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OPTIMIZATION OF ENERGY AND WATER SUPPLY SYSTEMS IN S. VICENTE, CAPE VERDE

R. Segurado[1]*, J. F. A. Madeira[1,2], M. Costa[1], N. Duić[3] and M. G. Carvalho[1]

1: IDMEC, Department of Mechanical Engineering
Instituto Superior Técnico, Universidade de Lisboa
Av. Rovisco Pais, 1049-001 Lisboa, Portugal
e-mail: raquelsegurado@tecnico.ulisboa.pt, web: http://www.tecnico.ulisboa.pt

2: Department of Mathematics
Instituto Superior de Engenharia de Lisboa, Instituto Politécnico de Lisboa
Rua Conselheiro Emídio Navarro, 1, 1959-007 Lisboa, Portugal

3: Department of Energy, Power Engineering and Environment
Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb
Ivana Lučića 5, 10002, Zagreb, Croatia

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Abstract *S. Vicente is an island of the Cape Verde archipelago with significant problems regarding the electricity and water supply systems. The island has important wind resources that are difficult to integrate in the electricity grid because of the wind intermittency. In addition, this island does not have any source of fresh water and all water that is provided to the population is desalinated seawater. The penetration of the wind power in the electricity supply system depends on the dynamic penetration limit that is usually applied for grid stability. This limit is the maximum wind power directly supplied to the electricity grid at each hour; it is expressed as a percentage of the hourly load and should not surpass 30%. The excess wind power is the one that cannot be injected in the electricity grid due to that limit. If this wind power is not stored or used to desalinate seawater, it will be curtailed. This work evaluates the possibility of using the excess wind power to produce fresh water that is stored in a lower reservoir of a pumped hydro system. The remaining wind power can be stored in this energy storage system. The objective is to minimize the curtailed wind power that will be a function of the dynamic penetration limit of the grid and of the characteristics of the pumped hydro system, namely its operational strategy. This paper proposes a methodology to optimize the operation of this system, minimizing the curtailed wind power, hence minimizing the annualized costs. To solve this optimization problem two algorithms were used: a recent method for global optimization GLODS (Global and Local Optimization using Direct Search) and a multi-objective optimization method DMS (Direct Multisearch Method). GLODS was used to determine the initial solutions for the DMS.*

1. INTRODUCTION

The integration of wind power in the electricity system of isolated locations is limited mainly due to dynamic limit that is applied for grid stability (intermittent limit) [1]. Intermittent limit is the hourly intermittent energy penetration, i.e., the maximum wind power, at each hour, which is directly supplied to the electricity grid, and is a percentage of the hourly load.

The case study analysed in this study is the island of S. Vicente that has important wind resources that are not fully used due to its intermittent nature. This island does not have any source of fresh water so all water supplied to the population is desalinated seawater. For this island, Segurado et al. [2] proposed an integrated system that uses wind power that cannot be injected in the electricity supply system (excess wind power) to feed the desalination units that produce fresh water, and pumps in a Pumped Hydro Storage (PHS) system.

This study concentrates on the operational strategy and sizing optimization of the integrated electricity and water supply system so that the total annualized cost for electricity and water supply of this island are minimized. To solve the optimization problem two derivative-free methods were used: the single objective method was used for global optimization GLODS (Global and Local Optimization using Direct Search) [3] and the multi-objective optimization method DMS (Direct Multisearch Method) [4]. GLODS was used to determine the initial solutions for DMS.

2. CASE STUDY

The case study analysed in this study is the Island of S. Vicente, a 227 km^2 island of the Arquipelago of Cape Verde, located about 450 km of the West African coast. Cape Verde's power and water tariffs are among the highest in Africa. These high prices reflect the high dependency on fossil fuel based plants, which in turn rely on the importation of expensive fuel, and desalination units to produce fresh water. Table 1 presents the electricity and water demand of 2012 for S. Vicente, as well as the value forecasted for 2020 [2].

Year	2012	2020
Electricity demand (MWh)	66,089	88,518
Water demand (m^3)	1,250,804	1,736,061

Table 1. Electricity and water demand for 2012 and forecast for 2020 [2].

In 2012, S. Vicente had 6.85 MW of installed wind power. Obviously, the excess wind power is highly dependable on the wind power installed and decreases as the intermittent limit increases since there is more wind power that can be directly supplied to the grid.

