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학 술

A Solar Energy System with Energy Storage System for Kandooma Island, Maldives*

Tae Yong Jung** · Donghun Kim***

Abstract

Small Island Developing States (SIDS) are the most vulnerable to climate change and their capacity to adapt climate change is very limited. This is the main reason why the global community pays special attention to SIDS. Maldives is a typical example of SIDS where eco-tourism is the main economic activity. However unfortunately, Maldives heavily rely on imported oil and fossil fuels for power generation, which means that the energy system of each island in Maldives is sensitive to the volatile oil price. It is common to use diesel generators, at small islands in Maldives. The selected site is a resort island, Kandooma where we assume to replace one diesel generator with a solar system with ESS in a hotel. We compare the conventional diesel generation and with a solar energy system equipped with the most advanced Energy Saving System (ESS) to demonstrate the

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** Professor, Graduate School of International Studies, Yonsei University, Seoul, Korea
*** Professor, Graduate School of International Studies, Yonsei University, Seoul, Korea
(Corresponding Author: dhkim2@yonsei.ac.kr)

application of leap-frogging technology in SIDS. In addition, the result of financial simulation analysis provides feasible financial options to install a solar energy system in a remote island.

Key Words : SIDS, energy system, financial analysis
JEL : Q42, Q55

Ⅰ. Introduction

Maldives is a SIDS of 1,192 islands located in Indian Ocean. The population of Maldives was about 370,000 in 2016 and per capita income in 2014 was about $14,000. Maldives has the highest cost of power generation in South Asia due to heavy dependence on diesel. Unlike other countries in this region, Maldives has achieved 100% electrification. Each island has its own powerhouse and distribution facility, but the disparity between large and small islands in terms of the cost of power generation, fuel efficiency and reliability exists. Maldives strongly promotes renewable energy options to ensure stable power supply with domestic energy sources, as well as mitigate CO_2 emissions. In 2009, the government of Maldives announced the ambitious program to make the Maldives carbon neutral by 2020, meaning all electricity generation must be from non-diesel sources.

An independent off grid power system is common in Maldives, where most of the existing systems are based on diesel generators. However, many of such remoted islands are located in tropical zones, which makes solar feasible as energy sources. A recent development in renewable energy technology make an independent power system reach to grid parity quickly with the use of hybrid energy system, which integrates the conventional diesel generator with renewable energy sources such as solar Photovoltaic (PV) or wind options. The new technology of energy storage system (ESS) makes unreliable renewable sources stable with the existing energy supply system.

The objective of this study is to analyze alternative energy options for a resort hotel in Kandooma Island, Maldives. Kandooma Island in Maldives is located in South Male Region, which is about 35km south from the capital, Male. Since the economic activities of the island is based tourism, the stable and environmentally friendly energy system is the key factor. The existing diesel generators are not environmentally friendly, nor the economically viable energy option. Sustainable energy options will be examined with feasible financial resources to install new energy systems.

Various researches on the application of hybrid energy systems in remote islands were conducted. Jung, et al. (2017) conducted a study on the economic feasibility of a hybrid PV-Diesel-ESS system for Kumundhoo, Maldives. An economic analysis was examined with different discount rates, feed-in tariff (FIT) rates, the benefit-cost ratio, net present cost (NPC), and internal rate of return (IRR). Lal (2012) studied a techno-economic analysis of a Wind-PV-Diesel hybrid mini-grid system for Fiji Islands, Nabouwalu. Blechinger, (2014) found that hybrid power systems showed higher reliability of the system and lower cost of generation than those that use only one source of energy, since different energy sources could be complimentary during the power generation. Wichert et al. (2001) studied techno-economical characteristics of hybrid power systems. They found that the hybrids power systems were more favorable when the cost of the transportation of fuel was incorporated in the analysis. Akikur (2013) presented comparative case studies of independent solar and hybrid solar systems implemented at various locations over the last twelve years. He found that the diesel as a stand-alone source involved high maintenance demands for rural populations, who are often poor with low levels of education and capacity for modern technology. Even if a diesel-based power system is difficult to be replaced due to its reliability as a source, both the stand-alone solar-PV system and the hybrid solar-PV system are getting competitive in terms of the cost of power generation and low maintenance cost.

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. Rehman (2010) found that diesel only system was un-economical and for hybrid systems since the major part of the total system cost was for solar PV panels and batteries. Recent studies emphasized that battery storage in designing an independent power system need to overcome many barriers before it can be integrated as a mainstream option. In the case of Nigeria, Adaramola (2014) showed that the cost of generating electricity using the hybrid energy system was significantly cheaper than using a generator only based energy system with and without battery. However, it was also found that the cost of energy system is highly dependent on the interest rate and diesel price. Shakarchi (2014) found that an independent power system in remote islands got benefits from the renewable energy options in the long run and additional implementation of batteries leads to further cost reductions.

In the following sections, solar energy options and their costs for Kandooma Island are analyzed with HOMER (Hybrid Optimization of Multiple Electric Renewables). After the optimal energy option is identified, the simulation analysis for feasible financial options are conducted. Conclusion and policy discussions will be made based on the results of the energy system analysis.

