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A real options approach to renewable electricity generation in the Philippines

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Abstract

Background: The Philippines is making a significant stride to become energy independent by developing more sustainable sources of energy. However, investment in renewable energy is challenged by competitive oil prices, very high investment cost for renewable energy, and high local electricity prices. This paper evaluates the attractiveness of investing in renewable energy sources over continue using oil for electricity generation.

Methods: This paper uses the real options approach to analyze how the timing of investment in renewable energy depends on volatility of diesel price, electricity price, and externality for using oil.

Results: The result presents a positive net present value for renewable energy investment. Under uncertainty in oil prices, dynamic optimization describes how waiting or delaying investment in renewables incurs loses. Decreasing the local electricity price and incorporating negative externality favor investment in renewable energy over continuing the use of oil for electricity generation.

Conclusions: Real options approach highlights the flexibility in the timing of making investment decisions. At the current energy regime in the Philippines, substituting renewable energy is a better option than continue importing oil for electricity generation. Policies should aim at supporting investment in more sustainable sources of energy by imposing externality for using oil or decreasing the price of electricity.

Keywords: Dynamic optimization, Price uncertainty, Renewable energy, Externality tax

Background

Environmental problems associated with emissions from fossil fuel, along with limited supply, volatile prices, and energy security, prompted developed and developing countries to find more reliable and sustainable sources of energy. Renewable energy (RE) sources, being abundant, inexhaustible, cleaner, and readily available, emerge as a promising alternative energy source. According to International Energy Agency (IEA), RE accounted to 13.7% of the world energy generation mix in 2015 [1]. With a rapid decline in RE costs, this percentage mix is expected to double by 2040 [2]. In the Philippines, the development and optimal use of RE resources is an essential part of the country's low emission strategy and is vital to addressing climate change, energy security, and access to energy [3]. In 2015, renewable energy accounts to 25% of the country's total electricity generation mix, only 1% from wind and solar energy [4]. Since the country is highly dependent on imported fossil fuels, sudden changes in the price of fuels in the world market may eventually affect the country's energy security. Renewable energy serves as a long-term solution by introducing localized RE sources. However, despite the country's huge potential for RE generation, investments in RE projects are challenged by competitive prices of fossil fuels, more mature technology for fossil fuels, and very high investment cost for renewable energy. These give us the motivation to make a study that analyzes the attractiveness of RE investments to address the country's concern on energy sufficiency and sustainability.

One of the most common techniques in analyzing investment projects is the net present value (NPV). This technique is widely used by developers, financial institutions, and government agencies under the condition of definite cash flow. Since RE investment in

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emerging economies involves high risk from volatile energy prices and changing RE technologies, NPV undervalues investment opportunities and thus considered inappropriate for assessing RE projects in developing countries including the Philippines [5]. Real options approach (ROA) overcomes this limitation as it combines risks and uncertainties with flexibility in the timing of investment as a potential factor that gives additional value to the project [6]. Recent studies use ROA renewable energy investment particularly for wind, solar photovoltaic (PV), hydropower, concentrated solar power (CSP), and combination (hybrid) of RE with uncertainties in non-RE cost, certified emission reduction (CER), feed-in tariff (FIT), energy production, operations and maintenance (O&M) cost, research and development (R&D) grants, production tax credit (PTC), RE credit (REC), among others (see Table 1).

This paper contributes to the existing literature by proposing a ROA framework for analyzing RE projects for developing countries, particularly, island countries that are highly dependent on imported oil for electricity generation. While previous studies proposed a full system switch to RE [7] or applied the ROA model to large-scale RE projects [8–11], this study takes the case of Palawan island in the Philippines and focuses on a smaller scale project which is particularly more realistic to developing countries. Whereas previous works' approaches used coal and gas for fuel price uncertainty [7, 9, 10, 12], this work uses uncertainty in oil prices as the world energy mix is dominated by liquid fuel, more developing countries are dependent on imported oil, and that investments in renewable energy is affected more by volatility in oil prices than coal prices. Finally, this paper proposes an externality tax for using fossil fuels as it more applicable in developing countries than introducing CER price, PTC, REC, CO_2 price, and emission/externality cost as proposed in previous works [7, 9, 10, 13, 14].

Applying ROA, this study aims to evaluate whether investing in RE is a better option than continue using diesel for electricity generation by considering various uncertainties in diesel fuel price, local electricity prices, and imposing externality tax for using diesel. This finally aims to recommend various government actions to address environmental problem, supply chain, and national security regarding energy.

