sustainability

Article

Energetic Sustainability Using Renewable Energies in the Mediterranean Sea

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Abstract: The paper is focused on the analysis of the electrical energy sector in the Maltese islands, focusing on the employment of Renewable Energies in order to increase its energy independence. The main renewable source here proposed is wave energy: thanks to its strategic position, Malta will be able to generate electrical energy through the use of an innovative type of Wave Energy Converter (WEC) based on the prototype of linear generator designed and developed by the University of Palermo. This new technology will be able to cut down the electrical energy production from traditional power plants and, consequently, the greenhouse gas emissions (GHG). Wave energy source and off-shore photovoltaic (PV) technology are proposed here. Particularly, the installation of 18 wave farms, for a total installed capacity of 130 MW, will generate about 5.7% of Malta's energy requests in 2025, while the installation of 60 MW of off-shore PV will generate about 4.4%.

Keywords: wave energy; renewable energy; Mediterranean Sea; WEC; point absorber; Malta

1. Introduction

Electrical energy is an essential requirement to satisfy the needs of human beings, such as the production of goods and services. Despite the technological developments, in remote areas or in small islands, the electrical energy production is based on outdated technologies, powered by fossil fuels. This way of producing energy generates negative effects for the environment, like pollution of air, water and soil, as well as the generation of noise [1].

In this context, many small islands in the world are almost completely powered by old diesel generators [2]. The fuel is usually shipped from the mainland and long underwater cables sometimes connecting the small islands to the mainland [3]. Due to these reasons, on small islands, such as in remote areas, the electrical power production shows higher operating costs and losses than on the mainland [4]. The use of Renewable Energy Sources (RES), in particular wind, solar, biomass and also sea waves, will produce the reduction of energy dependence from fossil fuels and the improving of the efficiency of the electrical grid [5]. The RES also contributes to the reduction of greenhouse gas (GHG) emissions and environmental pollution. Samsø, a small island in Denmark, is a famous example of a community, electrically linked to the mainland and totally powered by renewable sources (wind in particular).

Many islands around the world are working on important projects in order to achieve energetic independence from fossil fuels, thanks the utilization of renewable energy sources. Some examples are: Maldives, Graziosa (Portugal), Gotland (Sweden), the Canary Islands (Spain) and Sumba (Indonesia).

In other countries, several studies have investigated the possibility of constructing small stand-alone electrical grids, powered only by renewable energy sources [6–10].

Zhao et al. [6] proposed a micro grid electrical system for Dongfushan Island, located in Zhejiang Province, in the eastern part of China. The system proposed is composed of solar panels, wind turbines, diesel generators and a battery storage system. The optimization is realized by using a genetic algorithm that minimizes the life cycle cost and maximizes the production of electrical energy by renewable resources.

Similarly, using the HOMER (Hybrid Optimization Model for Electric Renewable) tool, Ma et al. [7] investigated a particular solution based on a hybrid solar-wind system with battery storage. The study is applied on a small island in Hong Kong. The electrical energy is produced by photovoltaic arrays and wind turbines. The direct current output is used to satisfy the electrical demand. If the energy produced is greater than the request, the energy surplus is accumulated in battery. Conversely, if a deficit occurs, the battery is discharged. If the electrical production by RES is excessive, such as to not allow the accumulation in the battery, the surplus of energy is directed to a dump load. An inverter system is necessary to connect the power plants by RES and the battery to the electrical grid, which works in alternative current. In other study, Ma et al. [8] analyzed a different solution for the storage energy system, proposing a hydroelectric pumped storage, supported by a battery storage system.

Using the HOMER tool, Bin et al. [9] studied the electrical energy demand of Hainan Island, located in the southern part of China. This region is rich of renewable resources (hydro, wind, solar). However, the electrical energy production is mainly based on coal. Hainan has natural gas reserves and is electrically connected to the mainland by a submarine interconnector (transmission capacity 600 MW). The study shows the energy potential of available renewable sources, in particular that it is possible to avoid the building of other nuclear power plants, thanks to the employment of renewable sources.

In other interesting study, Petrakopoulou [10] simulated a hybrid power plant to satisfy the electrical demand of Skyros, a small Greek island, located in the middle of Aegean Sea. The system proposed is composed by solar thermal and photovoltaic, hydroelectric generators and wind turbines. In this way, it is possible accumulate solar energy in thermal storage system, reducing the daily fluctuation of electrical power production by solar sources.

In this paper, we focus our attention on the Malta archipelago, where the electrical energy production is currently almost totally based on fossil fuel. After the ratification of the Kyoto Protocol, the European Union is committed to reducing its GHG emissions by 8% of 1990 levels [11]. According to the European Directive 2009/28/EC (Annex I), Malta is obliged to generate 10% of its energy from RES in gross final consumption by 2020 [12]. Malta's target is considerable, although it is lower than other European Countries, because Malta presents quite particular conditions, such as other Mediterranean islands: high population density, a growing primary energy consumption and a low free surface to install new plants. In order to achieve the environmental and energetic targets [13], Malta will have to use all available renewable sources [14]. Moreover, Malta's electrical grid needs several developments, in order to minimize the electrical problems caused by randomness of many RES, such as wind and solar [15].

Taking into account the peculiarities of Malta, in this paper, we analyze a new frontier of renewable energy sources: sea wave. As known from literature, sea wave energy is extremely underused, despite its great energy potential [16,17]. Furthermore, sea wave energy presents many advantages for small islands—in particular, the installation of plants not requiring land employment and that the energy converters present a very limited visual and environmental impact [18]. According to this vision, the following Figure 1 shows a possible future structure of Malta's electrical grid. Every available RES will be used to produce electrical energy [19]. In order to match the electrical load and the electrical production by RES, new innovative storage systems have to be developed.

