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Technical and Economic Evaluation of Electricity Generation and Storage Using Renewable Energy Sources on Socotra Island, Yemen

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Abstract

Renewable energy sources are a promising hope for avoiding many environmental and economic problems such as the problems of climate change and environmental pollution resulting from fossil fuels combustion, in addition to the problems of oil derivatives high prices and their absence in many countries, which in turn affected the rise in electricity prices. Yemen is considered one of the countries most affected by electricity prices rise due to lack of oil derivatives as a result of the ongoing wars in Yemen. This paper presents a technical and economic study of renewable energy sources for producing and storing electricity. It gives a clear scientific and economic vision for implementation of these projects in one of the Yemeni islands, Socotra. This study has proven the high efficiency of energy sources in this region, which encourages their use to produce electricity to cover the region needs at low prices compared to the current prices of electricity in Yemen., where the cost of electricity from renewable energy sources ranges between 0.073 to 0.25 $ / kWh. The study also provides an assessment of the expected decline in electricity prices until 2030. It should be noted that this study can be applied to many coastal cities and other islands in Yemen at a cost close to this cost.

Keywords: Renewable Energy, Wind Energy, Solar, Tidal, Biomass, Hydroelectric, Hydrogen, Yemen.

التقييم الفني والاقتصادي لتوليد الكهرباء وتخزينها باستخدام مصادر الطاقة المتجددة في جزيرة سقطرى، اليمن

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الخلاصه

مصادر الطاقة المتجددة هي أمل واعد في تجنب العديد من المشاكل البيئية والاقتصادية مثل مشاكل تغير المناخ والتلوث البيئي الناتج عن احتراق الوقود الأحفوري، بالإضافة إلى مشاكل ارتفاع أسعار المشتقات النفطية وغيابها في كثير من الدول، والتي بدورها أثرت على ارتفاع أسعار الكهرباء. تعتبر اليمن من أكثر الدول تضررا من ارتفاع أسعار الكهرباء بسبب نقص المشتقات النفطية نتيجة الحروب الدائرة في اليمن. تستعرض هذه الورقة

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دراسة فنية واقتصادية لمصادر الطاقة المتجددة المستخدمة في إنتاج وتخزين الكهرباء ، مما يعطي رؤية علمية واقتصادية واضحة لتنفيذ هذه المشاريع في إحدى الجزر اليمنية المسماة سقطرى ، حيث أثبتت هذه الدراسة كفاءتها العالية في المنطقة التي تشجع استخدامها لإنتاج الكهرباء لتغطية احتياجات المنطقة بأسعار منخفضة مقارنة بالأسعار الحالية للكهرباء في اليمن ، حيث تتراوح تكلفة الكهرباء من مصادر الطاقة المتجددة بين 0.073 إلى 0.25 دولار / كيلوواط ساعة ، وكذلك لتقديم تقييم لانخفاض أسعار الكهرباء حتى عام 2030. وتجدر الإشارة إلى أنه يمكن تطبيق هذه الدراسة على العديد من المدن الساحلية والجزر الأخرى في اليمن، بتكلفة قريبة من هذه التكلفة.

1. Introduction

Using renewable energy is increasing day by day due to the risk aggravation of using fossil fuels to produce energy [1,2], the most important of which is electric energy, which is the primary source used for daily consumption without any interruption, and a development sign of any country as it is the most significant energy that can be converted into several different energies[3].

Yemen had long suffered from a shortage of electric power even before the problems and wars that have occurred since 2014, which led to power plants destruction in major and remote cities, forcing people to live in darkness for years under harsh environmental conditions and an extremely hot climate in all coastal cities and islands, in addition to health services reduction in hospitals, the spread of epidemics and diseases as a result of the destruction of essential energy facilities[4]. Many Yemenis have used photovoltaic systems as a successful alternative for the production of electricity for lighting, cooling and heating in some areas. But these projects are individual, random and expensive, especially since Yemenis live below the poverty line, so not all Yemenis can fully cover their needs of lighting, entertainment, cooling and heating. Therefore, giant projects that can cover the needs of cities and villages must be established at the lowest cost and can be invested and continued appropriately for a long period of time so that people can live with an adequate standard of living that enables them to continue to lead a safe and dignified life[5,6]. Despite the tragedies that occurred in Yemen, it could be an appropriate and excellent opportunity to produce electricity with renewable energy sources such as wind, solar, tidal, biomass, hydroelectric, hydrogen and other sustainable, clean and environmentally friendly sources[7].

Table (1) shows the economic studies of renewable energy sources between 2010 and 2020 for both the International Renewable Energy Agency (IRENA) and the Lazard website, where they made a comparison of electricity prices during ten years by calculating the Levelized Cost of Energy (LCOE), in addition to percent change in those costs. It should be noted that these values differ from one region to another according to the efficiency and availability of natural renewable resources for that region, as well as its topography and geographical location.

Table 1: LCOE between 2010 to 2020 (IRENA), (Lazard).

	Energy Sources	LCOE ($/kWh)		Reduce %	Ref
		2010	2020		
IRENA	*onshore Wind*	0.089	0.039	-68	[8, 9]
	offshore Wind	0.162	0.084	-48	
	Concentration solar	0.34	0.108	-68	
	Photovoltaic	0.381	0.057	-85	
	Hydropower	0.038	0.044	18	
	biomass	0.076	0.076	0	
	Tidal	0.36	0.2	-44	
Lazard	*Wind*	0.137	0.041	-30	[10]
	Concentration solar	0.17	0.14	-18	
	Photovoltaic	0.38	0.04	-90	
	Hydropower	NA	NA	NA	
	biomass	NA	NA	NA	

In this research, the possibility of applying renewable energy sources in one of the largest and most densely populated Yemeni islands, Socotra island, was studied. Socotra island is characterized by its scenic beauty and strategic location in the Arabian Sea. However, like other Yemeni cities, it suffers from a significant electric power shortage, which has made its residents suffer greatly. This study proved that the island has a considerable wind speed for several months that enables the production of electricity by turbine technology. In addition to solar energy, which has always proven successful at the general level of the region; tidal, although relatively low, is sufficient to produce power using modern technology; biomass can also be exploited. It is available on the island to produce energy and dispose of harmful waste using biomass-to-energy technology.

Since renewable energy sources are not fixed and change permanently, storage is a necessity to ensure hourly and uninterrupted electricity production. The best sustainable and clean storage methods, which are hydroelectric and hydrogen, were studied in this work. It should be noted that the research was carried out through two studies: the first is a technical and analytical study for the information obtained from renewable sources, and the second is an economic and investment study through calculating Levelized Cost of Energy (LCOE) for 2020 and cost forecasting till 2030. The main aim of this research is to give an economic comparison of renewable energy sources and their storage (as hybrid systems) with other sources used in Yemen, which is the fossil fuel that Yemen depends on for electricity production.

2. Method

An economic study of any project is one of the most important things that must be accomplished before starting any project to give an economic plan that enables the understanding of the annual payment rates and the benefits of the project. The most important projects are the energy projects, which have a vital role in the establishment and growth of the economy of any country; rather, it is considered a measure of people's sophistication. If the energy is more available, the economy and development will be greater.

In renewable energy projects, Levelized Cost of Energy (LCOE) can be calculated by Equation (1) which shows that the cost of energy increases with the increase in the investment cost, operation, maintenance, and the fuel used. The cost decreases by increasing the energy produced, capacity factor, and project lifetime. those parameters will be studied in detail [11, 12, 13].

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \quad (1)$$

Where: I_t is the investment expenditures, M_t s the operations and maintenance expenditures in time t, F_t is the fuel expenditures, E_t is the electricity generated, r is the discount rate, and n is the system economic life.

Of course, it must be taken into account that the parameters affecting the energy cost differ from one country to another. Also, it differs according to the technology type used, and the efficiency of the resources available in the country in which the project is implemented, in addition to the methods of deducting financial flows (annual, quarterly or monthly) and the interest rate imposed by institutions funded for the projects. It should be noted that this applied approach is just a relative approximation of the cost currently prevalent in the market and the common method used in the energy market.

Capital costs and other auxiliary costs for the initial establishment are calculated to get the investment costs, which are affected by a factor called the Capital Recovery Factor (CRF), which is illustrated in Equation (2) [14]:

$$CRF = \frac{i(1+i)^t}{(1+i)^t - 1} \quad (2)$$

Where: i is the interest rate which takes values between (0.02 to 0.1), t is the project lifetime or deduction time of the amount paid according to the agreement.
One of the most important costs that must be studied after the investment costs are the operating and maintenance costs, which vary from one project to another. There are also other added costs such as taxes, insurance and other attributes that have an impact on LCOE. Their ratios range between 1 to 5%. Among the parameters that have a dominant effect on LCOE is the so-called discount rate; it takes values from 2 to 30%.

The most important aspect of this topic is the amount of energy produced, which is directly affected by the capacity factor. Increasing the energy produced decreases the LCOE.
Therefore, all efforts must be focused on how to increase the efficiency of the generators that produce the energy, which can be done by raising the capacity factor to obtain the largest amount of energy at the lowest costs[15].

$$Energy\ production = Generator\ Nominal\ power\ (kW)\ \ x\ Cp\ (\%)\ \ x\ 8760\ (h) \quad (3)$$

3. Renewable Energy Sources

3.1. Wind Energy

When studying the distribution of wind speed in any region, there are two important ways to know the performance of wind speed. The first is the Weibull distribution functions which depends on the variables scale parameter c (m/s) and shape parameter k (called Weibull Parameters). Equation (4) and (5) are the equations expressing the probability density and the other cumulative distribution[16,17]:

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \times exp\left[-\left(\frac{v}{c}\right)^k\right]. \quad (4)$$

$$F(v) = 1 - exp\left[-\left(\frac{v}{c}\right)^k\right]. \quad (5)$$

Where v is the wind speed

The second is the Rayleigh distribution functions which depends on speed variables v and mean wind speed v_m in the region, as in Equations (6), (7)[16,18]:

$$f_r(v) = \frac{\pi v}{2v_m^2} exp\left[-\left(\frac{\pi}{4}\right)\left(\frac{v}{v_m}\right)^2\right] \tag{6}$$

$$F_R(v) = 1 - exp\left[-\left(\frac{\pi}{4}\right)\left(\frac{v}{v_m}\right)^2\right] \tag{7}$$

3.1.1. Wind Energy Cost

Wind turbine costs vary according to industry, power, and tower height. Table (2) shows the costs of wind turbines by nominal power and tower height. Equation (8) is used to find the total cost of wind turbines and knowing the energy produced from wind turbine farms, Levelized Cost of Electricity (LCOE) can be deduced by Equation (9)[19].

Table 2: Cost (by $) of Wind Turbines with Nominal Power and Tower by $.

Nominal power (MW)	Tower Height (m)			Ref
	<100	100- 120	>120	
<2	1218	1341	-	[19, 20, 21]
2 – 3.5	1128.5	1285	-	
>3.5	-	1425	1550	

$$PVC = C_{inv} + C_{omr} \times \left(\frac{1+i}{r-i}\right) \times \left[1 - \left(\frac{1+i}{1+r}\right)^t\right] - C_s \times \left(\frac{1+i}{1+r}\right)^t. \tag{8}$$

Where: PVC is the Present Value of Costs, C_{inv} is the investment cost, C_{omr} is the operation and maintenance costs, C_s is additional costs, i is the interest rate =1.5 %, t is the turbine lifetime = 20 years, and r is the inflation rate = 2%.

$$(LCOE) = \frac{PVC}{PE}. \tag{9}$$

Where: PE is the energy production in a rated lifetime.

3.2. Solar Energy

Solar energy is the first and largest source of energy as it can be used for electricity production in any sunny area in the world[22]. The costs of producing electricity from this source vary according to system used. Three systems, photovoltaic (PV), Stirling Dish and Power Tower systems used for electricity production are reviewed.