Methods

Real options approach

Myers [15] first referred ROA or real options valuation as the application of option pricing theory to valuate non-financial or "real" assets. Real option itself is "as the right, but not the obligation, to take an action (e.g., deferring, expanding, contracting or abandoning) at a predetermined cost, called exercise price, for a predetermined period of time – the life of the option" [16]. Investment decisions, in the real world, have main characteristics: irreversible, high risk and uncertain, and flexible [17]. These characteristics are not captured by traditional methods of valuation, such as NPV, discounted cash flow (DCF), internal rate of return (IRR), and return on investment (ROI) leading to poor policy and investment decisions. ROA, on the other hand, combines uncertainty and

Table 1 Summary of ROA in literature

Author	Year	Country	RE type	Uncertainty	Ref.
Detert and Kotani	2013	Mongolia	Hybrid	Non-RE cost	[7]
Lee et al.	2013	Korea	Hydro	CER price	[13]
Abadie and Chamorro	2014	UK	Wind	FIT, energy production, subsidy	[28]
Kim et al.	2014	Korea	Wind	Non-RE cost	[12]
Jeon et al.	2015	Korea	Hydro	FIT, energy production, interest rate, risk free rate, exchange rate	[29]
Weibel and Madlener	2015	Germany	Hybrid	Energy production, FIT, investment cost	[8]
Wesseh and Lin	2015	Liberia	Hybrid	Non-RE price, R&D funding	[9]
Barrera et al.	2016	Europe	CSP	R&D grant	[30]
Eryilmaz and Homans	2016	USA	Wind	PTC, REC	[31]
Ritzenhofen and Spinler	2016	Germany	Wind	FIT	[32]
Zhang et al.	2016	China	PV	Non-RE cost, FIT, investment cost	[10]
Kim et al.	2017	Indonesia	Hydro	Energy production, FIT, CER, O&M cost	[5]
Kitzing et al.	2017	Europe	Wind	Energy price, wind speed	[11]
Tian et al.	2017	China	PV	Investment cost	[14]

option flexibility which characterize many investment decisions in the energy sector.

This research applies ROA to analyze investment decisions whether to continue using diesel for electricity generation or invest in RE. We use the uncertainty in diesel prices as a main factor that affects investment decisions. Using dynamic optimization, we evaluate the maximized value of investment at each price of diesel, identify the trigger price for shifting technology from diesel-based electricity to RE, and analyze the value of waiting or delaying to invest in RE. Finally, we incorporate sensitivity analyses with respect to electricity prices and externality tax for using diesel.

Dynamic optimization

We follow the method described by Dixit and Pindyck [18] and adopt the work of Detert and Kotani [7] on optimizing investment decision under uncertainty using dynamic programming. In this research, we describe a model of an investor that identifies the optimal value of either investing in RE or continue using diesel for electricity generation as shown in Eq. 1 (see Table 2 for the list of variables and parameters).

Table 2 Description of variables and parameters

Notation	Description
C_D	Annual marginal cost of electricity production using diesel, in US$
C_R	Annual marginal cost of electricity production using renewable energy, in US$
I_R	Investment cost for renewable energy, in US$
NPV_R	Net present value of investing in RE, in US$
$P_{D,\,t}$	Stochastic price of diesel, in US$/barrel
P_E	Electricity price, in US$/MWh
Q_D	Quantity of diesel needed to produce Q_E, in barrels
Q_E	Quantity of electricity produced, in MWh
$V_{D,\,t}$	Option value of investment at each price of diesel, *D*, at each period of investment, *t*, in US$
$\mathbb{E}\mathrm{NPV}_{D,t}$	Expected net present value of continuing diesel for electricity generation, in US$
$\mathbb{i}_{\tau\le T}$	Indicator equal to 1 if switching to RE is made, otherwise, equal to 0
$\pi_{D,\,t}$	Profit of using diesel for electricity generation from initial period of investment, 0, to period of switching to RE, τ, in US$
T	Total period of investment
tax	Externality tax for using diesel
ρ	Discount factor
τ	Period of switching from diesel to RE

