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Energy Management using storage to facilitate high shares of Variable Renewable Energy

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ABSTRACT

Remote islands are a very lucrative market for Variable Renewable Energy (VRE) resources. These islands rely on expensive fossil fuels, primarily diesel, to suffice their electrical generation demands and to ensure reliability. This not only makes them vulnerable to the fluctuating oil prices in the international market but also depletes their environment. The paper aims to establish a renewable energy-based power generation system facilitated by storage and takes the Island of Bonaire as the case study. Bonaire has good solar resource summing up to a Global Horizontal Irradiation (GHI) of around 1,826 kWh/m^2. The wind resource during the months between September and December stays low. Using the actual load profile obtained from the utility at Bonaire, WEB Bonaire, two scenarios are generated using Homer Pro software. The first scenario; business-as-usual, is based on replicating the current power system and establishing a baseline for further comparison. The second scenario; Renewable Energy Scenario (RE Scenario), aims to facilitate high shares of wind and solar using storage technologies. Hydrogen to be used when the wind resources are low as a seasonal storage, and Lithium Iron Phosphate batteries to absorb surplus energy by VRE technologies and to be used when they are not available on short term basis. The RE scenario lowers the share diesel-based power generation from 65.78% to 0.53% and results in an LCOE of 12.55€ cents/kWh. The RE scenario demonstrates the efficient use of Hydrogen production and storage over longer periods of times and illustrates its feasibility.

Keywords:

Variable renewable energy;
Energy storage;
Green hydrogen;
Lithium-ion battery;
Energy management;
Energy economics;

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1. Introduction

Technological advancements and exponential cost reductions have aided in massive deployments of solar PV and wind technologies following the global energy transition to clean energy sources. The markets for variable renewable energy technologies have evolved over the years and have gained massive investments. Economically, the shift to renewable energy resources for electricity generation appeals highly to remote islands. This is because the primary source for electricity generation are fossil fuels [1] who not only are expensive but also make the remote islands' economically vulnerable to the internationally fluctuating electricity prices [2]. The supply chain to transport fossil fuels for power generation ends up being too costly and eventually results in high costs of electricity consumption for the end consumer. To add, the operation of fossil fuel based power plants results in a series of environmental impacts that affect ecosystem and human health of the island [3]. This has a direct effect on the economy of the island as it primarily relies upon tourism.

2. Literature Review

There are challenges that need to be met with the variable renewable energy resources; primarily wind and solar. Wind and Solar are intermittent and variable sources of energy. Intermittency refers to fluctuations

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and changes in a short span of time such as minutes, hours while variability refers to changes over longer periods of time for example daily and seasonal availability [4]. This makes them less reliable for grid operators for provision of electricity in the required moment to balance generation and load, when compared to conventional fossil fuel based power generation technologies [4]. Koivisto et al. [5] discuss the variability and uncertainty in power systems due to high shares of wind and solar generation and stress on grid flexibility. Similar challenges of VRE are discussed in the IRENA report titled "Integrating Variable Renewable Energy: Challenges and Solutions [6].

Zsiborács et al. [7] illustrate the role of energy storage in European electric grid mix to incorporate a large share of variable renewable energy sources – primarily wind and solar. They showcase that how storage, of different types, can aid in decarbonizing the European power system by the year 2040. Concurrently Bryant et al. point out the challenges that certain utilities would have to meet in order to incorporate high shares of wind and solar in their grid mixes [8].

Leeuwen et al. provide a methodology towards communities using 100% renewable energy sources to suffice their energy needs of electricity and heating & cooling using storage, smart grid technologies, and biofuels based Combined Heat & Power (CHP) systems [9]. Lund et al. provide a methodology of incorporating pumped hydro, electro-mechanical, and electro-chemical storage types to facilitate VRE share [10].

Duić et al. provide a case study of implementing VRE through hydrogen storage on the island of Porto Santo [11]. Almehizia et al. illustrate load shifting methodology through storage for renewable energy resources and tackle the related variability and uncertainty [12]. Maximov et al. discuss long term energy storage's role in facilitating larger shares of VRE and concurrently decarbonization of the Chilean electric grid [13].

Garcia and Barbanera discuss the use of Hydrogen generated from clean energy as a storage mean for Europe [14]. Ferrero et al. discuss Hydrogen's potential towards sector coupling in a power to gas application and how hydrogen produced from electrolysis can be used to store energy and then using fuel cells be used for electricity production [15].

The literature review clearly points in the direction of energy storage coupled with renewable energy sources playing a vital role to sustain green electricity generation and meet the related challenges of uncertainty and variability associated with Wind and Solar. The literature also suggests that energy services such as cooking, heating & cooling, and transport would also turn to electricity generated from clean and renewable energy sources. Storage, in this scenario, would be necessary to meet reliability and to enable a fleet of green electricity production infrastructure.

3. Aim of research

The aim of the study is to develop a hybrid power generation system by coupling in Variable Renewable Energy (VRE) technologies; Wind and Solar, to offset the Diesel Generators based power operation.

Energy storage serves as a key role in increase of share of renewable energy over fossil fuels due to short term autonomies, ranging from hours to days, and long-term storage autonomies, expanding along seasons. Storage coupled with VRE resources increases their firm capacity and allows use of clean and renewable energy over longer periods of time [10]. The paper aims to demonstrate the use of short-term and seasonal energy storage to facilitate an increasing share of clean energy for electricity production. Using lithium-ion batteries to store energy on short-term basis – performing peak shaving for Solar and Wind generation, and Hydrogen gas storage from water electrolysis using excess Solar and Wind generation to be used on seasonal basis.

Remote islands provide interesting and very lucrative business opportunities to replace conventional power generation fleet with renewable energy-based technologies. This not only reduces dependence of island's economy over fuel imports but also reduces its vulnerability to international fluctuations in fuel prices. Use of renewable energy for power generation also assists in preserving the environment, ecosystems, and natural habitats of the island by replacing emissions from fossil fuel-based power generation technologies. This also aids to the islands' economy as it is mostly dependent on tourism.

The island of Bonaire provides as an optimal case study to demonstrate short term and seasonal storage to facilitate decarbonization of the electricity mix through an increase of renewable energy resources. With a population around 19,500 in 2018 [16] the island of Bonaire roughly spends 2.6% of its GDP on fuel imports [17]. The average consumer electricity price is around 0.34 Euro/kWh [18]. The only utility that operates on the island is government owned and is called Water-En Energiebedrijf (WEB) Bonaire N.V.

