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An Economic Analysis of a Hybrid Solar PV-Diesel-ESS System for Kumundhoo, Maldives*

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The conventional, large-scale, fossil fuel based grid system cannot be sustainable especially in small island countries (SIDS). Despite high costs and volatility of fossil fuels, SIDS continue to power 90% of economic and social activities with imported fossil fuels. The Maldives is one of the most vulnerable countries to climate change impacts as a small island country and their low height above sea level. This study provides a concrete example of 'leap-frogging' strategies, suggesting application of new climate technologies and implementation of an adaptation and GHG mitigation integrated project for off-grid areas. The objective was to evaluate whether a hybrid system combining diesel and renewable energy power generation with ESS (Energy Storage System) is economically viable as a sustainable energy system. An economic analysis using cost-benefit indicators and a sensitivity analysis showed that a hybrid solar PV-diesel-ESS energy system is more economical for users as well as the provider, the Maldives government.

JEL Classification: Q42, O44, Q54, Q55
Keywords: hybrid solar energy, energy storage system, economic analysis, off-grid electrification, Maldives

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1. INTRODUCTION

The Maldives, as a small island developing country in the Indian Ocean, is one of the most vulnerable countries to climate change impacts such as rising sea levels and extreme weather conditions. Like other small island developing states, the Maldives depends overwhelmingly on petroleum imports for their electricity production, which creates serious economic and financial difficulties with great uncertainty of oil price. High dependence on petroleum generation is due to the dispersed habitation of Maldivians (among the 1,192 dispersed tropical islands, 190 are inhabited by a total population is 298,968). In fact, the government indicates that dependency on imported fuels has worsened since the early 1990s, with petroleum products accounting for 15.8% of total imports in 1990, rising to 31.0% of total imports in 2012 (ADB, 2015). Additionally, the investment costs of large power plants, which are built to meet the peak daily demand and thus inefficient with demand fluctuations, and the high operation and maintenance costs are often passed on to the users (van Alphen, 2007).

Given this background, the Maldives has been promoting alternative energy sources as a diversification strategy and to support energy efficiency initiatives. For example, in 2009, the government announced an ambitious program to make the Maldives carbon neutral by 2020, meaning all electricity generation must be from non-diesel sources. Luckily, renewable resources such as solar radiation and wind are abundant (Blechinger, 2014). To meet this goal, national, regional and multilateral efforts including technical assistance, investments and actual projects on renewable energy have been made. Yet such efforts do not fully meet Maldives' target thus further renewable energy deployment studies of specific islands, especially ones in the outer regions are still in demand.

With the background abovementioned, in this paper, the potential for a hybrid power system with renewable energy (RE) and diesel generation with an energy storage system (ESS) for Kumundhoo Island, which is one of small islands in Maldives, is studied. The technical feasibility of the power system was pre-evaluated and the economic analysis of the system is considered. First, local conditions such as the energy demand and climate conditions are examined. Then, monetary costs and benefits of the project's renewable energy sourced hybrid power system are determined from the perspective of a business entity. Economic analysis is conducted by calculating a set of financial indicators such as benefit-cost ration (B/C ratio), net present value (NPV), internal rate of return (IRR). Finally, sensitivity analyses using different discount rates and feed-in tariff (FIT) subsidy prices are done to determine the economic feasibilities under different conditions.

2. LITERATURE REVIEW

Solar photovoltaic (PV) energy generation is now a mainstream and mature technology. Due to the continuously declining costs, solar PV is increasingly commercially attractive to project developers and to small-scale residential or commercial consumers. According to International Renewable Energy Agency (IRENA), in 2010-2015, the capacity weighted average Levelized Cost of Electricity (LCOE) for the technology fell by more than half. In fact, many major markets are experiencing significant year-on-year increases in electricity prices, making renewable energy based electricity generation a profitable and clean investment. Yet, the variability in solar energy supply remains a challenge (Grothoff, 2015). Thus, smoothing renewable energy production helps maintain system reliability and voltage concerns. It does so by mitigating the very short-term fluctuating nature of variable renewable energy before feeding it into the grid (Jaffe and Adamson, 2014).

Wichert *et al*. (2001) studied techno-economical characteristics of hybrid power systems and outlined the expected future directions for the development of hybrids. The authors found that the hybrids power systems were more favorable when the cost of diesel fuel transportation was incorporated in the analysis. Further, Shaahid (2009) found that hybrid power systems exhibit higher reliability and lower cost of generation than those that use only one source of energy. Higher reliability came from the mix of energy sources covering the lack of one source with another. Akikur (2013) presents comparative case studies, project examples and demonstrations of stand-alone solar and hybrid solar systems implemented at various locations throughout the world over the last twelve years. He finds that the diesel as a stand-alone source involves high maintenance demands for rural populations, who are often poor with low levels of education and lack of familiarity with modern technology. Though diesel cannot be replaced due to its reliability as a source, both the stand-alone solar-PV system and the hybrid solar-PV system are found to provide a cost-competitive, eco-friendly, low maintenance, alternative power solution for any load in rural locations far from the grid.

