Optimal Design of a Wind Farm to supply power to a Reverse Osmosis-based Desalination Plant connected to Grid: A case study of Lanzarote, Spain

F.J. Asensio[1], J.I. San Martín[1], I. Zamora[2], J. García-Villalobos[2], and O. Onederra[1]

Department of Electrical Engineering - University of the Basque Country (UPV/EHU)

[1]Engineering School of Gipuzkoa – Section of Eibar
29 Otaola Avenue, 20600 Eibar (Spain)
phone: +34 943 033010, fax: +34 943 033110, e-mail: joseignacio.sanmartin@ehu.eus

[2]Engineering School of Bilbao
Alameda Urquijo s/n, 48013 Bilbao (Spain)
phone: +34 946 014063, fax: +34 946 014200, e-mail: inmaculada.zamora@ehu.eus

Abstract. This paper is focused on the optimal design of a wind farm aimed at supplying power to a reverse osmosis-based desalination plant connected to the grid, located in the Lanzarote island, Spain. For the optimal design, there have been used electricity consumption and water production real profiles of the already existing desalination plants on the island, which are owned by INALSA. It has been simulated the system in order to perform a profitability study for several models of wind turbines, which has allowed to select as optimal design the one that has minimized the total net cost of the installation for a lifetime of 25 years. In this sense, there have been compared the energy and economic results of the base case in which the desalination plant is supplied by the conventional energy grid, with the designs obtained by simulation.

Key words: Wind Farm, Wind Turbine, Optimal Design, Reverse Osmosis, Desalination Plant.

1. Introduction

Currently, 20% of humanity have no freshwater because of its scarcity or difficulties access in certain regions of the world, and according to IPCC (Intergovernmental Panel on Climate Change), by 2025 about 60 % of world population will be living in water-stressed countries [1]. These problems were already addressed in the Johannesburg summit (2002), in which the water crisis was the protagonist and fundamental changes in the way water resources are produced and consumed were proposed.

In the case of Canary Islands, the problem of the water scarcity has been solved thanks to a massive desalination of seawater using reverse osmosis processes. However, these processes are very expensive in terms of energy, which has led to a significant increase between the relation of fossil fuel consumption and regional GDP (Gross Domestic Product) [2]. To mitigate this effect, in the current literature, several models proposed that include renewable energy sources for this purpose can be found, braking the dependence on fossil fuels and reducing substantially CO_2 emissions [3], [4]. Even in [5], it is presented the operational analysis of a prototype of reverse osmosis-based desalination plant powered by wind energy, installed in the Canary Islands. However, it is focused on describing the operational strategies rather than on the optimal sizing of the system itself, in order to maximize the economic efficiency of the freshwater production system throughout its lifetime.

This paper shows the methodology carried out for the optimal sizing of a wind farm to supply power to a reverse osmosis-based Lanzarote III, IV and V desalination plants, located in Lanzarote. This optimizing methodology is scalable and replicable in any other location with access to sea water and with enough wind resources.

2. Location and Wind Resource

In order to set the optimal location of the wind farm, it has been used GIS (Geographic Information System) provided by the Canary Islands Government and the electrification maps provided by the TSO (Transmission System Operator) of Spain, REE (Red Eléctrica de España - Electricity Network of Spain) [6], [7]. In this sense, maps of the wind resource of the island, protected natural areas, land occupation, orography and existing power lines have been superimposed.

A. Location

Figure 1 shows the overlapping of the maps of the wind resource at 80 meters high, protected natural areas and power transmission lines of REE.