Bonaire has diesel rich power generation infrastructure which accounts for 67% of total annual electricity generation and the rest 33% is through wind turbines. However, in the later months of the year the island does not have enough wind resource which is a constraint towards moving on to renewables.

The idea is to reduce the share of diesel-based power generation share for Bonaire by incorporating larger shares of VRE coupled with short-term and long-term storage. Hydrogen, generated from renewable means, over a long period of time to be used in months where there is low wind resource. Lithium-ion battery storage systems to show hourly or daily energy storage through peak shaving of excess energy generation through Solar PV plants and Wind Turbines. Both storage technologies would exhibit their function to provide an economical solution to increase share of renewable resources in the grid mix of Bonaire and show their reliable use with increased firm capacity. This should not only decarbonize the electricity generation but should also result in a cheaper end-price of electricity for the consumer – by cutting out high fuel costs of diesel.

4. Methodology of research and Case study

Bonaire's electricity generation is primarily relied on diesel as 14 MW out of the total 25 MW installed capacity are diesel generators and about 11 MW of Wind Turbines are installed on the island [17]. The annual electricity demand sums up to 112.39 GWh as per the hourly load profile for the year 2017 that was obtained from WEB Bonaire. Table 1 [17,19] describes the power generation infrastructure for the island of Bonaire.

The weather data was obtained from Meteonorm [20]. As can be seen from Figure 1 that from months of September to December, Bonaire has lower wind

Table: Electric power generation for island of Bonaire (Sources: [17,19])

Parameter	Value	Unit
Total Installed Capacity	25	MW
Peak demand (2017 load profile)	17.637	MW
Total Generation (2017 load profile)	112.39	GWh
Wind Power Installed Capacity	11	MW
Diesel Power Installed Capacity	14	MW
Solar PV Installed Capacity (2015)	200	kW
Power Cut-outs (2015)	78	hours

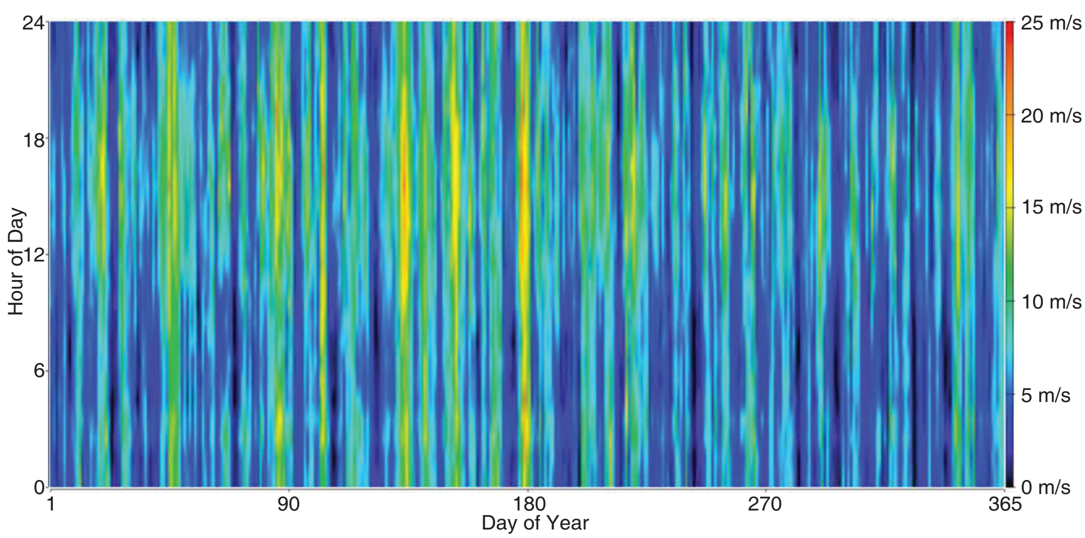

Figure 1: Wind resource Bonaire (Meteonorm)

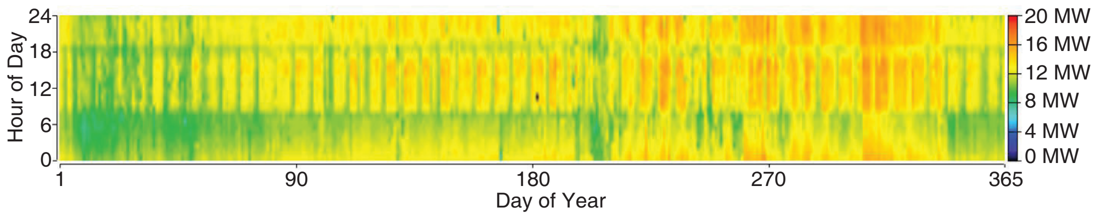

Figure 2: Load profile 2017 – Bonaire island

resource. This requires for a long-term storage of renewable energy to suffice the energy needs in lower end of the year.

Homer Pro software was used to model the Business-as-usual (BAU) scenario which is the current operational scenario for the island. And then using the same software a renewable energy and storage-based grid mix was prepared to increase share of renewables which would also be economically viable. This scenario was named Renewable Energy (RE) scenario. Simulating both the scenarios in Homer Pro allows a fair comparison on both technical and economic grounds.

The hourly load profile as obtained from WEB Bonaire utility is shown in Figure 2.

As can be seen from Figure 2 that the load increases in the lower end of the year where the wind resource (refer to Figure 1) is also low. This requires the diesel generators to operate at their full capacity to suffice the loads – increasing their share in electric energy generation for the island.

4.1. Business-as-usual Scenario Simulation methodology

The BAU scenario serves as a baseline to compare the techno-economic effectiveness of the RE scenario. In the BAU scenario the power generation infrastructure of Bonaire Island is simulated in Homer Pro as it exists. The scenario is expected to start from the current timestamp; year 2019. The load profile from the year 2017 has been assumed to be the same for the year 2019 – forming the baseline for BAU scenario simulation. The 4 diesel generators summing up to a capacity of 14 MW [19] were installed in the year 2004. So, it has been assumed that they are to be replaced as they would be ending their lifetime. Hence their capital cost (CAPEX) is added in the simulation. The CAPEX and replacement costs have been kept the same under the assumption that diesel generators are matured technology and significant cost reduction in the future is less likely. However, wind turbines installed in 2004 as well, are expected to complete 15 years of their lifetime and are expected to have 10 years left assuming a 25 year lifetime for wind turbines [19]. Hence, their CAPEX is not added at the project start timestamp. They are expected to be replaced after 10 years of operation. The replacement costs for Wind Turbines have been obtained from IRENA report titled “Future of Wind” and is a reflection of projection of reduction in costs of technology [21]. The costs obtained in USD from different sources were converted to Euros as per the current rate of 2019.

