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Energy Production Analysis for a Zero Emission Island, Istanbul Adalar District

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Abstract- In this study, the energy needs of the island were analyzed in two grid-connected and off-grid scenarios using wind, solar, biogas resources and energy storage methods. In this context, the electricity and natural gas consumption values of the Adalar district for 2019 were obtained from the relevant institutions. Wind measurement values of 5,74 m/s were obtained from the Adalar buoy station between 2017-2019. Average solar radiation values were determined as 4,02 kWh/m2/day between 1983-2005. The amount of waste that can be converted to biogas was determined as 24,90 tons/day. In this context, the offshore wind power plant capacity was determined as 124,2 MW with the micro-positioning study carried out on the offshore Democracy and Liberty Island. The solar panel capacity that can be applied to the roof of the houses on the island is calculated as 64,9 MW. The Li-Ion storage capacity in the grid-independent system is determined as 2,373 MW. As a result of the analyzes made with the Homer program, the energy need of the Island can be provided from its own resources as 100%, and with this situation, the Island model that produces zero emissions has been created. According to the zero emission Island scenario, the levelised cost of energy is calculated as $0,886/kWh.

Keywords Emission, Renewable Energy, Homer, Island

1. Introduction

With the Paris Climate Agreement signed by 177 countries in the world, it is planned to reduce global carbon emission values until 2038[1]. In this context, it is foreseen that the increase in global warming will be limited to 1,5 °C, and EU countries have set a zero emission target until 2050[2]. energy demand has been continuously increasing and different types of energy sources are used in electricity generation[17] Renewable energy sources should be given importance in order to reach the current target. Figure 1 shows the distribution of use of renewable energy resources in Turkey.

Clean air quality problem arises especially in metropolitan cities (Istanbul, Ankara and Izmir). The number of PM (Particulate Amount) measured daily in Istanbul has reached very high values, and carbon emission values are at high values. The main reason for these is the waste gases resulting from the use of fossil fuels in industrial facilities, and the other reason is the waste gases emerging from vehicles and residences.[5] In the last 15 years, the installed capacity of renewable energy has almost tripled[3].

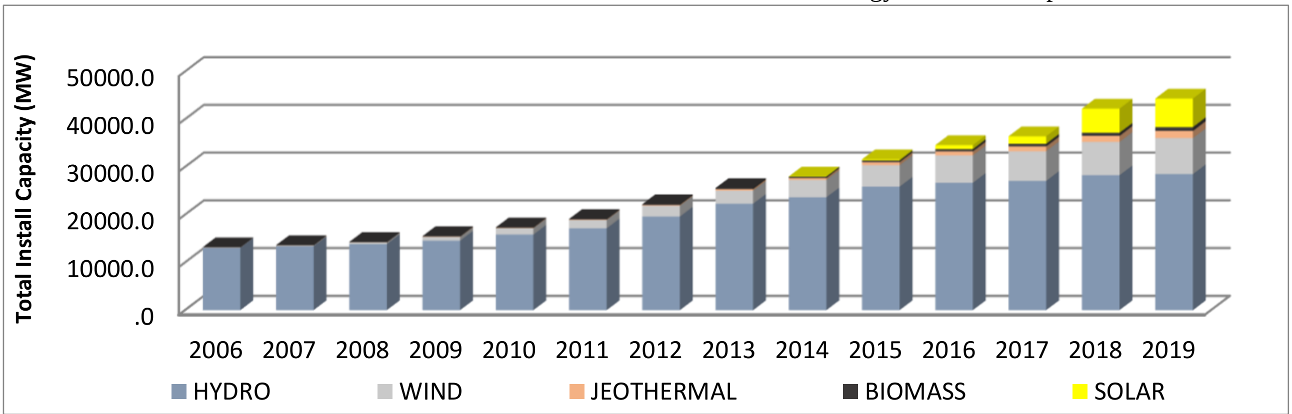

Fig. 1. Use of Renewable Energy Resources in Turkey in terms of Installed Power

According to a recently released report by Global Data, the global distribution transformers market for national energy grids is anticipated to expand at a compound annual growth rate of 1.6 percent, reaching $14.33 billion in 2022[21]. The global PV market has had a tremendous development the last 10 years.[18]

The increase in the use of renewable energy sources in Turkey will also contribute to the global emission reduction target. The use of renewable energy sources is also an environmentally friendly and sustainable energy system[4].

