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Türkiye's Offshore Hybrid Energy Potential and Cost Estimation in the Eastern Mediterranean

Soner ÇELİKDEMİR[1*], Mahmut Temel ÖZDEMİR[2]

[1] Bitlis Eren University, Adilcevaz Vocational High School, Electric and Energy Department, Bitlis, Türkiye
[2] Firat University, Engineering Faculty, Electrical and Electronics Engineering Department, Elazığ, Türkiye
Soner ÇELİKDEMİR ORCID No: 0000-0002-1419-3398
Mahmut Temel ÖZDEMİR ORCID No: 0000-0002-5795-2550

**Corresponding author: celikdemirsoner@gmail.com*

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Offshore Renewable Energy Sources, Hydrogen Production, Hydrogen Transmission, Cost Analysis

Abstract: In this study, for the first time, the focus is on determining the potential of renewable energy-derived hybrid energy in the Eastern Mediterranean region and conducting cost analysis for sample locations. The most important motivation of this study is that the Eastern Mediterranean zone has a significant hydrocarbon potential in addition to its geopolitical value, energy lines, and being a transportation route. Providing the energy needs of hydrocarbon platforms to be established in the region constitutes the main framework. For this, 6 zones determined were examined. Wind, solar, and wave energy potentials of these zones have been determined. If the energy is produced more than the needs of the platforms, it is planned to produce hydrogen by electrolysis. In this case, cost analyses of the system were carried out taking into account the situation of the hydrogen produced being transmitted to the mainland by different transport methods in the form of liquids or gases. According the results of the analyzes, it has been shown that the Eastern Mediterranean has a very high wind, solar, and wave energy potential due to the fact that Crete and Rhodes Islands form a natural strait. As a conclusion different transmission scenarios of the hydrogen to the mainland shows that the energy required by the platforms can be provided by renewable energy sources, regardless of their power.

Türkiye'nin Doğu Akdeniz'deki Açık Deniz Hibrit Enerji Potansiyeli ve Maliyet Tahmini

Anahtar Kelimeler
Açık Deniz Yenilenebilir Enerji Kaynakları, Hidrojen Üretimi, Hidrojen Taşınması, Maliyet Analizi

Öz: Bu çalışmada ilk kez Doğu Akdeniz bölgesinde yenilenebilir enerji kaynaklı hibrit enerji potansiyelinin belirlenmesi ve örnek lokasyonlar için maliyet analizi yapılmasına odaklanılmıştır. Bu çalışmanın en önemli motivasyonu, Doğu Akdeniz bölgesinin jeopolitik değeri, enerji hatları ve ulaşım güzergahı olmasının yanında önemli bir hidrokarbon potansiyeline sahip olmasıdır. Bölgede kurulacak hidrokarbon platformlarının enerji ihtiyacının karşılanması ana çerçeveyi oluşturmaktadır. Bunun için belirlenen 6 bölge incelenmiştir. Bu bölgelerin rüzgar, güneş ve dalga enerjisi potansiyelleri belirlenmiştir. Platformların ihtiyacından fazla enerji üretilmesi durumunda elektroliz ile hidrojen üretilmesi amaçlanmıştır. Bu durumda üretilen hidrojenin farklı taşıma yöntemleriyle sıvı veya gaz halinde anakaraya iletilmesi durumları dikkate alınarak sistemin maliyet analizleri yapılmıştır. Analiz sonuçlarına göre Girit ve Rodos Adaları'nın doğal bir boğaz oluşturması nedeniyle Doğu Akdeniz'in çok yüksek bir rüzgar, güneş ve dalga enerjisi potansiyeline sahip olduğu gösterilmiştir. Sonuç olarak, hidrojenin anakaraya farklı iletim senaryoları, platformların ihtiyaç duyduğu enerjinin, gücü ne olursa olsun yenilenebilir enerji kaynakları ile sağlanabileceğini göstermektedir.

1. INTRODUCTION

Nowadays, the desire for energy is increasing worldwide. This reality leads increase the importance of Renewable Energy Sources (RES), which can produce energy through natural cycles and low negative environmental impacts [1–3]. The main kinds of RES can be listed as; wind, solar, wave, geothermal, and biomass energy. These energy sources vary according to geographical and geological characteristics. Many studies have been carried out to determine the potentials of energy resources, especially by running the techno-economic analysis of single or multiple resources, and then find alternative solutions to increase their overall efficiency.