The lifetime of the project or the timeframe for both the scenarios is kept 20 years.

Table 2 discusses the different costs and lifetimes assumed for the diesel generators and wind turbines involved in the grid mix for the island of Bonaire. The schematic for BAU scenario is provided in Figure 3. Load following dispatch strategy is used to operate the power generation infrastructure. The power generation output by the resources is as to produce enough to meet the instantaneous load. The lifetime of components input is taken as number of years and as number of hours of operation. The component is replaced if the number of hours of operation exceed the lifetime in years or vice versa.

4.2. Renewable Energy Scenario simulation methodology

The RE scenario aims to decarbonize the grid mix for the island by minimizing the share of diesel-based generation and cutting off fuel import costs. The RE scenario aims to provide a hybrid operation of wind and solar PV. During the day times solar PV suffices the required electrical load and when the sun is not shining the available wind resource is used to generate electricity. The costs obtained in USD from different sources were converted to Euros as per the current average rate of 2019.

The 12 Enercon Wind Turbines, installed in 2004, are kept operational with an expected lifetime of

Table 2: BAU Scenario power generation economics (Sources: [19] [22], [23], [21], [22])

Type	Make	Capacity (kW)	CAPEX (Euro/kW)	Replacement Cost (Euro/ kW)	OPEX (Euro/ operation hour)	Lifetime left (years)	Lifetime (hours)
Diesel Generator 1	N/A	4,000	1,100	1,100	0.01	20	30,000
Diesel Generator 2	N/A	3,500	1,100	1,100	0.01	20	30,000
Diesel Generator 3	N/A	3,500	1,100	1,100	0.01	20	30,000
Diesel Generator 4	N/A	3,500	1,100	1,100	0.01	20	30,000
Source	N/A	assumed to be total to 14.5 MW	[22]	[22]	[22]	assumed to be re-installed at current timestamp	[23]
Type	**Make**	**Capacity (kW)**	**CAPEX (Euro/kW)**	**Replacement Cost (Euro/ kW)**	**OPEX (Euro/ kW)**	**Lifetime left (years)**	**Lifetime (years)**
Wind Turbine 1 (12 in number)	Enercon	900	2,000	1350	30	10	25
Wind Turbine 2 (1 in number)	XANT	330	2,000	1350	30	10	25
Source	[19]	[19]	[24]	[21]	[24]	assumed to complete half-life at current timestamp	[24]

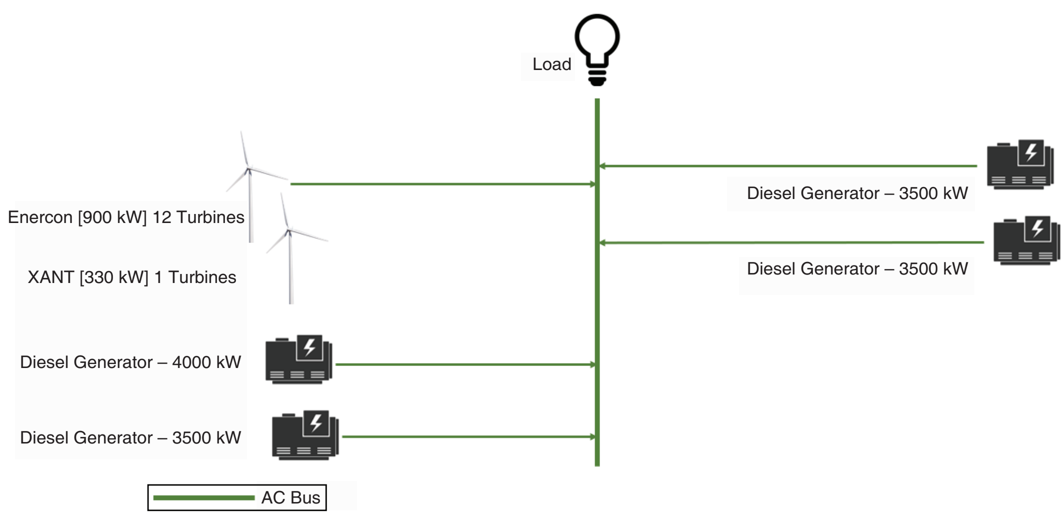

Figure 3: BAU Scenario schematic

10 years left. While 15 new Wind turbines are added of 1 MW capacity each to the grid. The cost source for the wind turbines is the Fraunhofer ISE report on LCOE of renewable energy technologies [24]. The replacement cost source for wind turbines is the IRENA report titled Future of Wind that provides cost reduction projections for wind turbines [21]. Table 3 describes the modelling input details for wind turbines in Homer Pro software.

37 MW of solar PV capacity is added to increase clean and renewable energy share in the grid mix. The costs source is the Fraunhofer ISE report on LCOE of

Table 3: Wind power input details (Source: [24], [21])

Type	Make	Number	Capacity (kW)	CAPEX (Euro/kW)	Replacement Cost (Euro/kW)	OPEX (Euro/kW)	Lifetime left (years)	Lifetime (years)
Wind Turbine 1	Enercon	12	900	2,000	1350	30	10	25
Wind Turbine 2	Leitwind 77	15	1,000	2,000	1350	30	25	25

Table 4: Solar PV plant input details (Source: [24])

Type	Make	Capacity (kW)	CAPEX (Euro/kW)	Replacement Cost (Euro/kW)	OPEX (Euro/kW)	Lifetime left (years)	Lifetime (years)
Solar PV Plant	Sun Power	37,000	765	0	12.5	25	25

Table 5: Lithium Iron Phosphate battery input details (Sources: [27], [30])

Type	Make	Capacity (kWh)	CAPEX (Euro/kWh)	Replacement Cost (Euro/kWh)	OPEX (Euro/kWh)	Number of Cycles	Lifetime left (years)	Lifetime (years)
Battery Storage	Lithium Iron Phosphate	20,000	545.47	300	0	10,000	20	20

renewable energy technologies and provides the cost for the whole system as a function of kW [24]. Table 4 describes the solar PV plant modelling input details for Homer Pro software. The replacement costs have been kept zero because the lifetime of the solar PV plant is 25 who exceeds the lifetime of the project which is 20 years.

