A renewable energy mix to supply the Balearic Islands: Sea Wave, Wind and Solar

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***Abstract*—The paper investigates the status of the electrical energy sector in the Balearic Islands (Spain). In order to improve the energetic sustainability, this work analysis the availability of renewable energy sources, focusing the attention on sea wave, wind and solar. For the utilization of sea wave source, an innovative device is proposed.**

Keywords— Balearic Islands; Renewable Energy; Sea Wave.

I. Introduction

During the last two decades, renewable energy sources have increased their role for the electrical energy production in Industrialized Countries, especially in European Union.

Thanks to the use of specific policies [1], the diffusion of technologies supplied by Renewable Energy Sources (RES) is contributing to the challenge of reduction of energy dependence from fossil fuels, avoiding the emission of several polluting substances and greenhouse gases (GHG).

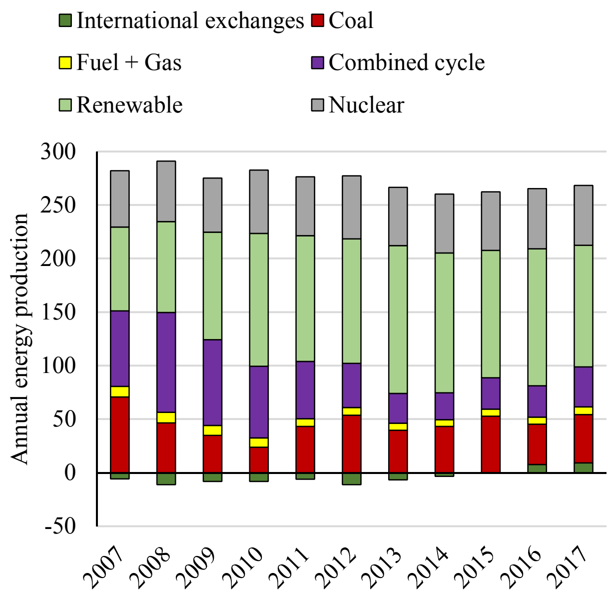

Fig. 1. Electrical energy production in Spain.

RES have a very remarkable role in several sectors, for example the indoor heating (using solar thermal panels) or the transport (thanks to the production of biofuel) [2]–[4].

As example, focusing the attention on the statistics of electrical energy production in Spain, reported in Fig.1 [5], the renewable energy sources are playing a very important role. Generally, the production from renewable energy sources has grown, representing about 27.7% of the electrical production in 2007 and 44.0% in 2017. Fluctuations in this decade are connected to the contribution of hydroelectric, that is deeply influenced by precipitations.

Fig.2 shows the main energy sources used in 2017 to satisfy the electrical energy demand. The main items are renewable energy sources (42.5%, corresponding at 113.8 TWh/y), nuclear power (20.7 %, equivalent to 55.6 TWh/y) and traditional thermoelectric plants (33.4%, equivalent to 89.5 TWh), finally a marginal role is played by import exchange (3.4%, representing 9.1 TWh/y).

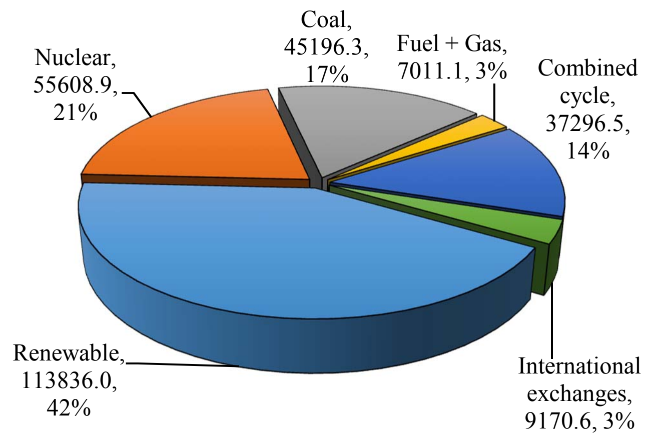

Fig. 2. Electrical energy production in Spain during 2017, divided by categories.