3.2.1. Photovoltaic system

The photovoltaic system converts solar energy into continuous electricity using semiconductors of positive and negative types and generates a potential difference that enables charge transfer and electricity generation[23]. PV system is considered one of the most famous and easiest systems to exploit power sources. It needs a converter to convert DC into AC to operate the various electrical devices and a storage system to ensure continuous electrical power supply throughout the day, even after the sun absence.

Photovoltaics are experiencing rapid growth, from ones of small capacity to a great global capacity of 138 MW at the end of 2021, which represents more than 0.6% of global electricity demand. More than 100 countries use solar photovoltaic energy, sometimes for agriculture or irrigation or built on the roof or building walls (building integrated with photovoltaics). Photovoltaic energy has become the cheapest energy source in regions with high solar radiation, with prices reaching 0.01567 $/kWh in 2020[24]. The cost of photovoltaic panels has decreased by one-tenth within one decade. This competition opens the door to a global shift to sustainable energy, which will help limit global warming. Use of photovoltaic panels as the main energy source faces the dilemma of the need for energy storage or energy distribution systems with a high-pressure network in the world, which requires additional costs[8].

Calculated costs of PV are from 2.30 to 3.35 $/W according to the statistics for each type of photovoltaic in the global market. Capital cost of photovoltaic is between 900-2100 $/kW, Operations and Maintenance [O&M] 9.5-1$/kW/Year, and Converter 300-800 $/kW, Table (3).

Table 3: Cost of PV System at 2021

Description	Cost	Unite	Ref
Capital Cost	995 - 2100	$/kW	[25, 26, 27]
O&M	9.5 – 18.3	$/kW/Year	[25]
	1-1.5	%	[28, 29]
Life Time	25	Years	[29, 30]
Converter	300-800	$/kW	[5, 15, 31]

3.2.2. Stirling Dish system

Stirling dish systems have shown high efficiency in converting solar energy into electricity approaching 30%. Development of this system has continued over the past decades to reduce capital costs from 35,000 to 2,000 $/ kWh [32,33]. This system consists of several parts, a Reflector which is the thermal receiver; it is a solar parabolic dish to collect and concentrate the sun's rays at one point (Absorber), then a Stirling Engine, Control system and Electric Generator, as shown in Figure (1). There are several different types of these systems which differ from one industry to another [33,34,35].

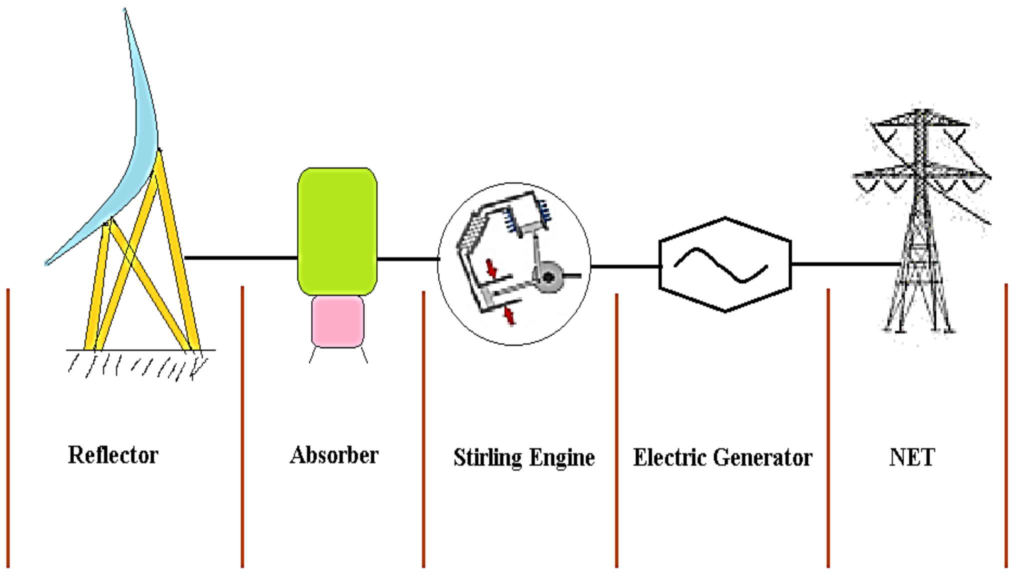

Figure 1: Stirling dish labor Mechanism.

Solar rays are collected at the focal point by the condenser in which the solar receiver is fixed

Then the large energy coming from the sun is collected as concentrated heat and converted into mechanical energy, as it works on adiabatic gas pressure inside the engine. The mechanical energy is then converted to electricity through an electric generator.

This energy-producing source is clean, gas emissions are almost non-existent, and it is a highly efficient system, as the condenser efficiency reaches more than 95% and that of the receiver is more than 65%. But with these specifications, the practical annual efficiency production of electricity does not reach 25%. In addition, the large motors are costly, and it is clear that they only operate in bright sunshine hours, so they are more profitable in sunny areas. Sizes and shapes of Stirling dish differ according to manufacturers, either in the parabolic single mirror form or of multiple mirror form up to 16 mirrors to take advantage of the porosity between the mirrors to avoid wind loads [36].

The area of the mirror is between 50 to 120 m^2, while the area required for the system, in general, is between 50 to 150 m^2, depending on project type, height is between 8 to 15 m, system weight is 2000 to more than 8,000 kg, focal length is 4 to 12 m, and interception factor is more than 90 %. As for Stirling engine, it contains 2 or 4 cylinders and uses either hydrogen or helium as working fluid inside the cylinders, as the rotations of these cylinders range from 800 to 2200 revolutions per minute so that the estimated output is approximately 8 to 25 kW, annual efficiency is between 14% to 25%, and annual energy ranges between 17 to 37 MWh. Production values vary according to the solar radiation in region. so that the production starts at 200 W/m^2 and reaches peak output at values more than 1000 W/m^2[33].
Table (4) shows details of all direct and indirect costs required to construct and install a Sterling dish system for the year 2020 and the expected costs for the year 2030.

Levelized cost of electricity has remained high when using these solar systems, as the cost of energy production by Stirling dish ranges from 0.2 to 0.36 $/kWh until 2014; these costs are reduced by up to 0.14 for excellent solar resources. This cost is expected to be reduced by 50% by 2025 [37].

Table 4: Direct and Indirect Cost for Stirling Dish Installation.

<table>
<tr><th colspan="5">Direct cost</th><th colspan="4">Indirect cost</th></tr>
<tr><th></th><th>Collector</th><th>Receiver</th><th>Stirling engine</th><th>Contingency</th><th>Engineering civil</th><th>Other cost</th><th colspan="2">O&M</th></tr>
<tr><td>2020</td><td>350-400 $/m²</td><td>220-250 $/kW</td><td>400-500 $/kW</td><td>10 %</td><td>10 %</td><td>3 %</td><td>35 $/kW.y</td><td rowspan="2">0.01-0.02 $/kWh</td></tr>
<tr><td>2030</td><td>250 $/m²</td><td>180 $/kW</td><td>350 $/kW</td><td>8 %</td><td>9 %</td><td>3 %</td><td>30 $/kW.y</td></tr>
<tr><td>Ref</td><td colspan="8">[33, 36,38, 39]</td></tr>
</table>

3.2.3. Power Tower System

The power tower system is one of the solar energy concentrating systems and it consists of several mirrors(about 500000), called Heliostats, installed in a circular arrangement to track the solar rays and focus them on the power tower positioned in the center of this grouping of Heliostats, where it receives sunlight and evaporates water and uses steam to move turbines to generate electricity. This process is called direct configuration. Or to heat a gas like air or CO_2 to drive a turbine like the Brayton or Rankin cycle [40].

Figure (2) shows the five systems which a power tower is installed, which are Collector system (Heliostats), receiving system (power tower), thermal storage is a thermal tank used to exchange energy, Steam generator, and electric power generator [41].

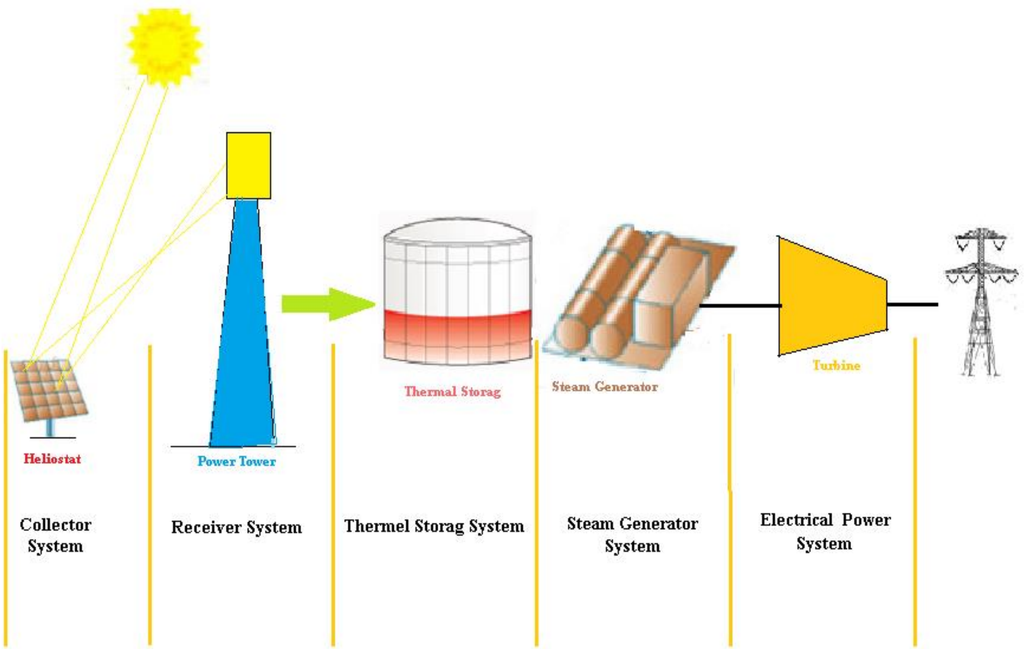

Figure 2: Power Tower System Installation

To know and evaluate the total cost of producing electricity from power tower systems, one must first detail total direct and indirect costs of constructing and installing the station, and total energy estimated to be produced during the lifetime assumed for station's production. The price of Heliostats is 200 $/m^2$ (2020), while Tower cost is 200 $/kW, Thermal storage costs from 30 to 20 $/kWh. As for Electric Generator, its cost is 1,000 $/kW, steam generator costs 350$/kW. Operating and maintenance costs are estimated at 65 $/kW per year in 2020 Indirect costs represent approximately 58% of direct costs and are percentages estimated from capital and investment costs[13,14]. Table (5) shows Power Tower Installation cost for 2020 and forecasting cost at 2030, where decreases are expected at different rates for each component of the Power Tower, ranging from 15 - more than 20%.

Table 5: Power Tower Installation Cost.

Year	Heliostat Field	Tower	Thermal Storage	Electric Generator	Steam Generator	O&M
2020	200$/m^2	200$/kW	30$/kW.y	1000$/kW	350$/kW	65$/kW.y
2030	100$/ m^2	150$/kW	20$/kW.y	800$/kW	250$/kW	50$/kW.y
Ref	[41-44]					

3.3. Tidal Energy

Tides phenomenon arises as a result of the exchange of attraction force between the earth and the moon, which leads to the appearance of deformation on the earth surface, some places are high for sea level and some are low, where the largest bulge of water mass is in the area closest to the moon, and another bulge is formed on another side of the land to maintain balance of gravity and shape Earth[45, 47].