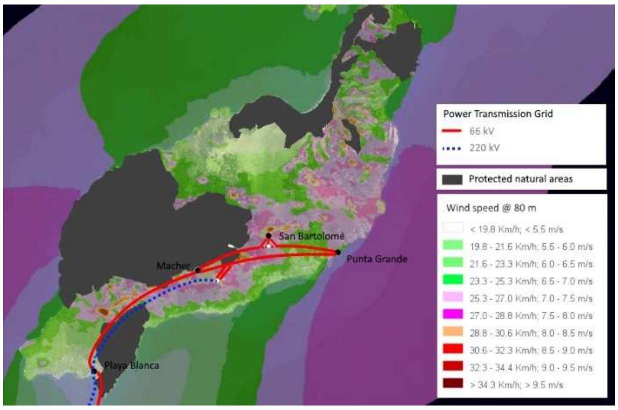

Figure 1. Overlay of the maps of wind resource, protected areas and transport networks in Lanzarote island.

Below are described the factors that have been taken into account to select the optimum location.

1) *Proximity to grid.* The proximity of an electric network capable of evacuating the power generated by the windfarm.
2) *Protected areas.* The minimum distance to respect both protected natural parks as well as neighboring developments.
3) *Available space.* Land space available for optimal installation of each wind turbine.
4) *Wind direction.* The prevailing wind direction determines the amount of space needed, since the turbines will be distributed perpendicular to that direction.
5) *Wind resource.* A wind resource abundant and stable throughout the year.
6) *Obstacles.* The minimum number of obstacles that can stop the wind that reaches the turbines or may divert its path by creating turbulences, such as trees, hills or buildings.
7) *Proximity to consumption.* The maximum proximity to the desalination plants are to be supplied.

In Figure 2, the geographical location of the chosen optimum location (UTM, X:637350, Y: 3209550, Zone: 28, Hemisphere: N) is shown.

Figure 2. Optimal location of the wind farm.

Considering all the factors mentioned above, the location indicated in Figure 2 has been chosen. The area chosen, it is an unobstructed location, is 6 km away from the nearest protected area and 2.3 km away from the nearest urbanized area. In regard to the proximity to the power grid, it is 2 km away from a 66 kV grid network through which energy could be evacuated to desalination plants, which are located at a distance of about 6.5 km. Moreover, the wind conditions in the area chosen are suitable, being the predominant direction NNE, so that the wind turbines will be distributed perpendicular to that direction. Given that the minimum distance to maintain between each turbine is three diameters on the sides and five diameters between turbines arranged in parallel to the prevailing wind direction, it is concluded that necessary space conditions are met.

In Figure 3 it is shown the 3D terrain modeling, in which is highlighted a yellow rectangle representing the boundary of the wind farm.

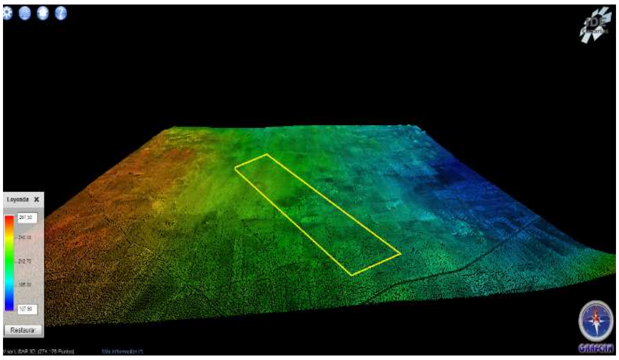

Figure 3. 3D terrain modeling and delimitation of the site.

In the cartography of the Figure 3, it can be seen that there are no obstacles that could cause a reduction in wind speed or generate harmful interferences to the operation of wind turbines.

B. *Wind Resource*

To study the wind resources, data provided by IDAE (Institute for Diversification and Saving of Energy) and IRENA (International Renewable Energy Agency) have been used [8], [9].

Figure 4 shows the wind rose of the site chosen, in which can be appreciated that the prevailing wind direction is NNE.

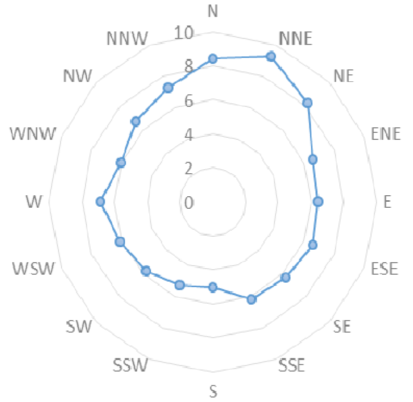

Figure 4. Wind rose of the selected site.