Fig. 3 shows the renewable energy mix used to produce electricity in Spain during 2017: the main items are wind (42% equivalent to 47.9 TWh/y), cogeneration (25%, 28.2 TWh/y),

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hydropower (15% 17.0 TWh/y) and solar (divided in photovoltaic and thermodynamic plants, respectively 7%, 8.3 TWh/y and 5%, 5.3 TWh/y).

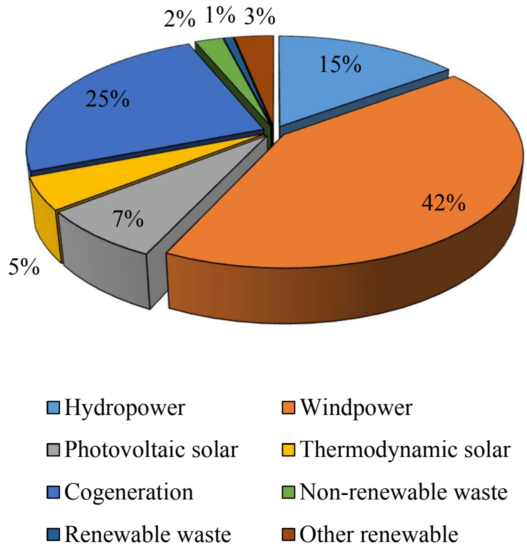

Fig. 3. Electrical energy production from renewable energy sources in Spain during 2017.

Despite these results, in different Spanish areas the ratio of electrical energy production from renewable sources respect the total is very low. This condition is common in all small islands of the Mediterranean Sea [6]–[8].

The low development of renewable sources is due to several reasons, as the environmental restrictions (reserved area for flora and fauna) that prevent the realization of extensive power plants, the availability of energy resources and the presence of a single local producer [9].

Many small islands are not connected to the mainland; in this case, another priority problem is the balancing of energy demand and energy production: an energy storage is required, especially in a small electrical grid, increasing the investments and obstructing the introduction of renewable sources.

In this context, the paper examines the technologies currently used to produce electrical energy in the Balearic Islands. Analyzing the availability of renewable energy sources, the paper proposes an energetic mix based on solar, wind and sea wave. In order to exploit the last source, an innovative energy converter is presented.

II. The Case Study

The Balearic Islands are a Spanish archipelago, located in the western part of the Mediterranean Sea, as shown in Fig.4.

The main islands are: Majorca, Menorca, Ibiza and Formentera. The archipelago includes also several minor islands as Cabrera, Dragonera and S'Espalmador. The data of main islands are reported in Table I.

From a political point of view, the Balearic Islands have been an autonomous region of Spain since 1983.

Thanks to its position, the Balearic Islands are characterized by a Mediterranean climate, with a temperature ranging from 8.3°C (in January) to 29.8°C (in August) [10].

Fig. 4. Balearic Islands.

TABLE I. Data of Main Balearic Islands [11]

Island	Surface [km^2]	Population	Highest peak [m]
Majorca	3,640.11	894,867	1445
Menorca	695.7	93,516	358
Ibiza	571.6	149,464	475
Formentera	83.24	12,993	119

As shown in Fig. 5, the rainfalls are mainly concentrated in autumn and very limited in summer. Thanks to wonderful landscapes, Balearic Islands are a famous tourist destination, especially in summer.

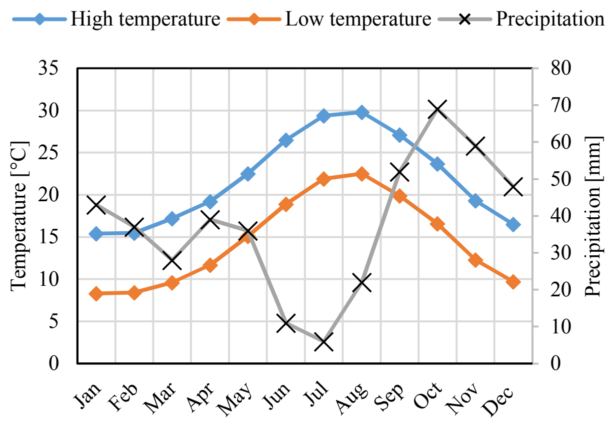

Fig. 5. Trends of monthly average maximal and minimal temperaturews and monthly precipitation in the Balearic Islands (Spain).