To address the low reliability of renewable energy sources, battery storage technologies have been introduced. For example, Schmid (2004) suggested that in Northern Brazil, PV systems with energy storage connected to existing diesel generators allow them to be turned off during the day and provide the lowest energy costs; Bala and Siddique (2009) presents an optimal design of a solar PV-diesel hybrid mini-grid system for a fishing community in an isolated island Sandwip in Bangladesh; Lau *et al*. (2010) study a remote areas of Malaysia to demonstrate the impacts of PV penetration and battery storage on energy production, cost of energy and number of operational hours of diesel generators for the given hybrid configurations. Rehman (2010) and the aforementioned studies find that diesel only system was found to un-economical and for hybrid systems, the major share of the cost was for solar panels and batteries. Thus, battery storage in the power sector needs to overcome many barriers before it can be integrated as a mainstream option (Sioshansi *et al*., 2012; Kempener, 2013).

Among the barriers for more widespread battery storage use in the power sector, financial considerations including the lack of monetary compensation, cost-competitiveness, and financial support schemes are highlighted. Therefore, local conditions influencing the techno-economic system components and financing options become ever more important. In the case of Nigeria, Adaramola (2014) show that the cost of generating electricity using the hybrid energy system is significantly cheaper than using a generator only based energy system (with and without battery) but highly dependent on the interest rate and diesel price. In all the aforementioned case studies of the hybrid power systems, economic analyses were done by calculating the revenues and costs (variable and fixed) to find evaluation indicators such as, net present cost (NPC), LCOE and internal rate of return (IRR).

Despite the fiscal barrier of battery use, islands represent a unique opportunity for battery storage. Many islands that operate mini-grids have weak interconnection and a lack of flexible power sources, which means that they can benefit from reliable storage source. Balza (2014), Shakarchi (2014) finds that islands profit from the introduction of REs in the long run and additional implementation of batteries leads to further cost reductions. These battery installationsare expected to smooth power fluctuations as well as provide frequency response. Lal (2012) specifically investigates the feasibility of a wind/solar photovoltaic/diesel generator-based hybrid power system in a remote location in Fiji Islands. This study indicates that for the chosen location, the most feasible system consists of a 200kW PV, 170kW diesel generators and battery storage if no capacity shortage is demanded. Allowing for 10% capacity shortage, a fully renewable energy-based system becomes feasible.

Furthermore, according to Richard Martin, senior editor of MIT Technology Review, finds that electricity storage at a decentralized level allow for effective sharing of electricity of virtual communities where buying and selling of electricity can be further realized. Yet the challenges remain such as, the remote location condition making replacement more difficult due to transportation inefficiency (Gielen, 2016). Other challenges are the ambient conditions (particularly temperature), lack of installation infrastructure for equipment transportation and costly maintenance due to travel requirements.

3. METHODOLOGY

Kumundhoo, an island part of the Haa Dhaalu Atoll administrative division and located in the north, is selected to evaluate whether there is an economically feasible sustainable energy option was selected, the conditions in Kumundhoo Island such as its size, density, energy demand, and outer-island status suggests that the present study could be applied to other outer islands of Maldives and other small island developing states (SIDS).

Technical specifications of the renewable energy sourced power system considered in the paper were selected based on literature review, local conditions, available technology and site specifications. Additionally, Kumundhoo's electricity consumption demand was the basis of setting the generation and storage capacity of the power system.

Economic analysis starts with calculating the cost and benefits lost and gained in monetary terms. First, selection of what inputs are considered cost items and benefits must be decided. Then, to analyze the feasibility of a project, commonly used indicators such as the B/C ratio, net present value (NPV), and internal rate of return (IRR) are evaluated. In the case of the B/C ratio a number larger than one means that the benefits are greater than the costs, the greater the NPV value the more profitable a project is and finally, an IRR greater than the market interest rate or discount rate applied means the project delivers greater returns than the market (Yoon, 2015).

In order to determine what constitutes as cost and benefits of the project in this paper, economic analysis is conducted from the viewpoint of the business entity. The costs and benefits items of the project from the perspective of the business entity are summarized as follows:

Table 1 Items for Cost and Benefit

Cost	Revenue
Capital cost	FIT subsidy = (RE production × subsidy)
Replacement cost	
Operation & Management cost (D&A)	