Capital and installation costs of tidal turbines differ according to manufacturers, operating and installation costs. A significant reduction in these costs has been observed from 2010 until 2020, as capital costs decreased from 10,000 $/kW to 5,000 $/kW, due to the technological development in the manufacture and installation of these turbines. These costs are reduced whenever the production capacity is greater than 1000 MW. It should be noted that the cost of electricity production in these turbines is affected by sea waves height in addition to turbines generation efficiency. Tidal Barrage technology is characterized by low costs, whether capital, maintenance, or operation, as the capital costs are approximately 4400 $/kW and operation and maintenance are 50$/kW. However, this technology is not suitable for all areas depending on tide height and area terrain. Tidal stream shallow technology, installed at depths less than 50 m, costs 5260$/kW, and the operation and maintenance costs are 250$/kw. As for tidal stream deep technology, installed at depths of more than 50m, capital costs are 5420 $/kW, while operation and maintenance costs are 200 $/kW. Table (6) shows capital costs for installing high-capacity turbines, and other variables such as maintenance and operating costs, port activities, in addition to other costs through which electricity can be generated to cover the region's need for electricity.

Table 6: Cost Detail of Tidal Turbine.

Technology		Capital cost ($/kW)	O&M ($/kW/year)	Ref
Tidal Barrage		4400	50	[47]
Tidal Stream Shallow (<50m Depth)		4292-5260	250-310	[47, 48, 49]
Tidal Stream Deep (>50m Depth)		3460-5420	157-200	[47, 49]
Indirect cost	*License fee*	4% I_{nvs}		[50]
	Port activity	31% I_{nvs}		
	Other cost	12% I_{nvs}		

3.4. Biomass

Study of biomass types and methods of exploitation to produce energy for heating and electricity, a clear variation in capital costs, investment costs, maintenance, operation and fuel used, in addition to a difference in operating efficiency and capacity factor for electricity production can be noted. Table (7) shows the investment costs for each type studied in this research for the year 2020, as the lowest cost is 1460 $/kW in (Stocker Boiler) and the largest value of costs is 5700 $/kW in (Combined Heat and Power), in addition to expectations of a decrease in those prices between 18- 20% until 2030.

In order to study the costs of electricity production, the capacity factor for electricity production and operating and maintenance costs for each year must be known. A detailed study of the standard costs of electricity production for each type will be given.

Table 7: Detail Costs of Different Biomass Stations

Technology	2020	2030	Electricity		Ref
	Investment cost $/kW	**Investment cost $/kW**	**Capacity Factor %**	**O&M %**	

		Min	Max	Min	Max	Min	Max	per year	
Stocker Boiler		1860	4260	1630	3120	23	33.9	2	[51, 52]
Gasification	*Updraft Fixed Bed*	1800	3820	1440	3250	18	39	2	[51,52, 53, 54]
	Downdraft Fixed Bed	2000	5500	1600	4400	17	38	3	
	Bubbling Fluidized Bed	1600	4750	1500	3800	24	33	3	
	Circulating Fluidized Bed	1945	4500	1200	2300	32	41	3	
Combined Heat and Power		3000	5700	3920	4560	16	36	5	[51,52]
Landfill		1660	2100	1480	1900	26	32	12	[51]
Digester		2574	6104	1650	3820	25	33	7	[51, 55]

3.5. Hydroelectric System

Since hydroelectric system depends on pumping and flowing water, this system needs a portion of the electricity generated from renewable sources in the off-peak period to operate the pump. The pump raises water to a high tank to be stored for use in the peak period and to move a water turbine that generates electricity as a hybrid system. Thus, electricity can be generated and stored in a renewable, clean, and hybrid system, Figure (3).

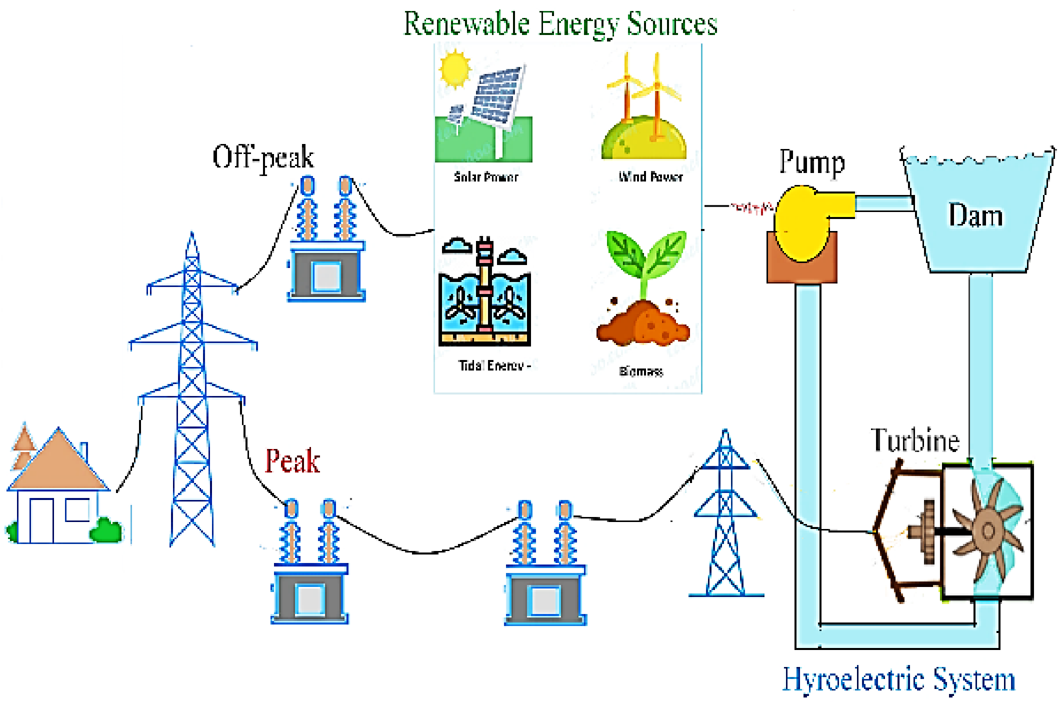

Figure 3: Storage by Hydroelectric System.

Economic Hydroelectric system consists of a reservoir of a cost rate between 26-32.2% of the system total cost, Tunnel at a rate of 5.1-14%, the largest percentage is of the power house, which has a ratio between 30-33.3%, while engineering and construction range between 7-14.6% and the cost of owner cost is 13.9-23%.

Table (8) shows the total cost of the Hydroelectric project, which shows the costs according to the production capacity (Less 1 MW, 1-10 MW, more 10 MW), the range of Investment costs, Operation and Maintenance costs, Lifetime, Efficiency and electrical Capacity Factor.

Table 8: Details of Total cost of the Hydroelectric Project.

Descriptions	Less 1 MW	1-10 MW	More 10 MW	Unit	Ref
Investment cost	2500.- 10000	2000–7500	1750– 6250	$/kW	[56,57]
O&M	1.5– 6.5	1.8-2	1.5–2.8	% I_{nvs}	[11, 57,58]
	50– 270	20– 60	20– 270	$/kW/year	[11, 57]
Lifetime	More 30	More 30	More 30	Years	[58]
Efficiency	92	92	92	%	[57]
Capacity Factor	40 – 60	34 – 56	34 – 56	%	[58]

3.6. Hydrogen System

Figure (4) shows the storage method using the Hydrogen system produced by electrolysis of water. This system is clean and results in only oxygen and water. It is one of the best systems that can constitute a scientific revolution in the field of energy production and storage. In this study, Proton Exchange Membrane (PEM) system analysis method is used to produce high purity hydrogen, study the best economical hydrogen storage, transportation methods, and finally electricity is produced when needed using fuel cells.

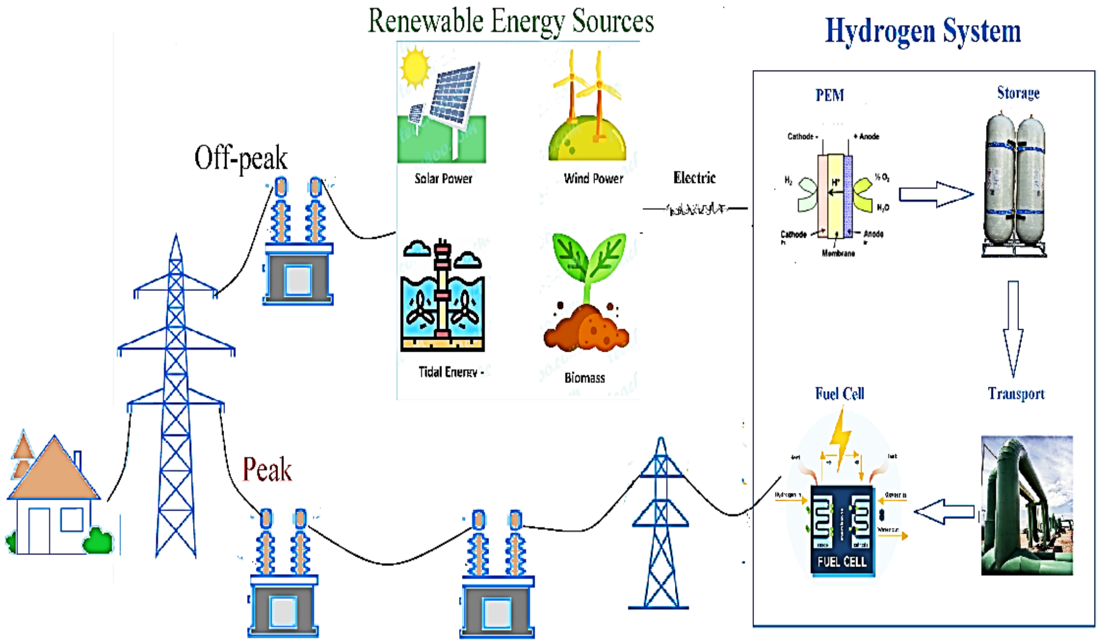

Figure 4: Storage by Hydrogen System.

*3.6.1. Proton Exchange Membrane (*PEM*) Technology*

Proton exchange membrane (PEM) technology only needs to supply water and electricity to the process of producing electricity under different temperatures. Table (9) shows all the technical and economic details of this system.

Table 9: Technical Economic Detail for PEM Technology.

Data	Description	Unit	Ref
Electrolysis Type	**PEM**		

Materials	Electricity + Water		[59]
Operation Temperature	70-80	^0C	[59, 60]
Efficiency	65-76	%	[61]
Purity	99.99 %	%	[13]
Capital cost	700-1400	$/kW	[61, 62]
Installation cost	10-12	$\%I_{nvs}$	[63]
Energy consumption	50	kWh/kg	[63,64]
Compressor and rectifier	170	$/kW	[65]
Lifetime	7-10	years	[63]
	50,000 - 90,000	hours	[63]
O&M	15-45	$/kWyear	[64, 66]
	1.5-5	$\%I_{nvs}$	[63, 67]
Operation Time	8300- 8600	Hour/Year	[61]

3.6.2. Hydrogen Storage

There are different methods for storing hydrogen depending on stored hydrogen state, Solid, Liquid or Gaseous. Storage costs are also different according to the situation and the energy consumed for storage, but the cheapest methods are compressed gas stored in tanks, pipes or underground. This research focuses on using compressed gas storage because it is the cheapest method.

The compressed gas storage method is considered the most economical, as storage costs in cylinders reach from 0.21 to 0.6 $/ kg, and more than 4.25 $/ kg for pipes for one day. But for longer periods, which range from 30 days, the costs reach from 1 to 5 $/kg; as for pipes, they are more than 7 $/kg [43]. While maintenance and operating costs range from 0.1 to 0.5 $/ kg, and other costs 0.1 to 0.3 $/ kg[68]. In 2020, the capital costs became low, equal to 0.2 $/kg for 30-day storage, and there are no significant differences in other costs, Table (10).

Table 10: Costs of Storing Hydrogen as a Compressed Gas

Time	1 Day		30 Day		Ref
Description	**Cylinders $/kg**	**Pipes $/kg**	**Cylinder $/kg**	**Pipes $/kg**	
Capital Costs	0.21-0.6	More 4.25	1-5	More 7	[43]
O&M	0.1-0.5	0.1-1	0.1-0.5	0.1-1	[68]
Other Cost	0.1-0.2	0.1-0.3	0.1-0.2	0.1-0.3	[68]

3.6.3. Underground Compressed Gas Storage

underground gas storage systems are the most appropriate and the best for large quantities if hydrogen is to be stored for long periods. The capital costs for these are estimated from 2 to 11 $/ kg, which is a low value if it is estimated with previous means because this method enables preservation for several months with high efficiency. In the short term, the cost is not more than 0.2 $/ kg [43,69].

