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Research Article

Decision Support for Investments in Sustainable Energy Sources Under Uncertainties

Kenneth Ian Talosig Batac[a], Angelie Azcuna Collera[b], Resy Ordona Villanueva[c], Casper Boongaling Agaton[d,*]

[a] *Department of Science Education, Br. Andrew Gonzalez FSC College of Education, De La Salle University, Manila, Philippines*

[b] *Center for Human Development, University of Science and Technology of Southern Philippines, Cagayan de Oro, Philippines*

[c] *Ceriaco A. Abes Memorial National High School, Calapan, Oriental Mindoro, Philippines*

[d] *Department of Community and Environmental Resource Planning, College of Human Ecology, University of the Philippines Los Baños, Laguna, Philippines*

Abstract. Investment in sustainable energy sources is one of the climate mitigation strategies that can significantly reduce greenhouse gas emissions in the energy sector. However, in developing countries, investment is challenged by high capital expenditures and several uncertainties. This paper aims to provide decision support for investment in sustainable energy projects by evaluating the comparative attractiveness of shifting energy sources from fossil fuels to renewables and nuclear. Applying the real options approach (ROA), this paper calculates the value of the flexibility to postpone the investment decision and identifies the optimal timing (described here as the trigger price of coal) for shifting to sustainable energy sources. Then, various uncertainties are considered, such as coal and electricity prices, negative externality of using fossil fuels, and the risk of a nuclear accident, which are modelled using geometric Brownian motion, Poisson process, and Bernoulli probability. Applying the ROA model in the case of the Philippines, results find that investing in sustainable energy is a better option than continuing to use coal for electricity generation. However, contrary to conventional option valuation result that waiting is a better strategy, this study found that delaying or postponing the investment decisions may lead to possible opportunity losses. Among the available sustainable energy sources, geothermal is the most attractive with trigger prices of coal equal to USD 49.95/ton, followed by nuclear (USD 58.55/ton), wind (USD 69.48/ton), solar photovoltaic (USD 72.04/ton), and hydropower (USD 111.14/ton). Also, the occurrence of jump (extreme) prices of coal, raising the current feed-in-tariff, and considering negative externalities can decrease the trigger prices, which favor investments in sustainable energies. Moreover, the risk of a nuclear disaster favors investment in renewable energy sources over nuclear due to the huge damage costs once an accident occurs. Results provide bases for policy recommendations toward achieving a more secure and sustainable energy sector for developing countries that are highly dependent on imported fossil fuels.

Keywords: renewable energy, nuclear energy, real options, nuclear disaster, negative externality, Poisson jump, dynamic optimization

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1. Introduction

Fossil fuels have been driving economies for centuries and currently supply approximately 80% of the world's energy demand. However, the accumulated greenhouse gas (GHG) emissions from the combustion of fossil fuels for generations have brought dramatic changes to the world's climate and are now considered the "dominant cause of the ecological crisis facing humanity" (Singh *et al*., 2019). From the energy sector alone, GHG emissions accounted for 76% (37.2 $GtCO_2e$) of emissions globally, the majority coming from the production of heat and electricity with 31.9% (15.6 $GtCO_2e$, followed by transportation with 14.2% (6.9 $GtCO_2e$), and manufacturing and construction with 12.6% (6.2 $GtCO_2e$) (Ge *et al*., 2022). Curbing global warming will necessitate major shifts in the energy sector by reducing the use of fossil fuels, widespread electrification, enhanced energy efficiency, and the utilization of sustainable energy sources (IPCC, 2022).

To attain a sustainable future, a lot of effort should be devoted not only to finding out energy resources that maintain ecological balance but also to enhancing the productivity of processes as these resources are used (Bilgen & Sarıkaya, 2018). Renewables, such as wind, solar, geothermal, hydropower, and ocean, are among the sustainable energy sources that are consistent with the Sustainable Development Goals adopted by the United Nations in 2015. With almost negligible emissions, their utilization has been increasing both in terms of capacity and geographic spread (Singh *et al*., 2019). Several countries have set energy policies and capacity targets in

* Corresponding author
Email: cbagaton@up.edu.ph(C.B.Agaton)

their electricity supply mix to encourage investments in renewable energy technologies. However, in developing countries, many of such targets are abandoned or fell short of the target date, primarily due to issues of financing, cost of electricity, and level of unmet demand (Afful-Dadzie *et al*., 2020).

Besides renewable energy, the literature also shows that nuclear energy helps reduce GHG emissions (Menyah & Wolde-Rufael, 2010). Nuclear, another sustainable energy source, is a low-carbon technology that can be utilized extensively during the period needed to provide the world with unpolluted, dependable, and inexpensive electricity (WNA, 2022). Empirical study shows the causality that nuclear energy plays an important role in reducing CO2 emissions where nuclear energy consumption has a negative and statistically significant impact on emissions (Apergis *et al*., 2010). Hence, it can spur the delivery of sustainable energy transitions, long before climate change became a matter that needs attention (WNA, 2022). However, it has risks concerning waste disposal, melting of nuclear reactor fuel rods, production of weapons, and mining-related health issues such as lung cancer (Jacobson, 2020). Investment in this type of clean energy, thus, requires thoroughness to address the risks, uncertainties, and challenges involved in its adoption.