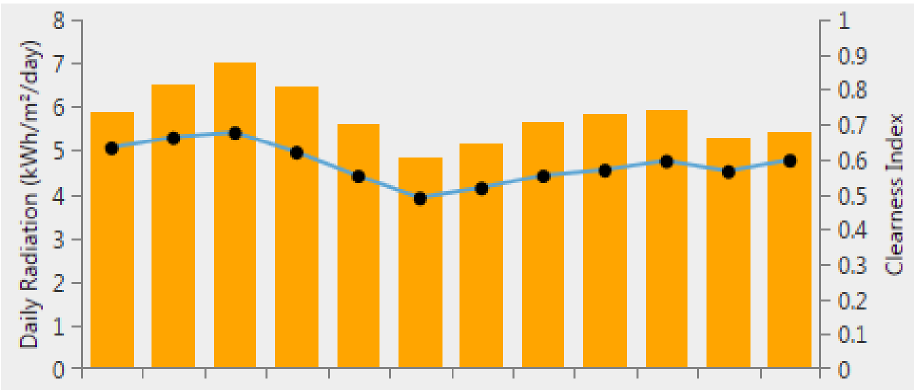
It is common for project entities to pay for initial equipment and system construction costs, initial transportation and installation costs, equipment and system replacement costs, and annual operation and maintenance expenses. Meanwhile, the electricity generated by the system, exchanged into monetary terms as the Feed-In-Tariff (FIT) subsidy provided by the Maldivian government can be regarded as the benefit of the project.

3.1. Kumundhoo Island

In 1990, only about six islands of the 190+ islands in the Maldives had regular 24-hour access to electricity. By 2008, Maldives achieved universal access of electricity with total installed capacity of 141MW of diesel generators. However, due to the fact that there is no existing national grid, each island is effectively a mini-grid with a diesel-based generation system. Thus outer islands are the most vulnerable to technical and economic fluctuations due to their much lower energy demand (14-23,000MWh per island, while total consumption is 181.57GWh per year) and lower generation capacity compared to the capital Male with annual consumption of 247.17GWh and installed capacity of 69.82MW (ADB, 2014).

SIDS and the Maldives have much potential to scale up renewable energy

Figure 1　Kumundhoo Solar Radiation and Clearness



Source: NASA database.

Table 2 Kumundhoo Monthly Electricity Demand

(unit: kWh)

Month	Electricity Consumption	Index
January	49,564	94.3
February	44,490	84.6
March	46,679	88.8
April	52,572	100.0
May	53,098	101.0
June	53,342	101.5
July	56,656	107.8
August	54,308	103.3
September	51,839	98.6
October	54,650	104.0
November	51,081	97.2
December	50,915	96.8
Year Total	619,192	–

generation thanks to the climate conditions — high solar radiation, wind and geothermal capacities. As for Kumundhoo, a steady daily radiation of over five hours across seasons.

According to 2006 census, 889 people inhabit the island. It is located approximately 269km from Male, the capital of Maldives but can only be accessed via air or sea travel. The inhabitation of Kumundhoo is for residential purposes thus the energy demand of Kumundhoo is quite constant during the day (with a small peak in the afternoon). Currently, the utility company, FENAKA supplies the island its electricity.

3.2. Cost Components

In this paper, four cases of system design specifications were considered based on an estimated 3% annual increase in households, thus buildings, for Kumundhoo Island. The maximum power output of the system was set as

Table 3 Four Cases for System Configuration

Case	Diesel Production	PV capacity	ESS capacity	Life
1	30%	150kW	860kWh	10 year
2	30%	150kW	1.1MWh	20 year
3	−	200kW	1.5MWh	10 year
4	−	200kW	2MWh	20 year

120kW when designing the power system configurations.

The optimum construction plan was selected based on the assumption that the existing diesel generator be combined with solar power system and ESS in conjunction for Kumundhoo Island. Among the four cases, a 30% of diesel generator operation rate was selected as the optimum specification. Then, for the remaining two cases — 20 years PV usage and 30% diesel generation, the costs (system cost, transportation cost, construction cost, installation cost, and replacement cost) of each system configurations were computed for evaluation.

The system construction cost consists of system cost, transportation cost, construction cost, installation cost and replacement cost are presented in Table 4. Such system construction costs are expected to occur only in 2017 because the period required for system transportation and installation is expected to be one year. Installing a 1.1MWh size battery with 20 year PV costs a total of $1,086,000, approximate 16% less than the cost of installing and after

Table 4 Costs Scenarios for Different ESS Specifications

(unit: $)

	ESS 10 year use			ESS 20 year use		
	PV 150kW	ESS 860kWh	Total	PV 150kW	ESS 1.1MWh	Total
System cost	183,000	600,000	783000	183,000	696,000	879,000
Shipping cost[1)]	15,000	11,000	26,000	15,000	11,000	26,000
Construction cost	80,000	−	80,000	80,000	−	80,000
Installation cost	38,000	63,000	101,000	38,000	63,000	101,000
Replacement cost	−	305,000	305,000	−	−	−
Total	316,000	980,000	1,296,000	316,000	770,000	1,086,000

Note: [1)]$3600/40ft container.