The duration curve wind graphed in Figure 5, expresses the probability that the wind speed exceeds a certain value for a certain period of time. In this particular curve, it is seen that it is unlikely that the wind speed reaches or exceeds the speed of 14 m/s. However, it would be usual to reach a value of 8 m/s. These data are used to simulate the behavior of the wind farm throughout each year of the life of the system.

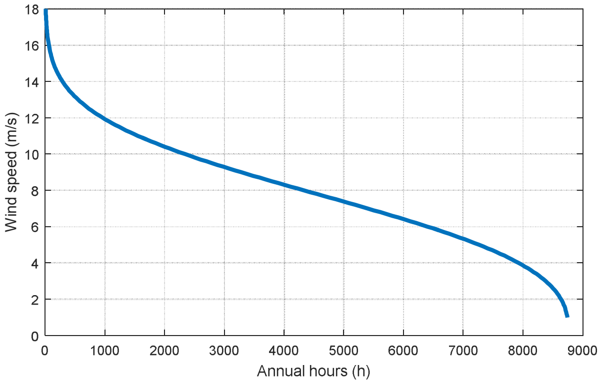

Figure 5. Wind speed duration curve of the selected site for a height of 120 m.

3. Optimization Methodology

Optimization methodology is based primarily on two tasks: simulation and economic analysis.

A. Simulation

During the simulation, starting from the entered scheme and settings, the system is modeled step by step per unit time to determine its behavior and viability annually, depending on the wind resource availability, costs associated to electric energy consumption and each system element, efficiency of each device, electric energy generation and injection into the grid, etc.

During simulation, it is taken into account the energy demand per unit time and the ability of the system to supply that demand. In this sense, energy flows between components are calculated in order to decide their behavior depending on whether exists or not excess or deficit of power generation by the windfarm. As long as system constraints do not indicate otherwise, the demand will be supplied from the windfarm.

The energy produced by the windfarm is calculated by summing the multiplications of the power curve of each wind turbine by the wind speed distribution.

The wind speed distribution is characterized by a two-parameter Weibull distribution. Equation (1) represents the Weibull probability density function, given as:

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \cdot exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{1}$$

where:

v is the wind speed [m/s], k is the Weibull shape factor [unitless] and c is the Weibull scale parameter.

The power curves offered by manufacturers typically specify wind turbine performance under conditions of standard temperature and pressure (STP). To adjust to actual conditions, it is multiplied the power value predicted by the power curve by the air density ratio, according to following equation (2):

$$\boldsymbol{P_{WTG}} = \left(\frac{\rho}{\rho_0}\right) \cdot \boldsymbol{P_{WTG,STP}} \tag{2}$$

where:

$\boldsymbol{P_{WTG}}$ is the wind turbine power output [kW], $\boldsymbol{P_{WTG,STP}}$ is the wind turbine power output at standard temperature and pressure [kW] and $\left(\frac{\rho}{\rho_0}\right)$ is the air density ratio, which is calculated in equation (3) given as:

$$\frac{\rho}{\rho_0} = \left(\mathbf{1} - \frac{Bz}{T_0}\right)^{g/RB}\left(\frac{T_0}{T_0 - Bz}\right) \tag{3}$$

where:

$\boldsymbol{g}$ is the gravitational acceleration [9.81 m/s^2], $\boldsymbol{B}$ is the lapse rate [0.00650 K/m], $\boldsymbol{z}$ is the altitude [m], $\boldsymbol{T_0}$ is the standard temperature [288.16 K] and R is the gas constant [287 J/kgK].