The integration of renewable energy resources in grid system enables the fossil fuel power generation plants to decrease the CO_2 emissions in way of less producing the energy.[19]

Smart grid system improve environmental compatibility and economic efficiency, achieve a stable energy supply and at the same time reduce CO_2 emissions[20]

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In this context, there are many studies in the literature. In 2019, Ioannis Kougias and his colleagues determined that the islands of Rhodes, Lesvos, Chios, Karpathos, Patmos do not have a grid electricity connection. These islands provide the majority of their electricity needs from fossil fuels. In their study, they determined the electricity needs of the islands between 2016 and 2036 with the Harmony Search Algorithm. They studied wind, solar and storage options by evaluating each of the islands on their own, and found that the most appropriate energy source was wind[6].

AA. In 2020, Chen et al. investigated renewable energy sources in Jamaica, which is isolated from the electricity grid. Jamaica supplies most of its energy needs from fossil fuels. They have determined that the most suitable energy option for Jamaica is the Battery Energy Storage System working with Li-Ion technology[7].

A. Çolak, in her work in 2019, designed an offshore wind farm for Gökçeada and Gaziköy. According to the data obtained from the meteorological observation station, VESTAS V116-2.0 MWIEC IIB wind turbine was found to be the most suitable turbine for the region. As a result of his study, he found that Gökçeada is suitable for an offshore wind farm[8].

In 2020, M. Alves et al. investigated grid-connected or off-grid renewable energy generation possibilities on the Portuguese islands of Pico and Fail. According to the results of their research, they determined that the grid-connected system is 6,5% more costly in 2050[9].

In 2020, H. Mehrjerdi proposed to meet the clean water need for an isolated island and the electricity need of the island with a hybrid system using PV panel, Wind Turbine, Diesel generator and battery storage system. In their study, they thought to provide the drinking water need of the island through the distillation unit[10].

There is no comprehensive energy analysis and modeling study in the Adalar District of Istanbul in the literature. In this study, this deficiency has been tried to be eliminated.

This study is planned as a continuation of my previously published work titled “Adalar onshore and offshore wind power plant (WPP) micro-positioning study and energy production analysis”[11].

Homer an international brand that is the global standard in decision making for decision making in the microgrid and distributed energy resource (DER) space. Using the Homer program, models and analyzes were carried out to meet the energy needs of the Adalar district of Istanbul in a zero-emission manner. The island's wind, solar and biomass resources were evaluated for energy production analysis. As storage methods, pumped storage hydroelectric power plant and Li-Ion type storage method are emphasized. In addition, two grid-connected and grid-independent scenarios were studied, and energy production and cost analyzes were performed on them. The schematic of the study in general is shown in figure 2. The price of electricity purchased from the grid is assumed to be \$0.112/kWh, and the price of electricity sold to the grid as \$0.049/kWh.

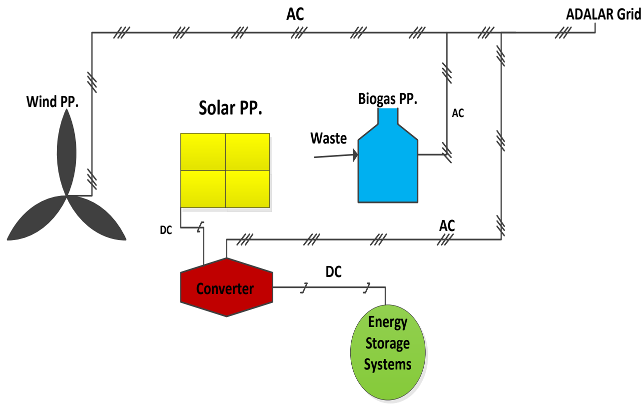

Fig. 2. Hybrid Power Generation System Schematic

2. Theory

The wind farm energy production analysis and modeling was done according to the following principles. Here, P is the power (in watts), A=the area swept by the propeller ($A=\pi r^2$, r the propeller radius), and V (m/s) is the wind speed. (Where ρ=1,225 kg/m^3 is the density of air at sea level. Theory

$$P=\frac{1}{2}\times\rho\times A\times V^3 \quad (1)$$

Equation 2 is used in the calculation of the wind coming into the turbine body.