Table 5 Annual Costs of Operations

(unit: $)

	ESS 20 year use			Notes
	PV 150kW	ESS 1.1MWh	Total	
Depreciation & Amortization	–	17,400	17,400	- Replacement cost after 20 years is 50% of system cost
Yearly Operation cost	3,660	34,000	38,460	- 2% of PV system cost - 5% of ESS system cost

10 years replacing an 860MWh size battery. Thus, the power system most appropriate for further evaluation for Kumundhoo Island is a 150kW PV-1.1MWh ESS with 30% diesel generation system.

Besides calculating the cost of initial construction, annual operation and management costs and depreciation costs must also be considered. For the purposes of this study a project lifetime of 20 years, starting the year of 2017 and ending in 2036 has been set. The following Table 5 is a summary of the estimated annual costs.

First, total replacement costs for the ESS were estimated to be 50% of the system costs system and were depreciated as yearly costs for the 17 years of the project, which came out as $17,400/year. For the PV system, depreciated replacement costs were included in the yearly operation cost.

Second, the annual operation cost, which includes labor and maintenance, was estimated as 5% of ESS system and 2% of PV system costs — each $34,000 and $3,660 per year. In addition, PV and ESS are assumed to have a steady increase in annual operation costs because it is necessary to operate for longer periods of time in order to produce equal amounts of electricity due to the decreased efficiency of the systems. The annual efficiency reduction for ESS is estimated to be around 1% while for PV a reduction of 0.5% annually. Therefore, annual operating costs are assumed to increase by 1% for ESS and 0.5% for PV.

Other costs related to the construction site were calculated as investment costs so the residual value was not separately indicated in the cost-benefit analysis. Appendix A summarizes all cost items across the project lifetime. Based on these criteria, Appendix B shows the total cost for operating the power system by year. A total of $2,244,663 is expected for investment and operation for the next 20 years.

3.3. Benefit Components

In the paper, it is assumed that the amount of subsidy received from the Maldivian government through the suggested PV-Diesel-ESS system is the most direct benefit. To calculate such benefits, it is necessary to estimate the annual electricity generation from the 150kW PV-1.1MWh ESS system and considering Kumundhoo’s monthly electricity consumption. Appendix C outlines Kumundhoo’s 2015 monthly consumption.

Monthly electricity usage is highest in the summer and winter while relatively low in the spring and fall. The total annual electricity usage of Kumundhoo Island in 2015 is approximately 619,192kWh, with an average annual increase of 11.7% since 2013 (backwards calculated using 2013 consumption of 496,088kWh). In other words, the amount of electricity to be generated by the PV-ESS system portion is 70% of the total demand because 30% will be generation via diesel. Therefore, PV-ESS power generation for this project is approximately 433,435kWh in the first year.

FENAKA Ltd. Estimates annual electricity demand to grow by approximately 4% annually in the next 3-4 years (12-15% in 3 years) for Kumundhoo Island. This is a conservative estimation compared to the current trend in electricity consumption of Kumundhoo so for the purposes of this study an annual increase of 4% in electricity consumption was assumed. As a result, the total electricity consumption of Kumundhoo Island will reach 1,410MWh by 2036, and the PV + ESS constructed through this project will cover 70% of the total electricity consumption and will generate electricity of 989MWh per year by 2036.

The monetary benefits from the renewable power system will come from the FIT scheme for renewable energy implemented by the Maldives

Table 6 Feed-in Tariff (FIT) Subsidies by Region in Maldives

(unit: $/kWh)

State Electric Company Limited	0.22
North Region	0.29
Central Region	0.26
South/Upper Central Region	0.35
South Region	0.26
AVERAGE	0.29

government (Ministry of Environment and Energy, 2013) of the amount of FIT subsidy provided by the Maldives is different according to the type of power supply and the region as shown in the following Table 6.

In this paper, the average of the FIT subsidies, $0.29/kWh, was used as the FIT benefits of the energy systems.

4. RESULTS

Based on the calculations from the previous section, the suggested renewable energy power system of 150kW PV-1.1MWh ESS realizes an annual income between $149,391 and $286,432 from FIT subsidies and a total of $3,912,462 for the total 20years' project period. The following Table 7 shows the annual revenue calculations.

For cost-benefit analysis, a 5.5% discount rate was applied to calculate the costs and benefits at present value (2017 — starting year of the project). Beginning in the year 2017, the total cost required for system construction (fixed) and operation (variable) came out as $2,244,663, while the total revenue expected from FIT subsidies was $3,912,462. Although the difference maybe smaller due to the high initial investment costs, which when calculated at present value will be even larger; the benefit of the power system over the 20-year project lifetime is much larger than the cost. The differences between cost and benefits are calculated in the Table 8 with 5.5% discount rate.

