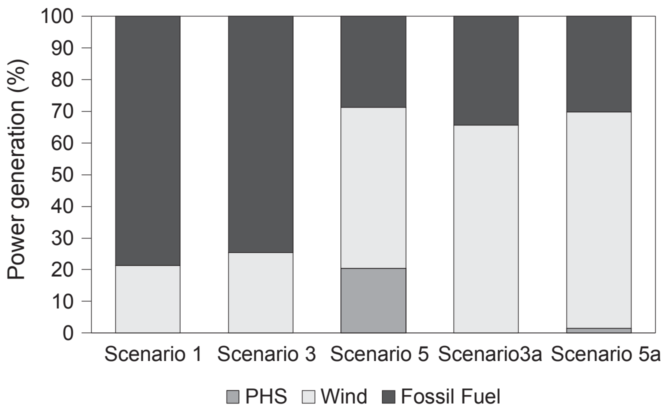

Fig. 8. Power production in S. Vicente in 2020 for different scenarios.

Comparing the scenarios that only consider desalination but have different intermittent limits, a 100% intermittent limit allows a significantly higher penetration of wind power. However, for the scenarios that consider desalination and pumped hydro, the penetration of RES is almost the same.

Fig. 9 shows the desalinated water production in 2020 for four different scenarios. The desalination and pumped hydro scenarios allowed for a higher percentage of water desalinated from wind power than the scenarios with only desalination, for both intermittent limits.

5. Conclusions

The main objective of this work was to find a solution that minimized the total annualized costs of the energy and water supply systems, while keeping the wind power penetration the highest possible in the island of S. Vicente, Cape Verde. The study intended to understand how the electricity and water production costs vary with the wind power curtailed and with the load of the desalination units in order to find an optimum configuration. The results indicate that it is better to keep the load of the desalination units higher than to minimize the wind power curtailed by adding more desalination units. Obviously, the solutions proposed to increase the penetration of wind power are greatly affected by the capacity of the water reservoirs.

The results also reveal that, with the current installed wind power and desalination capacity on S. Vicente, it is possible to have, by 2020, more than 25% of wind power production, together with more than 56% of the water supplied to the population produced from wind power, with slightly lower costs than the ones foreseen for this year. With a pumped hydro system, the RES production can reach 36% (31% wind power and 5% PHS), with 56% of wind powered desalinated water and with about 7% decrease of costs in relation to the ones foreseen for 2020. If the installation of more wind power and desalination capacity is considered, renewable energy sources production can reach 72% (51% wind power and 21% PHS), with 92% of wind powered desalinated water, with about 19% decrease of costs in relation to those predicted for 2020. This configuration avoids about 49% of CO_2 emissions forecasted for 2020.

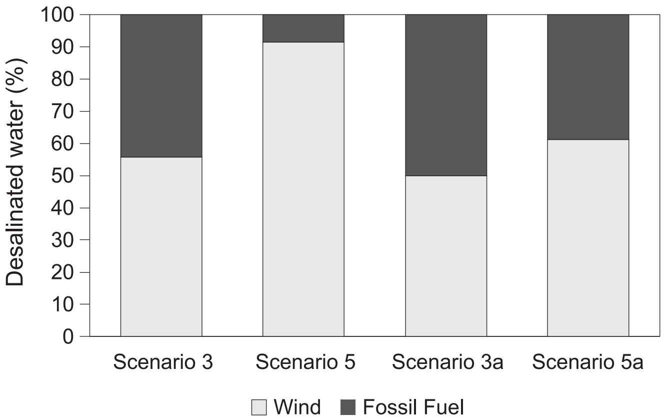

Fig. 9. Production of desalinated water in S. Vicente in 2020 for different scenarios.

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