However, due to their intermittency and variability the VRE resources require a short-term energy storage facility to not only provide energy when both the resources are not instantaneously available but also aid in storing excess energy when available - peak shaving. This aids in grid flexibility [25] and aids in frequency regulation for the grid as well – keeping a balance between supply and demand by storing the excess and discharging when needed [26]. This requires for a storage technology that has high response times (specific power) and can charge and discharge quickly along with high cycle life. Lithium Iron Phosphate battery technology has been chosen on the mentioned criteria as it fulfills the purpose [27]. The lithium-ion technology has high energy and power density with high cycle life ranging up to 10,000 cycles [27] with a calendar life between 5 to 20 years [27].

Buss et al. [28] provide a comprehensive analysis of different storage types installed along the world where lithium-ion and REDOX flow batteries are found to dominate the electro-chemical storage types by the year 2016. Müller also discusses a wide range of stationary applications for lithium-ion battery technologies and favors its application for the required purpose in the scenario [29]. Table 5 describes the lithium-Ion battery storage modelling input details for Homer Pro Software. The indicated costs include the cost of battery management system, the battery inverter, the associated costs of installation, profit heads, and other soft costs [27]. The cost of lithium-ion battery systems are expected to decrease roughly 50% by the year 2030 as per the IRENA report Electricity Storage and Renewables: Costs and markets to 2030 [27]. The lifetime of lithium-ion battery system is expected to be 20 years which would end in the year 2039. The cost projection for replacement costs of the lithium-ion battery storage system were taken from the European Commission report titled Li-ion batteries for mobility and stationary storage applications [30]. The year for the replacement cost was chosen to be 2040 which is the closest to 2039. The expected lifetime of the lithium-ion battery as per [27] is kept to be 20 years. However, the battery might also run out of its life if the number of cycles is finished earlier than 20 years due to more intense and improper use of battery. Homer Pro uses the parameter "Battery throughput" which is the defined as the total energy that would cycle the battery system throughout the year and eventually its lifetime.

The low wind resource as identified in Figure 1 between the months September and December

Table 6: Alkaline electrolyzer input details (Source: [31])

Type	Make	Capacity (kW)	CAPEX (Euro/kW)	Replacement Cost (Euro/ kW)	OPEX (Euro/kW)	Lifetime (years)	Efficiency	Opr Hours (hrs.)	Output Pressure (atm)
Electrolyzer	Alkaline	28,000	681.84	194.5	13.64	20	65%	80,000	1

Table 7: Hydrogen storage input details (Source: [32])

Type	Make	Capacity (kg of H2)	CAPEX (Euro/kg)	Replacement Cost (Euro/kg)	OPEX (Euro/ kg)	Lifetime left (years)	Lifetime (years)	Storage Pressure (bar)
Hydrogen Storage	N/A	120,000	455.57	0	0	20	20	350

establishes the need for a long term or seasonal energy storage. The paper aims to demonstrate the use of green Hydrogen for energy storage. For this Alkaline Electrolyzer has been used to produce Hydrogen from VRE. The choice of Alkaline Electrolyzer was made on rationales of being a more established technology and on account of having a longer stack life than Polymer Electrolyte Membrane (PEM) Electrolyzer [31]. Also as per the IRENA report on Hydrogen from renewable power the Alkaline Electrolyzer technology is cheaper than PEM [31]. This allows for a larger capacity of the Electrolyzer to be deployed. The Alkaline Electrolyzer operates at an efficiency of 65% as per the Lower Heating Value of Hydrogen – not taking into account the heat generated. Table 6 describes the modelling input details for the electrolyzer in Homer Pro software. The Alkaline Electrolyzer system comprises of Electrolyzer stack which is the combination of electrolysis cells, water supply, power electronics and control, and instrumentation. The electrolyzer stack has a lower lifetime, depending on the duty cycle of the Electrolyzer, as compared to rest of the assembly. Hence, only the electrolyzer stack cost is mentioned as the replacement cost as per the IRENA report [31]. The IRENA report provides a cost projection figure for the year 2025. Alkaline Electrolyzer produces Hydrogen gas at atmospheric pressure. While the lifetime for the electrolyzer system is about 20 years, the operation hours refer to electrolyzer stack use. When the operation hours are completed before then the stack would require to be replaced not the whole system.

The green hydrogen produced from the VRE is stored at 350 bar pressure for a storage with a lifetime of about 20 years. The storage system for Hydrogen comprises of Hydrogen tanks, compressor systems and other balance of system as taken from the report U.S Department of Energy Hydrogen Cost Analysis [32]. The compressor input energy has not been considered owing to restrictions in the Homer Pro Software. Table 7 describes the modelling input details for the Hydrogen storage tank in Homer Pro software. The replacement costs for Hydrogen storage are kept zero as the system is assumed to last through out the lifetime of the project.

Polymer Electrolyte Membrane Fuel cell was selected to produce electrical power. The selection is based on the ability of the PEM Fuel cell to be more responsive to the intermittency of the VRE output [31]. The PEM fuel cell costs were modelled using the Manufacturing Cost Analysis of 100 and 250 kW Fuel Cell Systems for Primary Power and CHP Applications report prepared by Battelle Memorial Institute for Department of Energy USA [33]. From the report a 250 kW PEM fuel cell system was considered using 50 kW fuel cell stacks. The costs were modelled using a scenario where 50,000 annual units were expected to be manufactured [33]. The cost components include stack, water supply, power electronics, control & instrumentation, assembly corporation, and additional work estimate. Table 8 describes the modelling input details for the PEM fuel cell in Homer Pro software. The replacement costs refer to replacement of the stack component of the PEM fuel cells due to only the stack being replaced.

Two of the four diesel generators are kept online to provide power where the combination of instantaneous power generation from VRE sources and battery storage types does not fulfill the required demand. The diesel generators are expected to be installed at the current timestamp; the start of operation of the project.

Table 9 describes the modelling input details for diesel generators in Homer Pro software.