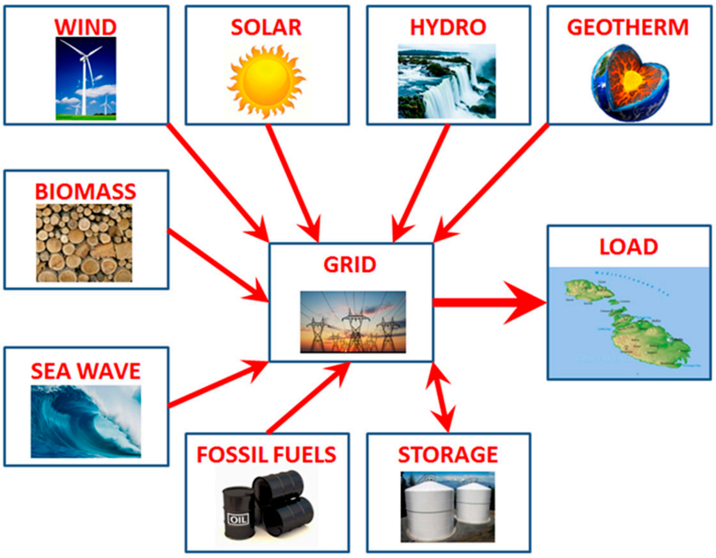

Figure 1. Electrical grid with main renewable energy source and storage systems.

This work analyzes the sea wave source in Malta's archipelago, exploitable to generate electrical energy through the use of an innovative device that directly converts the mechanical energy of sea waves into electrical output, minimizing the energetic conversion losses. This system is based on an innovative prototype designed and developed by the Department of Energy and Information Models (DEIM) of the University of Palermo (Italy).

This paper shows a preliminary evaluation of electrical energy production through the installation of wave farms based on DEIM converters along the Maltese coasts. In this system, photovoltaic panels can be integrated, increasing the electrical output.

2. Maltese Archipelago

Malta's Country is an archipelago, in the middle of the Mediterranean Sea. It is located at about 80 km south from Sicily, 333 km north from Libya and 284 km east from Tunisia. The capital city is Valletta, having the geographical coordinates 35°53′N–14°35′E. It is situated in the largest island (also called Malta) of the archipelago. Malta covers an overall area of 316 km^2; thus, it is one of the smallest European countries. The Maltese archipelago is characterized by a very high population density (1318 inhabitant/km^2, 2012). The state of Malta has a population of about 416,515 inhabitants (in 2012), and about 416,515 live on the principal island [20].

The Maltese archipelago is composed of several islands, but essentially only three of them are populated: Malta Island (245.8 km^2), Gozo (67.1 km^2) and Comino (2.8 km^2) are shown in Figure 2. The archipelago also includes 18 uninhabited smaller islands; some of them are: Manoel Island ("Il-GżiraManoel", in Maltese language, 0.3 km^2), St Paul's Island ("Gżejjer ta' San Pawl" or "Selmunett", in Maltese, 0.101 m^2), Cominotto ("Kemmunett" in Maltese, 0.099 km^2), Filfla (0.02 km^2), and Fungus Rock ("Il-Ġeblatal-Ġeneral", in Maltese, 0.007 km^2). Malta's islands are mainly rocky, with terraced fields, dry vegetation, rock and limestone. The highest Maltese peak is Ta' Dmejrek, with 253 m (830 feet from sea level, located near Dingli). Maltese coasts are fairly indented with several bays. In Maltese Country, lakes and permanent rivers are absent, although there are some inland waterways, having fresh water during all year, at Lunzjata Valley in Gozo, at l-Imtaħleb and San Martin, and at Baħrijanear Rasir-Raħeb [20].

Figure 2. View of the Maltese archipelago.

In order to overcome the limited availability of water on the inhabited islands of Malta, six desalination plants are installed, two of which are always on. Due to its latitude and the central location in the Mediterranean Sea, the Maltese climate is Subtropical–Mediterranean, so winters and summers are temperate. The rainfall happens usually in autumn and winter season, about 578 mm per year. The main yearly temperature is about 23 °C in the daytime and 16 °C at night. January is the coldest month, while August is the hottest. The main yearly temperature of the sea is 20 °C, ranging from 15 °C in February to 26 °C in August. Winters in Malta are usually mild, but, during the winter months, it tends to get pretty windy from wind blowing from the northeast.

In Malta's archipelago, thanks to the latitude, the solar radiation is very high, with about 3000 sunlight hours per year. The daylight hours range from a minimum of 5.2 h during December to a maximum of 12 h in July [21]. The Maltese woods were cut down centuries ago, so the only trees that survive nowadays are the olives, citrus, carob trees, pine, fig trees and tamarisk. On Gozo and Malta, the hills are cultivated for vegetables and grapes.

The economy is essentially based on tourism, which generates around 15% of Gross Domestic Product (GDP). Other important sectors are foreign trade, electronics, manufacturing, shipyard and pharmaceutical industry. Italy is among the main trading partners. As a result of the limited freshwater sources, Maltese food production is very low, satisfying only 20% of the national needs.

Transport, public administration and industry are the main sector, employing, respectively, 28.6%, 26.6% and 15.7% of the total workforce. Fishing and agriculture are marginal sectors [20].