Ⅱ. Methodology

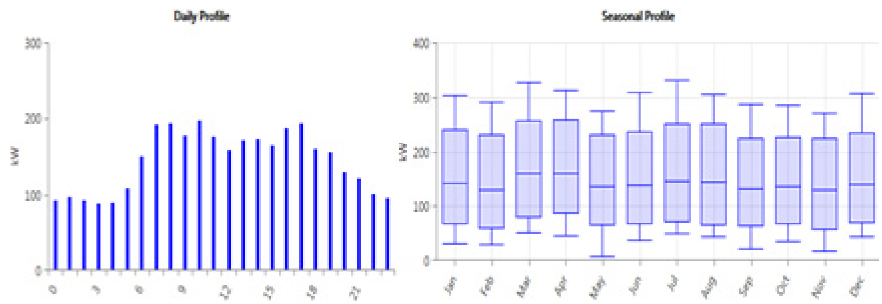
HOMER is a linear optimization program to analyze technical feasibility of various energy systems, which was developed by the National Renewable Energy Laboratory, USA. Hourly load and monthly load variations are critical input parameters for HOMER to design a power system configuration to determine its technical feasibility and life-cycle cost. HOMER analyzes different energy system configurations in search of the one that satisfies the technical constraints at the lowest life-cycle cost. Hence, multiple optimizations under a range of input assumptions to measure the effects or changes in the model inputs could be examined. (Sureshkumar et al, 2012).

HOMER program optimizes the total NPC to represent the life cycle costs of energy systems that are specified by the users, which includes all costs that could occur during the project lifetime, with future cash flows discounted to the present. Levelized Cost of Electricity (LCOE) is the average cost per kilowatt-hour of electricity generation by the energy systems, which can be calculated by HOMER. (HOMER® Pro 2016).

1. Input Assumptions for HOMER

Given the daily load patterns measured and its monthly variation calculated, the input variables for HOMERS are shown in Figure 1. Since the site is a resort hotel, the daily load pattern is relatively stable and the gap between peak and off-peak is not huge. In addition, the monthly load pattern is not varying significantly, because Maldives is located in the tropical zone. Furthermore, in this study, it is assumed that one diesel generator is replaced with solar PV and ESS system to check the initial impact of the change of power system in terms of stable power supply.

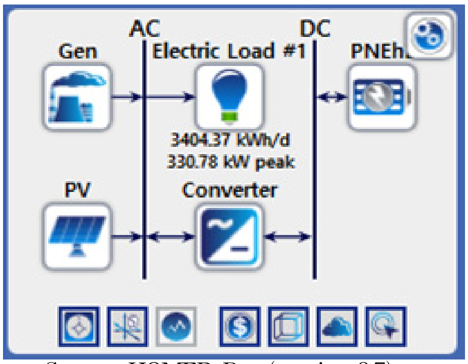
〈Figure 1〉 Daily and Monthly Load Patterns of Kandooma Island



To determine the feasibility of energy system configurations, the NPC of the energy system options was calculated with 8% discount rate and project lifetime of 20 years. The current energy option in this resort island is to generate electricity with 5 diesel generators. The cost for diesel used for power generation in remoted island is very sensitive and relatively high with volatility of both international and domestic diesel price. In this analysis, the diesel price is assumed to be 0.61$/liter.

Energy system configuration is designed to include each component of different power system for simulation as shown in Figure 2.

〈Figure 2〉 Schematic Diagram Energy Systems for HOMER



Source: HOMER Pro (version 3.7)

To provide sustainable and low carbon energy options for this remoted island, solar PV with ESS was considered, which can be also designed with the existing diesel generators to set up a hybrid energy options. With the basic components of various energy options, the initial capital cost, replacement cost of some components during the lifetime of the system and the operation and maintenance (O&M) cost are identified and summarized in Table 1. Since the diesel generators are already installed, the capital cost is assumed to be zero, while its replace cost and operation and maintenance cost, including the cost of diesel are reflected. All cost components of PV and ESS as new components for the alternative energy options are shown in Table 1.

〈Table 1〉 Summary of System costs for Energy Options

Cost	Diesel Generator (per kW)	PV (per kW)	ESS (per unit)
Capital	$0	$1,881	$858,974
Replacement	$500	$1,200	$200,000
O&M	$0.3/hr	$1.03/year	$342/year

Source: Jung et al. (2017)

2. Simulation for Financial Analysis

@RISK, a risk analysis and simulation for financial analysis, which is add-in tool for Microsoft Excel developed by Palisades Corporation, is used to evaluate the hybrid power system's financial "risk" due to uncertainty of various project conditions. Financial indicators such as the internal rate of return (IRR) and the net present value (NPV), which convey a project's viability/attractiveness to investors are tested through @RISK's simulation. @RISK combines all the identified uncertain variables with given probability density functions (pdf) in order to repetitively generate a probability distribution of output variables. This simulation method is known as the Monte Carlo technique, which allows risk to be described with a probability distribution. For any input variable, distribution functions can be added to any number of cells and formulas throughout excel work-sheets and can include arguments through cell references and expressions, which allows sophisticated specifications of uncertainty. Meanwhile for output calculations, @RISK's simulation involves repetitive recalculations, which is call an "iteration" of the worksheet. This recalculation process can run hundreds or thousands of iterations if necessary.