Table 8: PEM fuel cell input details (Source: [33])

Type	Make	Capacity (kW)	CAPEX (Euro/kW)	Replacement Cost (Euro/kW)	OPEX (Euro/ operation hour)	Lifetime (years)	Efficiency	Opr. hours (hrs.)	Input Pressure (bar)
Fuel Cell	PEM	12,000	473.22	166.7	0.06	20	60%	60,000	350

Table 9: Diesel generator input details (Source: [22], [23])

Type	Make	Capacity (kW)	CAPEX (Euro/kW)	Replacement Cost (Euro/ kW)	OPEX (Euro/ operation hour)	Lifetime left (years)	Lifetime (hours)
Diesel Generator 1	N/A	4,000	1,100	1,100	0.01	25	30,000
Diesel Generator 2	N/A	3,500	1,100	1,100	0.01	25	30,000

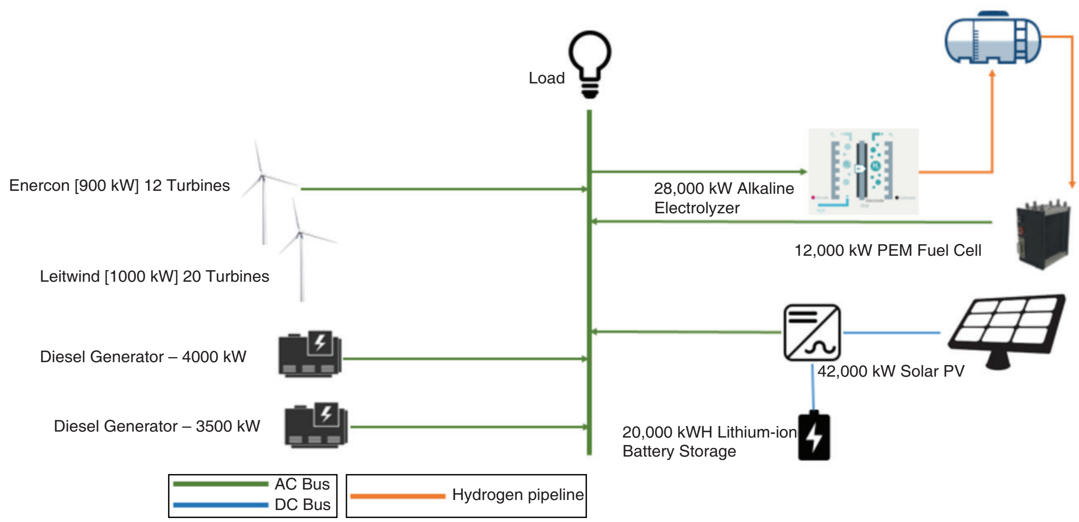

Figure 4: RE Scenario operation schematic

Load Following methodology has been used in Homer Pro which operates the power generation resources at necessary capacity needed to meet the load and then charge the storage types with surplus energy. The merit order for power generation is based on operational cost of power generation for the resource. Homer Pro does not allow to set a merit order manually when Hydrogen based technologies are involved.

Figure 4 describes the schematic RE scenario operation.

5. Results

The results for both the scenarios are discussed in different sections – illustrating the performance and share of each technology used for power generation and eventually storing energy. The economics for each scenario are discussed to highlight differences in investment costs and operating costs and to identify which solution results in a cheaper LCOE that would result in a cheaper price of electricity.

5.1. Results BAU Scenario

Figure 5 displays the monthly share of power generation as per the generation resources for the first year. Table 10 describes the first-year energy production and the share of power generation for each technology for the first year.

The renewable fraction sums up to be 34.22% while the diesel-based power generation sums up to 65.78%. Figure 6 shows the hourly annual operation for the operating wind turbines. While the wind turbines have high capacity factors, the low wind resource between September and December results in lower production as

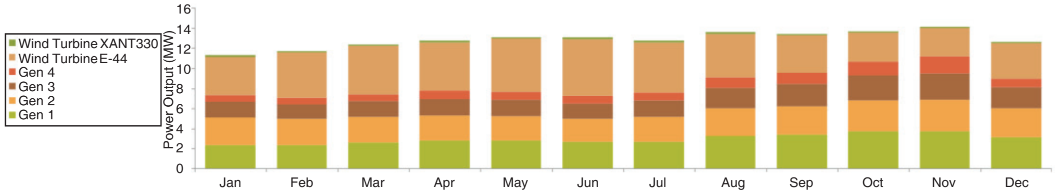

Figure 5: Share of power generation on monthly basis –BAU Scenario

Table 10: Annual production and share of power generation – BAU Scenario

Power Generator	Annual Production (GWh)	Percentage Share (%)
Gen 1 (4 MW)	25.97	23%
Gen 2 (3.5 MW)	23.427	20.77%
Gen 3 (3.5 MW)	16.397	14.60%
Gen 4 (3.5 MW)	8.350	7.41%
12 × Enercon E-44 [900kW]	37.155	33%
1 × XANT L-33 [330kW]	1.370	1.22%
Total Load met	112.668	100.00%
Unmet Load	0.461	0.41%

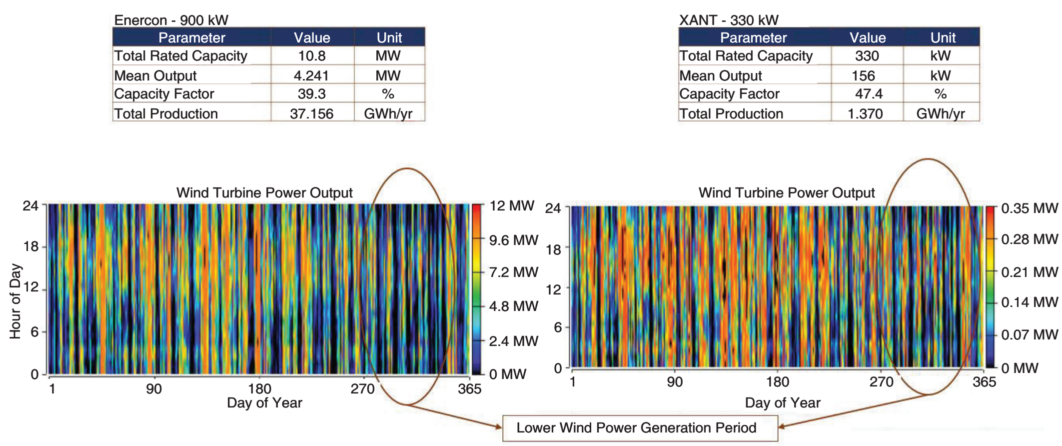

Figure 6: Wind operation – BAU Scenario

pointed out on Figure 6. The operation of diesel generators is amplified in these months to suffice the load as shown in Figure 7. As evident from Figure 7 diesel generators number 3 & 4 operate less when compared to diesel generators number 1 & 2. This is because of the Load Following dispatch strategy to operate a power generation infrastructure to the extent where it meets the load demands.

Figure 8 displays the diesel fuel usage pattern for the year in the BAU scenario. As expected, the use of diesel fuel is accelerated in the months September to December.

The lifetime of the BAU scenario project is expected to be 20 years. The discount rate is taken as per the Consumer Price Index based inflation rate – 1.5% [34]. The economics of the BAU scenario are presented in Table 11.