Hybrid use of renewable energy sources may have very different purposes. Especially hydrogen-producing systems have been discussed by many researchers in recent years. Today, different hydrogen production methods are involved. The most common method is 'gray' hydrogen, which is derived from natural gas and produces significant carbon emissions. Less harmful than this method is 'blue' hydrogen. The production process is similar to gray hydrogen. The difference is that it makes use of carbon capture and storage. Unlike these methods, it is defined as 'green' hydrogen produced by RES’s [4–19].

Although the past studies were mostly carried out for onshore wind power plants, some studies dealt with the amount of hydrogen production from offshore wind power plants [15,17,20,21]. Similarly, techno-economic analyses of hydrogen production from solar power plants were carried out [22,23]. Wave power plants, another renewable energy source, have also been discussed for different regions [24]. In addition to this situation, the hybrid operation of different renewable energy sources has been examined using commercial softwares [25–27]. By using hybrid energy systems together, energy potentials for selected regions and therefore hydrogen production potentials can be determined [13,16,28]. Hydrogen energy, as one of the RES, is of increasing interest due to its positive characteristics as an energy carrier [1,7]. As a result, it is an alternative for countries to diversify their energy resources.

The Motivation of The Study

Türkiye has a developing economy and its energy needs are constantly increasing. Türkiye is going through the process of developing energy resources. For this reason, the Eastern Mediterranean Exclusive Economic Zone (EEZ) is very important in terms of its potential. Hydrocarbon exploration is currently underway in the Eastern Mediterranean Barbaros Hayreddin Pasha and Oruç Reis Seismic Research vessels operating in the region, and Yavuz and Fatih Drilling also continue their exploration activities. In case of possible reserves, oil and gas platforms will be established in the region. The main motivation of this study is to supply the energy needs of these platforms and to produce green hydrogen.

The extraction of offshore hydrocarbon resources and the meeting of the energy needs of refined processes with RES is an issue considered by the researchers [24,28–33]. Despite this, it has that the determination of the RES potential of Türkiye's Eastern Mediterranean continental shelf and its cost analysis have not been investigated before. This is a very important deficiency that needs to be examined in detail.

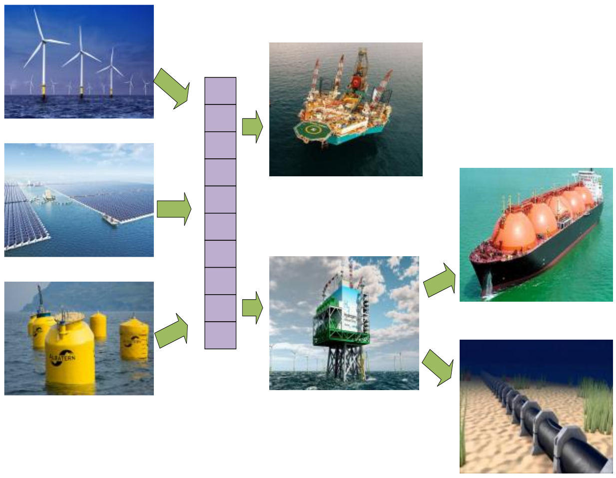

Figure 1. Systematic View of the Study

Offshore oil and gas platforms have different characteristics. These features are; varies depending on various features such as size, site conditions, and various features. These platforms have high power demands ranging from 1 MW to 100 MW [28,34]. These power demands are often met by stand-alone electrical systems using multiple redundant gas turbines when available at oil or gas exploration sites. These systems have higher fuel usage and lower efficiency. In addition, such a situation negatively affects the carbon footprint [29].

Firstly, information about the region is given in the study. In addition, wind, solar and wave energy potentials were investigated for six different regions. Designed to provide platform energy with existing renewable energy potential. Then the green hydrogen production situation is discussed with the excess energy that can be produced by RESs. In conclusion part, different transmission scenarios of the hydrogen produced to the mainland were examined. As a result, it has been seen that the energy required by the platforms can be provided by RES, regardless of their power. It has also been shown that there is much greater power generation potential. The systematic view details of the study are given in Fig. 1.