3. Electrical Energy Production in Malta

In Malta's archipelago, the electrical power production is almost completely based on fossil fuel power plants. For example, in 2005, the entirely electrical energy production was generated from oil [22], and, at the same time, the transport sector was fully based on petroleum. Furthermore, on the Maltese archipelago, the fossil fuels (natural gas, oil or col) are totally absent; therefore, all of these sources must be obtained from other countries, which are often characterized by geopolitical instability.

The Enemalta Corporation (EMC) (City, Country) is the owner of all Maltese thermoelectric power plants [23]. Electrical energy is mainly generated at the Delimara Power Station (with an installed power of 444 MW), located on the southeastern part of Malta. The power station is composed of conventional steam turbines (2 × 60 MW), open cycle gas turbines (2 × 35 MW), one combined cycle plant (110 MW) and four stroke medium speed diesel engines (144 MW, operating in a combined cycle mode with one steam turbine). In the past, another important plant was installed at the Marsa plant (with an installed power of 155 MW, 2010), but, nowadays, is in a decommissioning phase [23]. Therefore, the total traditional installed capacity was about 599 MW, while the renewable power plants capacity does not exceed 14 MW [24]. In Figure 3, the electric grid of the archipelago of Malta is shown.

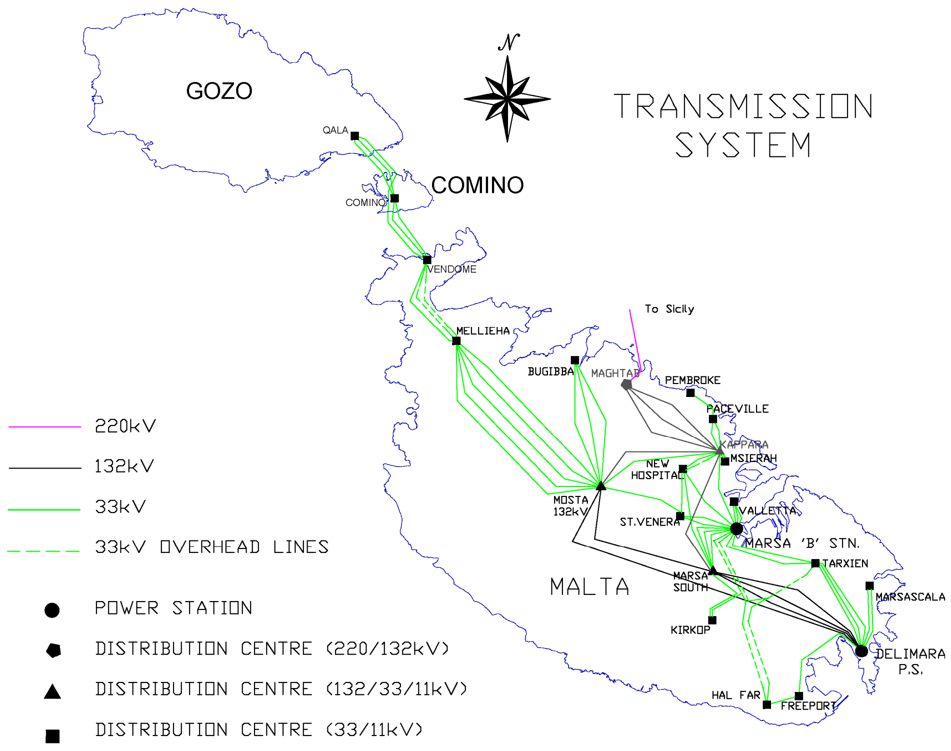

Figure 3. The electrical grid on Malta's archipelago [23].

In order to overcome the growing request for electrical energy, the Malta–Italy Interconnector was inaugurated in April 2015, connecting the Italian station located in Ragusa (Sicily) to the Maltese station located in Malta at QaletMarku, Baharic-Caghaq. This interconnector is composed of a submarine cable, having a length about 120 km. The system works in a high voltage alternating current (220 kV) and is capable of a bidirectional flow of electrical power, with a maximal flow rate of about 200 MW [21]. The electrical distribution grid in Malta is achieved on four voltage levels, which are: 132 kV; 33 kV; 11 kV; and 400/230 V. The frequency of the supply of electrical energy in Malta is 50 Hz, like the European electrical grid.

Figure 4 shows the trend of electrical energy consumption by sources in Malta during the period 1971–2015 [25]. This trend is characterized by an important increase from 300 GWh/year in 1971 to 2257 GWh/year in 2015. As shown in the figure, the electrical interconnector between Malta and Sicily has significantly changed the electrical energy production in Malta: in fact, during the year 2015, throw the interconnector, Malta has imported 1054 GWh, which is almost half as much as consumed in the same year; the remaining energy demand in Malta was satisfied by oil plants (1099 GWh), biofuels (9 GWh) and photovoltaic plants (95 GWh) [26]. Despite the huge collapse of electrical energy production by fossil fuel (oil) and the increase of energy production by solar plants, the use of renewable sources is very low, compared to European Countries.

Figure 5 shows the distribution of electrical energy consumptions to final users in the years 2000, 2007 and 2014. As shown in the picture, in the three reference years, self-consumption by industries represents only 5%–6% of total consumption. The residential sector stably consumes 28%–29%. The electrical energy consumed by industries has been progressively downsized, going from 504 GWh (which represents 27% in 2000) to 413 GWh (18% in 2014). Conversely, the commercial and public service has increased the electrical consumption, going from 504 GWh (26% in 2000), to 663 GWh (29% in 2007) and 940 GWh (42% in 2014). Electrical consumption is absent in the public transport sector; other sectors such as fishing, agriculture and forestry are negligible [25,26].