Ⅲ. Simulation Results

1. Simulation Results by HOMER

Four types of energy system are considered to simulate power generation and its cost profiles. System type 1 (ST 1) is the one to install solar PV with ESS by replacing one existing diesel generator among 5 generators. ST 2 and ST 3 are different system configurations with solar PV only or ESS only, respectively. ST 4 is the existing energy system that is sole dependent on diesel generators which is the reference case.

With the cost information of each component of power systems, depending on system type, the LCOE and NPC are shown in Table 2. HOMERS determines the share of renewables in each system type to meet the daily and monthly load patterns as optimum solution for the combination of power generation by different sources. As shown in Table 2, the LCOE of ST 1 is lower than the existing power system (ST 4), even if the initial capital cost of ESS is relatively high. The key factor for the LCOE is both capital cost and O & M cost of different systems. In case of ST 4, the LCOE is sensitive to the change of diesel price, which is normally very high in remoted island due to the transportation cost, as pointed out by many previous studies.

In ST 1, HOMER find that the LCOE is \$0.291 and the NPC is \$4.19 million with 16% of renewable shares. Since this type is also an environmentally friendly configuration, the reduction of CO_2 emission is expected, which may be another social benefit of this system, as well as the cost competitiveness. However, the high upfront cost of new advances technologies such as ESS takes higher portion of LCOE, even if ESS provides stable power supply. On the other hand, the existing power system, ST 4 has more burden of O&M cost, due to the fuel cost, which results in the highest LCOE among four energy system types.

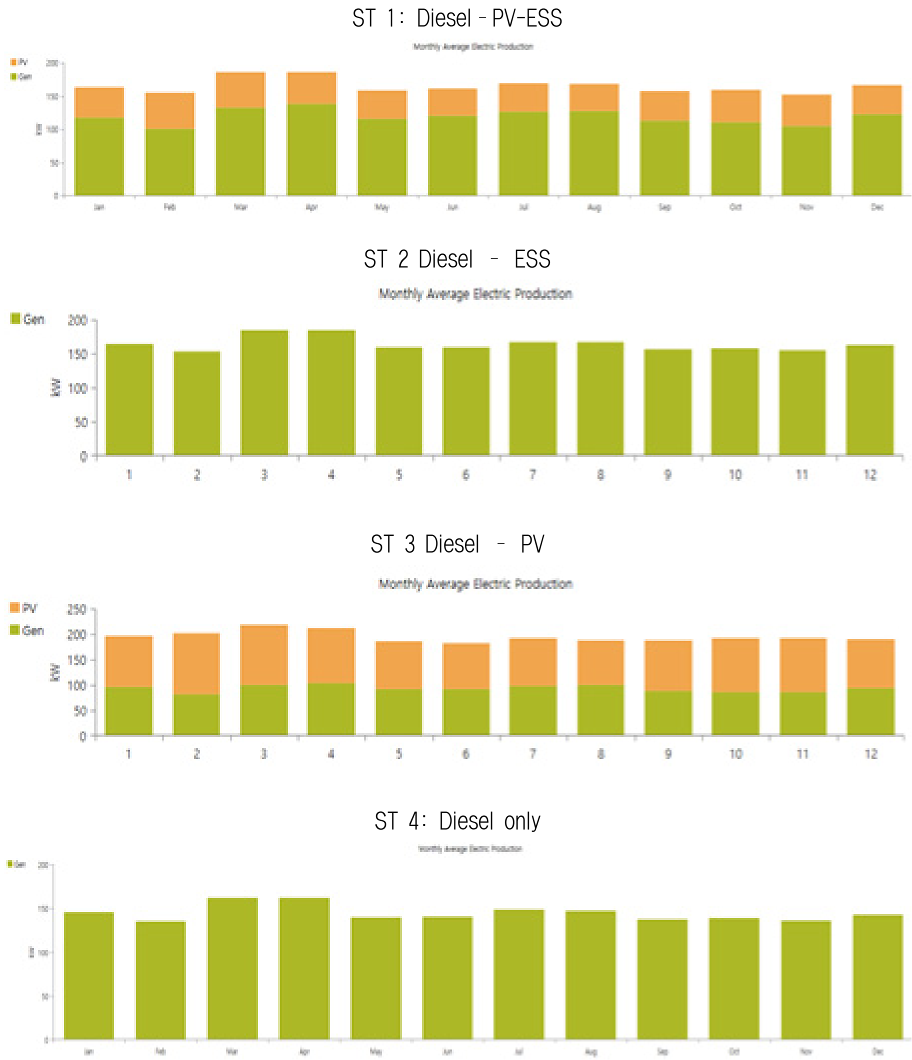
〈Table 2〉 Summary of Energy Systems by HOMER