As regard the energy sector, Fig. 6 reports the trend of electricity production in the last decade. The consumption is practically stable, about 6 TWh/y. Fossil fuels is currently the dominant energy source, representing about 72.9% of the total energy production in last year, divided in different technologies (diesel, coal, gas turbine and combined cycle).

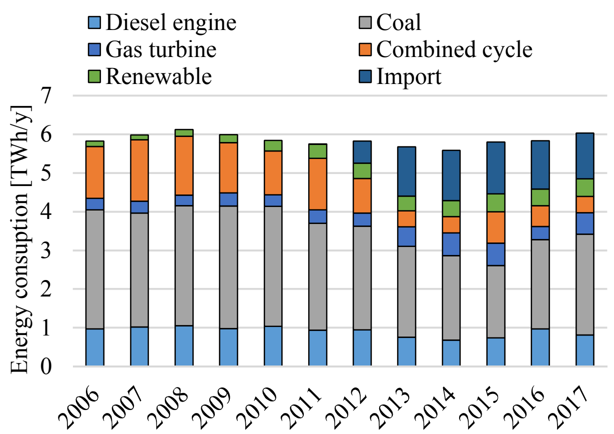

Fig. 6. Energy consuption by sources in Balearic Islands.

A significant change was introduced in 2012, thanks to the electrical connection between the Balearic Islands and Spain. This link is composed by a double line (direct current, working at 250 kV), with a length about 237 km, connecting the station of Sagunto (Valencia, Spain) and Santa Ponsa (Majorca). According data reported in Fig. 6, in 2017 this connection allowed the importation of an amount of energy equal to 1.18 GWh, corresponding to 19.6 % of the annual electrical consumption.

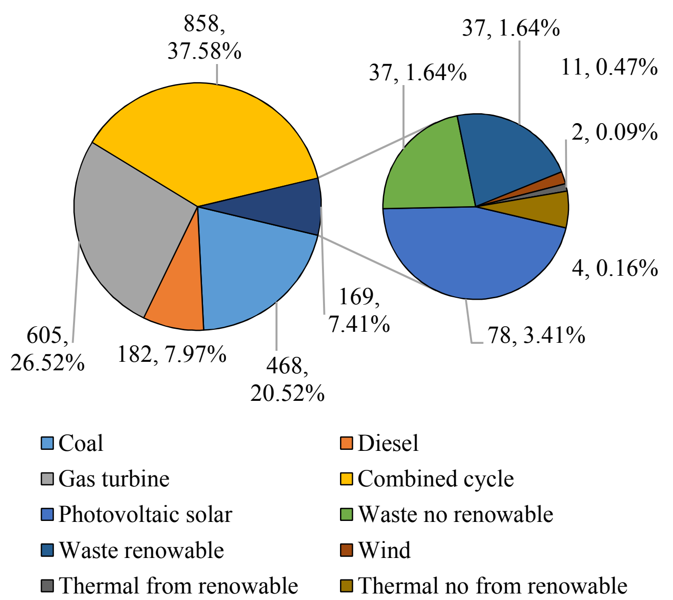

Fig. 7. Installed power in Balearic Islands (data in MW).

The Balearic Islands are also electrically interconnected: a line (three phases, 132 kV) links Ciutadella substation on Menorca with Es Bessons substation on Majorca (the doubling is programmed); a double line (three phase, 132 kV) links Santa Rosa substation on Majorca with Torrent substation on Ibiza; finally, two lines (three phase, 30 kV) connect Ibiza from San Jorge substation to Formentera (a double line from Torrent Station to Ibiza is programmed) [5].

As shown in Fig.7, in 2017 the installed power is practically based on fossil fuels: 468 MW by coal, 182 MW by diesel engine, 605 MW by gas turbine and 858 by combined cycle, representing altogether 92.6% of the global installed power.