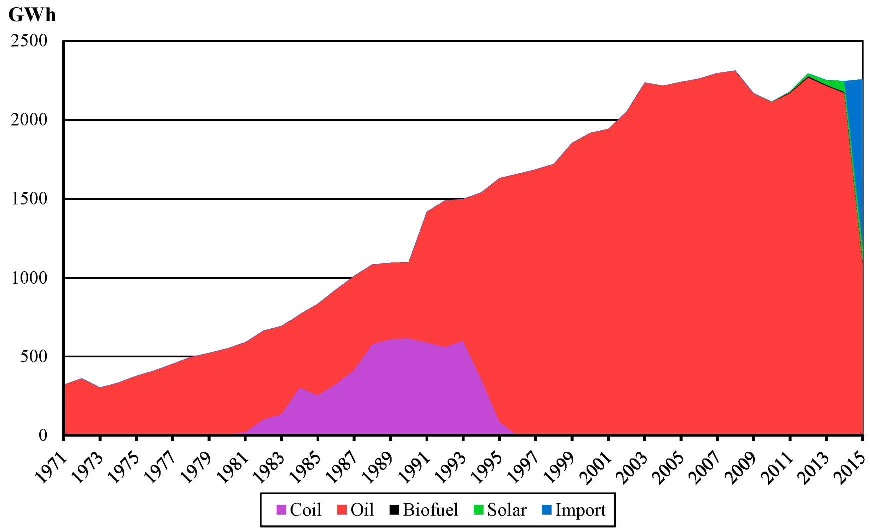

Figure 4. Electricity consumptions by sources in Malta (1971–2015) [25].

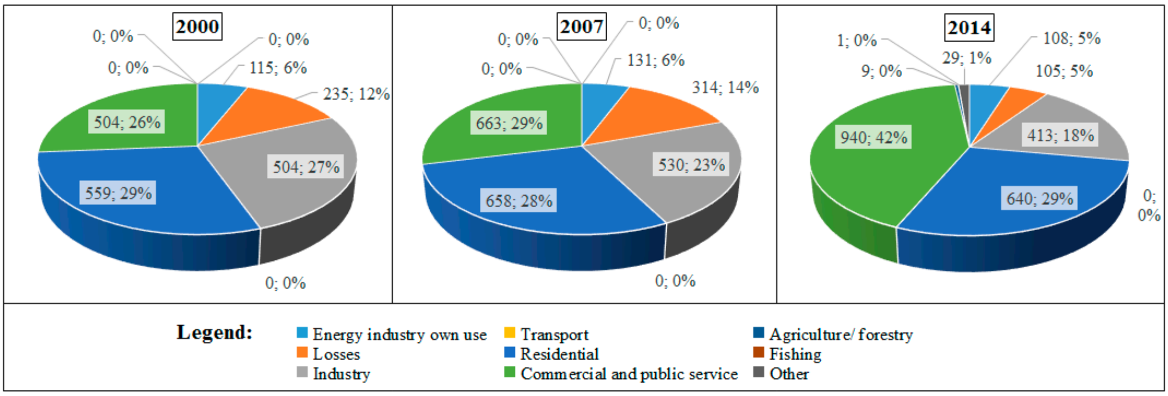

Figure 5. Distribution of electrical energy consumption to final users [25,26].

4. Sea Wave Energy Resources

The use of wave energy is able to reduce energetic dependence of Mediterranean islands from fossil fuels. This important target presents different advantages, such as the reduction of importations of exogenous fossil fuels from unstable countries, the abatement of greenhouse gas emissions (especially CO_2 emissions), and the creation of a working industry strongly linked to the territory. Nowadays, wave energy represents a renewable source totally unused in Malta, despite its 140 km of coasts. Moreover, the ratio of territorial waters to the land area in Malta is very high, approximately 10, with 3000 km^2 of territorial waters [27]. This means that the exploitable areas are characterized by a great extension, with a great total energetic potential that can be properly used in order to produce electrical output thanks to appropriate conversion devices. The additional advantage is linked to the preservation of the limited Maltese soil from the installation of further power plants.

During this time, several studies focused their attention on the assessment of the wave energy potential in the Mediterranean Sea. Indeed, a good confirmation of the energy theoretically extractable from sea waves is fundamental in order to increase the interest about this important renewable source and the improvement of new technologies of conversion. Different studies demonstrated that the off-shore wave energy resources near the northwest European coasts are the higher ones [28], while the Mediterranean is characterized by quite lower values. However, this particular condition involves different advantages: the calmer sea state defines less rigorous conditions for those Wave Energy Converters (WECs) that will be employed off-shore, with a lower risk of failure due to breakdown or malfunctions. A calmer sea state avoids an excessive oversizing of WECs too. Particularly, the central location of Malta in the Sicilian Channel determines a favorable wave climate in order to create the first commercial wave farms in the Mediterranean Sea.

The in situ measurements along Maltese coasts was realized with a single Datawell Waverider buoy (Datawell, Haarlem, The Netherlands), which was installed about 2 km west of the Gozo coastline, at a depth of 200 m [29]. The use of wave buoys has a fundamental role in order to obtain some of the first data about wave potential with an experimental measurement campaign. However, they are usually too expensive, so they are used only in the first part of an assessment, especially in order to validate software data. The Gozo wave buoy was able to define the wave climate in Gozo and in the northwestern part of the Maltese archipelago, while it was hopeful to know the wave energy potential along all the coasts. Additionally, maintenance costs usually reduce the measurement period to some years. In the case of Gozo's wave buoy, measurements were performed from 14 September 2011 to 13 September 2012 [29], recording the wave climate during the seasons.