$$V_{F,t} = \max_{0\le\tau<T+1}\Bigg[\Bigg\{\Bigg\{\sum_{0\le t<\tau}\rho^t\pi_{D,t}\ +\rho^T\mathbb{E}\mathrm{NPV}_{D,t}\langle 1-\mathbb{i}_{\tau\le T}\rangle\Bigg\}\Bigg|P_{D,t}\Bigg\} + \left\{\mathrm{NPV}_R\langle\mathbb{i}_{\tau\le T}\rangle\right\}\Bigg] \tag{1}$$

where

$$\pi_{D,t} = P_EQ_E - P_{D,t}Q_D - C_D, \tag{2}$$

$$\mathrm{NPV}_D = \sum_{t=T}^{T_D}\mathrm{PV}_{D,t} = \sum_{t=T}^{T_D}\rho^t\pi_{D,t} - \mathrm{tax}, \tag{3}$$

$$\begin{aligned}\mathrm{NPV}_R &= \sum_{t=\tau}^{T_R}\mathrm{PV}_{R,t} = \sum_{t=\tau}^{T_R}\rho^t\pi_{R,t}\\ &= \sum_{t=\tau}^{T_R}\rho^t[P_EQ_E - C_R] - I_R\end{aligned} \tag{4}$$

Using this model, we determine the option value, $V_{D,\,t}$, by maximizing the investment at each price of diesel, *D*, from 0 to US$1000/barrel, for each investment period, *t*. We set the dynamic optimization process to 40 years which represent a situation where an investor is given a period to make an investment decision. After that period, he has no other option but to continue using diesel for electricity generation. The choice is valued for another 25 years to represent the lifetime of power plant using diesel. We set the value of T_R to 25 years to represent the number of years of electricity generation using RE. Finally, we solve the problem backwards using dynamic programming from terminal period [7, 19]. The uncertainty in diesel prices in Eqs. 2 and 3 as well as the Monte Carlo simulation in the dynamic optimization process is discussed in the next subsection.

Stochastic prices and Monte Carlo simulation

In line with the previous studies, we assume that the price of diesel is stochastic and follow geometric Brownian motion (GBM) [20–22]. Dixit and Pindyck [18] present the stochastic price process as

$$dP/P = \alpha dt + \sigma dz \tag{5}$$

where α and σ represent the mean and volatility of diesel price, dt is the time increment, and dz is the increment of Wiener process equal to $\varepsilon_t\sqrt{dt}$ such that $\varepsilon_t{\sim}N(0,1)$. Using Ito's lemma, we arrive at

$$F(P) =\ \ln P\ \text{ and }\ dF = adt + sdz - \frac{1}{2}s^2dt \tag{6}$$

We approximate Eq. 6 in discrete time as

$$p_t - p_{t-1} = \left(\alpha - \frac{1}{2}\sigma^2\right)\Delta t + \sigma\varepsilon_t\sqrt{dt} \tag{7}$$

To determine the drift and variance of P, we use the Augmented Dickey-Fuller (ADF) unit root test using the following regression equation

$$p_t - p_{t+1} = c(1) + c(2)p_{t-1} + \sum_{j=1}^{L}\lambda_j \Delta y_{t-j} + e_t \tag{8}$$

where $c(1) = \left(\alpha - \frac{1}{2}\sigma^2\right)\Delta t$ and $e_t = \sigma\varepsilon_t\sqrt{\Delta t}$. We then estimate the maximum likelihood of the drift $\alpha = \mu + \frac{1}{2}s^2$ and variance $\sigma = s$, where α is the mean and s is the standard deviation of the series $p_t - p_{t+1}$ [23].

In this research, we use the annual prices of diesel from 1980 to 2016. The result of ADF test as shown in Table 2 implies that the null hypothesis that p_t has a unit root at all significant levels cannot be rejected. Therefore, P conforms GBM. We estimate the parameters $\alpha = 0.007614$ and $\sigma = 0.358889$ and use in identifying stochastic prices of diesel under GBM (Table 3).