$$\frac{Uhub}{Uanem} = \frac{ln\,(\frac{Zhub}{Z0})}{ln\,(\frac{Zanem}{Z0})}$$
(2)

U_{hub}= Wind speed at turbine body height [m/s],U_{anem}= wind speed at ananometer height [m/s],z_{hub}= turbine body height [m],z_{anem}= ananometer height [m],z_0= surface roughness length [m]

The Weibull distribution function is calculated according to equation 3.

$$f(v)=\frac{k}{c}\left(\frac{v}{c}\right)^{k-1}.exp\left[-\left(\frac{v}{c}\right)^{k}\right] \quad (3)$$

v= wind speed[m/h], k= the Weibull figure factor, c= the Weibull scale[m/s]

Wake effect are calculated according to equation 4.

$$\delta V = (1 - \sqrt{(1 - CT)}) / (1 + (\frac{2kx}{D}))^2 \quad (4)$$

CT = thrust (-) , k = $\frac{A}{ln(\frac{h}{z0})}$ (Attenuation Factor) A = 0,5 h = body height(m) z_0 = friction height (m) x= distance between turbines (m)

WPP and Biogas power plant annual capacity factor(CF) is calculated according to equation 5.;

$$CF = \frac{\text{POWER PLANT POWER GENERATION } (\frac{MWh}{yıl})}{\text{POWER PLANT CAPACITY (MWH)} \times 8760} \quad (5)$$

Solar power plant capacity analysis and modeling were done according to the following principles.

Average floor area (A.F.A) per building was calculated according to equation 6. TAKS is assumed 0,21

$$A.F.A = \frac{Residental\ Area}{Number\ Of\ Buildings}\,x\ TAKS \quad (6)$$

The GES system roof area was calculated according to equation 7. Ç.F = Exit factor is taken as 17%. K.A.F=The usable area factor is taken as 70%

$$\text{Solar System Roof Area} = [\text{A.F.A} + (\text{A.F.A} \times Ç.F)] \times Suitable\ Buildings \times U.A.F \quad (7)$$

The total number of PV was calculated according to equation 8.

$$\text{Number Of PV} = \frac{Solar\ System\ Roof\ Area(M2)}{PV\ AREA\ (M2)} \quad (8)$$

The installed power of the SPP is calculated according to the equation 9.

$$\text{The installed power of the SPP} = \text{Number Of PV} \times \text{Panel Power (kW)} \quad (9)$$

Solar panel efficiency and power calculation are calculated according to equation 10.

P_{max}=Maximum power output(W), E=İncident radiation flux (W/m^2), Ac=Area of collector

$$\eta\ (\%) = \frac{Pmax}{E \times Ac} \times 100 \quad (10)$$

The annual energy production value of the solar energy system was calculated according to equation 11.

E=Energy(kWh), η =solar panel efficiency (%), A=Total Solar Panel Area (m^2), H= Annual average solar radiation on tilted panels shadings not included (kWh/m^2/year) DF=Derating Factor coefficient for losses (range between 0,5 and 0,9, default value = 0,85)

$$E = A \times \eta \times H \times DF \quad (11)$$

The electrical efficiency of the biogas plant was calculated according to equation 12. LHV= Low Heating Value Biogas (5,5 MJ/kg), Fuel consumption (ton/years)

$$\eta\ (\%) = \frac{Electrical\ Production\ (kWh)}{\text{LHV} \times \text{Fuel Consumption}} \quad (12)$$

Pumped storage hydroelectric power plant capacity calculation is calculated according to equation (13,14). Discharge period (h) is assumed as 12 hours.. F=Discharge flow rate (m^3/s), ρ= density of sea water (1025kg/m^3), h_{head}= height from top to bottom (m), η= Pump efficiency (%90)

$$F = \frac{\text{Resarvoir Area (m3)}}{h \times 60 \times 60} \quad (13)$$

$$P(kW) = \frac{9{,}81 \times \rho \times \text{hhead} \times \eta \times F}{1000} \quad (14)$$

The following equations were used as the economic model.

$$i = \frac{i^1 - f}{1+f} \quad (15)$$

The actual discount rate is defined as “i”, ii = nominal discount rate (6%), f = expected inflation rate (0%)

$$CRF(i,N) = \frac{i \times (1+i)^N}{(1+i)^N - 1}$$
(16)