System Type (ST)	System Configuration	Component				Cost		Renewable Share (%)
		PV(kW)	Diesel Generator (kW)	ESS (kWh)	Converter (kW)	LCOE ($/kWh)	NPC(M.$)	
ST 1	Diesel-PV-ESS	260	370	978	396	0.291	4.19	16
ST 2	Diesel-ESS		370	978	193	0.332	5.02	0
ST 3	Diesel-PV	260	370			0.346	4.78	19
ST 4	Diesel only (base case)		370			0.349	4.98	0

Source: Jung et al. (2017)

Since ST 2 and ST 3 are partial replacement of ST 4 with two different renewable components, the values of LCOE and NPC are shown between those of ST 1 and ST 4. For example, technically, ST 2 is not a feasible option for the regular system operation. However, for the back-up of the system, ESS option with the existing diesel generators could be considered. ST 3 could be realistic, but without ESS the energy system configuration could not be stable. Furthermore, ST 2 and ST 3 are not economically competitive, compared with LCOE of ST 1. The different shares of power generation by diesel and solar are shown in Figure 3. To generate same amount of power, ST 4 is sole dependent on diesel, which is the main source of uncertainty for the case of ST 4. It is worthwhile to note that March and April are two peak months in this resort island, reflecting climate conditions and the demand for the hotel accommodations.

〈Figure 3〉 Power Generation by System Type



PV is used only in ST1 and ST3 system but because ST3 does not include ESS, the system generates more power, meaning a less efficient system than ST1. Since diesel-generation amount is similar in both ST1 and ST3, ESS determines how much PV power generation is necessary.

2. Economic Analysis

Based on the results calculated by HOMER, the comparison among 4 system types is shown in Table 3. NPC and IRR ST 1 is not only economically competitive with higher Internal Rate of Returns (IRR), but also the payback period of the system is shorter than any other energy system, which is 6.7 years. The IRR and payback period is obtained by comparing the total cost and revenues with the base case, which is ST 4. IRR of ST 1 is somewhat high to 13%, compared with those of ST 2 and ST 3. ST 4 is the most optimal energy system for the site, since it does not totally replace the existing system, but improve the stability and provide alternative energy source.

〈Table 3〉 Comparison of Economic Cost

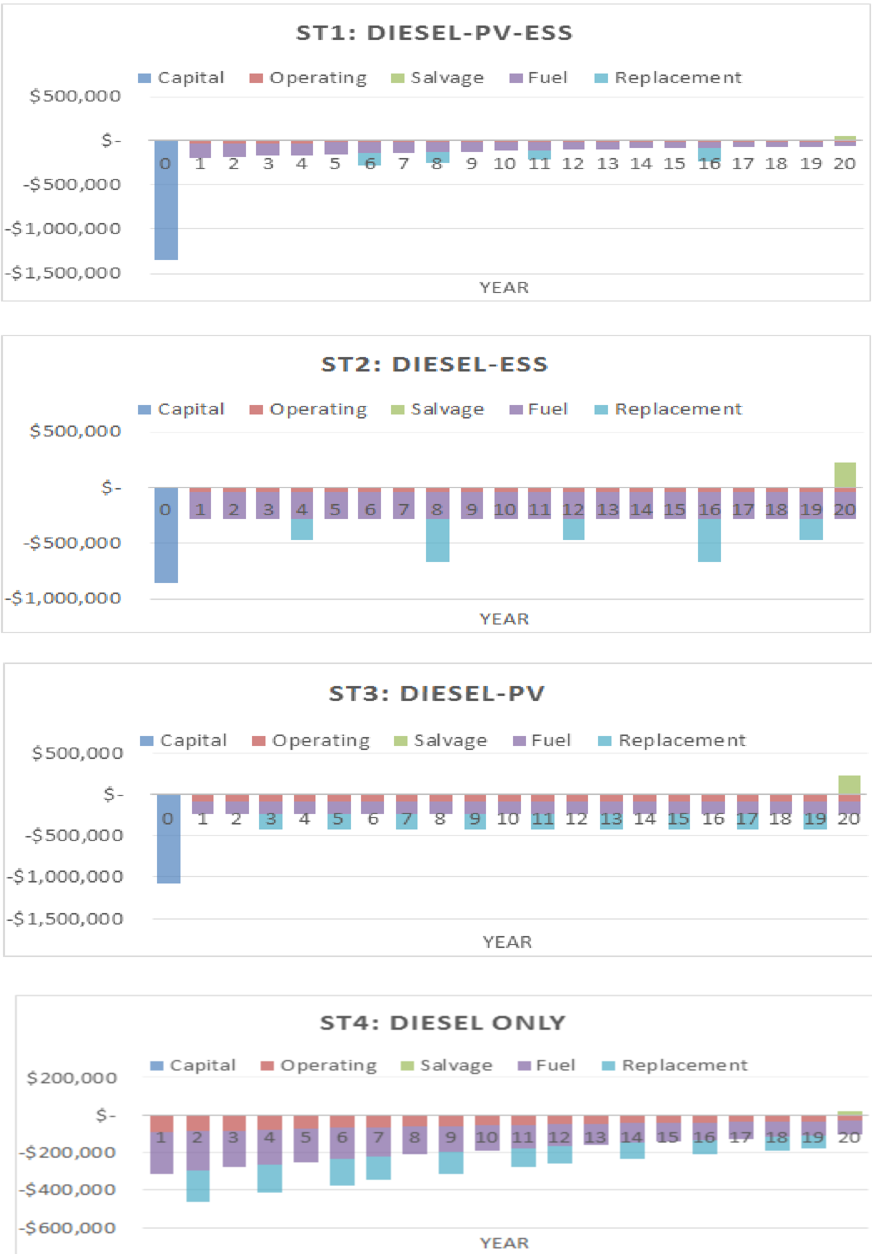
ST	System Configuration	Component				IRR (%)	Payback Period (Yr)
		LCOE ($/kWh)	NPC ($)	Capital ($)	O & M ($)		
ST 1	Diesel-PV-ESS	0.291	4.19M	1.3M	245,599	12.6	6.7
ST 2	Diesel- ESS	0.332	4.98M	858,974	338,920	8.9	6.8
ST 3	Diesel- PV	0.346	4.78M	489,060	387,845	7.2	11
ST 4	Diesel only (base case)	0.349	5.02M	0	433,146	-	-