The 20-year diesel cost sums up to be around 73.33% of the total Net Present Cost for the 20-year project. The LCOE sums to be 0.2069 €/kWh which results in higher consumer price of electricity summing up to be 0.34 €/kWh. To add, around 54,564 tonnes of CO_2 are emitted during the 20-year lifetime. Figure 9 shows the annual costs for the project implicating the operation

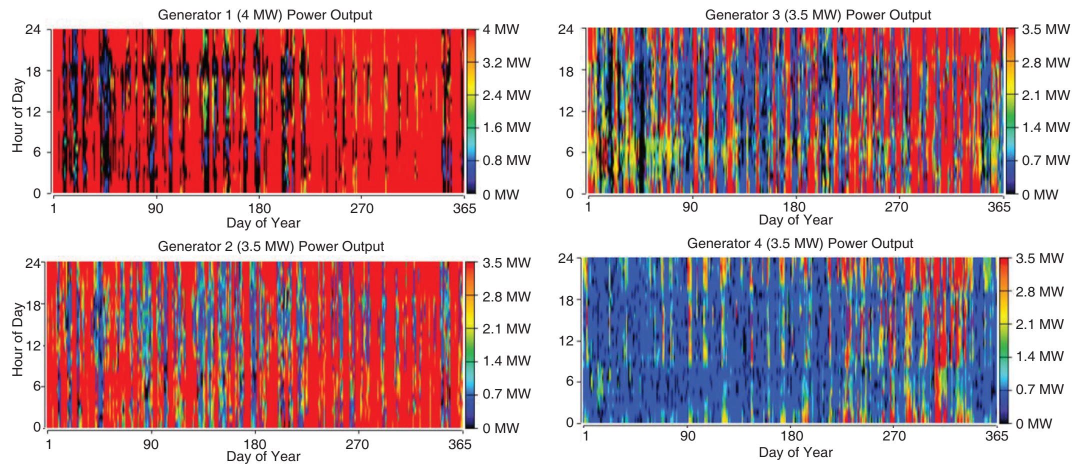

Figure 7: Diesel generator operation – BAU Scenario

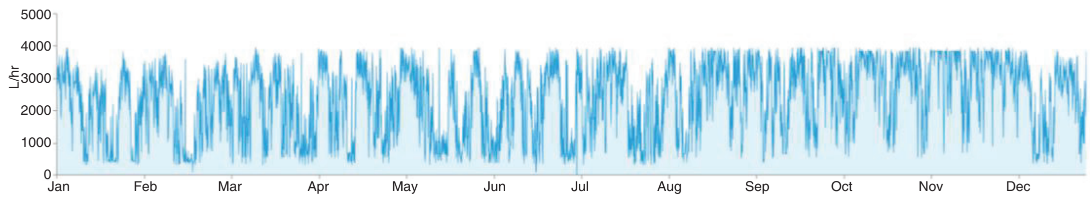

Figure 8: Diesel fuel usage – BAU Scenario

Table 11: BAU Scenario energy economics

Parameter	Value	Unit
Discount Rate	1.51%	%
Project Lifetime	20	Years
Consumer Electricity Price (2018)	**0.34**	Euro/kWh
Total Net Present Cost (20 years)	419	Million Euro
Total Diesel Fuel Cost (20 years)	307	Million Euro
Total Operating Cost (20 years)	25.14	Million Euro
Levelized Cost of Electricity	**0.2069**	Euro/kWh
Share of Diesel Cost	**72.20%**	%
CO_2 Emissions (20 years)	54,564	tonne CO_2

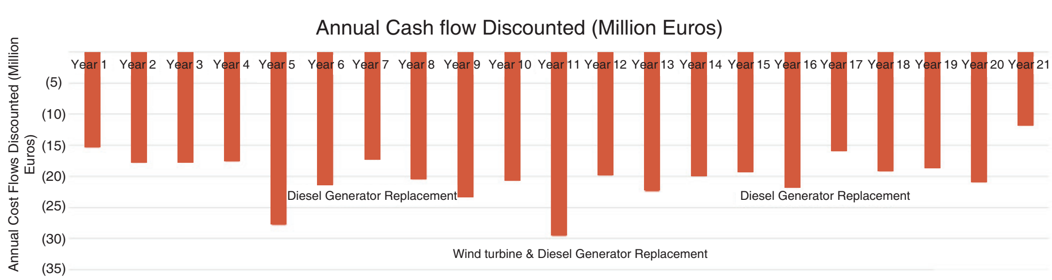

Figure 9: Annual costs BAU Scenario

Table 12: Annual production and share of power generation – RE Scenario

Type	Code	Installed Capacity (MW)	Generation (GWh)	Share of Generation (%)
Solar PV Plant	Solar PV Plant	42	62.947	29.00%
PEM Fuel Cell	FC	12	16.960	7.82%
Diesel Generator 1	Gen 1	4	0.671	0.31%
Diesel Generator 2	Gen 2	3.5	0.474	0.22%
Wind Turbine Enercon E-44 [900kW]	E-44	10.8	35.351	16.30%
Wind Turbine Leitwind 77 [1000kW]	LTW 77	20	100.508	46.30%
Total			216.911	100.00%

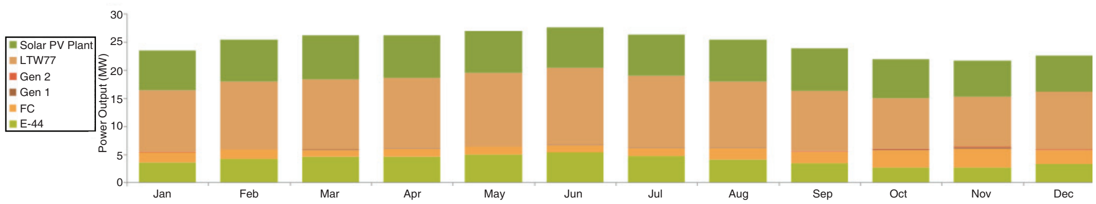

Figure 10: Share of power generation on monthly basis –RE Scenario

Table 13: Operation of solar PV plant – RE Scenario

Parameter	Value	Unit
Rated Capacity	42	MW
Mean Output	7.186	MW
Mean Output	172.458	MWh/day
Capacity Factor	17.1	%
Total Production	62.947	GWh/yr
Share of total Power Generation	29.00%	%

and maintenance costs along with replacement of wind turbines and diesel generators after they have fulfilled their lifetime.

5.2. Results RE Scenario

Table 12 describes the capacities installed and the annual share of power generation for different technologies adopted in the RE Scenario, for the first year.

The sum of renewable energy-based power production reaches up to 99.47% while the diesel share is reduced 0.53% on annual basis. Figure 10 displays the share of power generation for different technologies on monthly basis.