C_{NPC} = Net present value ($)

$$C_{NPC} = \sum_{t=0}^{n} \frac{Rt}{(1+i)^t} \quad (17)$$

R_t = Net cash flow ($/Year), t = number of time slots, CRF = Capital recovery factor, N = number of years,

$$C_{ann,\,tot} = CRF \times (i, R_{proj}) \times C_{NPC,tot}$$
(18)

$C_{ann,\,tot}$ = Total annual cost is the annual value of total net current cost. ($/year),$R_{proj}$ = Project lifetime(25 years)

$$COE(\text{cost of energy}) = \frac{\text{Cann,tot}(\frac{\$}{\text{year}})}{Eserved(\frac{kWh}{year})}$$
(19)

The grid O&M cost is equal to the annual cost of buying electricity from the grid (energy cost plus demand cost) minus any income from the sale of electricity to the grid. The price of electricity purchased from the grid is assumed as $0.112/kWh, and the price of electricity sold to the grid as $0.049/kWh.

$$C_{\text{grid O\&M}} = C_{\text{Energ Purchased}} - C_{\text{Energy Sold}} \tag{20}$$

The levelized cost of energy as the average cost per kWh of useful electrical energy produced by the system.(LCOE). ($ / kWh), E_{served} = Total electric load (kWh/Year)

$$C_{operating} = C_{ann,\,tot} - C_{ann,\,capital} \tag{21}$$

$$C_{ann,\,capital}\ (\$/\text{Year}) = C_{ann,\,tot} \times \text{CRF} \tag{22}$$

$$f_{renewable} = 1 - \frac{Enonrenewable\ (\frac{kWh}{year})}{Eserved(\frac{kWh}{year})} \tag{23}$$

$f_{renewable}$ = It is the rate of renewable energy in total energy production.

$$E_{nonren} = E_{produce} - E_{renewable} \tag{24}$$

As seen in Table 1, the total electricity consumption of Adalar district in 2019 was 171 MWH[12]. Adalar district consists of 5 neighborhoods. Maden and Nizam districts are located in Büyükada, apart from these, there are Heybeliada, Kınalıada and Burgazada districts. According to the 2019 census, 15.238 citizens live on the Island. However, in the spring, the population is up to 140.000 people. The climate is mild, a large part of the island is used as a forest area.

Table 1. Total Electricity Consumption in Adalar District in 2019 by Neighborhood

Year	Town	District	Annual Total Electricity Consumption (kWh/yıl)
2019	Adalar	Maden Mah,	48.618.492
2019	Adalar	Heybeliada Mah,	47.753.914
2019	Adalar	Nizam Mah,	38.962.163
2019	Adalar	Kınalıada Mah,	19.739.332
2019	Adalar	Burgazada Mah,	16.022.769
2019	Adalar	All Town	171.096.670

Figure 3 shows the distribution of electricity and natural gas consumption by months. Electricity consumption increased significantly in the spring months. Natural gas consumption peaked in the winter months.

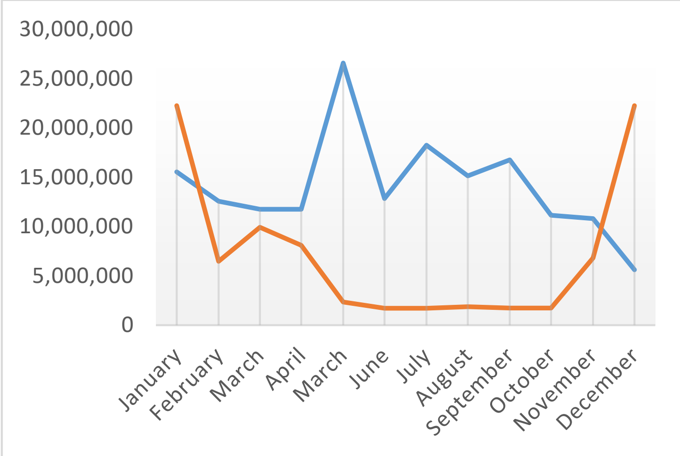

Fig. 3. Adalar District Total Electricity Consumption and Natural Gas Load for 2019 on a Monthly Basis

Figure 4 shows the monthly average wind speed distribution between the years 2017-2019, taken from the Adalar buoy meteorological observation station (h:2 m). The average wind speed was measured as 5,72 m/s[13]. The wind speed follows a non-variable course in the other months when it enters a downward trend in the spring months.