The current water supply system installed in S. Vicente, composed of desalination units with a capacity of 5,400 m^3/day, water distribution system with pumps and a number of reservoirs, requires about 5 kWh of electricity to produce and supply 1 m^3 of water to the population.

In Segurado et al [2] the baseline scenario for the energy and water supply systems of S. Vicente was modelled in order to compare the results of the proposed system with the current situation in the island. Table 2 presents the share of wind power in the power generation in 2020. This power generation refers to the power needed to supply the electricity demand and the desalination units to produce water that is supplied to the population.

2020	Power generation (MWh)	
Wind power	18,966	21%
Fossil fuel	69,552	79%
Total	88,518	100%

Table 2. Power generation in 2020 in the baseline scenario [2].

In this scenario, the wind power curtailed reaches 37% of the total wind power potential.

3. METHODOLOGY

The integrated electricity and water supply system proposed for S. Vicente was modelled for the year 2020, taking into account the electricity and water demand forecasted for that year. The current installed wind power and desalination capacity were considered. The operational strategy of this system was translated into the variables of the optimization problem.

3.1. Modelling of the integrated system

The proposed integrated system was modelled based on the hourly wind power excess that corresponds to the wind power that was not used to cover the hourly load. Based on these hourly values and on the hourly load and hourly water load, it was possible to calculate 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 was also calculated and the corresponding hydro production. The water produced from fossil fuel based units was 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 was possible to determine the annual load that is covered by the fossil fuel based units and the total annual costs of the system.
Figure 1 presents the scheme of the lower reservoir, as well as the definition of the three variables related with the operational levels of the wind desalination pumped hydro system. 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. 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 there is no water available in 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 1. Definition of variables n_{WB}, n_H and n_{FF}.

The level n_0 is the minimum level of the lower reservoir and it is fixed at 21,400 m^3, equivalent to about seven days of minimum water demand forecasted for 2020. Figure 2 shows typical values for the variables. The parameter a is the percentage of wind power excess that supplies the desalination units (the remaining power is supplied to the pumps) and the parameter b is the percentage of the total hydro capacity that is used.

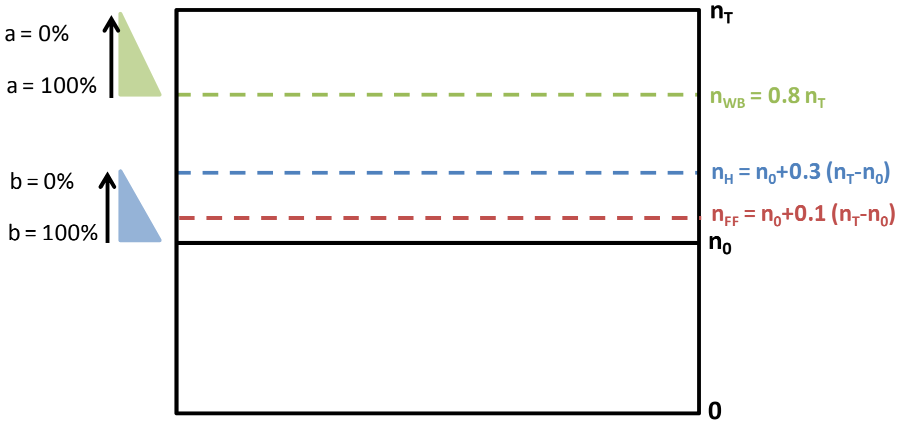

Figure 2. Typical values of n_{WB}, n_{FF} and n_H.

3.2. Optimization problem

3.2.1. Objective function

The objective function is the total annualized costs of the integrated energy and water supply system. The total annual costs were estimated 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 was adapted to consider the energy and water production costs. Each production cost includes the investment cost of the components used to produce the specific output (electricity and water). More information about the estimation of the costs can be found in [2]. The CO_2 emissions cost was also considered. The value used is the cost of the Certified Emission Reduction, whose average value is 6.96 €/ton of CO_2 emitted [5].

3.2.2. Variables

Table 3 lists the variables of this optimization problem. In a first approach, the capacity of the lower reservoir (LR) was also a variable of the optimization problem.

Variable	Range	Iteration step
f_{FF}	0.00 - 1.00	0.01
n_{WB}	0.00 - 1.00	0.01
f_H	0.00 - 1.00	0.01
LR (m^3)	50,000 - 100,000	1,000
Pump power (MW)	1 - 20	0.5
Hydro power (MW)	1 - 20	0.5

Table 3. Variables of the optimization problem in the first approach.