3.6.4. Hydrogen Transportation

Tube trailers, pipelines or pressurized cylinders are used for the transportation of compressed gas. High pressure, between 200-300 bar, is applied to the gas to increase the carrying capacity of the tanks or cylinders[70]. Cylinders are a very expensive technology because their carrying capacity is low. While, tube trailers, which are composed of several steel cylinders, have a capacity between 36-460 kg of hydrogen. As for pipelines transportation, a pressure of 10-30 bar is applied so that hydrogen flows with an amount of approximately 300-9000 kg/hour, as is the case in Germany, France, Belgium and the United States of America[70,71].

Transportation costs by tube trailer vary according to the applied pressure and delivery distance; however, these costs can be reduced by lower capital costs. The costs of a trailer containing between 180-460 kg range from 100,000 to 360,000 $, Table (11).

Table 11: Hydrogen Transportation Cost with Hydrogen Capacity/Size kg.

Descriptions	Cost	Unit	Size kg	Ref
Tube Truck	100000 - 150000	$	180 - 300	[70, 72, 73]
Truck Liquid	350000 - 650000	$	4,080	
Metal Hydride	2200	$/kW	454	
Truck Undercarriage	60000	$	Less 400	
Truck Cab	90000	$	Less 400	
Rail Undercarriage	60000 - 100000	$	-	
Ship Liquid Unit	350000	$	4,080	
Pipeline Cost	620000	$	-	
Compressor Cost	1000	$/kW	-	

3.6.5. Fuel Cells

Fuel cells that operate by cathode, anode and proton exchange membrane are one of the best ways to electricity production from hydrogen with high efficiency from 40% to 60% at temperatures up to 800C. According to manufacturers, there is a big difference between the prices of fuel cells, as costs range between 1150 to 8,500 $/kW[43]. The price of electricity produced from these cells differs according to their efficiency and capital costs, as LCOE amounted to between 0.07 to 0.3 $/kWh. In 2020, the cost of producing hydrogen by fuel cells was about 4 to 5 $/kg. Table (12) shows cost detail of fuel cells (for 2020) [59].

Table 12: Cost Detail of Fuel Cell

Parameters	Unite	Cost	Ref
Capital cost	$/kW	1100	[59]
Temperature	0C	70-80	[74]
Efficacity	%	40-60	[43, 74]
O&M	%	30	[75]
	$/kWyear	20-50	[76]

Other cost	%	10	[75]
lifetime	year	10	[43]
Control and communication	$/kw	1-1.7	[77]
Grid integration	$/kw	15-22	[77]
Inverter	$/kw	41-7	[77]

4. Result and Discussion

The amount of electricity consumption in a region and the time distribution of electricity consumption must be known in order to obtain accurate results for the use and investment of renewable energy sources. In addition, the peak and off-peak periods must also be known to know the periods during which electricity can be stored and the periods during which the stored electricity is used to cover the region with the electricity needed.

According to this information, the installation costs according to needs, the required equipment, and the efficiency of the renewable sources can be calculated. This is studied in detail. As was mentioned, wind, solar, tides and biomass will be used as sources, and hydroelectric and hydrogen will be used as storage methods.

4.1. Peak and Off-peak period for Electricity Consumption in Socotra

Following the hourly daily consumption, it was found that the peak period of up to 12 hours consumes a larger amount than the average daily consumption, which reaches 55,000 kWh. Figure (5) shows electricity consumption during 24 Hour in Socotra island, where the red lines symbolize the peak period. A slight rise at eight and nine in the morning is noticed, as well as between hours 12 noon until five in the afternoon, then the peak of use begins between six in the evening until nine in the night, when it begins to decrease from ten until seven in the morning, with a slight decrease from 10 and 11 in the morning.

The off-peak period can be used to store electricity, as it is a long period and provides a large amount of energy for a 12-hour period. The off-peak period reaches 55% of the daily energy production period. Thus, the off-peak period is used for electricity storage, which is used to cover the electricity needed during the peak period.

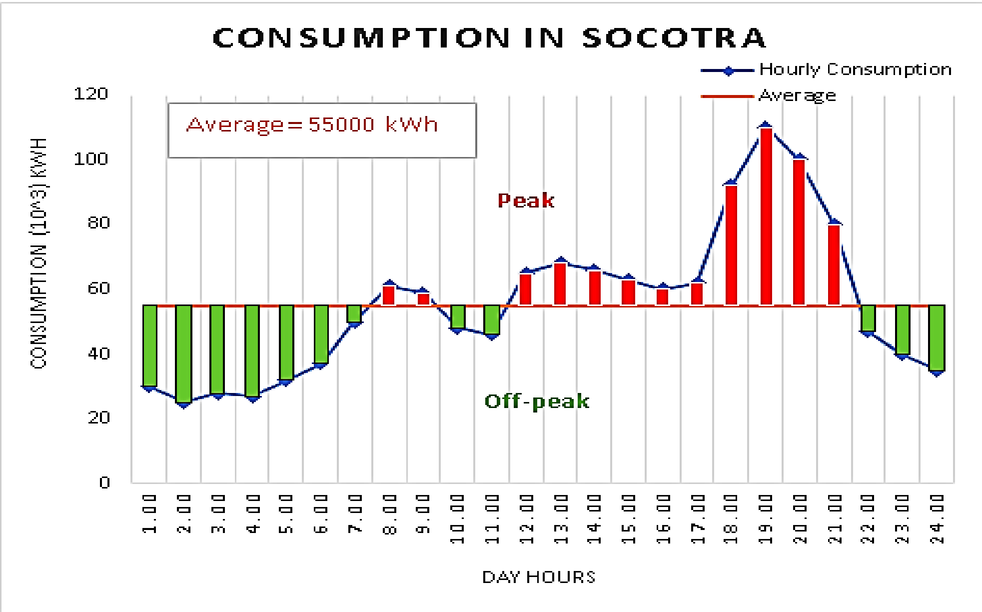

Figure 5: Electricity Consumption in Socotra.

4.2. Wind Energy

4.2.1. Wind Information

Information obtained from Yemeni meteorology shows that the average wind speed studied for nine years from 2006 to 2014 reached 9.5 m/s, which is a great value that enables the production of electricity by turbines with high efficiency. Figure (6) shows the average monthly changes in wind speed for nine years. The wind speeds in January (8.3 m/s), wind speed decreases in February to 6.8 m/s, in March to 5.6 m/s, in April to 4.3 m/s, and in May the wind speed is 6.64 m/s. It start to rise dramatically from June reaching 14 m/s, and in July it is 17.22 m/s, which is the maximum value of wind speed among all months, in August 15.9 m/s, in September 11.04 m/s, October 5.65 m/s, November 5.56 m/s and later in December 7.91 m/s, these values are very encouraging to exploit this source to produce electricity to cover the region's need.

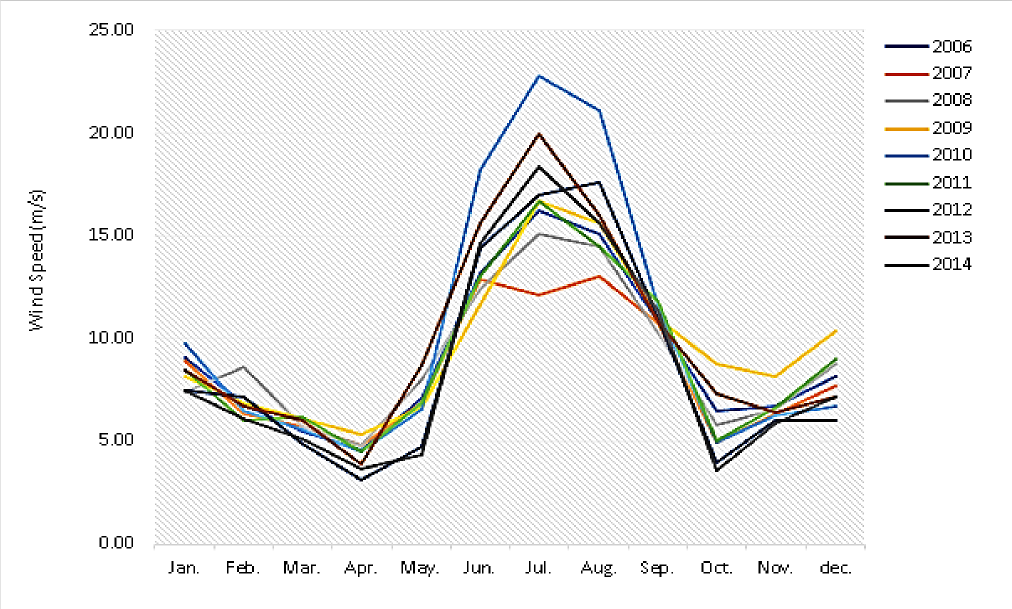

Figure 6: Mean Wind Speed for 9 years in Socotra Island.

4.2.2. Wind Distributions

Figures (7) show the statistical distribution of wind speed according to the application of Weibull and Rayleigh distribution functions, which enables us to know the annual distributions of speed for 2014. The probability of the monthly wind speed density distribution can also be observed in Figure (9, c, d), which is essential information for studying wind efficiency when using wind turbines.

Table (13) shows all details of power, annual energy produced, and capacity factor for each turbine, in addition to the number of turbines to be used with different capacities (1-1.5-2-6) MW, average speeds at these altitudes, and Weibull parameters k and c for different towers heights (65-80-100-120 -140) m.

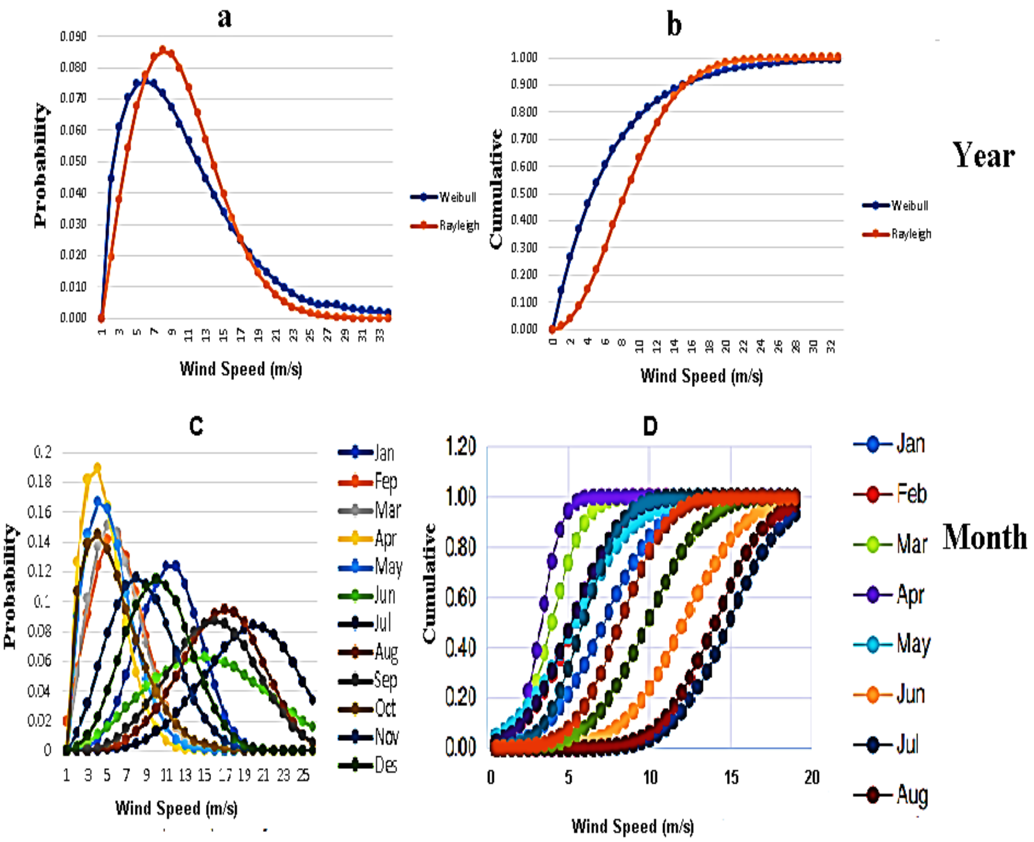

Figure 7: Probability and Cumulative Distributions by Weibull and Rayleigh function

Table 13: Details of Power, Annual Energy Produced, and Capacity Factor for Wind Turbines.