In order to calculate the wind power output for each corresponding wind speed, the wind speed at the hub height of the wind turbine is calculated by equation (4), given as:

$$U_{hub} = U_{anem} \cdot \frac{ln\left(^{Z_{hub}}/_{Z_0}\right)}{ln\left(^{Z_{anem}}/_{Z_0}\right)} \tag{4}$$

where:

U_{hub} is the wind turbine speed at the hub height of the wind turbine [m/s], U_{anem} is the wind speed at the anemometer height [m/s], Z_{hub} is the hub height of the wind turbine [m], Z_{anem} is the anemometer height [m] and Z_0 is the surface roughness length [m].

B. Optimization and Economic Analysis

The economic analysis allows choosing the design of the simulation that has maximized the economic and energy efficiency of the system. In this sense, it has been taken as determining factor the NPC (Net Present Cost) for a lifetime of the installation of 25 years. To do this, there have taken into account the present value of all the costs (€) that the system incurs over each year and the present value of all the revenue (€) that system earns over each year throughout its lifetime.

During the optimization task, the non-viable configurations are discarded and viable ones are classified regarding their NPC (€), which is defined by equation (5). In section 4-D are defined all the parameters of the costs taken into account to evaluate (5).

$$\boldsymbol{NPC} = \sum_{i=1}^{n}\left(\boldsymbol{C_{PV_i}} - \boldsymbol{R_{PV_i}}\right) \cdot \boldsymbol{f_{d_i}} \qquad (5)$$

Where $\boldsymbol{n}$ are the years of the system lifetime, $\boldsymbol{C_{PV_i}}$ is the present value of all the costs (€) that the system incurs over the year $\boldsymbol{i}$, $\boldsymbol{R_{PV_i}}$ is the present value of all the revenue (€) that system earns over the year $\boldsymbol{i}$ and $\boldsymbol{f_{d_i}}$ is the discount factor of each $\boldsymbol{i}$ year. $\boldsymbol{C_{PV_i}}$, $\boldsymbol{R_{PV_i}}$ and $\boldsymbol{f_{d_i}}$ are defined in the equations (6), (7) and (9), respectively.

$$\boldsymbol{C_{PV_i}} = \boldsymbol{C_{Capital}} + \boldsymbol{C_{O\&M}} + \boldsymbol{C_{grid}} \qquad (6)$$

Where $\boldsymbol{C_{Capital}}$ is the capital cost due to initial capital or equipment replacement; $\boldsymbol{C_{O\&M}}$ is the syste-m operation and maintenance cost, calculated by the sum of the multiplication of the hours of operation of each device by its O&M cost; $\boldsymbol{C_{grid}}$ is the cost associated with buying power from grid and it takes into account the variable and fixed cost of the electricity consumption and power contracted.

$$\boldsymbol{R_{PV_i}} = \boldsymbol{S_V} + \boldsymbol{G_{Sales}} \qquad (7)$$

Where $\boldsymbol{S_V}$ is the sum of the salvage value of each component and $\boldsymbol{G_{Sales}}$ is the grid sales revenue. $\boldsymbol{S_V}$ can be calculated from equation (8) given as:

$$\boldsymbol{S_V} = \boldsymbol{C_{rep}} \cdot \frac{\boldsymbol{R_{lt}} - \boldsymbol{t_O}}{\boldsymbol{R_{lt}}} \qquad (8)$$

where $\boldsymbol{C_{rep}}$ is the replacement cost of each component, $\boldsymbol{R_{lt}}$ is the lifetime (*h*) of each component and $\boldsymbol{t_O}$ are the hours of operation of each component.

$$\boldsymbol{f_{d_i}} = \frac{\boldsymbol{1}}{(\boldsymbol{1}+\boldsymbol{r})^{\boldsymbol{i}}} \qquad (9)$$

Where $\boldsymbol{r}$ is the real interest rate (%), which is defined by equation (10) given as:

$$\boldsymbol{r} = \frac{\boldsymbol{r'} - \boldsymbol{f}}{\boldsymbol{1}+\boldsymbol{f}} \qquad (10)$$

where $\boldsymbol{r'}$ is the nominal interest rate (%) and $\boldsymbol{f}$ is the annual inflation rate (%).