The main parameters that define wave energy resource are: significant wave high H_s and the main period T_m. The first one is measured in meters, the second one in seconds. For each sea state, using 1025 kg/m^3 for the density ρ and 9.807 kg/m^3 for the gravitational acceleration g [29], the corresponding wave power is calculated through this expression:

$$P = 0.49 H_s^2 T_m \left[\frac{kW}{m}\right]. \quad (1)$$

Finally, the annual average wave power must be multiplied by 8760 h (hours in one year) in order to have the total energy, expressed in MWh/year. The next step consists in the use of the SWAN (Simulating Wave Nearshore) model hindcast three-hourly fields, which is characterized by 89,701 grid point around the Maltese islands [29]. This model is particularly advantageous with propagation problems from deep water up to the coasts. Both buoy data and SWAN data have highlighted an important seasonal variability of sea wave power along Maltese coasts. Wave power is characterized by high values during winter season, which decrease in autumn and spring, while the minimum values are recorded in summer. Moreover, winter wave power is more than double the annual average, visible in Figure 6 and obtained from the data reported in [29].

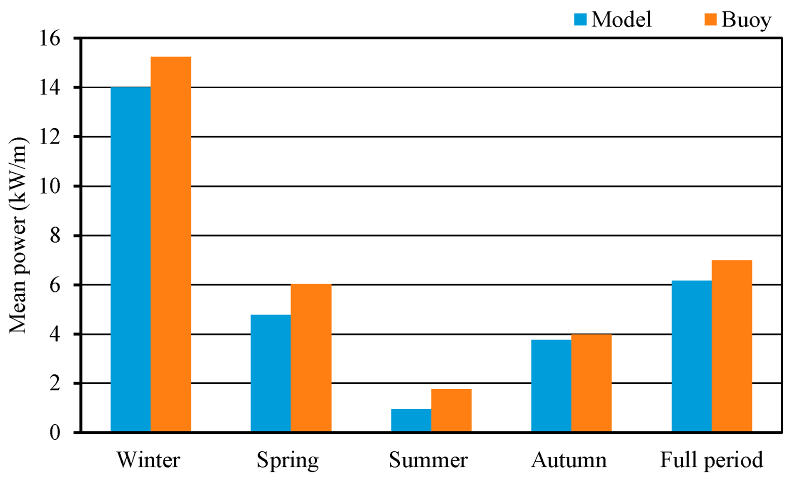

Figure 6. Seasonal wave power from buoy and SWAN model data in Gozo.

Therefore, mean power values obtained with SWAN model data are very similar to those obtained with the wave buoy, although slightly lower. Furthermore, this seasonal trend can be useful because it is opposite to the solar trend and the two trends may offset each other.

Finally, Figure 7 reveals that the most advantageous locations are the western coasts of the islands, caused by the northwestern prevalent direction of sea wave. An annual average power of 5 kW/m is considered here, which is a good value due to the high depth of the seabed even near the coast.