2. ECONOMIC EXCLUSIVE ZONE AND RENEWABLE ENERGY POTENTIAL

Considering the geography where Türkiye is located, the region has rich oil and natural gas reserves. In addition, the gas reserves found in the Eastern Mediterranean basin to date have further increased the geopolitical and geostrategic importance of the region. As a result, a Memorandum of Understanding was signed between the Government of the Republic of Türkiye and the Government of the State of Libya on 27th of November 2019, for the determination of the maritime jurisdiction areas in the Mediterranean Sea in Istanbul [35]. The working zone is given in Fig. 2.

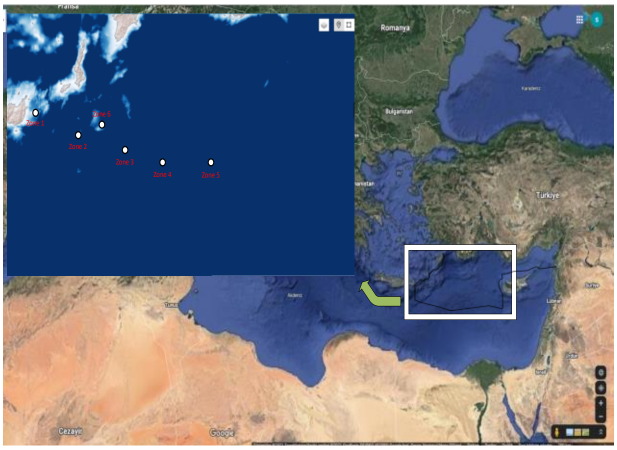

Figure 2. Exclusive Economic Zone of Türkiye and Working Zones

2.1. Wind Energy Potential

Obtaining Weibull distributions from field data is the first stage in determining the wind energy potential of regions [4,5,36–39]. In the next stage, energy density is calculated. If an original design is to be carried out, the annual amount of energy is calculated taking into account all parameters of the plant. In general, turbines of many brands and models that have already been manufactured and tried in different projects are taken into account. For those suitable from these turbines, Weibull distribution is applied and the amounts of energy to be produced for each different turbine are calculated. Then, the unit energy costs are found. As a result, the shape and scale parameters, capacity factors, and therefore energy amounts of each turbine will be different. In the literature, studies have been carried out to develop solutions with optimum energy costs for different sites. In these studies, different hybrid solutions such as wind-solar, wind-wave, wind-solar-hydrogen are discussed.

Wind speed is directly proportional to the height from the ground. As it approaches the Earth, it decreases due to the effect of friction force. The speed of the wind at a given altitude can be estimated by measuring the speed at any altitude. The most commonly used correlation for this is the Hellmann Equation [36]. Wind speed measurements are carried out at an altitude of 10 meters determined by the World Meteorological Organization. Rotor blades are directly effective in the transformation from wind energy to mechanical energy. The kinetic energy difference in cases where the wind touches the wings and leaves the wings is equal to the amount of wind energy that transforms into kinetic energy. Kinetic energy equations are used in the calculation of this power. The amount of energy that can be obtained from a wind turbine is given in Eq. (1).

$$E_e = \frac{q\,A}{2} v^3 \tag{1}$$

Where; q is the air density (kg m^{-3}), A is the swept area of the wind turbine (m^2), v is the wind speed value at the tower height (m s^{-1}), and t is the time (s).