〈Table 4〉 Comparison of Key Indicators by Discount Rate (%)

ST	LCOE ($/kWh)			NPC ($)		
	4%	8%	12%	4%	8%	12%
ST 1	0.263	0.291	0.323	5.37M	4.19M	3.46M
ST 2	0.315	0.332	0.352	6.42M	4.78M	3.77M
ST 3	0.335	0.346	0.359	6.82M	4.98M	3.84M
ST 4	0.348	0.349	0.349	7.09M	5.02M	3.74M

Figure 4 shows different cash flows for ST 1 – ST 4 with 8% discount rate. Since ST 1 requires high initial capital cost of more than 1 million US dollars, the cost burden at the initial stage is a challenge to install this system. On the other hand, the O & M cost is minimal, which makes this system is competitive in the long run during the lifetime period of 20 years. The cash flow of ST 4 shows the opposite trend. The initial capital cost is zero, but during the whole period, the shares of operation and fuel costs are consistently shown with extra burden of replacement of diesel generators. Especially, the uncertain future risk of volatile diesel price is not considered in ST 4. The clear distinction between two cash flows makes decision makers select options available for financial resources.

〈Figure 4〉 Discounted Cash Flows by System Types



To calculate IRR and consider the practical conditions, the energy system options in this island are designed, assuming two key stakeholders to install renewable energy options. The power utility who has provided electricity to this hotel with diesel generator with fixed rate of charges should consider the supplementary renewable option with ESS. The replacement of one diesel generator and the solar PV with ESS could be proposed by the project developer who should share the financial burden of initial capital cost. At the same time the project developer expects the same rate from the power utility for supplying electricity to the hotel. The choice of project developer to install the new renewable energy system depends on the expected revenues by providing electricity to the power utility against the initial capital and financial cost.