In order to satisfy the electrical energy consumption in a sustainable way, the paper proposes an energetic mix based on renewable energy sources, composed by solar, wind and sea wave, as shown in Fig. 8. The balancing of electrical request and production can be realized, using the local and mainland electrical grid (thanks to the submarine interconnection), a local energy storage and, as last choice, fossil fuel [12], [13].

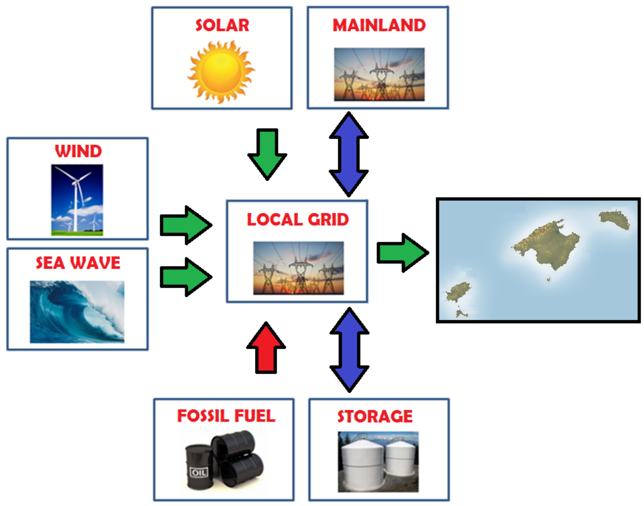

Fig. 8. Energetic mix for the Baleraric Islands.

For the exploitation of sea wave, an innovative energy converter is presented, showing its peculiarities. In particular, sea wave has several advantages, like:

- a more regular production during the day;
- a limited visual impact, thanks the shape of the energy converter (a floating buoy);
- high energy potential, thanks to the long coastline in comparison with the land surface of the islands.

All these conditions encourage the application of this innovative system.

III. Wave Energy Converter

Wave energy is a renewable energy source, with a great energy potential around the world, but not yet used. Several studies suggest that sea wave might have an important role for the electrical energy production, mainly in small islands [14]–[16].

Different technologies have been developed in the last decade; some of them have been also tested in the open sea [17], [18]. The most promising type of wave energy converter is composed by "Point Absorbers", having the peculiarity of working independently by the wave direction. Different solutions can be selected to convert the mechanical input of sea wave into electrical; among these, linear generators and fluid pumps are more common.

A new solution is proposed in this section. In fact, the Department of Energy, Information engineering and Mathematical models is designing an innovative Wave Energy Converter (WEC), proposing an alternative solution, based on a mechanical motion converter, transforming the bidirectional variable linear motion into a unidirectional rotary motion. In this way, the electrical production is entrusted to alternators, a commercial technology used in other sectors, as wind power.

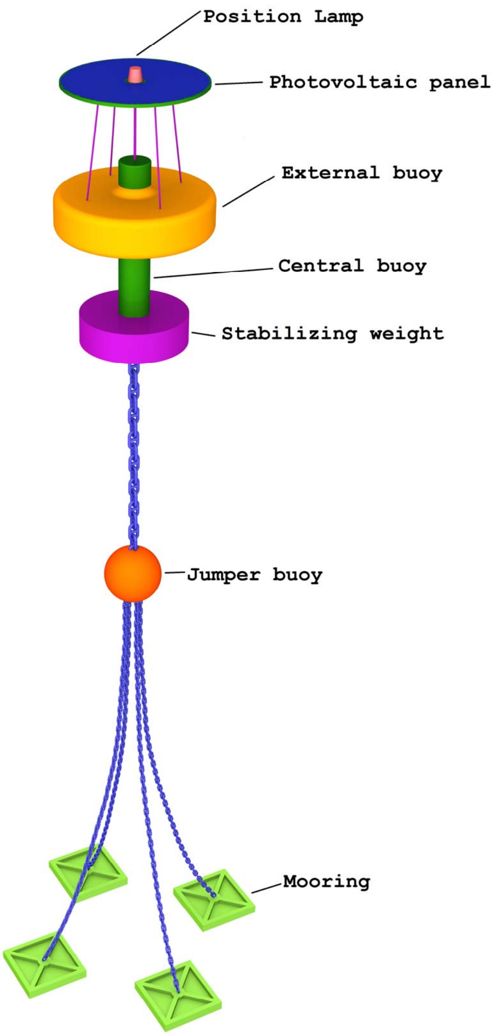

Fig. 9. External view of wave energy converter.