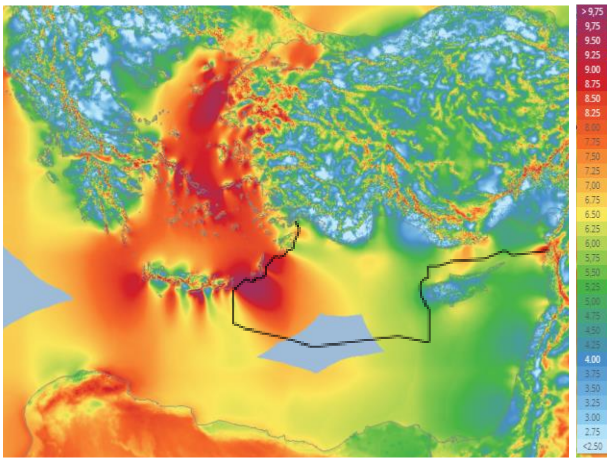

Figure 3. EEZ Wind Speed Map

The average wind speed of the determined areas at an altitude of 100 m is seen in Fig. 3 where the value is above 6 m s^{-1}. In addition, wind speed values are seen to be higher in the eastern region of Crete Island. The average monthly and hourly wind speed values of the regions are given in Fig. 4 and Fig. 5.

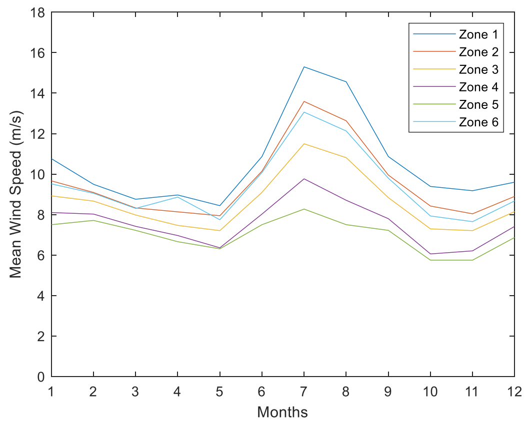

Figure 4. Average Monthly Wind Speeds

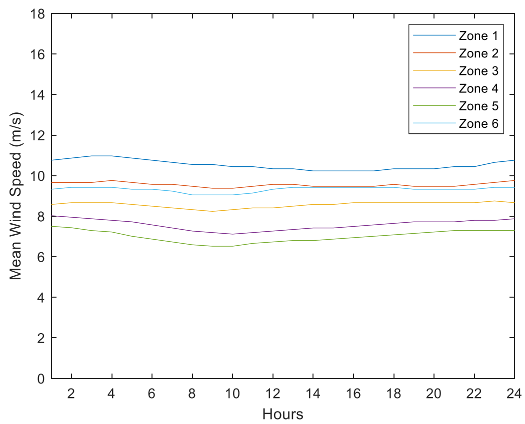

Figure 5. Average Hourly Wind Speeds

According to these values, the monthly and hourly wind speed values of Zone 1 are higher than than that in the other regions. In addition, it is seen that the average wind speed values of the regions in the summer months are higher than in other seasons. The characteristic information of the regions is given in Table 1.

Table 1. Information about the Zones

Zone	Lat.	Lon.	Mean Wind Speed (m sn^{-1})	Water Depth (m)	Power Density (W m^{-2})	Energy Density (MWh m^{-2} year)
Zone 1	35.14	26.38	10.55	-382	1245	10906.20
Zone 2	34.83	27.16	9.57	-2216	897	7857.72
Zone 3	34.52	27.79	8.58	-2558	618	5413.68
Zone 4	34.50	28.26	7.57	-2571	449	3933.24
Zone 5	34.40	29.11	7.01	-2683	364	3188.64
Zone 6	34.95	27.45	9.33	-618	799	6999.24

According to these data, the wind energy potential of the zones varies between 364 W m^{-2} and 1245 W m^{-2}. As a result of this, the eastern region of Crete Island, which is located in EEZ, has an assessable wind energy potential.

2.2. Solar Energy Potential

Solar energy, which is the source of many RES, is the radiation energy formed by the fusion process in the sun core. The energy production of a solar module depends on external factors as well as its structure. Solar radiation, cell temperature, and shading values are the main factors affecting the efficiency of solar modules. These factors should be taken into account when designing. The amount of energy to be obtained annually from a solar module is estimated using Eq. (2).

$$E_e = A_{tp} \,.\, A_v \,.\, \eta_f \,.\, GHI \tag{2}$$

Where, 'E_e' the annual electricity generation of the solar module (kWh $year^{-1}$), 'A_{tp}' the area of the total solar module (m^2), 'A_v' the availability of the solar module, 'η_f' the efficiency of the solar module and 'GHI' refers to the annual amount of global horizontal radiation (kWh m^{-2}). The annual efficiency of solar modules varies regionally. But, the efficiency of offshore modules is greater than onshore modules. This value may be over 95% [28]. The surface solar radiation information of the EEZ examined in the study is given in Fig. 6 [40].