We use the Monte Carlo simulation to compute the expected net present value of electricity generation using diesel in Eqs. 2 and 3. First, we approximate a vector of potential prices of diesel using the stochastic prices of GBM as follows:

$$P_{D,t} = P_{D,t-1} + \alpha P_{D,t-1} + \sigma P_{D,t-1}\varepsilon_{t-1} \tag{9}$$

This equation illustrates that the previous price affects the current price of diesel. Second, from the initial price of diesel, $P_{D,\ 0}$, we estimate the succeeding prices of diesel in each period using Eq. 9. We incorporate these prices in Eq. 2 and calculate the present values of using diesel for electricity generation. Finally, we estimate the expected net present value at each initial price node i and repeat the whole process in a sufficiently large number of $J = 10000$ times and take the average as given by the equation

$$\mathbb{E}\left\{NPV_{D,J}, \left|P_{D,0}\right.\right\} \approx \frac{1}{J}\sum_{j=1}^{J} NPV_{D,J} \approx \mathbb{E}\left\{NPV_D, \left|P_{D,0}\right.\right\} \tag{10}$$

Table 3 Augmented Dickey-Fuller unit root test of GBM for diesel prices

		t-statistic	Prob
Augmented Dickey-Fuller test statistic		− 1.5109	0.5168
Test critical values	1% level	− 3.6268	
	5% level	− 2.9458	
	10% level	− 2.6115	

Note: Complete ADF unit root test in Additional file 1 Table S1

Trigger price of diesel

Dynamic optimization process in the previous sections generates the maximized option values of investment. From these simulation results, we identify the trigger price of diesel for switching to RE as follows

$$\hat{P}_D = \min\left\{P_{D,t} \middle| V_0\left(P_{D,t}\right) = V_{\mathrm{T}_R}\left(P_{D,\mathrm{t}}\right)\right\} \tag{11}$$

where $\hat{P}_D$ is the trigger price of diesel or the minimum price where the option value in the initial period $V_0(P_{D,\ t})$ is equal to the option value in the terminal period of investment $V_{\mathrm{T}_R}\left(P_{D,\mathrm{t}}\right)$ [7, 18, 24]. From the given equation, we define trigger price as the minimum price of diesel that maximizes the profit of shifting the source of electricity from diesel power plant to RE.

Data and scenarios

To determine a suitable set of parameter values for the baseline scenario, we use data from various sources that nearly reflects the investment environment for renewable energy project in Palawan. This is the largest island province in the Philippines composed of 1780 islands and islets that are currently not connected to the national grid and only depend on imported diesel and bunker fuel. The recent Calatagan Solar Farm project in Batangas is set as a benchmark of the data for investment in RE, as this project is the latest RE project in the Philippines and has similar geographic features with Palawan; hence, investment cost estimations are up-to-date and relatively comparable [25]. This 63.3 MW solar farm, covering a total area of 160 ha, projects to generate 88,620 MWh of electricity per year. It costs US$120 million and will operate for at least 25 years. We use the data from Palawan Electric Cooperative (PALECO) [26] to approximate the local electricity price and the quantity and costs of generating electricity from diesel.

Electricity prices in the Philippines varies from island to island depending on the source of energy, as well as various charges including the generation, transmission, distribution, metering, and loss. In Palawan, effective power rates also vary across different municipalities [26]. We employ these variations in the electricity price scenario by changing the electricity price in the baseline model. In this scenario, we aim to describe how policy in imposing electricity price ceiling or price floor affects the investment decisions particularly in introducing RE as a source for electricity generation.

Lastly, we consider the externality tax of electricity generation from diesel. This value represents the negative

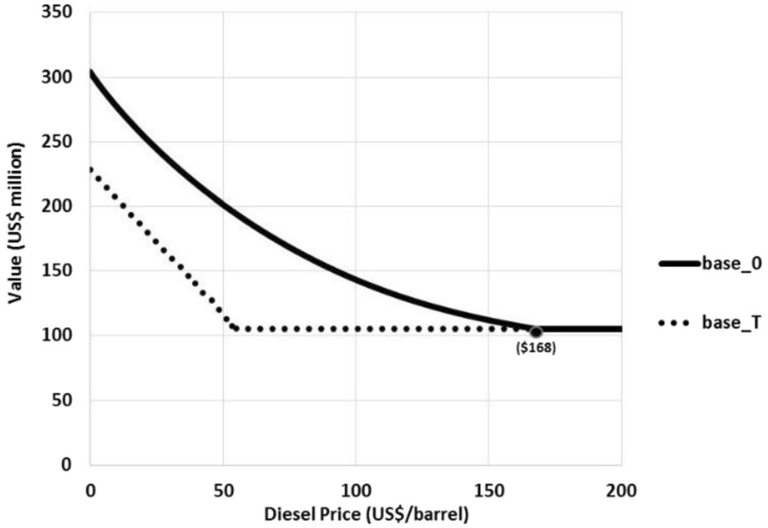

Fig. 1 Option values at the baseline scenario. Legend: base_0: option values of energy investment at the initial period; base_T: option values of energy investment at the terminal period