Table 7 Projected Electricity Demand + Annual Revenue*

(units: kWh, $)

	Year	A. Kumundhoo Total Electricity[1)]	B. RE Generation (kWh) [A*70%]	Yearly Profit ($) [B]*FIT
1	2017	669,719	–	–
2	2018	696,507	487,555	141,391
3	2019	724,368	507,057	147,047
4	2020	753,342	527,340	152,928
5	2021	783,476	548,433	159,046
6	2022	814,815	570,371	165,407
7	2023	847,408	593,185	172,024
8	2024	881,304	616,913	178,905
9	2025	916,556	641,589	186,061
10	2026	953,218	667,253	193,503
11	2027	991,347	693,943	201,243
12	2028	1,031,001	721,701	209,293
13	2029	1,072,241	750,569	217,665
14	2030	1,115,131	780,591	226,372
15	2031	1,159,736	811,815	235,426
16	2032	1,206,125	844,288	244,843
17	2033	1,254,370	878,059	254,637
18	2034	1,304,545	913,182	264,823
19	2035	1,356,727	949,709	275,416
20	2036	1,410,996	987,697	286,432
Total		19,942,933	13,960,053	3,912,462

Note: *Calculated by assuming 4% yearly increase based on 2015 electricity consumption.

Table 8 Present Value of Annual Profits (5.5% discount rate)

(unit: $)

	Year	Year to date Value			Present Value		
		Cost	Benefit	Cost-Benefit	Cost	Benefit	Cost-Benefit
1	2017	1,141,860	0	–1,141,860	1,141,860	0	–1,141,860
2	2018	56,071	141,391	85,320	53,147	134,020	80,872
3	2019	56,282	147,047	90,764	50,567	132,114	81,547
4	2020	56,496	152,928	96,433	48,112	130,236	82,124
5	2021	56,710	159,046	102,336	45,777	128,384	82,607
6	2022	56,925	165,407	108,482	43,556	126,559	83,003
7	2023	57,142	172,024	114,881	41,442	124,760	83,317
8	2024	57,360	178,905	121,544	39,432	122,986	83,554
9	2025	57,580	186,061	128,481	37,519	121,237	83,718
10	2026	57,801	193,503	135,703	35,699	119,513	83,814
11	2027	58,023	201,243	143,221	33,968	117,814	83,846
12	2028	58,246	209,293	151,047	32,321	116,139	83,818
13	2029	58,471	217,665	159,194	30,754	114,488	83,733
14	2030	58,697	226,372	167,675	29,264	112,860	83,596
15	2031	58,924	235,426	176,503	27,846	111,255	83,410
16	2032	59,153	244,843	185,691	26,496	109,673	83,177
17	2033	59,383	254,637	195,255	25,213	108,114	82,901
18	2034	59,614	264,823	205,209	23,991	106,577	82,586
19	2035	59,847	275,416	215,569	22,829	105,062	82,232
20	2036	60,081	286,432	226,351	21,724	103,568	81,844
Total		2,244,663	3,912,462	1,667,800	1,811,519	2,245,359	433,840

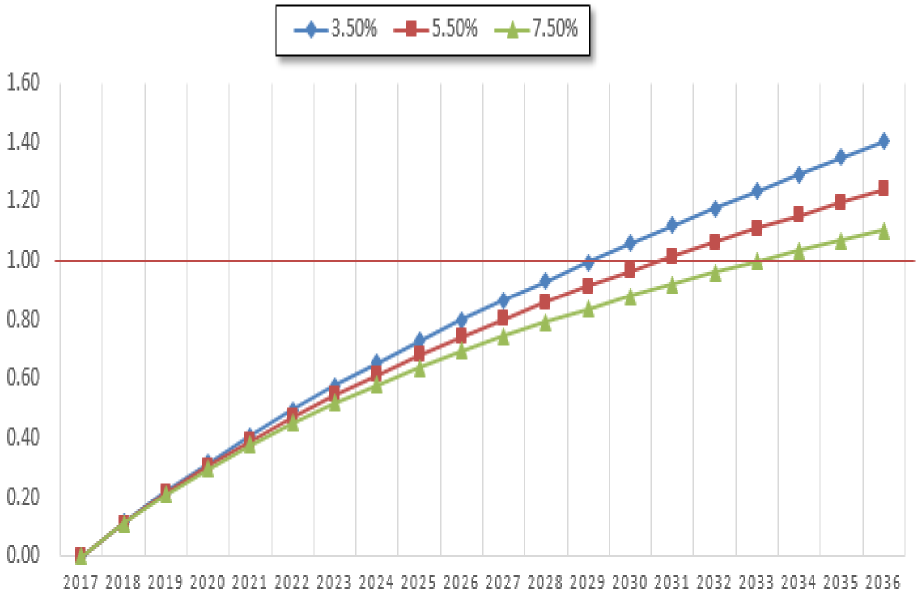
Table 9 Cost-benefit Analysis (B/C ratio, NPV, IRR calculations)