Table 2. Annual Irradiation Values of Zones

Zone	DNI (kWh m^{-2})	GHI (kWh m^{-2})	DIF (kWh m^{-2})	GTI (kWh m^{-2})
Zone 1	1933.3	1874	647.3	2069.8
Zone 2	2023.3	1939.3	650.2	2150.4
Zone 3	2036.7	1959.4	661	2172.7
Zone 4	2049.2	1967.2	661.5	2184.4
Zone 5	2053.1	1972.4	663.9	2190.6
Zone 6	2038.7	1942.7	649	2158.8

In addition, the direct normal irradiation (DNI), Spherical horizontal irradiation (GHI), diffuse horizontal irradiation (DIF), and spherical oblique irradiation at optimum angle (GTI) values of the zones specified in the EEZ are given in Table 2.

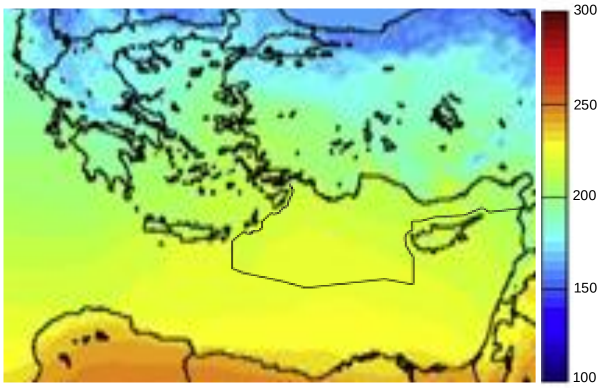

Figure 6. EEZ Solar Radiation Map

Table 3. Annual Direct Irradiation Values of Zone 5 (Wh m^{-2})

Hr. / M.	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
0 - 1												
1 - 2												
2 - 3												
3 - 4												
4 - 5												
5 - 6				1	47	108	68	9				
6 - 7			29	139	289	395	374	262	176	64	3	
7 - 8	57	113	233	335	433	549	545	488	436	317	175	69
8 - 9	254	300	374	454	541	658	667	622	575	467	366	271
9 - 10	367	389	475	547	620	736	753	716	669	557	471	376
10 - 11	419	461	537	612	669	784	804	776	727	614	534	432
11 - 12	448	492	567	636	698	805	827	802	751	629	546	442
12 - 13	448	496	569	631	690	808	829	803	752	623	535	434
13 - 14	436	480	546	609	675	785	815	783	724	595	494	408
14 - 15	392	437	524	558	635	748	775	733	666	530	418	358
15 - 16	311	363	445	479	563	682	704	652	573	415	297	254
16 - 17	131	246	333	382	463	588	605	539	430	209	94	67
17 - 18		31	134	226	327	455	463	356	155	3		
18 - 19				17	77	160	180	45				
19 - 20												
20 - 21												
21 - 22												
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Solar energy potential values of the determined zones vary between 1933 kWh m^{-2} and 2053 kWh m^{-2}. When these data are taken into account, it is seen that the studied region has a potential that can be evaluated in terms of solar energy. Although the energy densities of the zones are close to each other, the energy density of the 5th Zone is higher than the other zones. The monthly average energy density graph of the 5th Zone among the zones is given in Fig. 7 and the hourly average direct irradiation values are given in Table 3.