externality including, but not limiting to, health and environmental problems associated with combustion of diesel. We use the data of the estimated average external costs for electricity generation technologies from European Environmental Agency (EEA) [27]. For this scenario, we include externality costs, tax for estimating the net present value of using diesel in Eqs. 2 and 3. We arbitrarily assign values, between 0 (for baseline) to US$ 80/MWh, which are lower than those reported in literature to describe a more realistic condition. We assume that RE source, particularly solar PV, produces minimal or nearly no externality.

Results and discussion

Baseline scenario

Figure 1 and Table 4 show the result of dynamic optimization at the baseline scenario. The first point of interest is the positive net present value of RE. This implies that, using the traditional valuation method, renewable project is a good investment in the island of Palawan. This result is evident as the installation of solar energy projects grows rapidly in the recent years. In 2016, there are already 538.45 MW installed capacity of solar projects from the 4399.71 potential capacity in the whole country [25]. Caution must be applied as net present value is not the sole determinant of investment in ROA. The optimal timing that maximizes the value of investment opportunity under uncertainty must also be accounted for [18].

Table 4 Summary of dynamic optimization result at the baseline scenario

Net present value of renewable energy	US$104.97 million
Trigger price of diesel	US$168 million/barrel
Option value at initial period (at current diesel price)	US$141.38 million
Option value at terminal period (at current diesel price)	US$104.97 million
Value of waiting (at current diesel price)	– US$36.41 million

Figure 1 shows the dynamics of the option values at different initial prices of diesel. Result shows that the option values decrease over diesel price as the cost of generating electricity increases with fuel price. The trigger price as indicated by the intersection of option value curves indicates the minimum price of diesel that maximizes the decision of shifting from diesel based to RE generation. The result in the baseline scenario at US$168/barrel is higher than the current price at US$101.6/barrel. Intuitively, this implies that waiting to invest in RE is a better option than investing at the current price of diesel. However, the value of waiting to invest as describe by the distance between option value curves from initial to terminal period is negative. As seen in Table 4, the option value at the current price of diesel at the initial period of investment is US$141.38 million and decreases to 104.97 million at the terminal period. This results to a US$36.41 million loss from delaying or waiting to invest. This implies that waiting to invest in RE incurs losses.

Electricity price scenario

This scenario describes how adjusting the local electricity price affects the option values and the trigger price. Figures 2 and 3 show the dynamics of option values with

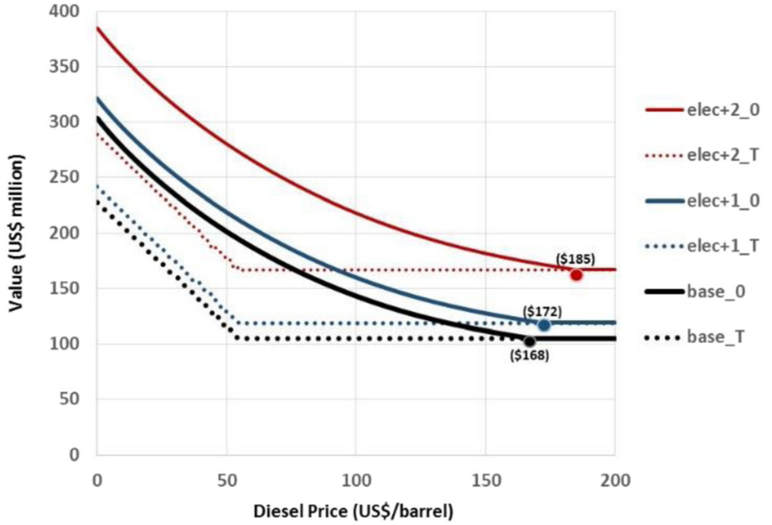

Fig. 2 Option values at increasing electricity price scenario. Legend: base_0: option values of energy investment at the initial period; base_T: option values of energy investment at the terminal period; elec+1_0: option values at 10% higher electricity price than the base at the initial period; elec+1_T: option values at 10% higher electricity price than the base at the terminal period; elec+2_0: option values at 25% higher electricity price than the base at the initial period; elec+2_T: option values at 25% higher electricity price than the base at the terminal period

increasing and decreasing electricity prices decreasing electricity prices (see Additional file 1 Table S2 for dynamic optimization result). Result shows that the option values shift upwards with increasing electricity prices. This shows that at higher electricity prices, the value of either renewable energy or diesel-based electricity both increases. However, the trigger prices of diesel also increase to US$172/barrel at US$220/MWh and US$185/barrel at US$250/MWh from the baseline electricity price of US$202/MWh. This suggests that increasing the electricity price encourages waiting or delaying to invest in RE.