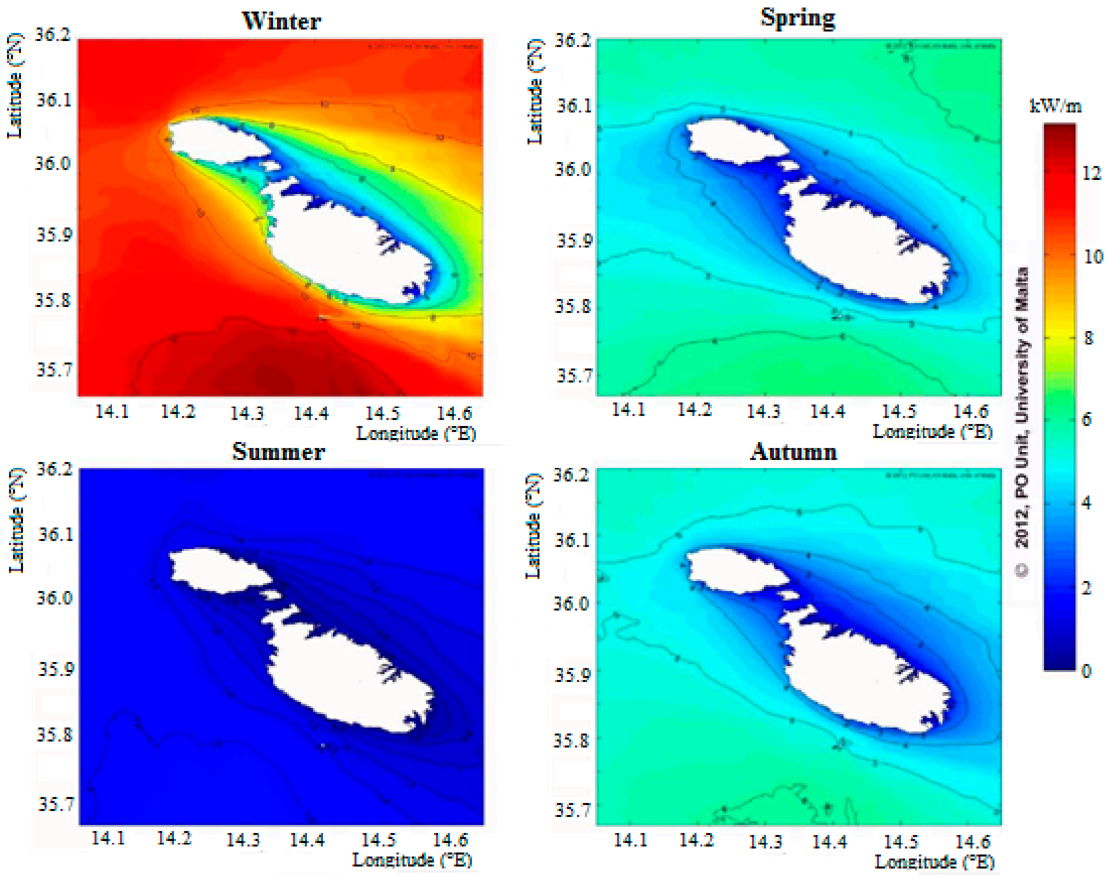

Figure 7. Seasonal wave power along the Maltese islands for the SWAN model domain [29].

5. DEIM Point Absorber

This work proposes an innovative WEC, nowadays at the design step, designed by the Department of Energy and Information Models (DEIM) of the University of Palermo [30]. Figure 8 shows a representation of a particular type of Point Absorber, a technology proposed thanks to its ability to convert wave potential in electrical output directly, without the use of pressurized liquids (such as oils or waters) or other intermediate devices [31]. Moreover, it is able to work adequately with any direction of wave propagation, which is a really important characteristic [32].

Figure 8. Three-dimensional (3D) representation of the DEIM converter.

The DEIM converter proposed here has a nominal size of 80 kW. In order to reduce the designing and developing costs for different sizes of systems, a modular approach is applied. In fact, the electrical converter is made from eight linear generators, each one with a nominal size of 10 kW. It consists of two floating buoys, independent of each other [33]. The external one (yellow buoy) intercepts the sea waves, while the internal one (green buoy) contains all of the eight linear generators. The alternate motion of the sea waves is transferred from the external buoy to the internal one thanks to the connecting rods (pink rods).

A hemispherical weight is installed in the lowest part of the central buoy, guaranteeing good stability to the system and its vertical position. This hemispherical weight is connected to a jumper (purple sphere) through a big chain, while the same jumper is connected to four moorings, placed on the seabed. In this way, the four chains connecting moorings and the jumper are constantly maintained in a vertical position, avoiding the risk due to the scraping of the seabed [34]. An intermittent red light is positioned on the top of the buoy, making visible the WEC up to several nautical miles away. The capture buoy has a useful diameter of 5 m, while the working stroke of the generator is about 4 m. This length also allows the production of electricity in most agitated and energetic sea states.

The innovative aspect of the project is related to use of a particular type of linear electrical generator that converts the mechanical energy of sea waves into electrical output without the use of brushes or other mechanical devices.

The linear generators are composed two parts: the translator and the stator. The first part contains 132 neodymium-iron-boron permanent magnets used to generate the magnetic field without any electrical energy consume. The second one contains the coils, with a three-phase connection, representing the magnetic circuit. In order to control the motion of translators avoiding possible damage from bad weather conditions, two end stop springs are installed inside the central buoy [35]. Figure 9 represents a cross section of the conversion buoy, in which the eight linear generators are visible, with the connecting road and the two end stroke springs.

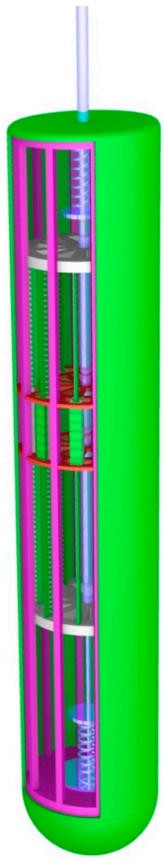

Figure 9. Cross section of the inner buoy of the DEIM Point Absorber.

Several experiments were conducted in a DEIM laboratory on a small scale linear converter, in order to evaluate the energetic performances. Depending on the load conditions, the machine is able to convert into electric energy even 70%–80% of mechanical energy in input.

In this work, as a precautionary level, the energetic previsions are based on an average efficiency, fixed to 50%.

6. Scenarios

The strategic position in the middle of the Mediterranean Sea and the quite high wave energy potential make Malta one of the best sites for the employment of the innovative Point Absorber here proposed. Moreover, DEIM WEC will be able to increase energetic independence of this country, currently at a very low level. The optimal collocation of the installation sites will be in choosing accordingly different standards, in order to not influence the main maritime routes and activities such as fishing [36]. It is important to say that fishing does not have a main role in the Maltese economy, and the off-shore installation of buoys (several kilometers away from the coast) will contribute to the reduction of visual impact from the mainland. Additionally, the development of renewable energy systems can produce direct economic benefits, with the creation of new jobs, related to installation and maintenance of power plants. Figure 10 shows the projections until 2035 of annual electrical energy request [GWh] and maximal peak power request [MW] in Malta. The projections are realized considering a growing rate equal to 1% per year in the base case scenario and 0.5% per year in the low case scenario [37].