3. Simulation Results by @RISK

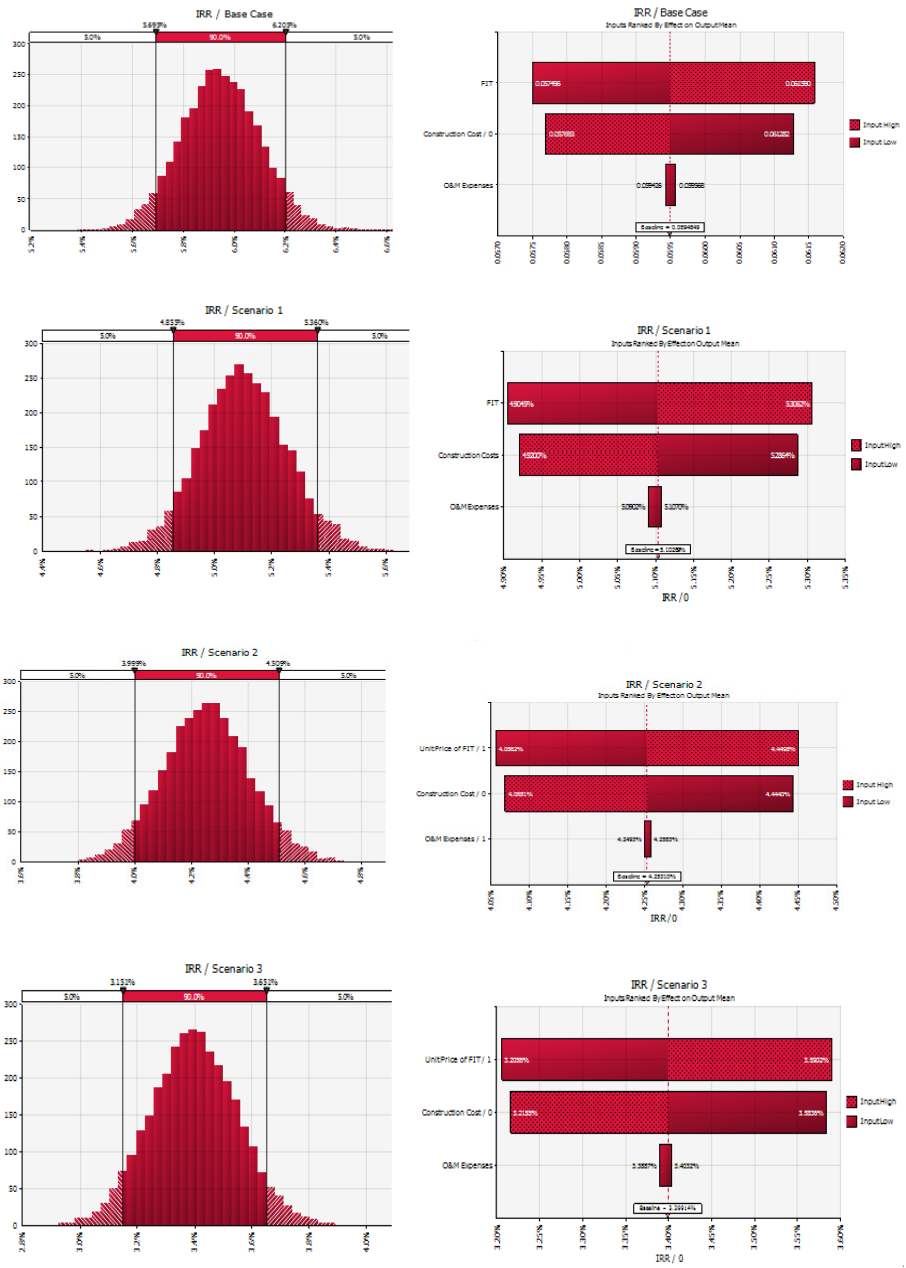
The ST 1 energy system selected as an optimum choice in terms of LCOE, IRR, payback period and the CO_2 mitigation potentials for this remoted island to implement an independent off grid power system. For the financial feasibility for ST 1, the following financial options are designed, assuming that the initial capital cost is covered by the project developer with different financial sources. The base case is that the project developer covers the 20% of the initial capital cost as equity and the remaining 80% is obtained from the multilateral development bank (MDBs) as concessional loan. If the commercial loan is available with higher interest rate, which makes this project financially more feasible, the different shares between the concessional loan and commercial loan are shown in Table 5.

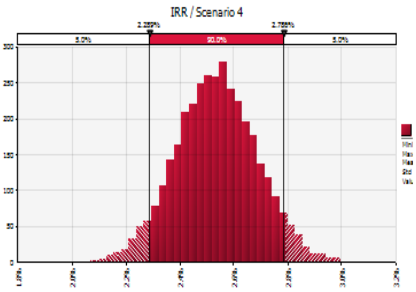
〈Table 5〉 Scenarios for Financial Feasibility

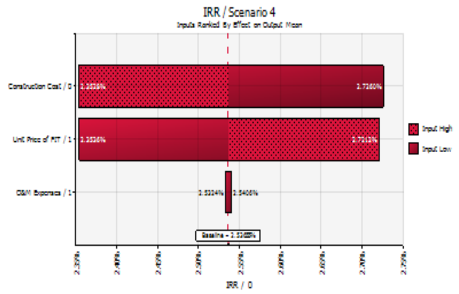
Scenario	MDB Loan	Commercial Loan	Project Developer Equity
Base Case	80%	0%	20%
Scenario 1	70%	10%	20%
Scenario 2	60%	20%	20%
Scenario 3	50%	30%	20%
Scenario 4	40%	40%	20%
Scenario 5	60%	10%	30%
Scenario 6	50%	20%	30%
Scenario 7	40%	30%	30%
Scenario 8	30%	40%	30%

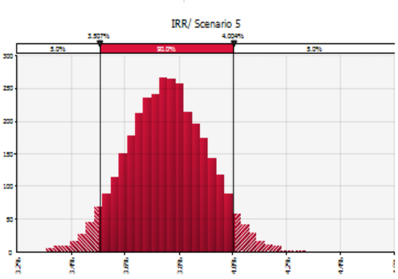
The simulation results of financial options for ST 1, using @RISK program is shown in Figure 5. For each scenario, @RISK sets up 10,000 simulations with key financial factors to determine FIRR. Based on simulation results from different scenarios, it is consistently found that key factors for the FIRR for this project are the rate for electricity that is crucial for the calculation of revenues of ST 1, the capital cost of ST 1. Relatively, the O & M cost does not play important role to determine the FIRR, since ST 1 is the energy system to minimize the use of diesel fuel among four energy systems. @RISK generates simulation results, assuming the probability density function of the normal distribution.