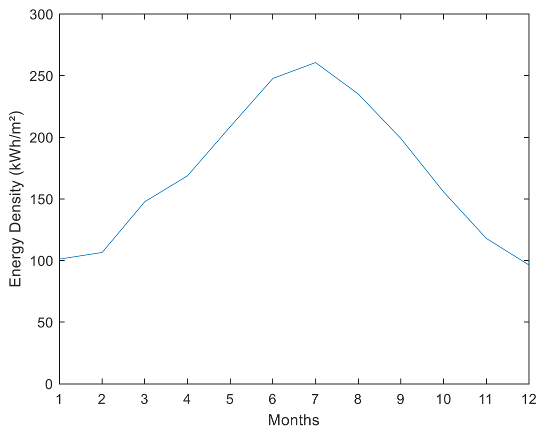

Figure 7. The Average Monthly Energy Density of Zone 5

2.3. Wave Energy Potential

Wave energy is an energy source generated by wind, seafloor movements, solar and moon gravitational forces, human activities, and different mass movements on the surface of the water. In general, the wave energy source is defined as the average wave power per unit of peak length. The wave energy source expression is given in Eq. 3.

$$E_w = \frac{\rho g^2}{64\pi} \sum_{i=1}^{N} \sum_{j=1}^{M} H_s^2 \, T_E \, f_{ij} \tag{3}$$

Where; ρ seawater density (kg m^{-3}), g refers to gravitational acceleration (m s^{-2}), H_s is the wave height (m), T_E is the energy period (s), f_{ij} is the wave formation frequency, and E_w is the wave energy. Accordingly, the average annual energy of the resulting wave is indicated by E_{ij} and given in Eq. (4).

$$E_{ij} = \frac{\rho g^2}{64\pi} H_s^2 T_E f_{ij} \tag{4}$$

Table 4. Annual Wave Energy Values

Zone	Average Wave Height (m)	Period (s)	Power Density (kW m^{-1})	Energy Density (MWh m^{-1})
Zone 1	1.11	4.7	8.9	77.964
Zone 2	1.12	4.6	9.3	81.468
Zone 3	1.05	4.6	8.95	78.402
Zone 4	1.03	4.5	8.9	77.964
Zone 5	1.00	4.45	8.01	70.1676
Zone 6	1.07	4.6	8.97	78.5772

There are two important components that determine the value of wave energy [41]. These are the wave height and the wave period value. These two components should be considered when examining the wave energy potential of a zone.

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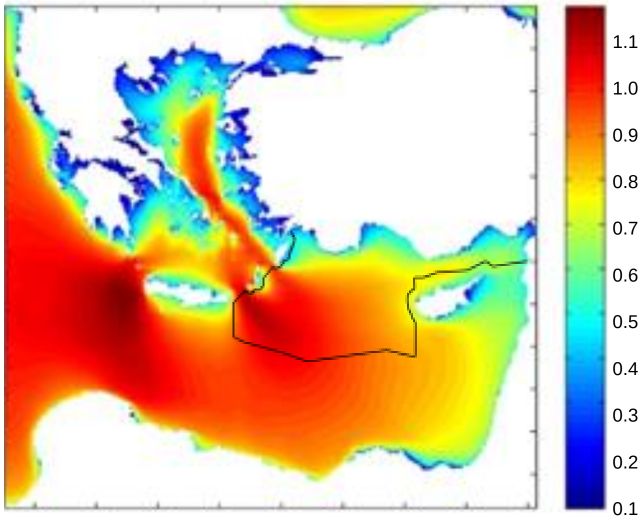

Figure 8. EEZ Wave Height Map

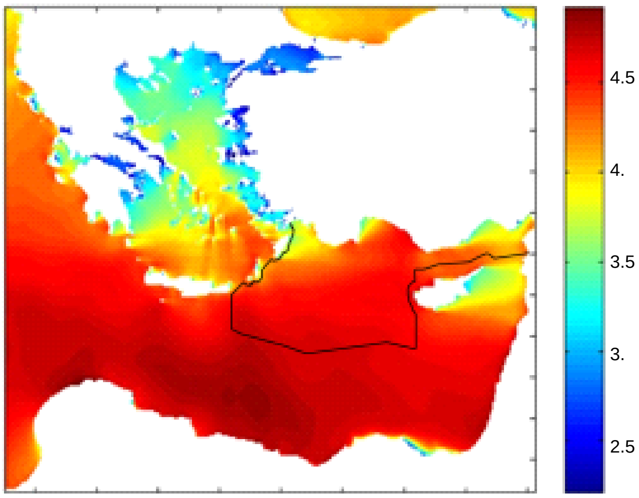

Figure 9. EEZ Wave Period Map

Wave height data is given in Fig. 8 [41]. Accordingly, the highest wave values are seen on the east and west coasts of Crete Island.