Table 13 describes the operation of the solar PV plant for the 20-year lifetime of the project. With ample solar resource available, solar PV plant contributes 29% of total power generation for the island.

Figure 11 shows the wind power operation of the enhanced wind turbine fleet summing up to a capacity of 25.8 MW. The total share of wind power generation in the grid mix is 62.6%. As anticipated the months from September to December have low wind power production due to low wind resource.

The operation of 28 MW Alkaline Electrolyzer to produce Hydrogen, along with Hydrogen storage tank level are shown in Figure 12.

The electrolyzer with a capacity factor of 21.7% operates mostly during the peak times of the 42 MW solar PV plant operation and also utilizes the surplus wind energy to produce and store Hydrogen. The Hydrogen tank level is assumed to begin operation to be filled with 20% of its full storage capacity and reaches high volumes during the early and mid-year time. During the periods when the wind resource is low the stored Hydrogen is used to produce power through the 12 MW fuel cell and meet the required demand.

Table 14 describes the operation and performance indicators for the fuel cell. Figure 13 illustrates the operation pattern of the fuel cell.

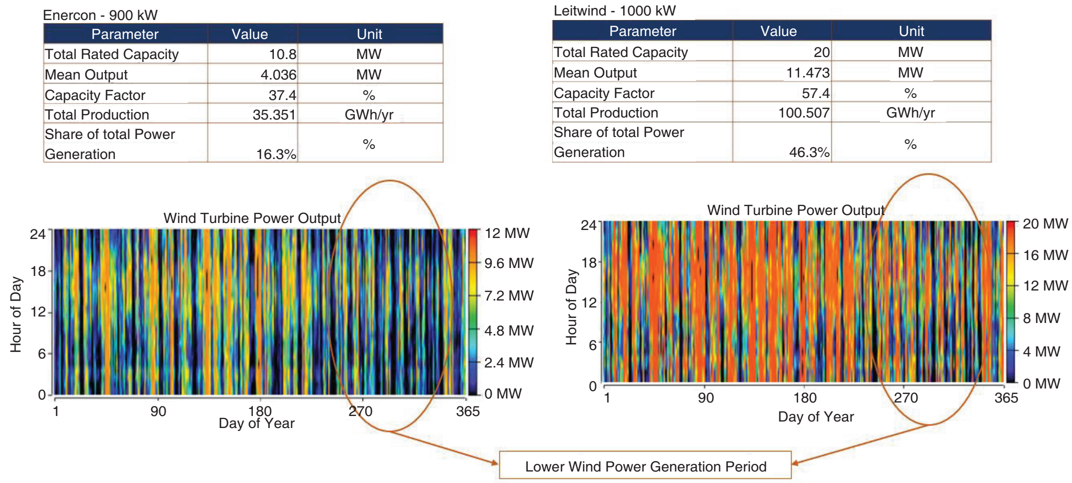

Figure 11: Wind power operation – RE Scenario

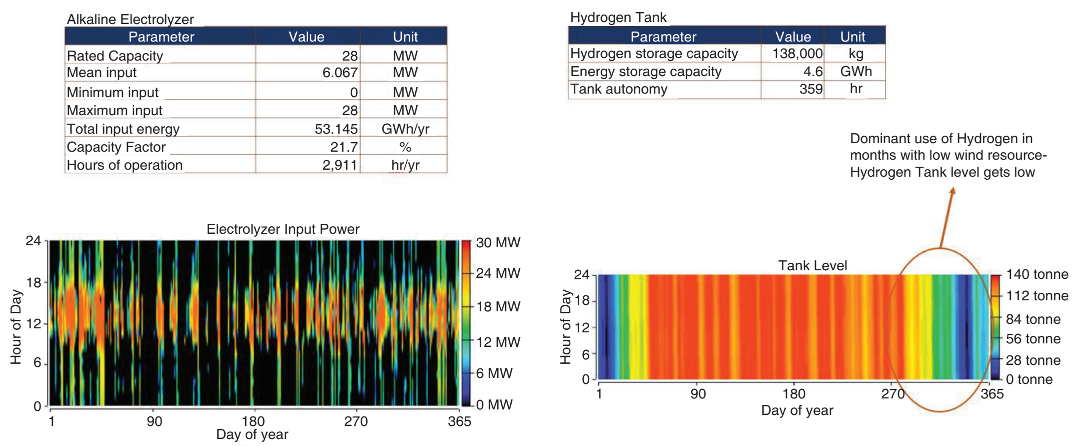

Figure 12: Electrolyzer operation and Hydrogen storage tank Level – RE Scenario

Table 14: Operation and performance indicators – Fuel cell

Parameter	Value	Unit
PEM Fuel Cell Rating	12	MW
Hours of Operation	1,760	hrs/yr
Number of Starts	282	starts/yr
Operational Life	34.1	yr
Capacity Factor	16.1	%
Electrical Production	16.960	GWh/yr
Mean Electrical Output	9.636	MW
Minimum Electrical Output	2.524	MW
Maximum Electrical Output	12	MW

The 12 MW fuel cell operates with an annual capacity factor of 16.1% and is aimed at fulfilling electrical power demand when there is no instantaneous production from solar PV and wind and the lithium-ion battery storage is empty. The partial load operation of fuel cell allows to meet demands in conjunction with wind and/or battery storage. The fuel cell operation intensifies during the low wind resource period as evident from Figure 13.

Table 15 discusses the lithium-ion battery storage operation parameters for the first year of operation. Figure 14 displays the state of charge for the 20 MWh lithium-ion battery storage.

The 20 MWh lithium-ion battery can be seen to discharge during night and morning times. The excess energy stored is primarily due to solar PV plant operation and the rest is due to excess electricity produced by the wind turbines – performing peak shaving. This is shown as the battery has 100% state of charge during peak times of solar PV operation. The battery's discharge operation is increased in later months of the year where wind resource is low as evident from Figure 14. The annual intake energy of the battery is about 4.8 GWh and the annual sum of discharged energy is around 4.3 GWh. This accounts for a 10% round trip efficiency loss. This allows the power produced by wind and solar to be used at times when these sources are not available and replace the potential diesel power operation which would be kept on sufficing the load – as is done in the BAU scenario. This substitution of operation in the RE scenario by the battery allows use of clean and cheaper energy to be used to meet the load demands.