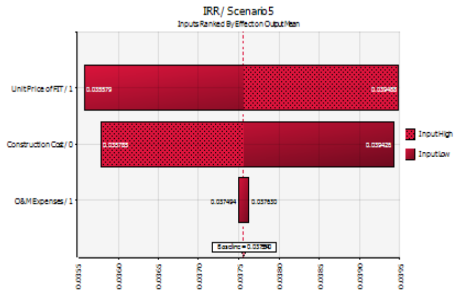
〈Figure 5〉 Simulation Results on Financial Factors for ST1

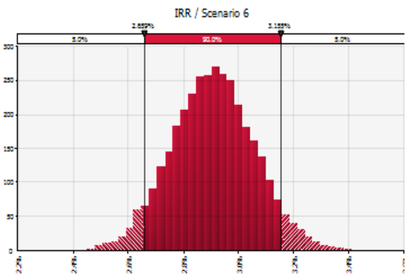


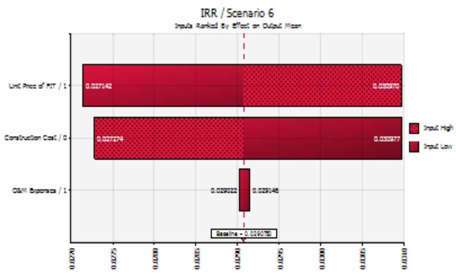

IRR / Scenario 4
5.0%
90.0%
5.0%

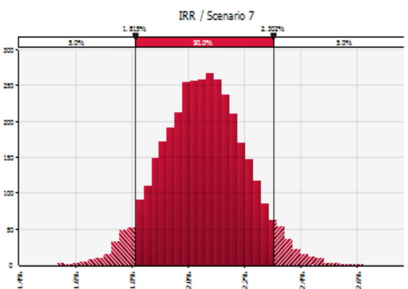

IRR / Scenario 4
Construction Cost / 0
Unit Price of FIT / 1
O&M Expenses / 1
Input High
Input Low
IRR / 0

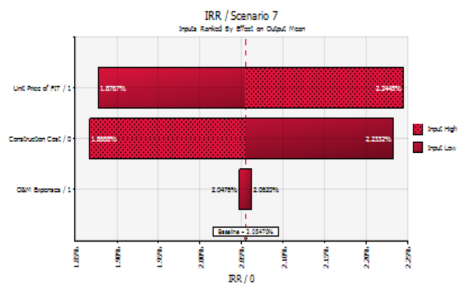

IRR/ Scenario 5
5.0%
90.0%
5.0%

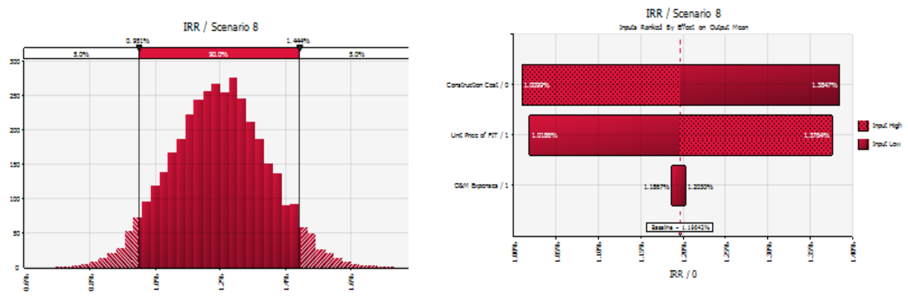

IRR/ Scenario5
UnitPrice of FIT / 1
Construction Cost / 0
O&M Expenses / 1
InputHigh
InputLow


IRR / Scenario 6
5.0%
90.0%
5.0%


IRR / Scenario 6
Unit Price of FIT / 1
Construction Cost / 0
O&M Expenses / 1
Input High
Input Low

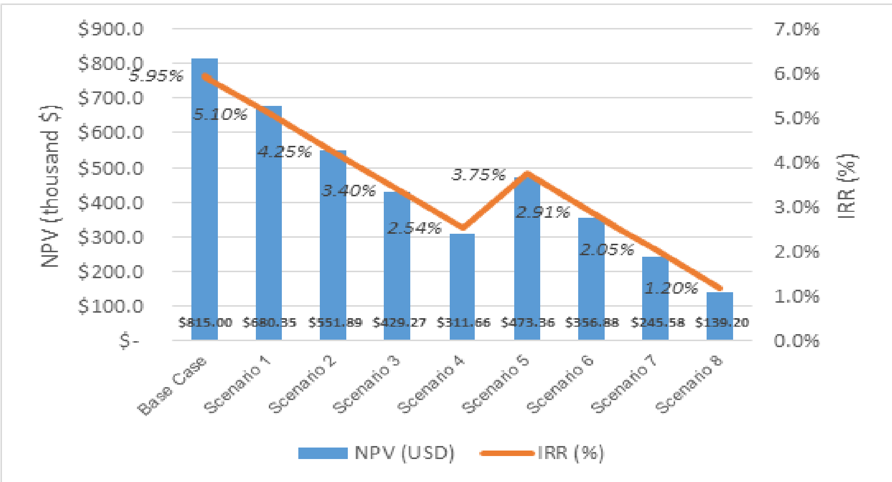

IRR / Scenario 7
5.0%
90.0%
5.0%


IRR / Scenario 7
Unit Price of FIT / 1
Construction Cost / 0
O&M Expenses / 1
Input High
Input Low
IRR / 0