As shown in Fig. 9, the device is composed by two floating buoys having an axial symmetry, in order to exploit sea wave independently of wave direction. The central buoy contains inside the energy converters and is fixed to seabed by moorings. The external buoy is able to move up and down according the local sea level, producing the vertical motion. The device has a rated power of 160 kW, with an external diameter of 20 m. This solution shows several advantages:

- A limited number of components;
- Absence of pressurized fluid;
- The use of commercial components, reducing the costs for designing and development.

IV. Renewable Energy Scenario

In order to evaluate the renewable energy potential in Balearic Islands, the authors collected data from GIS tools [19]–[21]. Fig. 10 shows the location of the reference points used in this evaluation. Data are reported in Table II, III and IV. Wind and sea wave sources can be exploited realizing concentrated farms in the points indicated in Fig. 10. As regard the solar sources, the authors suggest the realization of small photovoltaic plants, integrated in the residential buildings.

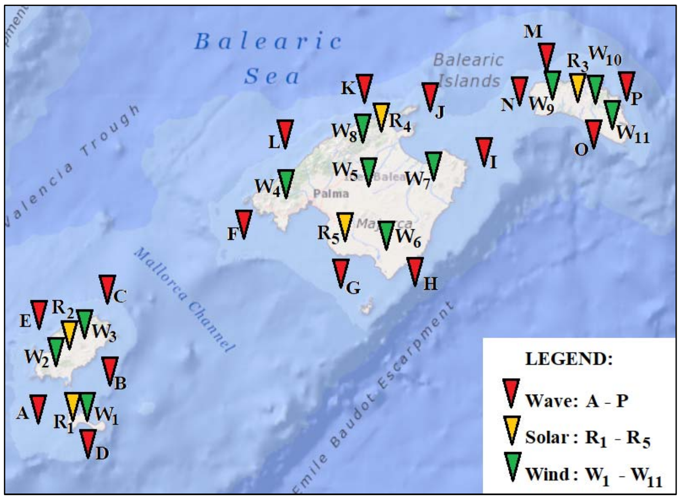

Fig. 10. Reference points for wave, solar and wind sources.

TABLE II. Sea Wave Energy Flux in the Reference Points.

Sea wave energy flux φ [kW/m]					
Point	**Annual Average**	**Jan-Mar**	**Apr-Jun**	**Jul-Sep**	**Oct-Dec**
A	2.48	3.77	1.76	0.81	3.59
B	1.97	2.38	1.59	1.06	2.84
C	3.63	5.15	2.18	1.41	5.82
D	2.03	2.63	1.81	1.02	2.69
E	3.26	4.82	1.83	1.04	5.37
F	2.08	3.40	1.25	0.57	3.13
G	2.47	3.75	1.88	0.74	5.37
H	3.05	4.40	2.32	1.05	4.46
I	5.44	7.56	3.50	2.37	8.34
J	6.23	8.61	3.48	2.64	10.20
K	5.65	8.21	2.79	2.16	9.47
L	4.28	6.31	2.09	1.56	7.18
M	8.84	12.8	4.71	3.57	14.3
N	5.56	8.14	3.11	2.23	8.77
O	2.87	4.20	2.15	0.81	4.36
P	9.23	13.20	5.49	4.21	14.1

TABLE III. SEA WAVE ENERGY FLUX IN THE REFERENCE POINTS.

Daily Solar Radiation H_d [kWh/d]					
Point	**R1**	**R2**	**R3**	**R4**	**R5**
Jan	2.6	2.6	2.3	2.3	2.5
Feb	3.7	3.8	3.2	3.3	3.5
Mar	4.6	4.8	4.7	4.3	4.6
Apr	6.1	6.2	5.4	5.7	6
May	7.6	7.6	7.6	7.5	7.5
Jun	7.8	8	7.5	7.4	7.5
Jul	7.9	7.9	7.8	7.8	7.9
Aug	6.6	6.8	6.6	6.5	6.7
Sep	5.2	5.3	5.1	4.9	5.1
Oct	3.7	3.9	3.4	3.3	3.6
Nov	2.8	2.9	2.6	2.6	2.7
Dec	2.2	2.4	2.1	2	2.2

TABLE IV. A PART OF DATA OF WIND CLIMATE (FREQUENCY AND WEIBULL CONSTANTS AS FUNCTION OF WIND DIRECTION).