Height (m)	Turbines Power (MW)	Average Power (kW)	Annual Energy (MWh)	Capacity Factor (%)	Turbine No	v_m (m/s)	k (m/s)	c
65	1	562.9	4930.6	56.3	5	11.36	13.04	1.63
	1.5	831.4	7282.8	55.4	4			
	2	980.8	8592.1	49	3			
80	1	825.7	7233.3	55	5	11.98	13.43	1.63
	1.5	830	7271.2	55.3	4			
	2	981	8594	49.1	3			

100	1	558.7	4893.8	55.9	5	12.37	13.87	1.63
	1.5	825.7	7233.3	55	4			
	2	977.9	8566	48.9	3			
	6	2302	20127	38.4	1			
120	6	2316	20293	38.6	1	12.6	14.1	1.63
140	6	2328.7	20340	38.8	1	12.81	14.5	1.63
LCOE ($/kWh)	1MW = 0.085		1.5MW = 0.079		2MW = 0.092		6MW = 0.12	

4.3. Solar Energy

Socotra Island has Direct Normal Irradiation (DNI) that varies on its surface according to the terrain; it is between 1300-1900 kWh/m^2. While, the Global Horizontal Irradiation (GHI) is between 1900-2300 kWh/m^2. Temperature varies according to season, but it has an average of 25 ° C and reaches 38 ° C in the summer and drops to 13 ° C in winter. The average period of solar radiation during the day is approximately 12 hours, a period that enables the exploitation of solar energy by about 4440 hours per year. Figure (8) shows all solar factors of Socotra Island inferred by applications such as Motonorm and Global Solar Radiation website.

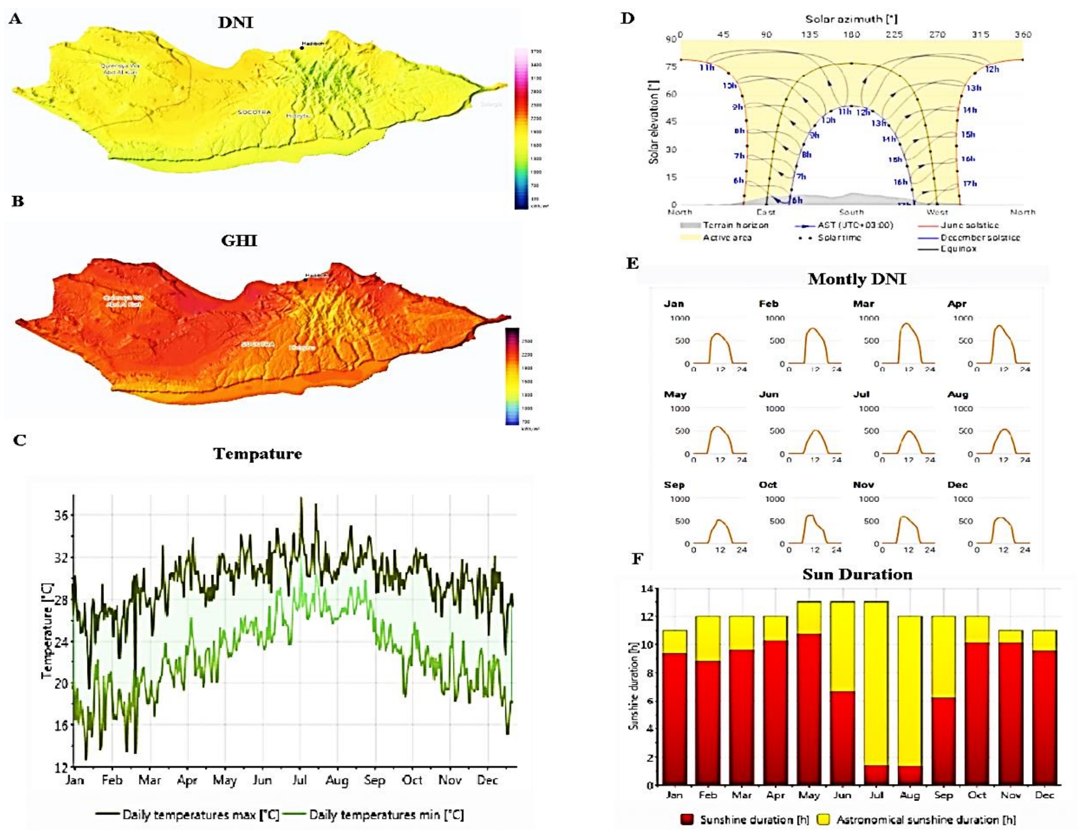

Figure 8: DNI, GHI, Temperature, Solar Azimuth, and Sunshine Duration, in Socotra Island Yemen.

4.3.1. Photovoltaic Panel

Since the Capacity Factor of photovoltaic panels is 21%, 1 kW will generate approximately 1840 kWh per year. Thus, approximately 10872 kW need to be installed to meet the needs of the region. So, if interest rate is 5%, LCOE will be equal to 0.12 $/kW. Table (14) shows costs details for capital costs, which amount to 63% of project total cost, converter 25%, operation and maintenance 8%, while other costs are 5%.

Table 14: PV System Information

Detail	Cost	Unite
Capital Cost	0.075	$/kWh
Converter	0.03	$/kWh
O&M	0.01	$/kWh
Other Cost	0.005	$/kWh
LCOE	0.12	$/kWh

According to the follow-up of prices and their decline over the past ten years, it is expected that the cost of the photovoltaic system will decrease by 20% so that the LCOE is less than 0.08 $/kWh.

4.3.2. Stirling Dish

Production values of Stirling dish vary according to the region and the amount of direct normal solar irradiance in the area so that the production starts at 200 W/m^2 and reach peak output at values more than 1000 W/m^2 [31].

By investigating and researching different types and companies, it has been concluded that the average investment costs for a Stirling dish are about 2000 $/kW for the year 2020 (wholesale), and they have decreased dramatically since 2015 when the cost reached more than 3000 $/kW[34]. As for the other costs, their percentage was calculated according to what is applied in large companies, as installation costs are 20%, civil engineering 23%, contingency cost 10%, and operation and maintenance 3%, as shown in Table (15), the total cost is 3120 $/kW, By applying Equation (1), the standard cost of electricity using a Stirling dish was calculated to be equal to 0.1 without storage system. The value of LCOE is expected to decrease to 0.08 by 2030.

Table 15: Detail Cost of Stirling Dish

Type		Cost	Unite
Investment	It	2000	$/kW
Installation	20% It	400	$/kW
Civil engineering	23% It	460	$/kW
Contingency	10% It	200	$/kW
Operation and maintenance	3% It	60	$/kW
Lifetime		20	Years
Interest Rate		5	%
CRF		0.08	
Capacity Factor		28	%
Total cost		3120	$/kW

LCOE	0.1	$/kWh

Figure (9) shows the detailed LCOE value for all the transactions that Stirling Dish project is installed from. It is clear that the investment cost for 2020 were between 0.04 to 0.062 $/kWh, while the installation cost was about 0.0095 to 0.015 $/kWh, and civil engineering was 0.01. To 0.015 $/kWh, contingency 0.005 to 0.008 $/kWh, operation and maintenance less than 0.005 $/kW, and it is noted that 2030 will witness a decrease in those values, making these sources one of the best competing sources for energy production in the near future.

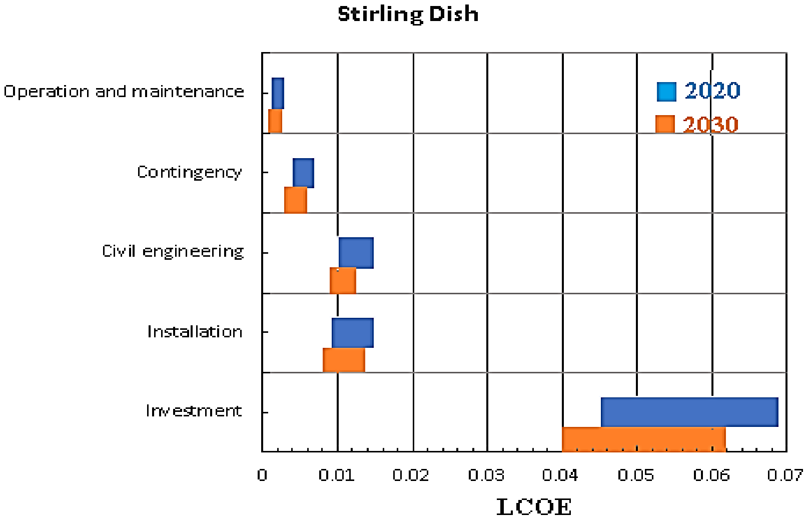

Figure 9: Detail of LCOE for Stirling Dish project.

4.3.3. Power Tower System

When using Power Tower system, the direct cost is more than $120 million and the installation cost is $125 million.

Figure (10) illustrates the method of arranging heliostats around the power tower. It also shows the total efficiency of the station's performance as a whole, which reaches 62.8%. Receiver circumferential position received an average value of 630.6 kW/m^2, maximum value received by station is 884.9 KW/m^2, and the minimum value is 103.2 KW/m^2.

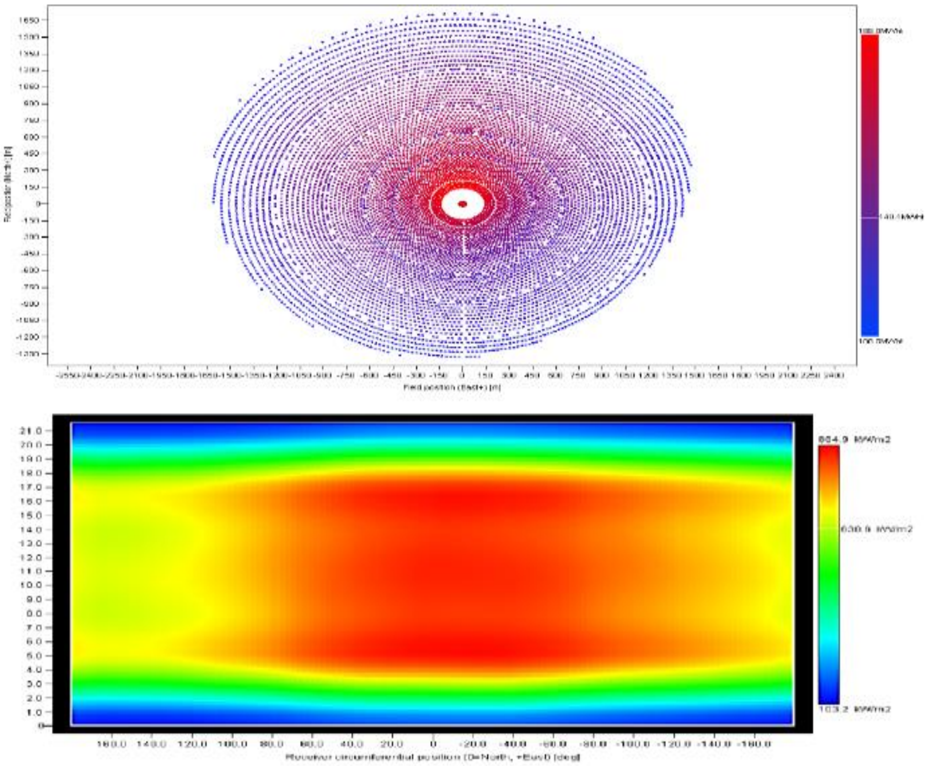

Figure 10: Receiver Circumferential Position. Heliostat position around of Power Tower

Table (16) shows that the cost of electricity produced from the power tower is low due to the high efficiency of the system for producing electricity and capacity factor, which is more than 40%.