Based on the simulation results, the average NPV and FIRR of 9 scenarios, including base case for financial options are presented in Figure 5. As expected, if the project developer could obtain 80 % of total loan from MDB as a form of concessional loan, the FIRR is about 6% with \$815,000 NPV. If the share of commercial loan is increasing, the FIRR could be dropped to 2.5%. If the equity portion of the total financing requirement is increasing from 20% to 30%, the FIRR is decreasing as shown in Figure 6.

〈Figure 6〉 NPV and FIRR by Scenario



Ⅳ. Conclusion

SIDS, such as Maldives are transforming to independent grid system for each island with sustainable, affordable, clean and renewable energy resources. Diesel power generation systems are conventional fossil-fuel based power systems for most small islands, which require higher O&M costs and show high uncertainty due to volatile fuel prices. In the small island, Kandooma, hybrid diesel with PV and ESS is found to be most economically viable, compared with other feasible energy systems. In this study, it is also worthwhile to note that a hybrid energy option could be beneficial to a resort island in Maldives, since the renewable energy option contributes to eco-tourism. In this study, a Hybrid PV-ESS-Diesel system is the most cost effective off-grid energy system for this resort island. The simulation results of financial feasibility analysis indicate that the key factor is the initial investment requirement to install the solar energy system with ESS in this island. It turned out that the rate of feed-in-tariff, financial modality and the cost of operation and maintenance are the key factors to determine the FIRR of the hybrid energy system with ESS.

This study compared the current typical diesel power generation system with solar energy system with ESS, and the most optimal energy system is the hybrid PV-Diese1-ESS system in terms of economic analysis and environmental effects. The LCOE of the hybrid PV-Diesel-ESS system is lower than that of any other energy system. The simulation results of financial feasibility show that the concessional loans from the multilateral development bank shows the higher FIRR for the optimal hybrid Diesel-PV-ESS system, depending on the share of equity of the company who runs the energy system. It is clear that the financial viability of the energy system depends on the tariff that the independent off grid system could obtain, compared with the cost of diesel power system.

For further studies, it is necessary to consider the social cost of CO_2 emissions from the diesel energy system. Another advantage of the hybrid PV-Diese1-ESS system is to emit CO_2 less with the solar PV and ESS that could optimize the use of diesel and solar to meet the daily power demand in the remote island. The shadow price of CO_2 could be considered to calculate the social cost of each energy system, which should be reflected in calculating LCOE. Additionally, the uncertainty of system costs, such as the ESS, and future prices of diesel, which influence the O&M costs, as well as other their financial uncertainties should be further examined with a specific sustainable energy option most applicable in a small island. The sensitivity analysis with different loan conditions and equity shares by the project developer may generate different financial feasibility for the ST 1, which should be examined.

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ABSTRACT

몰디브 칸두마섬의 에너지저장장치를 포함한 태양광에너지 시스템 경제성 분석

정태용* · 김동훈**

소도서국가들은 (Small Island Developing States: SIDS)기후변화에 매우 취약하고 기후변화적응 능력이 매우 제한적이다. 이런 이유로 국제사회는 소도서국가 문제에 관심을 가지고 있다. 몰디브는 전형적인 소도서국가이며 환경친화적인 관광산업이 주 경제활동이다. 그러나 몰디브는 전력생산에 있어 수입 화석연료에 주로 의존하고 있으며, 이는 몰디브의 각 섬들이 변동이 심한 석유가에 매우 민감하다는 것을 의미한다. 몰디브의 작은 섬들에서 디젤발전기를 사용하는 것은 흔한 일이다. 본 연구에서 선택된 몰디브의 칸두마섬은 리조트호텔이 있는 섬이다. 이 섬에는 기존의 5개 디젤발전기 중 하나를 첨단 에너지저장장치를 포함하는 태양광발전으로 전환한다는 가정하에 기존 디젤발전과 태양광발전을 비교하여 소도서국가에서도 앞선 기술의 적용이 가능하다는 것을 보여주는 것이다. 더불어서 프로젝트 금융을 위한 다양한 시뮬레이션을 통하여 멀리 떨어진 섬에서 태양광시스템을 설치하는 것이 금융옵션으로 타당성이 있음을 보이고 있다.

주요 단어 : 소도서국가, 에너지시스템, 에너지재무분석
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* Professor, Graduate School of International Studies, Yonsei University, Seoul, Korea
** Professor, Graduate School of International Studies, Yonsei University, Seoul, Korea
(Corresponding Author: dhkim2@yonsei.ac.kr