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

$$n_{FF} = n_0 + f_{FF}\,(n_T - n_0) \quad (1)$$

$$n_H = n_0 + f_H\,(n_T - n_0) \quad (2)$$

The pump power and hydro power variables are the installed power of the pumps and hydro of the PHS, respectively. This first approach was also used to fine tune the variables of the problem.

Based on the optimal results of the first approach, the capacity of the lower reservoir and the level n_{FF} were fixed and the range and iteration steps of the pump and hydro power were modified (Table 4).

Variable	Range	Iteration step
n_{WB}	0.00 - 1.00	0.01
f_H	0.00 - 1.00	0.01
Pump power (MW)	0.1 - 7	0.1
Hydro power (MW)	0.1 - 7	0.1

Table 4. Variables of the optimization problem.

3.3. Mathematical formulation and methods

A constrained optimization problem can be written in the following form.
Find n design variables:

$$x = (x_1, x_2, \dots, x_n)^T \quad (3)$$

which minimizes:

$$min_{s.t. x \in \Omega}\, F(x) = [f_1(x), f_2(x), \dots, f_m(x)\ ]^T \quad (4)$$

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.

In this study two objective functions were considered: f_1 that is the minimization of the total annualized costs of the integrated energy and water supply system and f_2 that is the minimization of the intermittent limit. f_2 was considered in order to obtain all possible values of the intermittent limit. Firstly, GLODS was used to solve f_1 with a fixed intermittent limit of 0%. Secondly, the solutions obtained were used in DMS with f_1 and f_2. A brief description of these two methods used is given below, and a detailed description of them can be found elsewhere [3, 4].

GLODS [3] is a new algorithm for single optimization, suited for bound constrained, derivative-free and global optimization. Using direct-search of directional type, the method alternates between a search step, where potentially good regions are located, and a poll step where the previously located regions are explored. This exploitation is made through the launching of several pattern search methods, one in each of the regions of interest. Differently from a multistart strategy, the several pattern search methods will merge when sufficiently

close to each other. The goal of GLODS is to end with as many active pattern searches as the number of local minimizers, which would allow to easily locating the possible global extreme value.
DMS [4] is a derivative-free method for multiobjective optimization problems, which 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.

4. RESULTS

In the first approach to this optimization problem, the optimal capacity of the lower reservoir obtained was 50,000 m^3 for most of the intermittent limits. Also in most cases, the optimal n_{FF} was equal to n_0, since, in this case, there was less water production from the fossil fuel based units, which reduced the overall costs. However, in some intermittent limits, the n_{FF} that optimized the costs was not n_0 because if n_{FF} was n_0, there was less overall water production, hence there was less pumping of water from the lower to the upper reservoir that originated less hydro production, increasing slightly the need for fossil fuel based units to supply the load, increasing slightly the costs. However this increase in costs was never more than 0.001% of the optimal value.
Due to the results presented above, the variables of the optimization problem were fine tuned. The capacity of the lower reservoir was fixed to 50,000 m^3 and the level n_{FF} was fixed to n_0. Based on the values obtained for the optimal pump and hydro power, the range of these variables was reduced and the iteration steps decreased (Table 2).
In regard to the sizing of the PHS, Figure 3 presents the optimal pump and hydro power for each intermittent limit.