According to the base case scenario, in 2025, the estimated electrical request will be about 2500 GWh/year. For the following evaluation, we use this value as reference. Here, wave source and off-shore photovoltaic (PV) technology are proposed. The installation of 18 wave farms based on the

80 kW DEIM Point Absorber along the western coast of Malta and Gozo, for a total installed capacity of 130 MW, will generate about 141,900 MWh/year. This production represents 5.7% of the overall electrical energy requests in 2025. The energy production is obtained with an overall efficiency of 40%, multiplying the diameter of the cut-off buoy by the local sea wave power. Moreover, every wave farm will consist of three lines of 30 WEC. The distance between each WEC (about 10 m) is equal to twice the diameter of the device itself (5 m). Thus, a single wave farm covers an area with a length of 300 m and a width of 30 m. At the same time, the installation of off-shore PV technology, for a total installed capacity of 60 MW, will generate about 108,300 MWh/year [27]. This production represents 4.4% of the overall electrical energy production in 2025. Therefore, the overall electrical production by sea wave and off-shore photovoltaic sources represents the 10.1% in 2025.

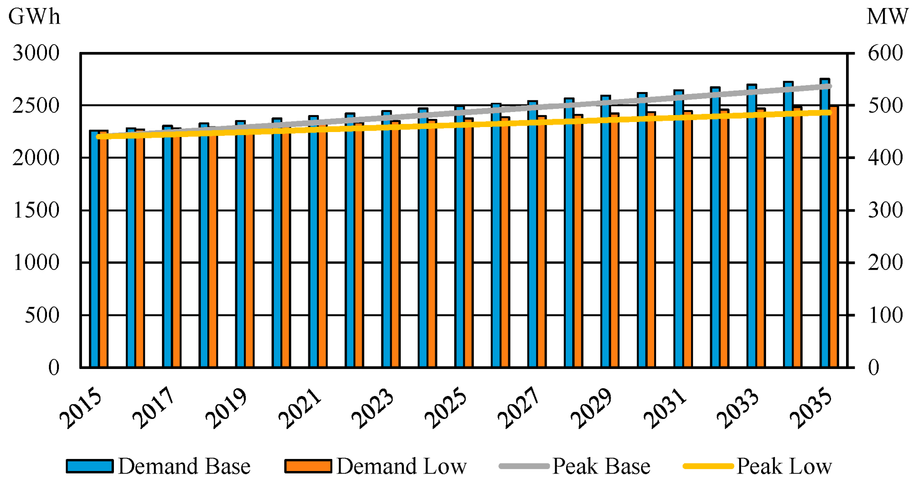

Figure 10. Projections until 2035 of Maltese electrical energy requests and peak requests [28].

Thanks to the large extension of territorial sea and the high daily solar radiation in Malta [27], the off-shore PV technology would be correctly integrated with the sea wave one. This solution will increase the installed power in a fixed area, improving the electrical energy output. Finally, considering the most recent CO_2 emission factor for the Delimara power plant estimated in [38], wave sources can avoid 68,700 tons/year of CO_2 emissions, while the off-shore PV one is 52,300 tons/year, for an accumulative reduction of about 121,000 tons/year.

7. Economic Assessment

The first preliminary economic assessment of wave farm is presented. Two possible scenarios are analyzed: the first concerns the construction of 18 wave farms, each one having 90 DEIM point absorbers; the second includes the integration of photovoltaic panels on wave converters.

In both scenarios, the discounted cash flow is evaluated, according the following equation:

$$DCF = -C_0 - \sum_{i=1}^{n} \frac{C_{annual}}{(1+\tau)^i} + \sum_{i=1}^{n} I_{annual} \frac{(1+\varepsilon)^i}{(1+\tau)^i}, \tag{2}$$

where C_0 is the initial investment, C_{annual} is the annual operative and maintenance costs, I_{annual} is the annual income generated from energy selling, τ is the discount rate, and ε is the discount rate in energy systems. In order to simplify the evaluation, C_{annual} and I_{annual} are considered stable in the years. According to [39,40], τ is fixed to 1% and ε to 3%.

Table 1 shows the main cost items required to install the wave farms. The costs are expressed for installed power. Table 2 shows the additional costs required to integrate the photovoltaic system into sea wave energy converters, increasing the overall installed power [41].

Table 1. Estimated costs for the installation of wave farms.

	[€/kW]	[€]
Onshore transformers and grid	18	2,332,800
Cables	12	1,555,200
Mooring	75	9,720,000
Building/facilities	150	19,440,000
Installation work	35	4,536,000
Sea wave energy converters	2500	324,000,000
Total	**2790**	**361,584,000**

Table 2. Additional costs to integrate photovoltaic panel (PVP) on wave farms.

	[€/kW]	[€]
PVP purchase	1500	90,000,000
PVP installation on sea wave	150	9,000,000
Total	**1650**	**99,000,000**

Table 3 reports the estimation of annual operative and maintenance costs of point absorbers, expressed as costs per installed power. Table 4 shows the additional costs for maintenance of solar panels.

Table 3. Annual operative and maintenance costs of wave farms.

	[€/kW]	[€]
Purchased components	1.80	233,280
Repair & maintenance	1.25	162,000
Technical consulting service	0.70	90,720
Transport by water	0.25	32,400
Engineering service	0.15	19,440
Commercial and industrial equipment	0.15	19,440
Analytical laboratory instrument	0.10	12,960
Others	0.85	110,160
Total	**5.25**	**680,400**

Table 4. Additional operative and maintenance costs of PVP.

	[€/kW]	[€]
Purchased components & maintenance	1.80	233,280

Finally, Table 5 shows the annual income from energy selling. In this evaluation, the selling energy price is fixed to 80 €/MWh [42].

Table 5. Annual income.