Point		N	NNE	NE	ENE	E	ESE	SE	SSE
W1	f	6.01	6.93	9.69	10.99	9.36	6.11	3.60	2.92
	C	7.388	7.126	7.381	6.965	6.032	4.811	3.858	3.952
	K	1.855	2.056	2.078	2.314	2.024	1.995	2.065	1.795
W2	f	7.37	7.67	7.80	8.57	8.39	6.41	4.69	4.06
	C	7.027	6.421	6.372	6.341	5.982	4.833	3.968	4.073
	K	2.186	2.224	2.030	2.273	2.217	2.324	2.507	2.273
W5	f	4.23	11.08	13.75	8.53	5.88	3.56	3.24	3.06
	C	6.512	7.252	6.542	5.802	5.171	4.510	3.954	3.660
	K	1.933	2.149	2.535	2.243	2.063	2.204	2.082	1.968
W10	f	14.67	9.86	6.80	5.85	5.28	4.23	3.65	3.72
	C	9.595	8.547	6.836	6.661	6.683	5.496	5.518	4.790
	K	2.113	2.093	2.162	2.014	2.038	1.840	1.958	2.060

Point		S	SSW	SW	WSW	W	WNW	NW	NNW
W1	f	3.66	5.09	9.15	8.05	5.71	4.69	3.36	4.68
	C	4.355	5.730	7.716	7.951	7.334	7.441	6.730	8.273
	K	1.996	1.865	1.924	1.972	1.754	1.847	1.809	1.704
W2	f	4.81	6.25	8.31	6.58	5.55	4.84	3.49	5.22
	C	4.468	5.655	7.255	7.076	6.891	6.798	6.087	7.787
	K	2.314	2.140	2.113	2.155	1.977	1.885	1.731	1.805
W5	f	3.96	5.97	9.56	8.83	5.50	5.74	4.37	2.74
	C	4.125	4.982	6.530	7.289	6.261	6.750	7.252	5.979
	K	2.389	2.569	2.329	2.288	2.186	2.266	2.193	1.992
W10	f	4.71	6.43	7.05	5.72	5.53	5.42	4.76	6.30
	C	5.489	6.552	7.549	6.960	7.768	7.236	6.203	7.659
	K	1.866	2.181	2.159	1.884	1.927	2.076	2.111	1.729

The annual electrical production from sea wave E_{sw} can be estimated through Eq. 1:

$$E_{sw} = \sum_{i=1}^{4} \varphi_{m,i} D_c n_c \eta_{hy} \eta_{e,w}\, t_i \quad (1)$$

Where $\varphi_{m,i}$ is the average wave energy flux in the quarter (see Table II), D_c is the equivalent diameter of wave energy converter, n_c is the number of wave energy converter installed in a single wave farm, η_{hy} is the hydraulic efficiency considering the mutual interferences of wave energy converters, $\eta_{e,w}$ is the electrical efficiency of the device, t_i is the interval considered (quarter).

As regard the electrical production from solar E_{PV}, using photovoltaic panels, the Eq. 2 suggests a simplified approach:

$$E_{PV} = \sum_{i=1}^{12} H_{d,i} S_{PV} \eta_{e,PV}\, t_i \quad (2)$$

Where $H_{d,i}$ is the monthly average daily solar radiation (see Table III), S_{PV} is the net area of photovoltaic plants, $\eta_{e,PV}$ is the average electrical efficiency of photovoltaic panels, t_i is the interval considered (month). This equation is used also to evaluate the electrical production from the photovoltaic panels, installed above the wave energy converters, considering the solar radiation in the area where the wave farm is placed.