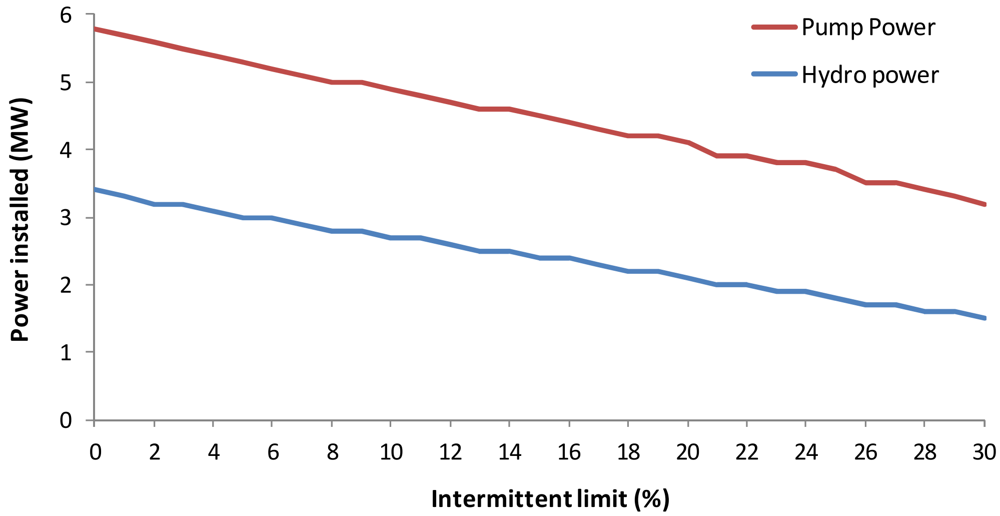

Figure 3. Optimal pump and hydro power for each intermittent limit.

The optimal pump and hydro power decreases with the intermittent limit, because the wind power excess also decreases, hence, there is less need to store wind power.

The optimal n_H, the level of the lower reservoir in which the hydro production stops, is 100% for almost all intermittent limits. However, there are intermittent limits where the optimal n_H is lower than 100%. Nevertheless, in these intermittent limits, the difference between the minimum cost found and the cost when n_H is 100% is only at most 0.0004% of the optimum value. Hence, it can be considered that n_H is 100% for all intermittent limits. This very small increase in the costs is due to a slightly lower hydro production that implies the use of more fossil fuel to supply the load. This lower hydro production occurs because there is less water pumped when n_H is lower than 100%. Although that might seem strange, it is related to the balance between wind power available to pump and water available in the lower reservoir to be pumped to the upper reservoir. When n_H is 100% at all hours of the year, the system can be turbinating water to the lower reservoir in times when there is no available wind power to pump back this water to the upper reservoir, decreasing the consequential hydro production. It would be very interesting to see what happens if the desalination capacity increases, having the system more capacity to produce water.

The optimal wind balance level of the lower reservoir (n_{WB}) is always 100%, which implies that this level has no influence on the operational strategy of this system. Because the desalination capacity is limited, there is no need to limit the wind power that is used in the desalination units. In this case, it would also be interesting to verify the behaviour of this variable with an increased desalination capacity.

Figure 4 shows the minimum total annualized costs for the integrated supply system for each intermittent limit. The intermittent limit that minimizes the costs is the maximum allowed, i.e., 30%. This is because the weight of the water production in this system is very low (~10%) so that the more wind power supplied to the load the better, since there is less need for fossil fuel based units.

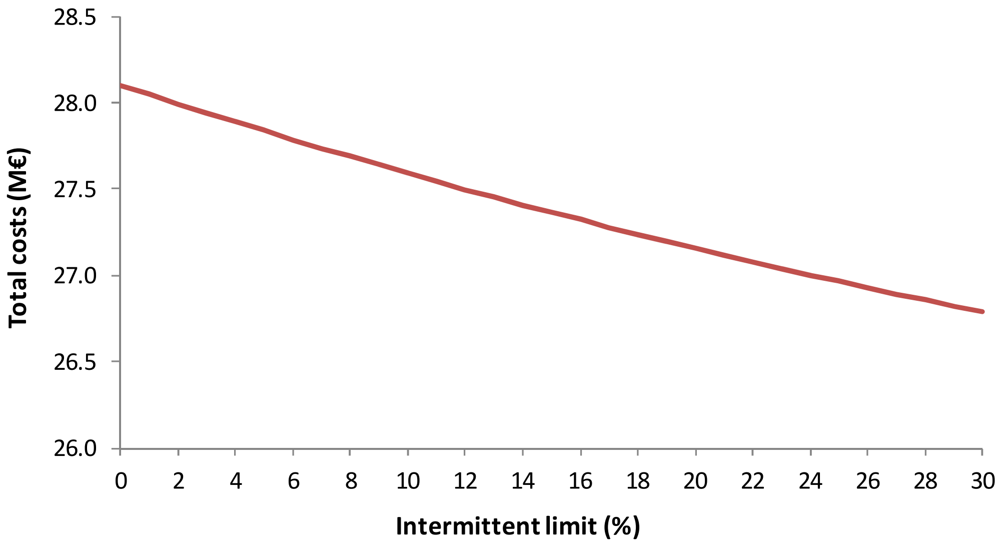

Figure 4. Minimum total annualized costs for the integrated supply system for each intermittent limit.