Table 15: Lithium Iron Phosphate battery storage operation

Parameter	Value	Unit
Capacity	20	MWh
Autonomy	1.48	hr
Storage Wear Cost	4.11	€/MWh
Nominal Capacity	20	MWh
Usable Nominal Capacity	19	MWh
Lifetime Throughput	91,341	MWh
Expected Life	20	yr
Energy In	4,795	MWh/yr
Energy Out	4,333	MWh/yr
Storage Depletion	17.7	MWh/yr
Losses	480	MWh/yr
Annual Throughput	4,567	MWh/yr

The two diesel generators tend to be operational at early morning and late-night times to fulfill the residual load requirement through their partial load operation.

The RE scenario economics are shown in Table 16.

The RE scenario reduces the share of diesel power generation to suffice the electrical load demands for the island of Bonaire to 0.53% of the total electrical power generation. While there is a demand of high capital expenditure of around 178 Million Euros, the total Net Present Cost (NPC) is around 246 Million Euros. The LCOE of the power generated from the RE Scenario is

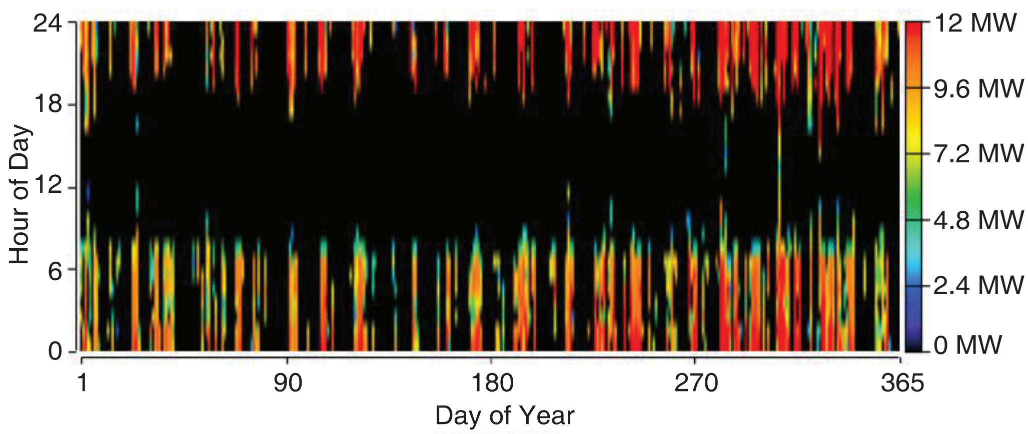

Figure 13: Fuel cell hourly operation

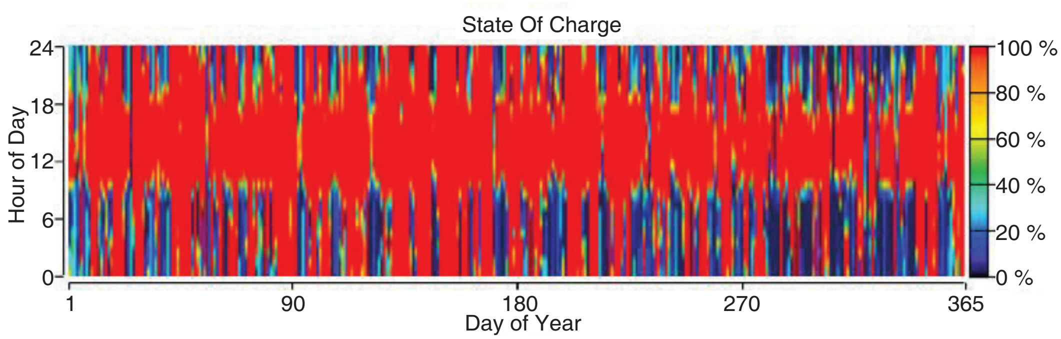

Figure 14: Hourly State of Charge – 20 MWh Lithium Iron Phosphate battery storage

0.1255 Euros/kWh. This is a result of reduction of use of diesel fuel and intelligent use of storage sources along with VRE. Not only does the RE scenario provides cheaper electrical energy, it also produces minimal CO_2 emission during its operational phase, due to minimalistic diesel generator operation, and makes the island's economy least vulnerable to international price changes for diesel fuel. The annual discounted cash flows can be seen in Figure 15. The cash flows indicate the initial investment, the replacement of the Enercon wind turbines after completing their last 10 years of lifetime and the annual diesel fuel costs. At year 20 the cash flows turn positive because of the salvage value for the Wind and Solar plants as calculated by Homer Pro software.

6. Conclusion

The RE scenario reduces the share of diesel-based power generation from 65.78%, in the BAU scenario, to 0.53%. This also decreases the cost of diesel fuel imports and the share in the NPC decreases from 72.2%, in the BAU scenario, to 2.29%. This results in a reduction in NPC, for the 20 years of operation for both the scenarios, of about 46.87%. This reduces the LCOE from 0.2069 €/kWh, in BAU scenario, to 0.1255 €/kWh in the RE scenario. However, due to operation of fuel cell, electrolyzer, and two diesel generators, the operation costs are twice in the RE scenario, when compared to BAU scenario.

The application of high shares of Wind and Solar PV have been possible due to different storage technologies incorporated. Hydrogen storage enables the long-term stored energy from solar and wind resources to be used in later part of the year when there is very low wind resource. While lithium-ion stores the excess energy from solar mostly, in the day times, and uses in the night times to facilitate high shares of clean and renewable energy which is also cheaper.

The lower LCOE results in a much cheaper price of electricity to consumer and furthermore sustains the economy of the island of Bonaire against fluctuations in the price of diesel in the international market. The 98.2% reduction in CO_2 emissions aids in the global effort against climate change and global warming. The reduction in operation of diesel generators reduces the emissions of toxic gases such as Nitrogen and sulfurous oxides and particulate matter helps the local ecosystem and climate of the island in preserving its ecosystem and sustain the natural habitats who are key towards the economy that sustains on tourism.

Table 16: RE Scenario energy economics

Parameter	Value	Unit
Discount Rate	1.51%	%
Project Lifetime	20	Years
Consumer Electricity Price (2018)	**0.34**	Euro/kWh
Initial Investment	179 Million	Euros
Total Net Present Cost (20 years)	242 Million	Euro
Total Diesel Fuel Cost (20 years)	4.8 Million	Euro
Total Operating Cost (20 years)	50.15	Euro
Levelized Cost of Electricity	**0.1255**	Euro/kWh
Share of Diesel Cost in NPC	**1.95%**	%
CO_2 Emissions (20 years)	916.623	tonne CO_2/yr
CO_2 Emissions reduction (20 years)	99.98%	%

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Figure 15: Annual discounted cash flows – RE Scenario

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