Selling energy prize	[€/MWh]	80
Sea wave energy production	[MWh]	141,900
Income by sea wave	[€]	11,352,000
Photovoltaic energy production	[MWh]	108,300
Income by photovoltaic	[€]	8,664,000

Using Equation (2), Figure 11 shows the Discounted Cash Flow, assuming the realization of the wave farm without the integration of solar photovoltaic. According to this evaluation, the breakeven time is estimated to be equal to 24–25 years, as shown in the following figure.

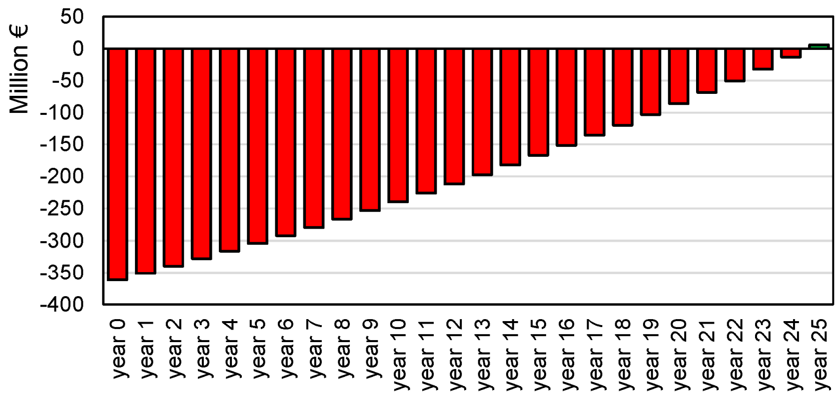

Figure 11. Discount Cash Flow of sea wave farms without solar photovoltaic.

Assuming the realization of the wave farm with the integration of solar photovoltaic, the economic evaluation shows significantly changes. As shown in Figure 12, the breakeven time is estimated to be equal to 19 years. This change is linked to the lower cost of photovoltaic solar technology, which has been commercially mature from several years.

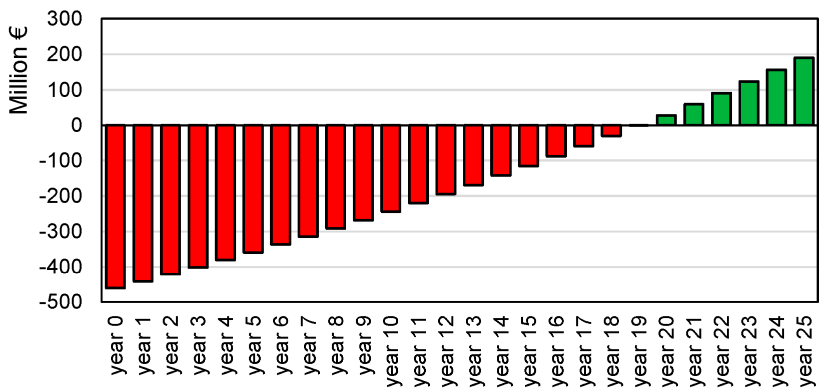

Figure 12. Discount Cash Flow of sea wave farms with solar photovoltaic.

It should be noted that the costs of realization of sea wave converters is the item cost with the greatest impact, which is due to the fact that technology is currently at a prototypal step. Assuming that, with development of technology, the building costs will reduce to 1500 €/kW (the same price assumed for photovoltaic panels), the breakeven time decreases to 13 years. In addition, other variables can have a strong effect in this evaluation. As stated in the previous section, the energetic efficiency is fixed conservatively to a lower value. Improving the electrical efficiency of the machine, of course, the electrical output increases and, consequently, the income from energy selling also increases. Furthermore, the previous assessment does not take into account the presence of any incentive mechanisms. Assuming an energy selling prize with incentives—for example, 240 €/MWh—the breakeven time falls to five years. This incentivized prize is supposed, considering that this value is very lower than incentivized prizes used in Italy for photovoltaic panels during the first years of the mechanism "Conto Energia" [43].

8. Conclusions

The sea wave energy potential has been evaluated along the Maltese coasts. According to our evaluation, the installation of 18 wave farms, based on DEIM converters, could produce 141,900 MWh/year. In addition, by installing off-shore photovoltaic panels on DEIM converters, another 108,300 MWh/year could be produced. The total electrical production from off-shore systems could amount to 250,200 MWh/year, which represents the 10.1% of the electricity demand expected for 2025.

The economic assessment shows that the breakeven time is currently high because this technology is currently at a prototypal step. However, with the introducing economic incentive, this technology becomes economically sustainable, allowing a more rapid commercial development.

The correct use of Renewable Energies will contribute to reducing the dependence of Maltese islands on exogenous fossil fuels, limiting the emissions of greenhouse gases due to the energy sector and global warming. Obviously, the installation of wind turbines and photovoltaic panels on Malta's archipelago can produce a very significant part of electrical energy demand.

Thanks to the presence of the Malta–Sicily interconnector, the energy storage system (not evaluated in this paper) plays a secondary role in the electrical energy, until the electrical energy production by RES becomes predominant.

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Nomenclature

H_s	Significant wave height [m]
T_m	Main period [s]
P	Power per front wave [kW/m]
ρ	Sea water density [kg/m^3]
g	Gravitational acceleration [m/s^2]
DCF	Discounted Cash Flow [€]
C_0	Initial investment [€]
C_{annual}	Annual operative and maintenance costs [€]
I_{annual}	Annual income generated from energy selling [€]
τ	Discount rate [%]
ε	Discount rate in energy systems [%]

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