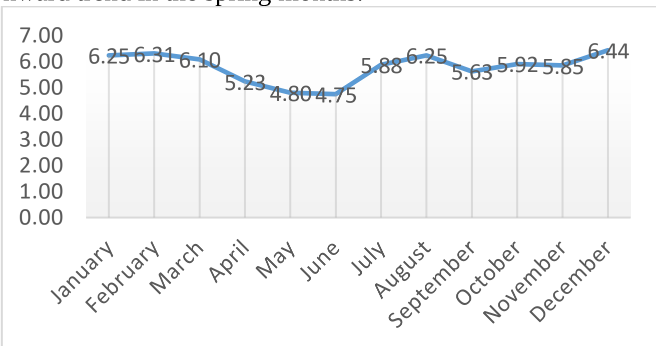

Fig. 4. Adalar Buoy Observation Station Wind Values (m/s)

Figure 5 shows the average insolation values of three different data sets. NASA's data set shows the average insolation values for the years 1983-2005. Meteonorm data shows the average insolation values between 2004-2010.

Existing PVGIS data is defined as TMY (Typical Meteorological Year) based on a re-evaluation of the latest data from the Joint Research Center of the European Commission (JRC). As seen in the graph, the values are similar. In this study, the data of the Nas moment obtained from the measurements made over a 22-year period were used. The fact that the measurement period was long and the average of 3 measurements were effective in the use of this data. In this respect, the average solar radiation value for the Islands was accepted as 4,02 kWh/m^2 /day.

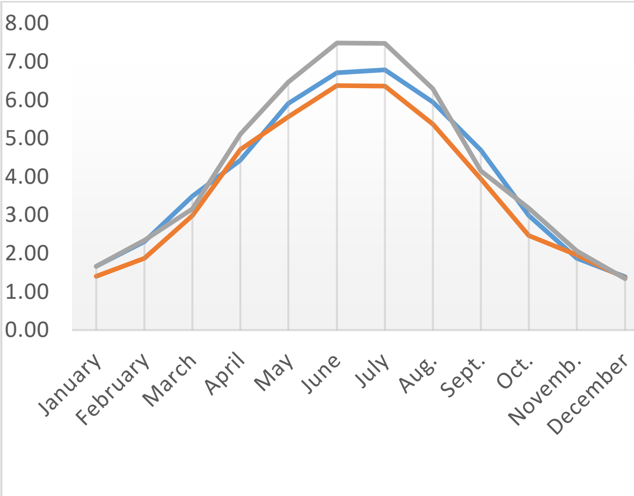

Fig. 5. Adalar Global Horizantal Irradation Value

The Building Structure Status of Adalar District is shown in table 2. As can be seen, the buildings consist of masonry, wooden, reinforced concrete and prefabricated structures. There are 6.393 buildings in total. These structures include only residences in terms of content. Buildings with any additional features (mosque, school, social structure, historical monument, etc.) are excluded[14].

Table 2. Adalar District Building Structure Status [14]

Buılding Structure	Numer Of Buildings
Masonory	2.269
Wooden	1.209
Concrete	2.908
Prefabricated	7
Total	6.393

When the building is examined in terms of construction years, there are 3.584 buildings before 1980, 1,741 buildings between 1980 and 2000, and 1.068 buildings after 2000. As can be seen, the majority of these structures were built before the year 2000. In the study carried out by IBB, it was assumed that in the event of a possible 7.5 MW earthquake, 3.050 of these buildings would be severely, heavily, or moderately damaged. It is recommended to apply solar panel systems to solid and long-lasting structures. In this respect, the number of suitable buildings on which solar panels can be built is calculated as 3.343.

In 2010, the amount of residential areas in the share of the land was 332 hectares, the average floor area coefficient of the Adalar district was 0,21.[15] There were a total of 5.796 residences on the Islands in 2010. Using Equation 6, the average floor area value was calculated as 120 m^2

It is assumed that the roof area value of Adalar district has increased by 17 percent compared to the building floor area. Considering the installation of the solar panel system in the roof area, it is thought that 70% of the total roof area can be used actively, considering the presence of parameters that prevent the solar panel system such as chimney systems, antenna, etc. on the roof. Using Equation 7, the GES system roof area was calculated as 334.634 m^2.