Table 16: Detail Cost of Power Tower System

Type		Cost	Unite
Investment	It	4000	$/kW
Installation	20% It	800	$/kW
Civil engineering	23% It	920	$/kW
Contingency	10% It	400	$/kW
Operation and maintenance	5% It	200	$/kW
Lifetime		20	Years
Interest Rate		6	%
CRF		0.087	
Capacity Factor		70	%
Total cost		6280	$/kW
LCOE		0.09	$/kWh

Power Towers are considered the best in investment cost, as their value ranges between 0.04 to 0.063 $/kWh, while, the cost of both civil engineering and installation converges, so that it is between 0.009 and 0.013 $/kWh, and the operating and maintenance values reach 0.005 $/kWh, and projections of lower costs to 2030, as shown in the Figure (11).

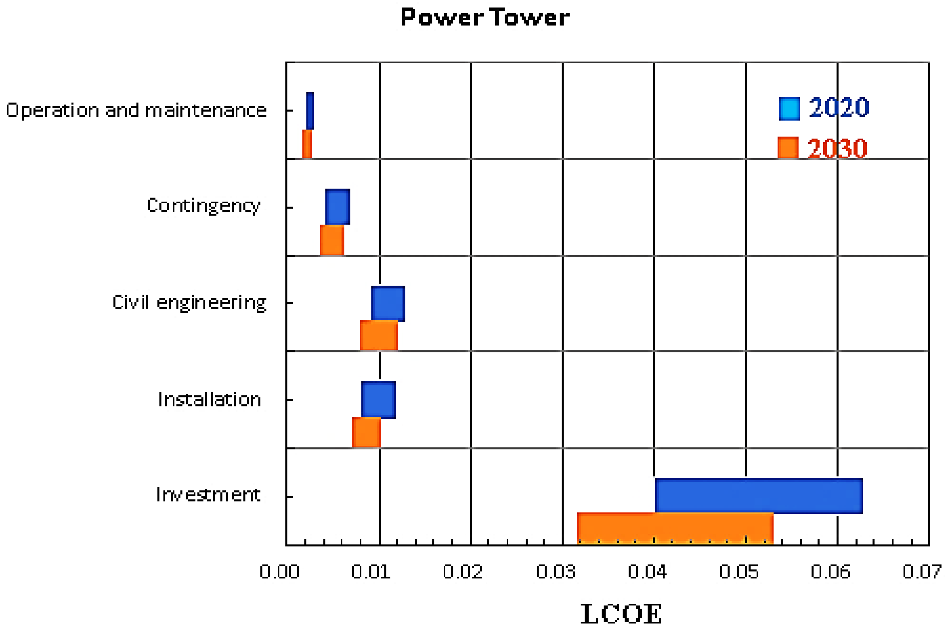

Figure 11: Detail of LCOE for Power Tower System.

Note: Power Tower project cannot be applied on Socotra island, as its terrain is mountainous and its area is small, it is not possible to install this system, which requires a flat land and a large area of approximately 1263135.1 m^2.

4.4. Tidal

All information about tides state of Socotra island shows that it can be used to produce electrical energy, but with low efficiency, of 25%, because tides do not reach great heights of up to 5 m except in some months (July and August), Figure (12). However, electricity can be generated using modern electricity generation technologies that have the potential to exploit low tides.

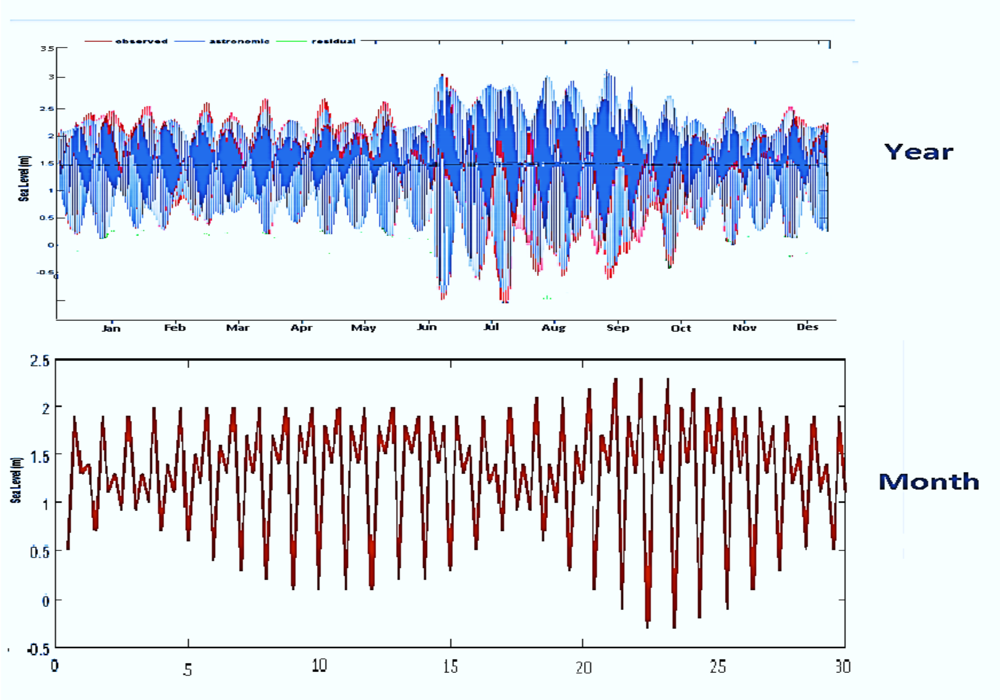

Figure 12: Tidal level in Socotra Island.

Table (17) shows the value of LCOE for all tidal system parameters. It is noted that the total cost of electricity production in this system costs 0.25 $/kWh, which is a relatively large cost compared to other renewable energy sources.

Table 17: LCOE Detail for Tidal System in Socotra.

Parameters	Cost	Unite
Capital Cost	0.11	$/kWh
O&M	0.055	$/kWh
Other cost	0.01	$/kWh
License fee	0.0044	$/kWh
Port activity	0.035	$/kWh
Capacity Factor	25	%
LCOE	0.25	$/kWh

Figure (13) shows the decrease in the cost of electrical energy between 2020 and 2030, a decrease of approximately 20% is noted. This possibility has been studied in comparison with the natural decrease resulting from industry development during the past years.

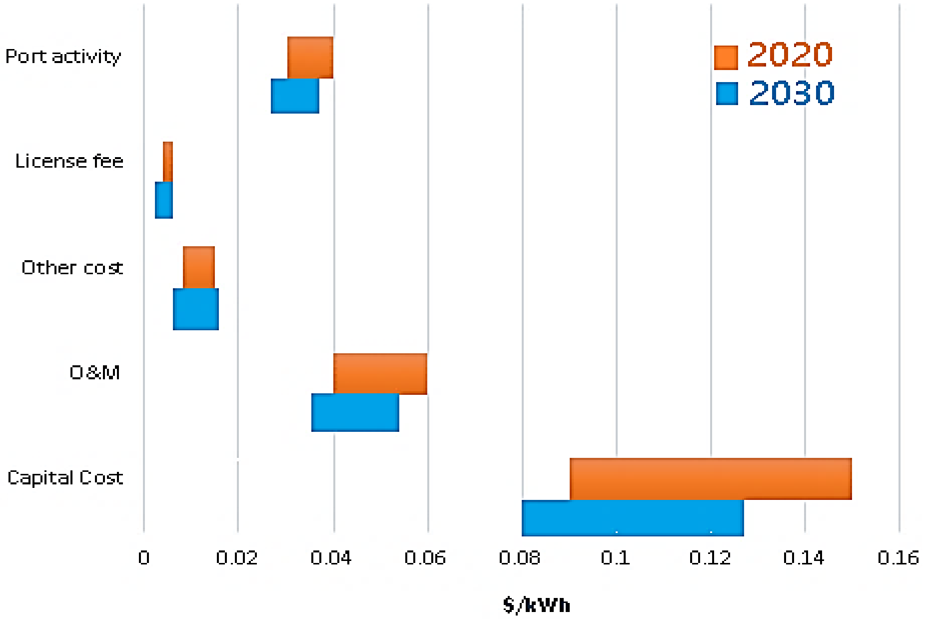

Figure 13: LCOE Difference between 2020 and 2030 for Tidal System.

4.5. Biomass

Daily waste production in Yemen is estimated to be 0.55-0.65 kg per capita in urban areas and 0.4-0.3 kg per capita in rural areas, with an expected annual increase due to the internal flow of 3% and the increase in the level of urbanization. On average, waste collection rates are 65% in major cities and 5% in rural areas. (Sweep-Net 2010-2014).

The percentage of waste production varies between cities and rural areas in Yemen, where the largest waste production was recorded in Sana'a, followed by Aden. The waste components varied between organic materials, paper, metals and plastic, as shown in Figure (14)[75].

LCOE values vary according to systems parameters used. Figures (19) show the costs of those parameters for each studied system. While Figure (15) shows the comparison of LCOE values for biomass systems for 2020, and the expected decline until 2030.

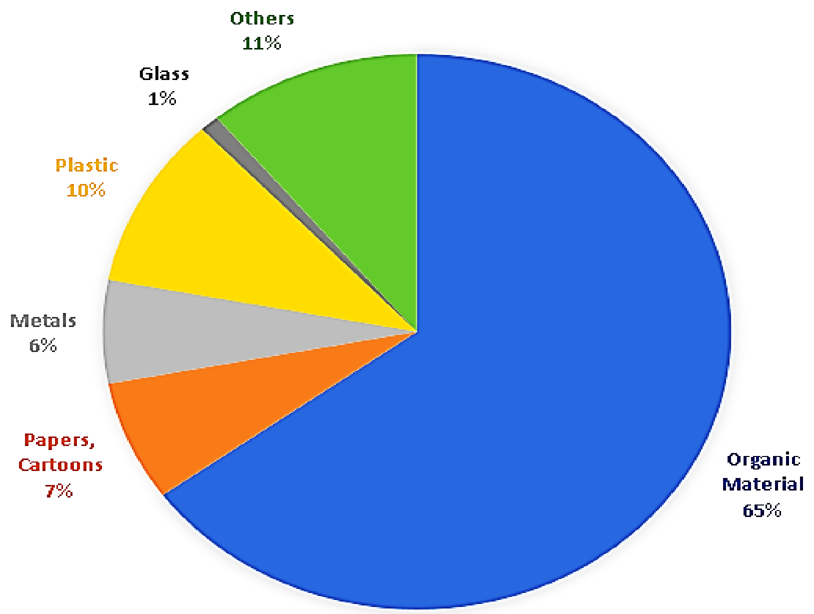

Figure 14: Percentage of Waste Production in Yemen.

Since Socotra island has a population density of about 80,000 people with a capacity of 20,000 MW, a factory with a power between 8000-12000 kW, depending on capacity factor, is needed to be installed. It should be noted that the calculated costs did not include the costs of purchasing feedstock, because these studied costs are considered only for a stock of the free biomass present in region, which can be exploited to produce electricity for the next twenty years.

Table (18) shows LCOE values for each technology used in biomass, which has a cost between 0.05 to 0.25 $/kWh.

Table 18: LCOE for Biomass Systems.