Year	Total Cost-Benefit Analysis		
	B/C	NPV ($)	IRR (%)
2017	0.00	–1,141,860	–
2018	0.11	–1,060,988	–92.5
2019	0.21	–979,440	–67.8
2020	0.31	–897,317	–47.2
2021	0.39	–814,709	–32.7
2022	0.47	–731,706	–22.5
2023	0.54	–648,389	–15.2
2024	0.61	–564,835	–9.9
2025	0.68	–481,117	–5.8
2026	0.74	–397,303	–2.7
2027	0.80	–313,457	–0.2
2028	0.86	–229,639	1.8
2029	0.91	–145,906	3.4
2030	0.96	–62,310	4.7
2031	1.01	21,100	5.8
2032	1.06	104,277	6.7
2033	1.11	187,178	7.4
2034	1.15	269,764	8.1
2035	1.20	351,996	8.7
2036	1.24	433,840	9.1

The economic feasibility of the energy systems considered in this paper is evaluated by calculating the B/C (benefit-cost) ratio, net present value (NPV), and the internal rate of return (IRR) each year from 2017 to 2036. When the discount rate of 5.5% is applied, the B/C ratio is greater than 1, the NPV is positive, and the IRR is greater than 5.5% from 2031. In addition, the B/C ratio until 2036, which is 20 years after the implementation of the project, is 1.24, indicating that the project is economically feasible. In the case of NPV, the net profit that can be expected until 2036 is equivalent to the current value of 2017 as $433,840. In addition, the internal rate of return for the same period is expected to be very high, at 9.1%.

In the case of economic analyses, there are uncertainties from external sources, such as market conditions, local politics, technological issues, etc. that have to be taken into consideration even if the project itself runs

Figure 2 Profitability Based on Different Discount Rates



smoothly. Therefore, it is necessary to carry out the sensitivity analysis reflecting such uncertainties using different discount rates. For this case, the discount rate of 5.5% has been assumed so for the sensitivity analysis a ±2% in discount rate has been applied. The following Figure 2 shows the results of analysis.

It was found from the sensitivity analysis that the B/C ratio and NPV decreases as the discount rate increases and still achieves a 1.10 B/C ratio and NPV of $170,587 with the highest discount rate. Appendix D shows the calculations of the Figure 2. From the point of Maldives, the profitability of renewable energy project is not changed substantially with different discount rates since the initial investment cost of renewable energy system is not high.

A sensitivity analysis with different FIT subsidy payments was also conducted to evaluate the economics of the monetary benefits from the project. The average FIT subsidy rate of $0.29/kWh, $0.26/kWh and the highest rate of $0.35/kWh were used. The results are summarized in the Table 10 below.

Table 10 Profitability Changes Based on FIT Payment Level

(unit: $)

FIT Subsidy Payment Level	Total Cost-Benefit Analysis		
	B/C	NPV	IRR
$0.26/kWh (Lowest region)	1.11	201,562	7.3%
$0.29/kWh (Avg.)	1.24	433,840	9.1%
$0.35/kWh (Highest region)	1.50	898,397	12.6%

Table 11 Electricity Price in Kumundhoo Island

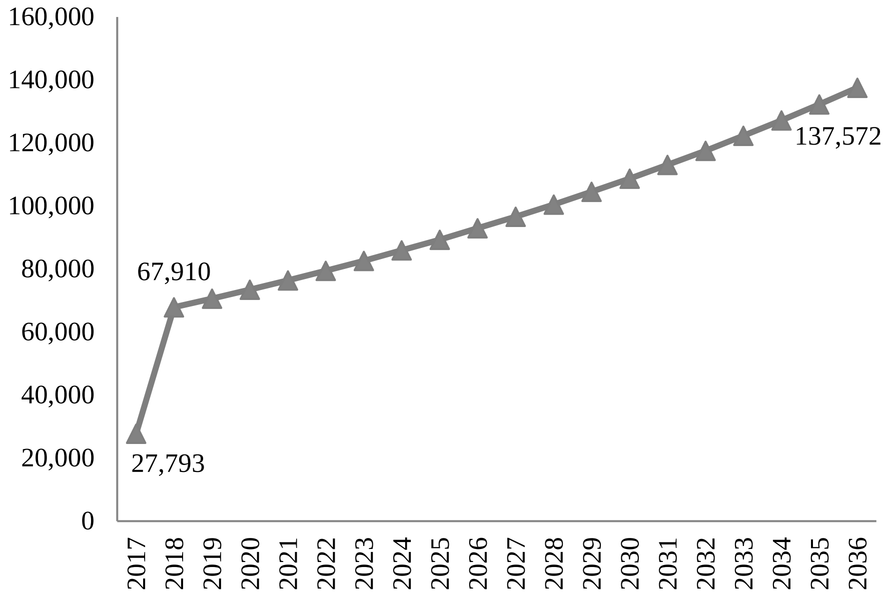
(unit: $)

	0-100kWh	101-200kWh	201-300kWh	301-400kWh	>401kWh	Average
Assumed Price	0.3445	0.38025	0.3575	0.4875	0.4875	0.41145
Subsidy Proportion of Assumed Price	29%	26%	18%	27%	27%	25%

In the case of minimum subsidy payment, the B/C ratio for the next 20 years is 1.11, which is still economically feasible. However, the benefits of the project vary greatly depending on the level of the subsidy, thus prior coordination with the government of the Maldives is important prior to project implementation.