Table 4 shows the amount of waste suitable for biomethanization. The amount of domestic waste was determined as 3.388 tons/year, and animal wastes as 5.700 tons/year. The energy equivalent of these wastes is calculated as 139,6 TEP(tons of oil equivalent)/year for domestic wastes and animal wastes. [16]

Table 4. Islands District Quantity of waste that can be converted into biogas [16]

Type of waste	Quantitity	Waste Quantitiy (ton/year)	Energy Value (TEP/Year)
Household Waste	15.238	3.388	109,3
Horse	1.033	5.655	30,3
Donkey	5	13,7	0
Cattle	30	2,73	0
Goat	21	15,4	0
Sheep	14	15,3	0

3. Results and Discussion

36 turbines were installed in the offshore wind farm micro-positioning and energy production analysis study. As a turbine type, it was concluded that the VESTAS V136 turbine with a 3,45 MW capacity is the most suitable turbine. In this respect, 36 turbines were placed according to Figure 6. Annual electricity production amount is calculated as 445 GWh/y using equation (1.4)[11].

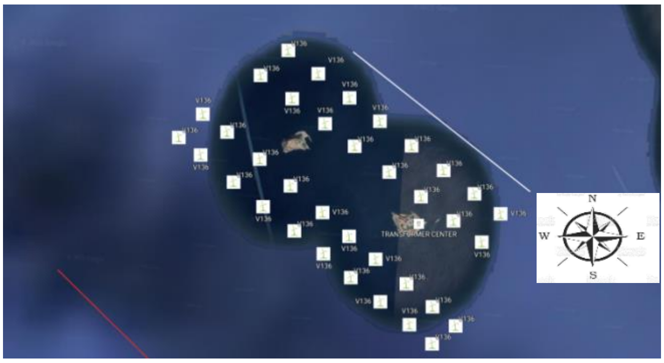

Fig. 6. Offshore Wind Power Plant Layout

The data of 3 types of solar panels are given in Table 4, when looked at, the installed power values for 3 types of panels were calculated using equation 9. As can be seen, no significant difference was detected in the installed power values. In this study, LG330 type solar panel, which has a slightly more power generation capacity, was preferred.

Table 4. Solar Panel Types

Panel Type	**CWT200**	**LG 330**	**CWT395**
Panel Type	Roof/Mono	Roof /Mono	Roof /Mono
Panel Power (kW)	0,2	0,33	0,395
Efficiency (%)	19,65	19,30	19,78
Panel Area (m2)	1,07	1,7	2,1
Number Of Panels	312.742	196.843	159.349
Install Power	62.548	64.958	62.943

In Table 5, biogas burning devices were evaluated in 3 different situations, and their capacity factors and efficiency were calculated using equation (5,12). For 20 MW and 240 MW biogas burners, the Island's own waste amount was determined to be insufficient. It has been determined that the 500 kW biogas plant works in accordance with the island's own waste amount.

Table 5. Capacity and Efficiency Analysis of Biogas Burner Devices

Biogas Genarator Type	**Generator 1**	**Generator 2**	**Generator 3**
Fuel Source	Icland Waste	Purchasing Biogas	Purchasing Biogas
Capacity (MW)	0,5	20	240
Fuel Price ($/kg)	Free	0,1	0,1
Minimum Load Ratio(%)	50	50	50
Capacity Factor	24	2,39	2,19
Mean Electrical Efficiency	31,2	10,1	38,2
Lifetime (h)	20.000	20.000	20.000

Table 6 shows the comparison of the two types of storage systems. It is seen that Li-ion type storage has higher storage capacity and faster response time. It has been observed that Li-Ion type storage technology has a longer lifespan. In this study, Li-Ion type storage type was preferred as the storage technology.

Table 6. Comparison of Storage Systems

Type Of Storage	Duration(h)	Max. Discha Power (kW)	Min. State of Chrge .(%)	Throughput (kWh)	Life Time (Years)
Li-Ion 1 kW	0,33	3	20	3.000	15
Lead Acid 1 kW	3,40	0,292	40	800	10

Table 7 shows the installation cost, replacement cost and annual maintenance and repair costs of energy systems. When viewed, the offshore wind farm has energy installation costs much higher than other energy systems. Rooftop solar power plant costs are half as much as an offshore wind farm. The cost of a biogas plant is half the cost of a solar plant. As energy storage systems, the cost of Li-Ion type storage is $700, and the energy cost of the power plant with pump storage is around $1.000. The converter cost hovers around $300.