In order to quantify the cost of power generation of the system for each configuration, it is also calculated the levelized Cost of Energy ($\boldsymbol{COE}$), which is the average cost per *kWh* of useful electrical energy produced by the system. The $\boldsymbol{COE}$ can be calculated from equation (11) given as:

$$\boldsymbol{COE} = \frac{\boldsymbol{C_{T\_ann}}}{\boldsymbol{E_S}} \qquad (11)$$

where $\boldsymbol{C_{T\_ann}}$ is the total annualized cost of the system (€) and $\boldsymbol{E_S}$ is the total electrical load served (*kWh*). $\boldsymbol{C_{T\_ann}}$ can be calculated by equation (12) given as:

$$\boldsymbol{C_{T\_ann}} = \boldsymbol{C_{RF}} \cdot \boldsymbol{NPC} \qquad (12)$$

where $\boldsymbol{C_{RF}}$ is the capital recovery factor based on the real interest rate $\boldsymbol{r}$ and the system lifetime years $\boldsymbol{n}$. $\boldsymbol{C_{RF}}$ can be calculated by equation (13) given as:

$$\boldsymbol{C_{RF}} = \frac{\boldsymbol{r}(\boldsymbol{1}+\boldsymbol{r})^{\boldsymbol{n}}}{(\boldsymbol{1}+\boldsymbol{r})^{\boldsymbol{n}} - \boldsymbol{1}} \qquad (13)$$

Once having classified the viable solutions with respect to the $\boldsymbol{NPC}$, the optimal configuration will be that which present a lower $\boldsymbol{NPC}$, which will allow choosing the optimal size of the windfarm that minimizes the total cost of the system over its lifetime. These values are shown in section 5.

It is interesting to analyze the viability that presents the system when it faces to a high degree of independence with respect to the grid. In this sense, it has been analyzed the minimum fraction of energy consumed from the windfarm $\boldsymbol{f_{min}}$ (%) with respect to the conventional consumption from the grid, which can be calculated from equation (14) given as:

$$\boldsymbol{f_{min}} = \left(\boldsymbol{1} - \frac{\boldsymbol{E_{grid}}}{\boldsymbol{E_S}}\right) \cdot \boldsymbol{100} \qquad (14)$$

where $\boldsymbol{E_{grid}}$ is the total electrical energy consumed from the grid.

The simulation is performed for all possible configurations, taking into account a predefined range of sizes and powers of wind turbines and the electrical power contracted.

Table I shows the range of power taken into account for each device in order to simulate various configurations of the system.

Table I. – Power ranges and number of wind turbines taken into account to implement various system configurations.

Element	Range
Power grid contracted	5 - 15 MW
Wind turbine power	3 or 7.58 MW
Number of wind turbines	1 - 5

4. Simulation Parameters

A. Energy Requirements

The set of resources in operation that currently provide desalinated water in the complex of *Inalsa* in *Punta de los Vientos*, is formed by the plants of Lanzarote III, Lanzarote IV and Lanzarote V, which have a combined total production capacity of 84,000 m^3/day of desalinated water for the island.

Table II shows the breakdown of water production and energy consumption of each desalination plant.

Table II. Desalinization plants data.

	Lanzarote III	Lanzarote IV	Lanzarote V
Daily production (m^3/day)	29,512	10,417	17,535
Specific consumption (kWh/m^3)	4,52	4,89	3,41
Daily consumption (kWh/day)	133,392.4	50,937.2	59,794.7
Annual consumption (kWh/year)	89,105,369.5		

For the simulation of the plant, it is assumed that water demand is constant and therefore also the energy consumption. In this regard, when the wind farm cannot supply all of the electricity demand of the desalination plants, the consumption of these will be complemented by the grid and when there is surplus power, it will be injected into the mains.