Figure 5 presents the load supply by source - wind power, PHS and fossil fuel (FF) - for S. Vicente in 2020, with the proposed wind powered PHS system. The share of RES increases with the intermittent limit, because more wind power is allowed to supply the load. RES penetration in supplying load demand reaches 28% with an intermittent limit of 30%.

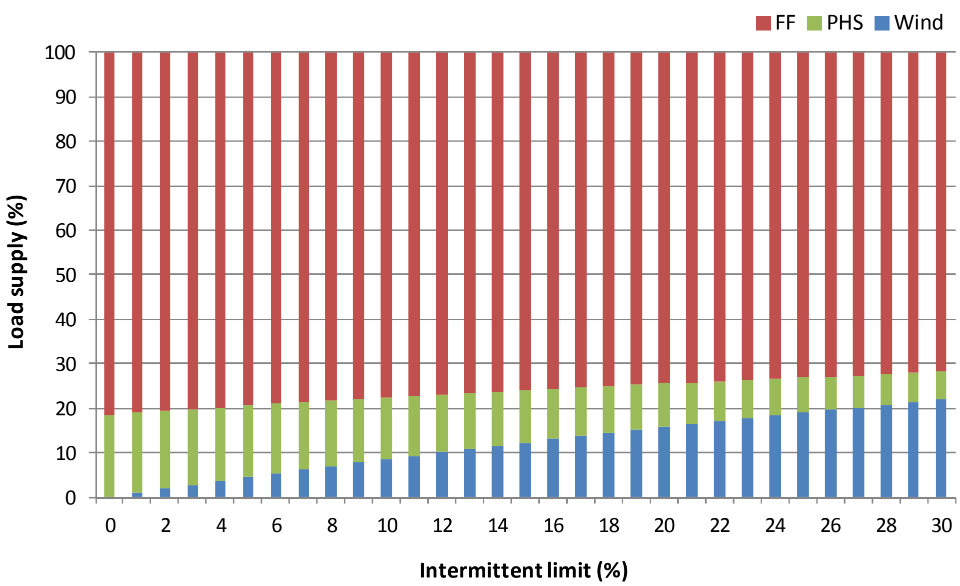

Figure 5. Load supply by source for each intermittent limit.

Figure 6 shows the water production supply by source for each intermittent limit. It is observed that the wind power penetration decreases with the intermittent limit. This is because when there is more wind power excess available, more water can be produced with wind power.

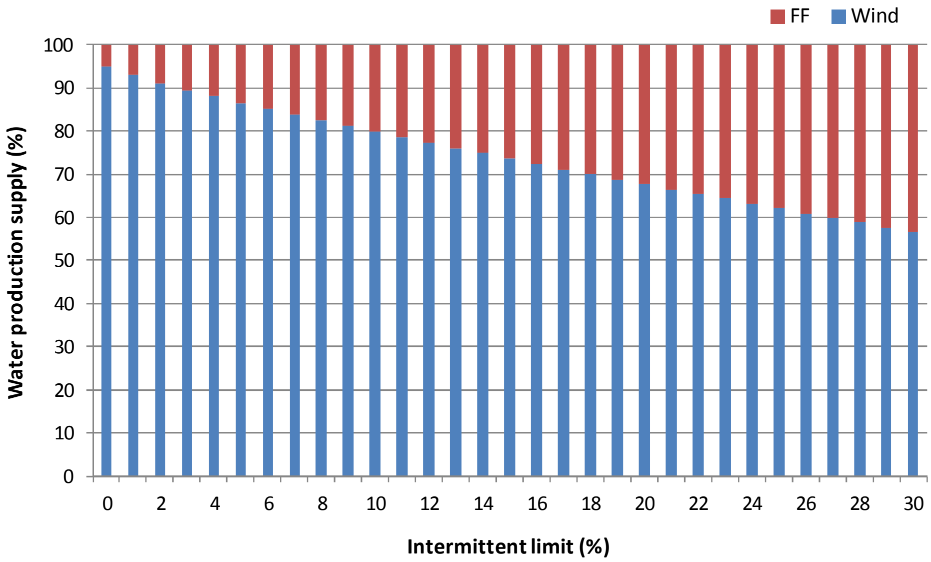

Figure 6. Water production supply by source for each intermittent limit.