Table 7. Energy Costs Analysis

Energy Systems	**Initial Cost ($/kW)**	**Replac. Cost ($/kW)**	**O&M ($/year)**	**Life Time (Years)**
WPP(Wind Power Plant)	1.995	0	4.957.768	25
SPP(Solar Power Plant)	1.000	0	974.376	25
BPP(Biogas Power Plant)	500	500	0,030($/opr.hours)	15.000(hours)
Energy Storage(Li-ION)	700	700	10.000	15
Energy Storage(PDHES)	1.000	1.000	2.000	7
Converter	300	300	0	15

Table 8 on a detailed study of the island's energy needs be met without the support and network support network was carried out. In the scenario where grid-supported wind and solar are used as hybrids, the energy cost reduced to a value of 0,0361 $/kWh was calculated using equation (19). The renewable energy rate was calculated as 91,9% using the equation (22). According to the grid-independent scenario, the cheapest energy generation wind, biogas and PDHES (pumping storage plant) systems were found to be the hybrid system. The renewable energy rate was calculated as 92,7 in this system. The energy cost reduced to one value is calculated as $0,228/kWh. Within the scope of zero emission island modeling, it has been seen that it is possible to use a hybrid system with wind, solar, biogas and Li-Ion storage together. However, it has also been determined that it is the most expensive system in terms of energy cost.

Table 8. Comparison of Energy Systems

Scenario	Wind (MW)	Solar (MW)	Biogas (MW)	Converter (MW)	Storage LI(MW)	Storage PDHES (MW)	Renewable Ratio (%)	COE Cost ($/kWh)
On Grid	124,2	64,9		41,9			91,9	0,0361
	124,2	64,9		41,8		3,4	91,9	0,0362
	124,2						88,3	0,038
		64,9		42,9			29,6	0,0896
Off Grid	124,2		240	90		1.143	92,7	0,228
	124,2		240	104	175		82,1	0,248
	124,2	64,9	240	92		1.203	94,7	0,249
	124,2	64,9	240	105	152		85,2	0,252
		64,9	240	145	164		18,9	0,425
	124,2	64,9	20	144	1.045		98,4	0,496
	124,2	**64,9**	**0,5**	**217**	**2.289**		**100**	**0,886**
	124,2	**64,9**		**170**	**2.373**		**100**	**0,906**

Figure 7 shows the annual energy production amounts of the wind, solar and biogas system together with the energy storage. Total electricity production is realized at the level of 41.500 MWh. Most of the energy needs are met from the wind. The share of the sun increases relatively in summer months. Since the biogas plant is 0,5 MW in this scenario, it meets the peak demands.

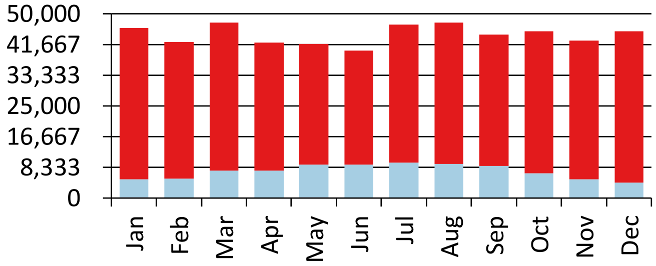

Figure 7. Wind, Solar and Biogas with Li-Ion Storage Scenario Energy Production of the year

4. Conclusion

In this study, zero emission island modeling was carried out. As a result of the analyzes, it has been determined that the electricity and natural gas needs of the island for 2019 can be met by using wind, solar and biogas resources. The energy cost was calculated as $0.886/kWh for this scenario. In today's conditions, this value is high.

The storage capacity has been calculated as around 2.300 MW, which does not seem possible to provide in today's conditions. With the development of energy storage technologies, it is predicted that this situation will cease to be a problem in the coming years.

It has been determined that the energy need of the island can be met with a renewable energy rate of over 90% at the end of all scenarios. In today's conditions, it has been seen that the most suitable and applicable scenario is the grid-supported wind, solar hybrid system.

The increase in carbon emission values increases global warming, and in order to reduce these values, electricity generation from renewable energy should be encouraged by the states. At the point of renewable energy costs, states should develop policies that support investors.

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