On the other hand, decreasing electricity prices shifts the option value curves downwards and decreasing the trigger price of diesel. This result is apparent as decreasing electricity price results to a lower revenue and thus

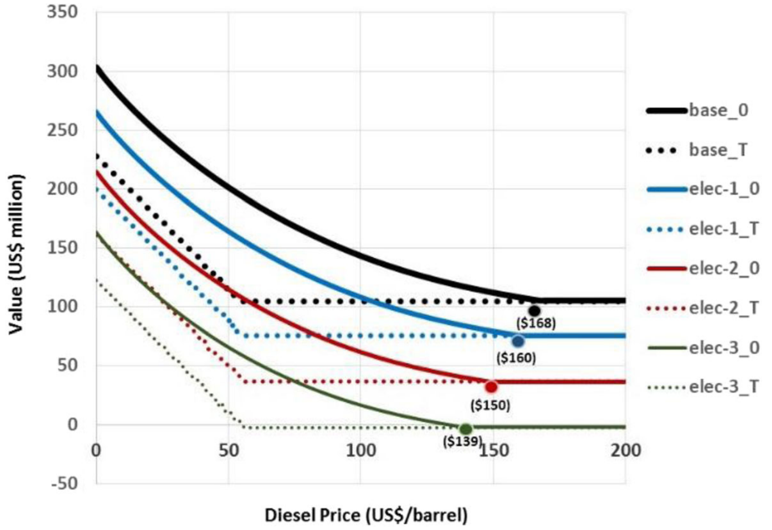

Fig. 3 Option values at decreasing electricity price scenario. Legend: base_0: option values of energy investment at the initial period; base_T: option values of energy investment at the terminal period; elec−1_0: option values at 10% lower electricity price than the base at the initial period; elec−1_T: option values at 10% lower electricity price than the base at the terminal period; elec−2_0: option values at 25% lower electricity price than the base at the initial period; elec−2_T: option values at 25% lower electricity price than the base at the terminal period; elec−3_0: option values at 40% lower electricity price than the base at the initial period; elec−3_T: option values at 40% lower electricity price than the base at the terminal period

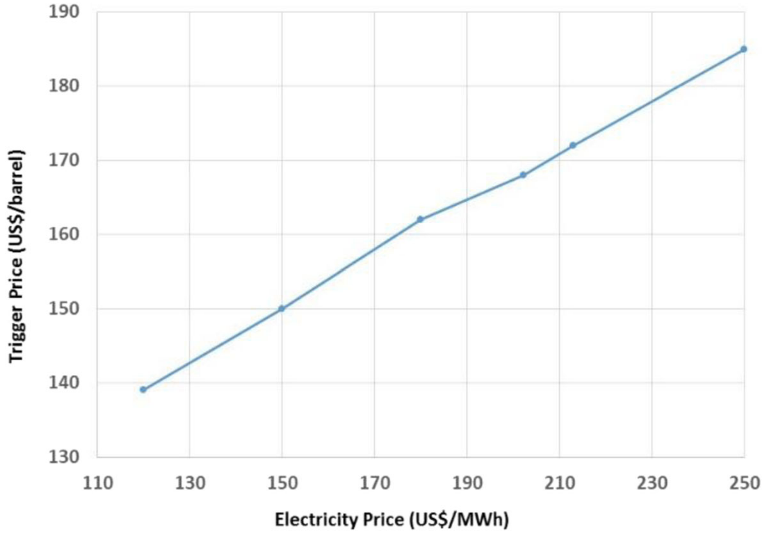

Fig. 4 Trigger prices of diesel over electricity price

lower profit for both options. The trigger prices of diesel decrease to US$160/barrel at US$180/MWh, US$150/barrel at US$150/MWh, and US$139/barrel at US$120/MWh price of electricity (Figs. 3 and 4). This suggests that lowering the electricity price decreases the timing to invest in renewable energy. Further, the option values become negative at electricity price below US$120/MWh. This implies that policy makers or power producers must not set an electricity price below US$120/MWh, as this will result to a loss for producing electricity from diesel as well as a negative investment for RE.