Figure 7 presents the power production by source for each intermittent limit. This power production is used to supply the load and to produce water. It is seen that as the power production decreases with the intermittent limit, the fraction of RES also decreases from about 41% to 36%.

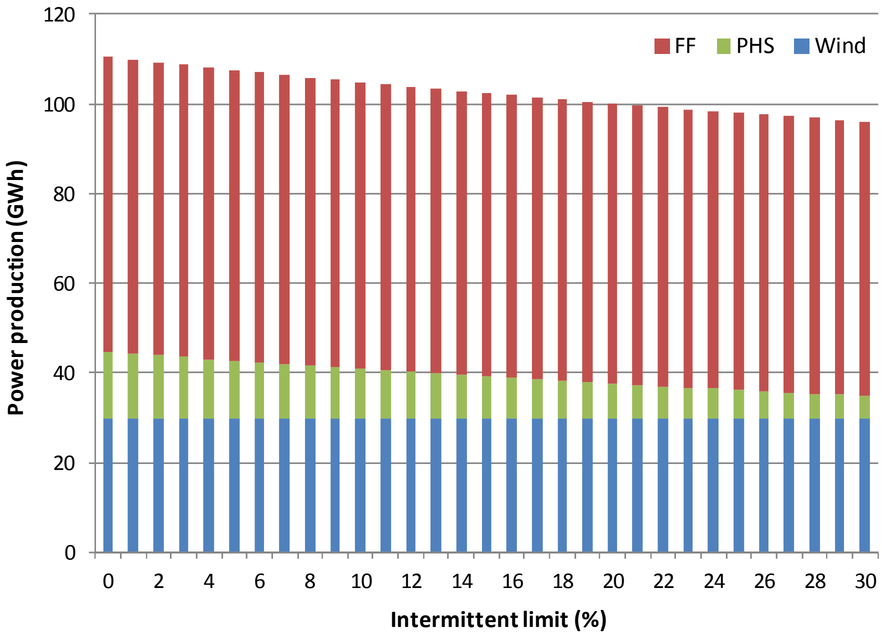

Figure 7. Power production by source for each intermittent limit.

5. CONCLUSIONS

- The optimal sizing of the pumped hydro storage varied according to the intermittent limit considered. The optimal pump power ranges from 5.8 MW to 3.2 MW, and the hydro power ranges from 3.4 MW to 1.5 MW.
- In regard to the variables designed to optimize the operational strategies of this integrated system, the optimal level n_H is almost always 100%, and the optimal level n_{WB} is always 100%, which implies that this level has no influence on the operational strategy of this system. This is due to the limited capacity of the desalination units.
- Since these results are constrained by the low water production capacity, this optimization problem will be analysed for increased capacities of the desalination units, namely for twice as much capacity (10,800 m^3/day) and three times as much capacity (16,200 m^3/day).
- Since the wind power available and the load and water load of this location vary considerably throughout the year, it is important to verify the influence of the seasonal changes in the operational strategies of this system. Starting from the results of this work, the operational levels of the system, n_{WB} and n_H, will be turned into monthly variables in order the assess the seasonal optimal operation of the system.
- A purely operational optimization will be performed. Based on the previous results, the pump and hydro power will be fixed and the optimal values of the operational levels of the system will be found based on a yearly and monthly analysis.

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REFERENCES

[1] S.A. Papathanassiou and N.G. Boulaxis, "Power limitations and energy yield evaluation for wind farms operating in island systems", *Renewable Energy* Vol. **31**, pp. 457-479, (2006).

[2] R. Segurado, M. Costa, N. Duić and M.G. Carvalho, "Integrated analysis of energy and water supply in islands. Case study of S. Vicente, Cape Verde", *Energy*, Article in Press (2015).

[3] A.L. Custódio and J.F.A. Madeira, "GLODS: Global and Local Optimization using Direct Search", *Journal of Global Optimization*, pp. 1-28 (2014).

[4] A.L. Custódio, J.F.A. Madeira, A.I.F. Vaz and L.N. Vicente, "Direct Multisearch for Multiobjective Optimization", *SIAM Journal on Optimization* Vol. **21(3)**, pp. 1109-1140, (2011).

[5] Carbon Dioxide Emission Allowances Electronic Trading System - SENDECO2 - http://www.sendeco2.com, accessed on 16th February 2015.