Finally, an economic analysis of the suggested project was done in the perspective of the Maldivian government. First, an electricity sales price for Kumundhoo Island was calculated based on the usage amount as shown below. The average price calculated based on $0.4115/kWh, which in fact is roughly the same price as the reported sales price, $0.42/kWh, of the current supplier FENAKA.

Figure 3 Annual Profit for Maldives Government ($)



The cost-benefit of the project is positive from the perspective of the Maldivian government. As show in the Figure 3 graph below as well as the calculations in Appendix E, the total cost equals $6,299,585 while the revenue from electricity sales equals $8,206,517.

5. CONCLUSION

Under the different conditions for the key parameters, a sensitivity analysis with different discount rates and different FIT rates, the B/C ratio, NPV, and IRR for the renewable energy project with different system configurations tell us that such renewable energy systems are economically viable. When the FIT rate is $0.29/kWh and the discount rate at 5.5%, the B/C ratio comes out to be 1.3, which proves that the project is indeed economically beneficial for the

Maldivian government. Because the initial investment costs are not applicable in the perspective of the government, the various discount rates do not relatively affect the economic analysis. The sensitivity analysis showed that FIT subsidy payment differences and electricity utility charges were more important. When the FIT subsidy was set at the highest price $0.35/kWh, the B/C ratio resulted in 1.15, which still means economic feasibility yet less profitable. Also, when the lowest electricity utility charge of $0.3445/kWh was applied the economic feasibility was still positive.

In this paper, an economic assessment on decentralized hybrid energy systems in Kumundhoo Island was conducted with cost-benefit analyses. The positive results of the analyses could be translated as the direct effects, in monetary units, when the suggested hybrid PV-Diesel-ESS power system is implemented in the Maldives. Additional benefits such as reduction of greenhouse gas emissions, stable supply of electricity, and reduced burden of fluctuating oil prices further demonstrate the advantages of the project, especially from the perspective of the Maldives government.

With growing attention and efforts to mitigate effects of climate change, especially in the small island states who are the most vulnerable, economic viability of renewable energy systems is a prerequisite to scale up deployment of sustainable, zero-carbon energy options such as the system examined in this paper. To meet the Maldives' government's ambitious program to make the Maldives carbon neutral by 2020, where electricity generation must be from non-diesel sources, the information gained from the present work maybe instrumental in the execution or development of a hybrid PV-Diesel-ESS power system in Kumundhoo Island, Maldives.

APPENDIX

A. Annual Cost Breakdown

	Year	Cost Item						Total Cost
		System	Shipping	Construction	Installation	D&A	O&M	
1	2017	879,000	26,000	80,000	101,000	17,400	38,460	1,141,860
2	2018					17,400	38,671	56,071
3	2019					17,400	38,882	56,282
4	2020					17,400	39,096	56,496
5	2021					17,400	39,310	56,710
6	2022					17,400	39,525	56,925
7	2023					17,400	39,742	57,142
8	2024					17,400	39,960	57,360
9	2025					17,400	40,180	57,580
10	2026					17,400	40,401	57,801
11	2027					17,400	40,623	58,023
12	2028					17,400	40,846	58,246
13	2029					17,400	41,071	58,471
14	2030					17,400	41,297	58,697
15	2031					17,400	41,524	58,924
16	2032					17,400	41,753	59,153
17	2033					17,400	41,983	59,383
18	2034					17,400	42,214	59,614
19	2035					17,400	42,447	59,847
20	2036					17,400	42,681	60,081
Total		879,000	26,000	80,000	101,000	348,000	810,663	2,244,663

B. Total Cost of Operations

	Year	System Capacity		Yearly Operation Cost		
		PV (kW)	ESS (MWh)	PV	ESS	Total
1	2017	1.100	150	3,660	34,800	38,460
2	2018	1.089	149.25	3,697	34,974	38,671
3	2019	1.078	148.5	3,734	35,149	38,882
4	2020	1.067	147.75	3,771	35,325	39,096
5	2021	1.056	147	3,809	35,501	39,310
6	2022	1.045	146.25	3,847	35,679	39,525
7	2023	1.034	145.5	3,885	35,857	39,742
8	2024	1.023	144.75	3,924	36,036	39,960
9	2025	1.012	144	3,963	36,217	40,180
10	2026	1.001	143.25	4,003	36,398	40,401
11	2027	0.990	142.5	4,043	36,580	40,623
12	2028	0.979	141.75	4,083	36,763	40,846
13	2029	0.968	141	4,124	36,946	41,071
14	2030	0.957	140.25	4,165	37,131	41,297
15	2031	0.946	139.5	4,207	37,317	41,524
16	2032	0.935	138.75	4,249	37,503	41,753
17	2033	0.924	138	4,292	37,691	41,983
18	2034	0.913	137.25	4,335	37,879	42,214
19	2035	0.902	136.5	4,378	38,069	42,447
20	2036	0.891	135.75	4,422	38,259	42,681
Total				80,590	730,073	810,663