The average wave height for the investigated EEZ is 1.12 meters. Similarly, the wave period is given in Fig. 9. Accordingly, although the highest wave period values are on the African coasts, the lowest wave period values are on the Turkish coasts. In addition, wave energy data of the zones determined in EEZ are given in Table 4.

In the southern region of Crete Island, the wave period value varies between 4.45-4.7 seconds. When wave height and wave period value are taken into account together for wave energy potential, it is seen that the region in question has an assessable potential.

3. HYDROGEN ENERGY

It was stated by Dinçer [42] that the Hydrogen age started with the Covid-19 pandemic. In addition, the global hydrogen economy is predicted to be $155 billion in 2022 [18]. Therefore, hydrogen production has now emerged as an important engineering application. Although hydrogen is abundant in nature, it is not easily found because it is dependent on other molecules [6]. Therefore, it must be produced before it can be used. There are various methods in the literature to produce hydrogen. However, in order to be an alternative energy source, it must have a renewable and sustainable structure. In this stduy, the water electrolysis method is the most applicable technology to produce large-capacity 'green and clean' hydrogen [19]. Water electrolysis is the process of decomposing water into oxygen and hydrogen with the effect of direct current. The water electrolysis method has many advantages such as high efficiency and the use of RES [14]. This has revealed the necessity of examining and investigating renewable energy-based hydrogen production in the Eastern Mediterranean region, which has high renewable energy potential. This situation has been the most important motivation of the study.

There are many electrolysis technologies in the literature. In this study, the most advanced and widely used Polymer Electrolyte Membrane (PEM) electrolysis is referenced [43]. PEMs have many advantages. These advantages can be listed as high efficiency, adaptability to electrical fluctuations, low pressure hydrogen generation and direct storage without the need to compress the produced hydrogen [5,44]. Details of the cost of producing hydrogen using PEM electrolysis are given in Table 5 [45].

Table 5. Hydrogen Costs for PEM Electrolysis

		Electricity Cost ($ kWh^{-1})	Capacity Factor (%)	System CAPEX ($ W^{-1})	H_2 Cost ($ kg^{-1})
Ongrid	Low	0.050	90.0	1.0-1.5	5.13-4.37
	High	0.070	90.0	1.0-1.5	6.27-5.50
	PV 1	0.032	31.8	1.0	6.09
	PV 2	0.029	35.1	1.0	5.54
Offgrid	Onshore Class 6	0.038	38.0	1.0	5.76
	Onshore Class 1	0.028	52.1	1.0	4.22
	Offshore	0.120	51.0	1.5	8.34
	Low	0.050	90.0	1.0-1.5	5.13-4.37

Today, the hydrogen produced is transported by using different methods. The produced hydrogen produced can be transported as compressed/liquefied by pipelines and cargo ships [46]. In addition, if there is natural gas that can be extracted in the region, it can be mixed with natural gas and transmitted to the mainland. In general, pipeline transportation is the most economical method. However, it requires high installation costs and low maintenance-operation costs [47]. The main limitation in liquid hydrogen transport is the high energy required for disposal [48]. Therefore, it can be said that pipelines are preferred for large-scale applications [49].

4. COST ANALYSIS

The RES potential of the regions determined in the Eastern Mediterranean EEZ is detailed in Section 2. In this section, the energy needs of the hybrid power plant to be established in the region and the platforms to be probable hydrocarbon extraction are examined. In addition, the scenarios of producing hydrogen and moving to the mainland from the excess energy produced are detailed. The installed power and cost values of the hybrid RES plant for 6 determined zones are approximately the same. For this reason, the cost of a zone is given in Table 6. Cost information was obtained from literature studies of regions with very similar geographical features [24,50,51]. In addition, unit costs were examined in the study.