B. Wind Resource

Since databases consulted for the calculation of wind potential provide data of wind speed for a height of 80 meters and the hubs of wind turbines installed will be located at a height of 120 meters, data have to be processed in order to fit them to the height under study.

Table III shows data of frequency (%), power (%), wind speed (m/s), Weibull C parameter (m/s) and Weibull K parameter, for 16 wind directions. The coefficient of terrain roughness is 0.1.

Table III. Wind data adapted from IDAE to study the wind resource of the chosen location.

	Freq. (%)	Power (%)	Vel. (m/s)	Weibull C (m/s)	Weibull K
N	15,37	16,39	8,406	9,415	2,990
NNE	36,00	53,15	9,28	10,37	3,13
NE	16,36	14,40	8,19	9,18	2,94
ENE	5,21	2,03	6,59	7,42	2,53
E	3,03	1,45	6,44	7,27	2,19
ESE	2,15	1,38	6,60	7,45	1,93
SE	1,52	0,83	6,28	7,03	1,68
SSE	1,32	0,68	6,19	6,95	1,75
S	0,64	0,24	5,01	5,66	2,31
SSW	0,77	0,47	5,29	5,96	1,82
SW	1,34	0,55	5,72	6,46	2,08
WSW	1,82	0,76	6,11	6,90	2,17
W	2,67	1,22	6,86	7,74	2,40
WNW	2,33	0,81	6,09	6,87	2,42
NW	3,42	1,79	6,66	7,52	2,21
NNW	6,05	3,84	7,23	8,14	2,66

C. Wind Turbine Models

In order to optimize the sizing of the wind farm, there have been taken into account two different models of wind turbine, the E-115 and E-126, both of the manufacturer Enercon [10].

In Figure 6, the output power curves depending on the wind for each model are shown.

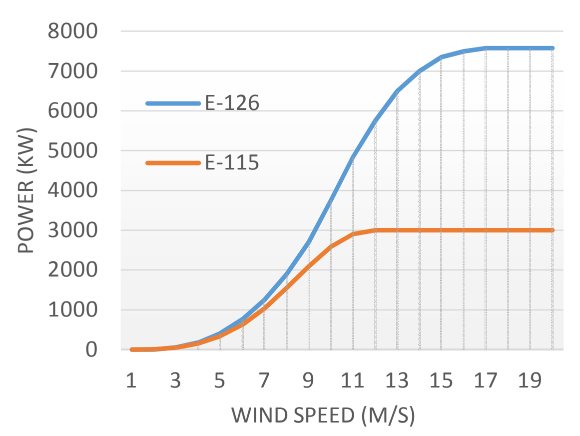

Figure 6. Power curves of the E-115 and E-126 wind turbine models.

D. Economic Parameters

The economic parameters are all those costs taken into account when calculating the $\boldsymbol{NPC}$ of each system.

Table IV shows the estimated costs per unit of the initial capital, O&M and replacement of each model of wind turbine. These costs are used for simulation and calculation of the $\boldsymbol{NPC}$, for each possible configuration, taking into account the power ranges and number of wind turbines defined in Table III.

Table IV. – Initial capital, O&M and replacement costs of each model of wind turbine.

Wind turbine model	$C_{initial}$ (M€)	C_{rep} (M€)	$C_{O\&M}$ (€/year)
E-115	3.75	3	131,250
E-126	8.75	7	306,250

Since desalination plants operate under constant flow, consumption throughout the day it is also constant, so that the power term of the grid can be compensated with a weighted average of prices in function of the daily hours in which each one are applied.

Table V shows the prices of the power term of the time-based tariff chosen.

Table V. – Costs of the power term of the grid.

	Period 1	Period 2	Period 3
Power term (€/kW/year)	59.173	36.491	8.368
Hours per day	6	10	8
Weighted avg. (€/kW/month)	2.732		
Electricity taxes (5.11%)	2.872		
After VAT (21%)	3.475 €/kW/month		

To achieve the costs of energy consumption (€/kWh), data provided by the company OMIE have been consulted, which are exposed to the public, available at [11]. It has been calculated the average of the final prices of reference marketers for 12 months from September 2014 to August 2015. The average cost of energy during this period, after taxes, is 0.08546 €/kWh.