C. Kumundhoo's Monthly Electricity Consumption

Month	Electricity Consumption	Index (100% - March)	PV・ESS Generation (70% of Electricity Consumed)
January	49,564	94.3	34,695
February	44,490	84.6	31,143
March	46,679	88.8	32,675
April	52,572	100.0	36,800
May	53,098	101.0	37,168
June	53,342	101.5	37,339
July	56,656	107.8	39,659
August	54,308	103.3	38,016
September	51,839	98.6	36,287
October	54,650	104.0	38,255
November	51,081	97.2	35,757
December	50,915	96.8	35,640
Year Total	619,192	−	433,435

D. Sensitivity Analysis of B/C Ratio and NPV

	Year	B/C			NPV		
		3.5%	5.5%	7.5%	3.5%	5.5%	7.5%
1	2017	0.00	0.00	0.00	–1,141,860	–1,141,860	–1,141,860
2	2018	0.11	0.11	0.11	–1,059,425	–1,060,988	–1,062,492
3	2019	0.22	0.21	0.21	–974,696	–979,440	–983,951
4	2020	0.32	0.31	0.30	–887,718	–897,317	–906,326
5	2021	0.41	0.39	0.38	–798,539	–814,709	–829,697
6	2022	0.49	0.47	0.45	–707,200	–731,706	–754,133
7	2023	0.57	0.54	0.52	–613,744	–648,389	–679,694
8	2024	0.65	0.61	0.58	–518,211	–564,835	–606,433
9	2025	0.73	0.68	0.64	–420,641	–481,117	–534,393
10	2026	0.80	0.74	0.69	–321,072	–397,303	–463,613
11	2027	0.86	0.80	0.74	–219,540	–313,457	–394,123
12	2028	0.93	0.86	0.79	–116,081	–229,639	–325,949
13	2029	0.99	0.91	0.84	–10,728	–145,906	–259,111
14	2030	1.06	0.96	0.88	96,484	–62,310	–193,623
15	2031	1.12	1.01	0.92	205,524	21,100	–129,497
16	2032	1.18	1.06	0.96	316,361	104,277	–66,740
17	2033	1.23	1.11	1.00	428,965	187,178	–5,355
18	2034	1.29	1.15	1.03	543,309	269,764	54,659
19	2035	1.35	1.20	1.07	659,363	351,996	113,305
20	2036	1.40	1.24	1.10	777,101	433,840	170,587

E. Cost-benefit Analysis (Maldives Government Perspective)

	Year	Yearly Generation (kWh)			Generation Cost ($)			Fee Income
		PV+ESS (70%)	Diesel (30%)	Total	PV+ESS FIT	Diesel Generation	Total Cost	
1	2017	–	669,719	669,719	–	247,796	247,796	275,589
2	2018	487,555	208,952	696,507	141,391	77,312	218,703	286,613
3	2019	507,057	217,310	724,368	147,047	80,405	227,451	298,077
4	2020	527,340	226,003	753,342	152,928	83,621	236,549	310,000
5	2021	548,433	235,043	783,476	159,046	86,966	246,011	322,400
6	2022	570,371	244,445	814,815	165,407	90,444	255,852	335,296
7	2023	593,185	254,222	847,408	172,024	94,062	266,086	348,708
8	2024	616,913	264,391	881,304	178,905	97,825	276,729	362,657
9	2025	641,589	274,967	916,556	186,061	101,738	287,799	377,163
10	2026	667,253	285,966	953,218	193,503	105,807	299,311	392,249
11	2027	693,943	297,404	991,347	201,243	110,040	311,283	407,939
12	2028	721,701	309,300	1,031,001	209,293	114,441	323,734	424,257
13	2029	750,569	321,672	1,072,241	217,665	119,019	336,684	441,227
14	2030	780,591	334,539	1,115,131	226,372	123,780	350,151	458,876
15	2031	811,815	347,921	1,159,736	235,426	128,731	364,157	477,231
16	2032	844,288	361,838	1,206,125	244,843	133,880	378,723	496,321
17	2033	878,059	376,311	1,254,370	254,637	139,235	393,872	516,173
18	2034	913,182	391,364	1,304,545	264,823	144,805	409,627	536,820
19	2035	949,709	407,018	1,356,727	275,416	150,597	426,012	558,293
20	2036	987,697	423,299	1,410,996	286,432	156,621	443,053	580,625
Total		13,960,053	5,982,880	19,942,933	3,912,462	2,387,123	6,299,585	8,206,517

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