Finally, the evaluation of annual electrical production from wind power E_w is based on the Eq. 3:

$$E_w = \sum_{i=1}^{16} f_i \int_{v_{cut\,in}}^{v_{cut\,off}} \frac{K}{C}\left(\frac{v}{C}\right)^{K-1} \exp\left[-\left(\frac{v}{C}\right)\right] c_p(v)\,dv \quad (3)$$

Where f_i is the annual frequency that wind comes from a given direction (N, NNE, NE, ENE, etc…), K and C are the two parameters used in the Weibull distribution, modelling the wind source for each direction (see Table IV), v is the wind speed and, finally, $c_p(v)$ is the power coefficient of wind turbine, function of wind speed and is usually evaluated by the turbine manufacturer.

Using the equations 1-3, the authors evaluated the extensions of the power plants supplied by renewable energy sources (wind, solar and sea wave) in order to archive an annual electrical production by RES equal to 66.8% of the total annual electrical demand. The plants are sized considering the extension and the population in each single island, trying to balance the electrical production and consumption.

For the exploitation of wind power, the authors considered wind turbines having a rated power of 2400 kW; as regard the photovoltaic panels the electrical efficiency is fixed to 17% in order to estimate the extension of the plants; finally, the wave energy converter, introduced in the section III has a rated power of 160 kW, with an external diameter equal to 20 m, as introduced in the section III.

Table V, VI and VII and Fig. 11 report the sizing of the renewable energy mix and the annual electrical production.

TABLE V. SIZING OF RENEWABLE ENERGY MIX: SEA WAVE

Island	Devices per wave farm	Number of wave farm	Total installed power [MW]	Electrical production [MWh/y]
Formentera	15	2	5.12	6,426
Ibiza	60	3	30.75	47,014
Menorca	30	4	20.50	67,456
Majorca	60	7	71.74	150,827

TABLE VI. SIZING OF RENEWABLE ENERGY MIX: WIND

Island	Devices per wind farm	Number of wind farm	Total installed power [MW]	Electrical production [MWh/y]
Formentera	3	1	7.2	22,805
Ibiza	18	2	86.4	261,134
Menorca	8	3	57.6	221,823
Majorca	35	5	420.0	1,170,633

TABLE VII. SIZING OF RENEWABLE ENERGY MIX: SOLAR

Island	Surface of the island [km^2]	Total surface of PVP [hm^2]	Total installed power [MW]	Electrical production [MWh/y]
Formentera	83.24	7.5	12.75	24,154
Ibiza	571.6	75	127.5	236,105
Menorca	695.7	60	102.0	181,264
Majorca	3,640.11	540	918.0	1,641,889

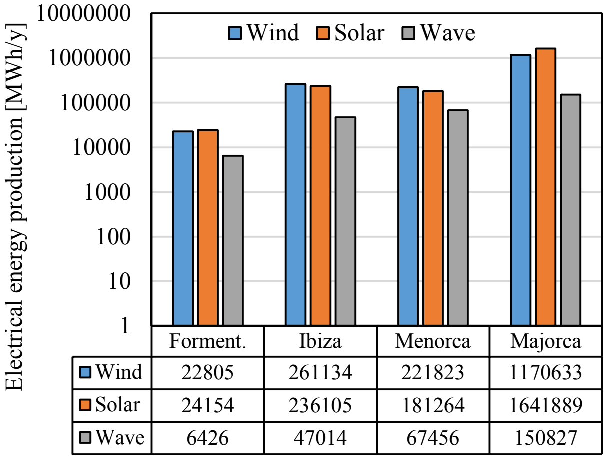

Fig. 11. Estimated electrical production by renewable energy sources in Balearic Islands.

V. CONCLUSION

The Balearic Islands hide a great renewable energy potential. The electrical mix proposed by the authors is able to cover the 66.8% of the electrical energy demand (data of 2017), avoiding the emission of 14062 tons of CO_2 per year (the emission factor is fixed to 3.488 kg/MWh) [22]. The balancing problem between the generation and the final consumption is not taken in account in this step, however a central role should be played by the existing power plants supplied by fossil fuels. An energy storage is required, preferring the pumping hydropower and chemical storage based on hydrogen.

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