E. Durability parameters

The lifetime of the wind turbines, for both models, has been stablished in 25 years.

5. Simulation Results

After simulation of all possible configurations, it has been concluded that the optimal system would consist of five wind turbines model E-115, being the optimal power grid to be contracted of 10 MW.

Table VI shows a summary of the results for the optimized system and the base case for a 25-year system lifetime.

Table VI. – Comparative summary of the optimized system based on wind energy and the base case system.

	Initial Capital (M€)	COE (€/MWh)	Total NPC (M€)	Renewable Fraction (%)
Base case system	-	90	102.775	0
Optimized system	18.75	59	66.661	65

In figure 7 it is shown the monthly average electricity consumption from grid and the windfarm.

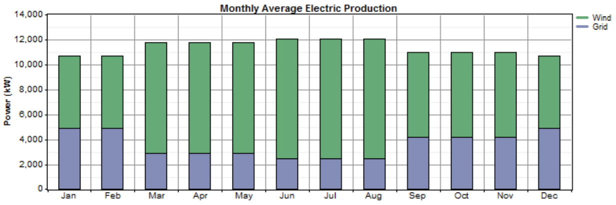

Figure 7. Average electricity consumption from grid and the windfarm.

6. Conclusions

This paper has presented the optimal design of a wind farm to supply electricity to the desalination plants Lanzarote III, IV and V located on the island of Lanzarote, Spain.

Optimization results have demonstrated the feasibility of the proposed system, resulting in a 34% reduction in the cost of energy, which in turn has led to a savings of approximately 36 M € in comparison to the current system of supply based on the electrical network, for a system lifetime of 25 years. Moreover, the fraction of renewable energy with the optimized system has been of 65%, which implies a reduction of the same order in CO2 emissions with respect to the base case when generating freshwater.

Although in this paper only have been taken into account two models of wind turbines for the optimal design of the system, the methodology developed to size this windfarm could be used to achieve an optimal design for any other desalination plant with similar energy requirements.

Acknowledgement

The authors acknowledge the financial support from the University of the Basque Country UPV/EHU (project EHU13/66).

References

[1] IPCC Fourth Assessment Report: Working Group II Report "Impacts, Adaptation and Vulnerability", Cambridge University Press, Cambridge, 2007.
[2] J. Schallenberg-Rodriguez, J.M. Veza, A. Blanco-Marigorta, Energy efficiency and desalination in the Canary Islands, Renew Sust Energ Rev, Vol. 40, pp 741-748, December 2014.
[3] M. P. Shahabi, A. McHugh, M. Anda, Environmental life cycle assessment of seawater reverse osmosis desalination plant powered by renewable energy, Renewable Energy, Vol. 67, pp 53-58, July 2014.
[4] N. Ghaffour, J. Bundschuh, H. Mahmoudi, M.F.A. Goosen, Renewable energy-driven desalination technologies: A comprehensive review on challenges and potential applications of integrated systems, Desalination, Vol. 356, pp 94-114, January 2015.
[5] J.A. Carta, J. González, V. Subiela, Operational analysis of an innovative wind powered reverse osmosis system installed in the Canary Islands, Solar Energy, Vol. 75, Iss. 2, pp 153-168, August 2003.
[6] Geographical Information System of Canary Islands. Available in: http://www.grafcan.es/
[7] Electrical Spanish Grid (REE). Available in: http://ree.es/en
[8] Institute for diversification and energy saving (IDAE). Available in: http://www.idae.es/
[9] International Renewable Energy Agency (IRENA). Available in: http://www.irena.org/
[10] ENERCON GmbH. Available in: http://www.enercon.de/
[11] Operator of the Iberian Electricity Market (OMIE). Available in: http://www.omie.es/en