Table 6. Hybrid System Installed Power and Cost Values

RES	Installed Power (MW)	Total Cost (M$)	Unit Power Cost ($ kW^{-1})	Energy (GWh)	Unit Energy Cost ($ kWh^{-1})
Wind[50]	500	2264.062	4528.125	2095.210	1.080
Wave[24]	150	192.093	1280.620	2.346	81.881
Solar [51]	10	9.364	936.400	3.810	2.457
Total	660	2465.520	3735.636	2101.370	1.173

Accordingly, the hybrid power plant consisting of a 500 MW wind power plant, 150 MW wave power plant, and 10 MW solar power plant in the region will produce an average of 2101.369 GWh of energy per year. Although the solar Photovoltaic (PV) power plant value is seen to be very low when the unit cost of installed power is taken into account, it is seen that wind energy is much more advantageous when considering the unit cost of energy produced annually. Power consumption in hydrocarbon platforms during the year is approximately constant. Daily power consumption ranges from 22 MW to 35 MW. It can be considered that the daily consumption for an average day is approximately 27 MW. In this case, a hydrocarbon platform with an average size is considered to have an average energy consumption of 237 GWh per year [24]. Thus, the rest of the energy produced from RESs, 1864.359 GWh, can be used in hydrogen production. In this case, while it is 39 kWh km^{-1} for 100% efficiency, the efficiency is around 70% in today's conditions. When this efficiency is taken into account, energy consumption is 49 kWh kg^{-1}. According to this energy value, 38.048x10^6 kg of hydrogen can be produced annually.

In addition, different scenarios are discussed to transmit increased energy from existing platforms to the mainland. These scenarios include pipelines, freighters and finally transporting the hydrogen produced to the mainland by mixing it with natural gas if natural gas reserves are in the region. In this case, if the hydrogen produced is transported by cargo ships, there are two different methods. These are transported as compressed or liquefied hydrogen. While the cost of transporting liquefied hydrogen is 0.584 M$ km^{-1}, the cost of transporting compressed hydrogen is 0.14 M$ km^{-1}. The cost is 0.96 M\$ km^{-1} if it comes to transportation by pipelines [8].

5. DISCUSSION AND CONCLUSION

In this study, for the first time, its cost estimation was carried out by examining the RES potential of the Eastern Mediterranean zone. The wind, solar and wave energy potentials of the 6 zones determined for this purpose were examined. It is seen that wind energy densities are high due to the fact that the zones are located between low pressure and high-pressure air currents and Crete and Rhodes islands are a natural strait. In determining solar energy potential, it is seen that the energy density of the zones is high when the latitude effect and daily irradiation are taken into account as the main criterion. Likewise, the energy density is high due to the offshore characteristics of the wave energy potential. Although the unit cost of the wind power plant is high as Although the unit cost of the wind power plant is high, the amount of energy produced is also higher than other RESs. However, although the unit cost of the solar power plant is low, the amount of energy produced is also low. Considering the high unit energy produced cost of the wave power plant, a RES hybrid study was proposed in the zone. In this case, the hybrid power plant consisting of a 500 MW wind power plant, 150 MW wave power plant, and 10 MW solar power plant in the determined zones will produce an average of 2101.369 GWh of energy per year. When the possible platforms in the zone have an average energy consumption of 237 GWh per year, the rest of the energy produced, 1864.359 GWh, can be used in hydrogen production. In this case, there is an energy consumption of 49 kWh km^{-1} for 70% efficiency. According to this energy value, 38.048×10^{6} kg of hydrogen can be produced annually. The transport of this hydrogen energy to the mainland has been examined for two different scenarios. While the cost of transporting liquefied hydrogen is 0.584 M\$ km^{-1}, the cost of transporting compressed hydrogen is 0.14 M\$ km^{-1}. The cost is 0.96 M\$ km^{-1} if it comes to transportation by pipelines. Since the distance of the zones to the mainland is 250 km, it is more economical to transport as compressed hydrogen by cargo ships.

Some important contributions of this research are given below,
• The RES potential of sample 6 zones in the Eastern Mediterranean region was examined,
• cost estimation was made for the hybrid RES,
• It was shown that RES can meet the energy needs of hydro-carbon platforms such as oil/gas and that hydrogen will be produced with excess energy,
• cost estimation of the conditions of transport of hydrogen produced to the mainland were made for different scenarios,
and as a result, the region has been shown to have a high energy potential. This situation will enable it to become an important center where hydrogen, the fuel of the future, is produced.

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