	Technology	Cost	Unit
LCOE	*Stocker Boiler*	0.05-0.2	$/kWh
	Gasification	0.06-0.2	$/kWh
	CHP	0.07-0.25	$/kWh
	Landfill	0.08-0.12	$/kWh
	Digester	0.08-0.12	$/kWh

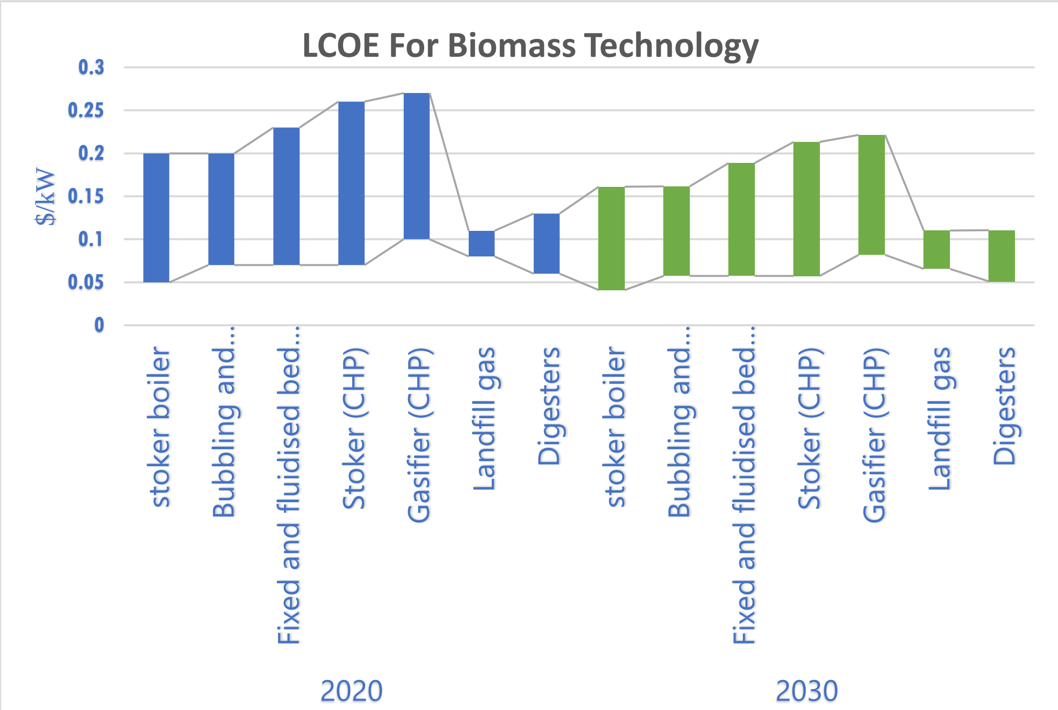

Figure 15: Expected Decrease in LCOE until 2030.

4.6. Hydroelectric system

Following up on the daily consumption of Socotra Island, it was found that the off-peak period can be used to operate the pumps to push suitable quantities of water to a high reservoir, where the stored quantity is discharged during the peak period. Figure (16) shows the periods of charge and discharge of the reservoir per day according to the peak and off-peak periods.

An economic study of hydroelectric system shows that the cost is low compared to production efficiency and the long life of this wonderful storage project. Applying LCOE equation, it was found that the investment cost is 0.0408 $/kWh, operation and maintenance is 0.0012 $/kWh, and the rest of other costs are about 0.0008 $/kWh. The total electricity generated from this storage system is 0.0428 $/kWh, Table (19). This storage value is added to the cost of electricity from the renewable source used, and by knowing the system prices studied, it was found that the costs expressed in Figure (17) give the cost range for all hybrid sources. A hybrid system can be used in the form of (Source-Hydroelectric) or a hybrid system from (Source-Source-Hydroelectric). Table (20) shows LCOE Details for Hydroelectric System. It can be noted that they are low-cost compared to the current price of electricity in Yemen, especially during the peak period when the price of electricity exceeds 0.3 $/kWh. The cost of the hydroelectric system may decrease by up to 10% of the current cost during the next ten years.

Table 19: LCOE Details for Hydroelectric System.

Description	Cost	Unit
Investment costs	0.0408	**$/kWh**
O&M	0.0012	**$/kWh**
Other cost`s	0.0008	**$/kWh**
Total	0.0428	**$/kWh**

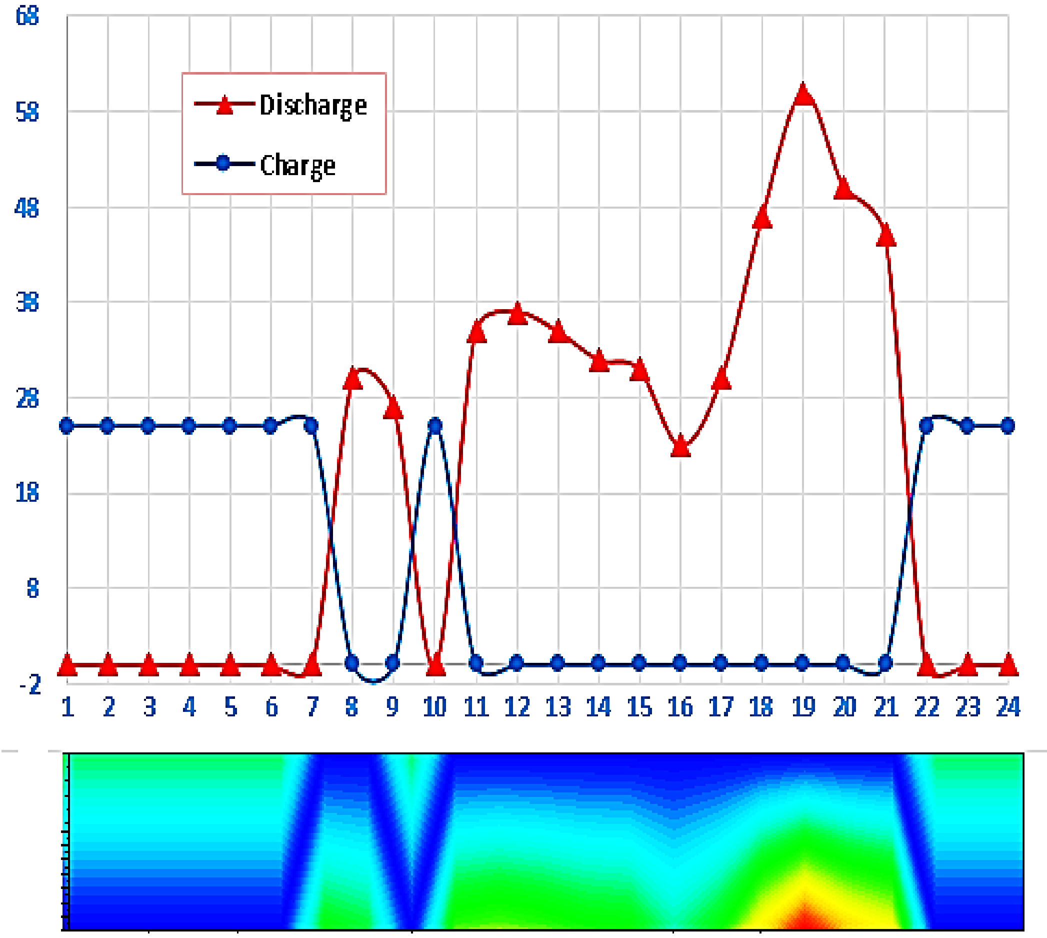

Figure 16: Periods of Charge and Discharge of Dam per Day.

Table 20: LCOE for (Renewable sources – Hydroelectric) Hybrid System.

Hybrid System	LCOE ($/kWh)
Wind - Hydroelectric	0.126
Solar - Hydroelectric	0.143
Biomass - Hydroelectric	0.13
Tidal - Hydroelectric	0.273
Wind - Solar - Hydroelectric	0.135
Wind - Biomass - Hydroelectric	0.128
Wind - Tidal -Hydroelectric	0.2
Solar - Biomass - Hydroelectric	0.137
Solar - Tidal - Hydroelectric	0.208
Biomass – Tidal - Hydroelectric	0.202

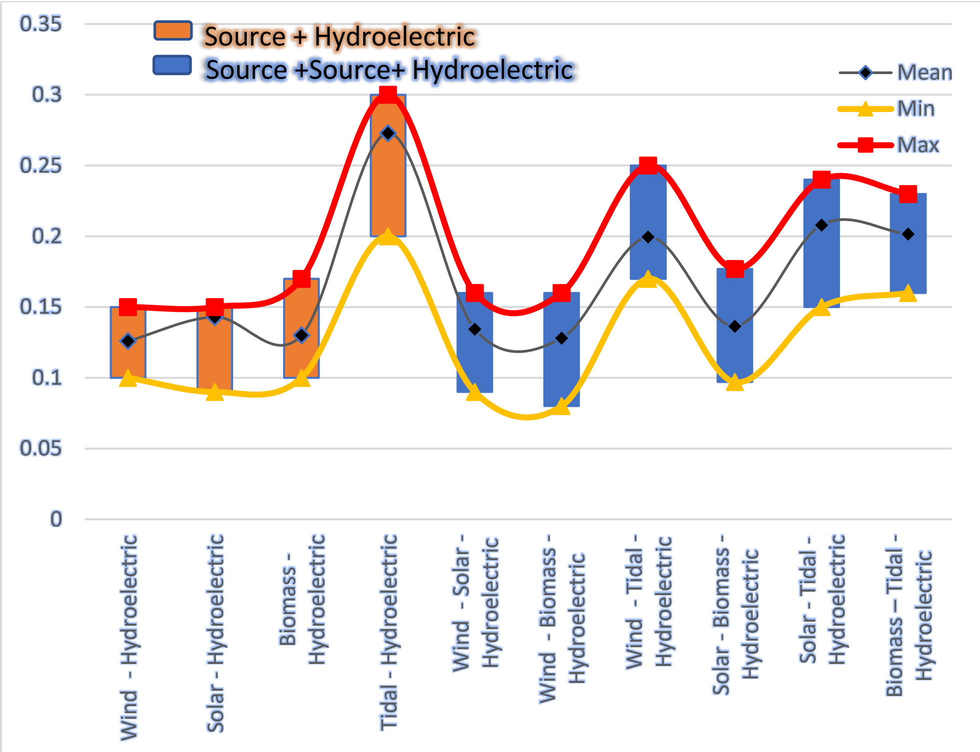

Figure 17: LCOE for (Renewable sources – Hydroelectric) Hybrid System.

4.7. 6. Hydrogen

Knowing the cost and the values , which appear in Tables 9, 10, 11, and 12, and applying the equation of total cost to total energy production in a lifetime (20 years), the results shown in Table (21) for mean cost value can be obtained.

Table 21: LCOE for all Hydrogen Production Stages

Input	Cost	Unit
Electrolysis	0.021	$/kWh
Storage	0.018	$/kWh
Fuel cell	0.012	$/kWh
Other	0.003	$/kWh
Transport	0.014	$/kWh
Total cost without transport	0.054	$/kWh
Total cost with transport	0.068	$/kWh

Figure (18) shows the standard cost of producing electricity by hydrogen station component, which gives a breakdown of the possible maximum and minimum values, in addition to the expected average values for every hydrogen station component (electrolysis, storage, fuel cell, transport, other cost). Figure (19) shows LCOE by hydrogen with transport and without transport.