Externality scenario

This scenario describes how inclusion of externality tax from combustion of diesel affects the option values and triggers prices in investment in RE projects. The result in Fig. 5 (see Additional file 1 Table S3 for dynamic optimization result) shows that option values shift to the

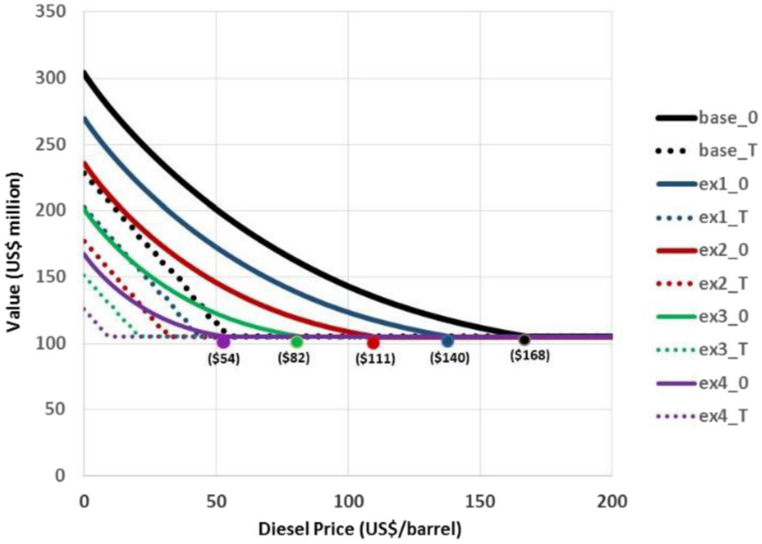

Fig. 5 Option values at negative externality scenario. Legend: base_0: option values of energy investment with no externality at the initial period; base_T: option values of energy investment with no externality at the terminal period; ex1_0: option values at 20$/MWh externality cost at the initial period; ex1_T: option values at 20$/MWh externality cost at the terminal period; ex2_0: option values at 40$/MWh externality cost at the initial period; ex2_T: option values at 40$/MWh externality cost at the terminal period; ex3_0: option values at 60$/MWh externality cost at the initial period; ex3_T: option values at 60$/MWh externality cost at the terminal period; ex3_0: option values at 80$/MWh externality cost at the initial period; ex4_T: option values at 80$/MWh externality cost at the terminal period

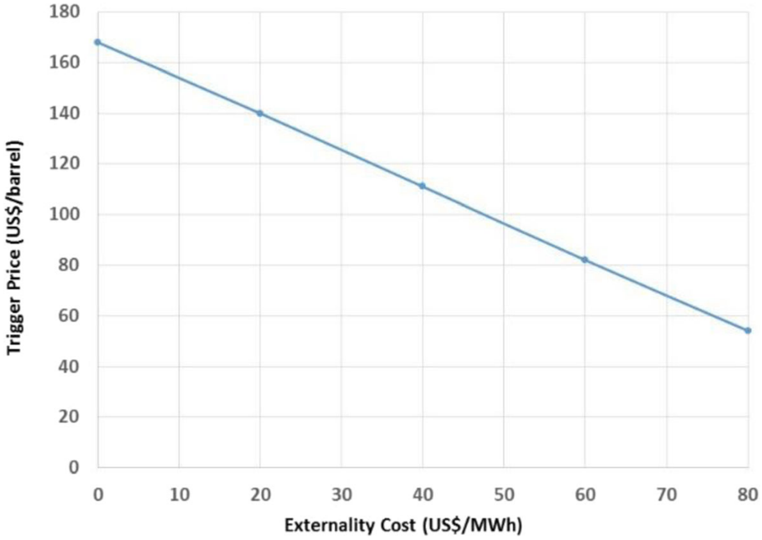

Fig. 6 Trigger prices of diesel over negative externality

left. First, this implies that imposing externality tax decreases the revenue from electricity generation using diesel and thus decreasing the option values. Second, the unchanged lower boundary of the curves implies externality does not affect the value of investment in renewable energy. This is due to our assumption that electricity generation from RE produces no externality.