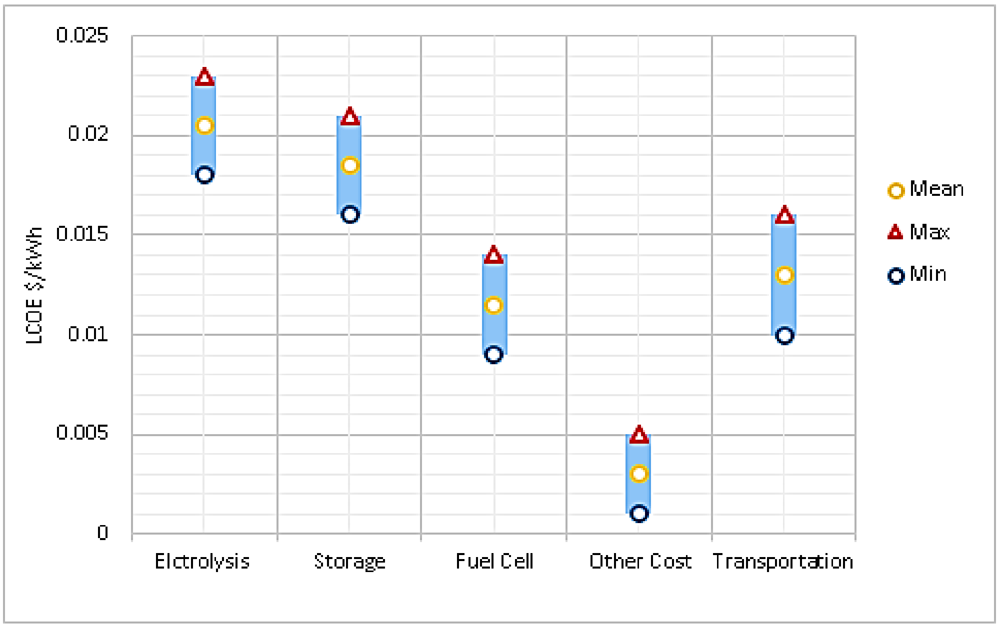

Figure 18: LCOE for every hydrogen station component.

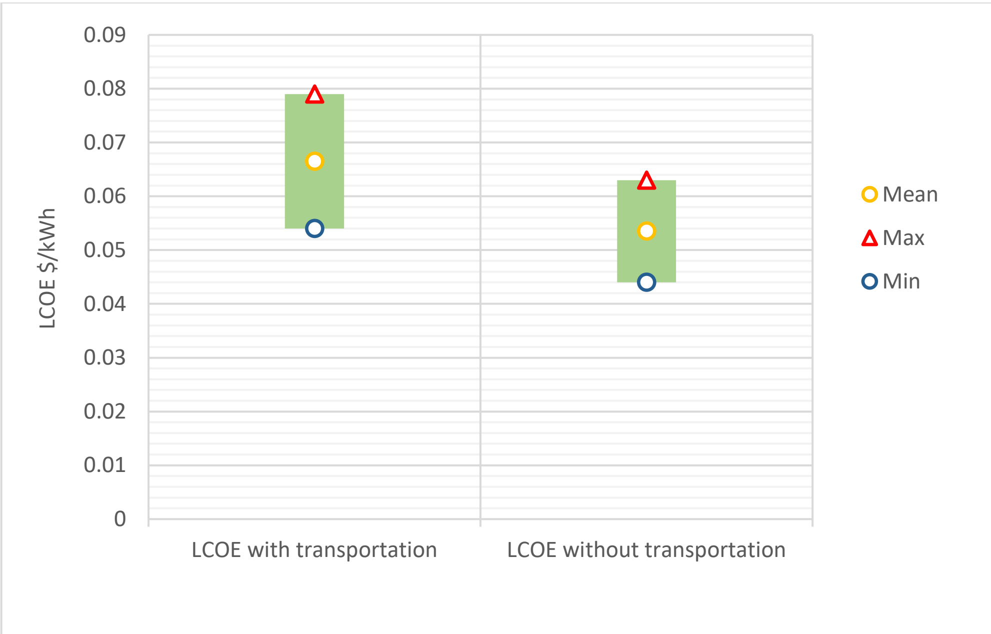

Figure 19: LCOE by Hydrogen System with Transport and without Transport.

4.8. Hybrid system (Renewable Energy Sources – Hydrogen)

It is normal to store the energy of renewable sources, as it was mentioned previously. When applying a renewable energy storage system by producing hydrogen, the cost of producing and storing hydrogen is added to the estimated standard value of electricity when using hydrogen to help those sources, especially during the period of peak use or in the case of a weak natural source of energy, whether wind energy, solar energy, tidal energy and biomass. Figure (20) shows the standard cost of the hybrid system consisting of renewable energy sources. By observing Figure (20), it is found that (wind - hydrogen) system has a cost between 0.118 - 0.17 $/kWh, and (Solar - Hydrogen)) is 0.125 - 0.2 $/kWh, (Biomass - Hydrogen) is 0.125 - 0.175 $/kWh, while the cost of electricity via the (Tidal - Hydrogen) system is 0.245 - 0.33 $/kWh and is the largest among the studied renewable energy sources. As for the three-hybrid system, from two sources of renewable energy and storage by hydrogen, it is noted that these values are low and reasonable within the global energy market, Table (22). The expected values of the standard cost of electricity from these hybrid systems for the year 2030 are estimated. It is noted that the prices will decrease by 18-20% of the costs in 2020.

Table 22: LCOE for Hybrid System.

Hybrid	Cost ($/kWh)
Wind Energy - Hydrogen	0.118 - 0.17
Solar Energy – Hydrogen	0.125 - 0.2
Biomass - Hydrogen	0.125 - 0.175
Tidal - Hydrogen	0.245 - 0.33
Wind Energy - Solar Energy- Hydrogen	0.121- 0.19
Wind Energy - Biomass - Hydrogen	0.121 – 0.172
Wind Energy - Tidal - Hydrogen	0.181 – 0.25
Solar Energy- Biomass - Hydrogen	0.125 – 0.19
Solar Energy- Tidal - Hydrogen	0.187 – 0.265
Biomass – Tidal - Hydrogen	0.185 – 0.252

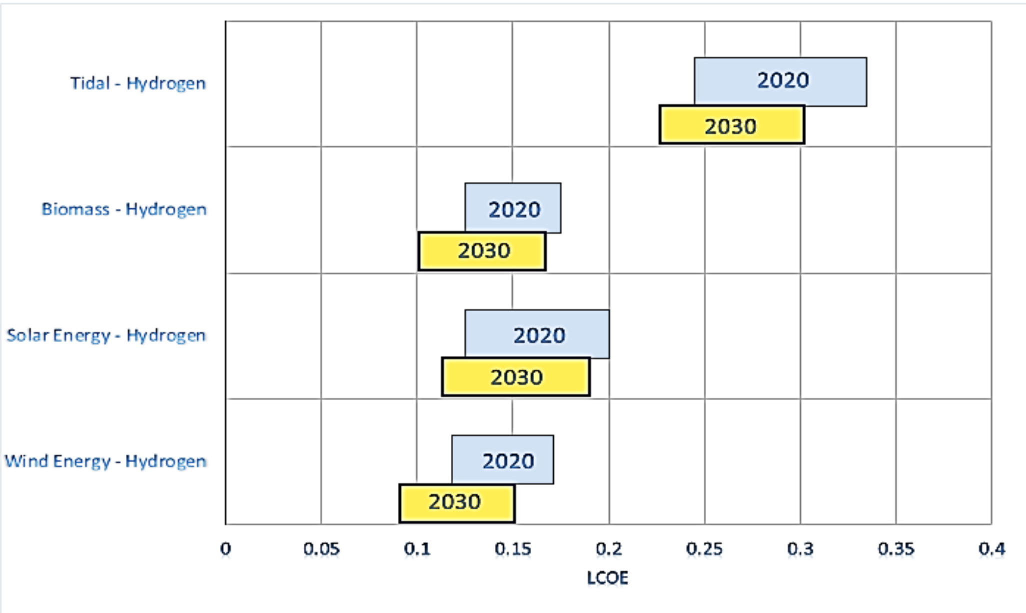

Figure 20: LCOE forecasting between 2020 to 2030

It is evident that the price of hydrogen produced varies according to the electric source used for hydrogen production and storage. Figure (21) shows the prices of hydrogen from different renewable sources. It was found that the highest price of hydrogen is in the case of using a tidal source of electricity due to the high price of electricity produced in this way on the island of Socotra. But the price can be reduced by integrating this source with another renewable source such as wind, solar energy, or biomass.

The minimum values for hydrogen for renewable sources are approximately \$4.8/kg.The maximum is 6 \$/kg, except for the tides, in which the minimum value is \$9.6/kg and the maximum is 11.4 \$/kg due to the high price of standard electricity. Still these values can be reduced by integrating it with a renewable source. Finally (source +source + H2), the minimum value will be approximately 7.2 $/kg, and the maximum value will be 8.6 $/kg, thus eliminating the rise resulting from a single source (source + H2) of high standard cost of electricity.

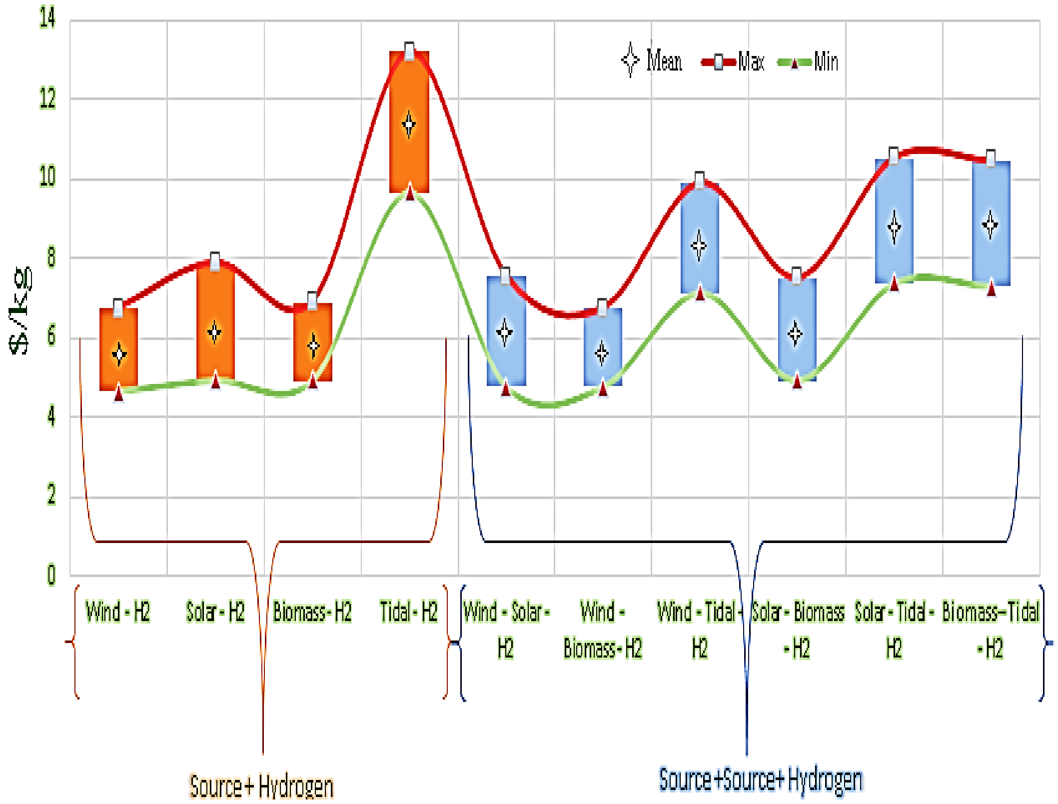

Figure 21: Hydrogen Cost ($/kg)

5. Conclusion

Statistical and analytical study of renewable energy sources found that Socotra Island has the potential to produce electricity by renewable energy sources with high efficiency and cheap cost compared to the prices of electricity produced by fossil fuels at the present time due to the high prices of oil derivatives and their absence, where the costs for electricity are more than 0.3 $/kWh. Storage methods by hydrogen production and storage or by hydroelectric system are considered the best methods in economic and environmental terms. They are considered one of the renewable and clean energy sources. The statistical results for the periods of electricity consumption showed that there is a sufficient period to store the electricity surplus, approximately 12 hours per day. This stock can be used to produce electricity during the peak consumption period.

Hybrid systems are characterized by the possibility of reducing prices of relatively high sources of energy and helps to exploit the largest number of energy resources available in the region.

This study showed that the prices of electricity produced from renewable energy sources have decreased by 10-20%. This decrease occurs due to efficiency increase of modern devices and decrease in capital and investment costs for them.

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