With externality, the trigger prices of diesel decrease to US$140/barrel at US$20/MWh, US$111/barrel at US$40/MWh, US$82/barrel at US$60/MWh, and US$54/barrel at US$80/MWh externality cost (Figs. 5 and 6). This implies that imposing externality tax for diesel makes investment in RE more optimal than continue using diesel. Finally, the threshold of externality cost is US$46.55/MWh at the current diesel price of US$101.64/barrel. This is the minimum externality cost that favors immediate investment in RE than continue using diesel.

Conclusions

We evaluate investment environments and decision-making process for substituting diesel power plant with RE for electricity generation in the Philippines. Using real options approach under uncertainty in diesel prices, we identify the option values, trigger prices of diesel, and value of waiting to invest in RE. We analyze the sensitivity of investment decisions with respect to various electricity prices and addition of externality tax for using diesel.

ROA highlights the flexibility in the timing of making investment decisions. Our analyses conclude that for a developing country that is highly dependent on imported fuel, shifting to RE is a better option than continue using imported diesel. Policies should aim at supporting investment in more sustainable sources of energy by imposing externality for using fossil-based fuel or decreasing the price of electricity. This may negatively affect the power producers but encourage them to shift from diesel to renewable energy.

We summarized a unique approach to energy investment by replacing diesel with RE for electricity generation. We believe that the ROA framework introduced in this research is a good benchmark for further application. First, ROA may take account of environmental and social costs. This may include the cost of deforestation for solar farm, wildlife and habitat loss, air and water pollution, damage to public health, and loss of jobs. Finally, analyzing investment decisions with several RE resources includes dynamic optimization with different scenarios of generation mix from various RE sources. We are optimistic that this research becomes one-step forward for further analysis of investment in more sustainable sources of energy.

Additional file

Additional file 1: Table S1. ADF unit root test result of oil prices from 1981-2016. **Table S2.** Note: elec+2_0: option values at 25% higher electricity price than the base at the initial period; elec+2_T: option values at 25% higher electricity price than the base at the terminal period elec+1_0: option values at 10% higher electricity price than the base at the initial period; elec+1_T: option values at 10% higher electricity price than the base at the terminal period; base_0: option values of energy investment at the initial period; base_T: option values of energy investment at the terminal period; elec-1_0: option values at 10% lower electricity price than the base at the initial period; elec-1_T: option values at 10% lower electricity price than the base at the terminal period; elec-2_0: option values at 25% lower electricity price than the base at the initial period; elec-2_T: option values at 25% lower electricity price than the base at the terminal period; elec-3_0: option values at 40% lower electricity price than the base at the initial period; elec-3_T: option values at 40% lower electricity price than the base at the terminal period. **Table S3.** base_0: option values of energy investment with no externality at the initial period; base_T: option values of energy investment with no externality at the terminal period; ex1_0: option values at 20/*MWhexternalitycosttheinitialperiod; ex*1$_T$: optionvaluesat20/MWh externality cost at the terminal period; ex2_0: option values at 40/*MWhexternalitycosttheinitialperiod; ex*2$_T$: optionvaluesat40/MWh externality cost at the terminal period; ex3_0: option values at 60/ *MWhexternalitycosttheinitialperiod;ex*3$_T$: optionvaluesat60/MWh externality cost at the terminal period; ex3_0: option values at 80/ *MWhexternalitycosttheinitialperiod; ex*4$_T$: optionvaluesat80/MWh externality cost at the terminal period. (DOCX 95 kb)

Abbreviations

ADF: Augmented Dickey-Fuller; CER: Certified emission reduction; CSP: Concentrated solar power; DCF: Discounted cash flow; EEA: European Environmental Agency; FIT: Feed-in tariff; GBM: Geometric Brownian motion; IEA: International Energy Agency; IRR: Internal rate of return; NPV: Net present value; O&M: Operations and maintenance; PALECO: Palawan Electric Cooperative; PTC: Production tax credit; PV: Solar photovoltaic; R&D: Research and development; RE: Renewable energy; REC: Renewable energy credit; ROA: Real options approach; ROI: Return on investment

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Authors' contributions

CA conceptualized the research objectives and modeling scenarios. All authors contributed to the data analysis and writing of the final manuscript. All authors read and approved the manuscript.

Competing interests

The authors declare that they have no competing interests.

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