Along with the reduction of GHG emissions, empirical evidence shows that there is a long-run relationship between nuclear and renewable energy and economic growth (Apergis *et al*., 2010). While it may be impossible to mitigate CO2 emissions without sacrificing economic development (Menyah & Wolde-Rufael, 2010), the relationship between sustainable energy consumption and economic growth indicates that proposed programs of action to enhance the generation and utilization of nuclear energy will have a favorable effect on the development of economy (Omri *et al*., 2015). Pao and Fu (2013) identify that a 1% increase in total renewable energy consumption increases real GDP by 0.20%. Succeeding studies support this showing a high positive relationship between sustainable energy consumption and economic growth (Bhattacharya *et al*., 2016; Ntanos *et al*., 2018). On the other hand, the reverse causality between economic growth to sustainable energy consumption implies that government policies accelerating economic growth and development lead to increases in sustainable energy consumption (Omri *et al*., 2015). Moreover, the growth in the utilization of sustainable energy not only decreases the reliance on imported energy sources but also reduces the risk involved in volatile oil and natural gas supplies and prices (Agaton *et al*., 2022; Apergis *et al*., 2010).

To evaluate the economic viability of investment in sustainable energy sources, several studies analyzed various technologies using different project valuation techniques. For instance, Abdelhady (2021) combined techno-economic analyses using the levelized cost of electricity and net present value (NPV) to evaluate the performance and cost of the solar dish power plant. In another economic analysis, Duman and Güler (2020) used discounted payback period, internal rate of return, and profitability index to analyze grid-connected residential solar photovoltaic (PV) under the current feed-in tariff (FIT) scheme. Kuang (2021) applied portfolio optimization using risk and return variation to generate the desired clean energy stock allocation and compare its performance with the equity market benchmark and dirty energy stocks. Moreover, Lee and Chang (2018) ranked various renewable energy sources based on efficiency, job creation, operation, and maintenance cost using the multi-criteria decision method. In another study, Assadi *et al*. (2022) combined economic with technical, environmental, and social attributes of decision-making processes in a Simultaneous Evaluation of Criteria and Alternatives for the optimal selection of renewable energy resources.

Despite their usefulness in decision-making, these methods do not capture important characteristics of energy investments such as irreversibility, uncertainty, and flexibility. On the other hand, the real options approach (ROA) addresses these issues as it combines risks and uncertainties as well as the flexibility in making an irreversible investment decision. This method has widely been used to evaluate sustainable energy projects considering different investment uncertainties. For example, Assereto and Byrne (2021) considered the uncertainty in electricity prices to assess the economic feasibility and the timing of investment in utility-scale solar in Ireland. In another study, Azari Marhabi *et al*. (2021) proposed a real options-based tool for policymakers to further manipulate the choice of investors in renewable resources to produce electricity under uncertainty in government policies. On the other hand, Zhang *et al*. (2022) complicated these by combining real options with portfolio optimization to evaluate the optimal renewable energy investment portfolio strategy, investment value, and conditional value at risk under uncertain changes in electricity price, fuel price, carbon price, investment cost, and renewable energy certificate price. Meanwhile, Najafi and Talebi (2021) considered the uncertainties in market price and operations and maintenance (O&M) cost in appraising the flexibility of nuclear energy generation in developing countries.

The above real options literature identifies the timing of investment in a renewable energy system and various investment drivers, such as market prices of input fuels, R&D, system cost, O&M cost, and government support and policies. Hence, this research identifies a gap in the application of ROA on shifting energy generation sources that integrate several investment drivers into one project valuation model. This paper aims to bridge this gap by proposing a general valuation framework for (a) switching energy sources from fossil-based to sustainable energy sources (a) comparing various energy sources, (b) applying the real options approach that integrates several sources of uncertainties, (c) using different uncertainty models, and (d) scenario analysis, from the perspective of a developing country, which highly depends on imported fossil fuels.

Specifically, this study aims to provide an investment decision support by calculating the value of flexibility and optimal timing of shifting energy sources from fossil-based to several sustainable energy options including solar PV, wind, geothermal, hydropower, ocean, and nuclear. Employing the ROA based on dynamic optimization and Monte Carlo simulations, this research integrates Black-Scholes, Poisson, and Bernoulli models to describe the uncertainties in coal and electricity prices, extreme prices, and the risk of a nuclear accident. This study applies the proposed ROA model using the Philippines as a case study with the following motivations: (a) it is a developing country with a huge potential to tap various available sustainable energy sources; (b) the country is archipelagic and several habited islands are not connected to the national grid; (c) the country is highly dependent on imported fossil fuel products, particularly coal and oil, (d) high capital cost for sustainable energy systems; (e) high electricity prices relative to neighboring countries; and (f) the country is aiming to achieve.

After the project valuation, this paper aims to answer the following research questions: (1) at what trigger prices of coal make the investment in sustainable energy sources a better strategy than continue using coal for electricity generation, (2) what investment scenarios make sustainable sources more attractive than coal, and (3) what government policies favor investment in sustainable sources that accelerate the energy transition towards achieving the climate targets while ensuring energy security and sustainability.

2. Methodology

This study compares the economic attractiveness of investing in various sustainable energy sources over continuing the use of coal for electricity generation. The simplest method when comparing two or more projects is the NPV, in which the one with the highest (positive) NPV is typically the best choice. Another method is the Profitability Index, a capital budgeting tool used to rank projects based on their profitability. Other traditional methods include internal rate of return, payback period, returns on investment, and least-cost method. While these methods are useful, they assume a multiyear investment with a fixed expectation of annual return leading to a one-time now-or-never decision based on static investment (Agaton, 2019).

However, investments in sustainable energy sources have numerous uncertainties that affect the future annual returns of the projects. Literature reviews identified these uncertainties including market prices (electricity, fossil fuels, CO_2), costs (capital, O&M), production and demand, learning (technology, R&D), and policies (subsidy, carbon tax, regulation) (Kim *et al.*, 2017; Kozlova, 2017). The ROA accounts for these uncertainties to make flexible managerial decisions such as the ability to delay investment and wait for the most favorable moment, abandon an unfavorable project; change the technology to a more profitable, and expand or reduce the project's operational scale based on the market conditions (Najafi & Talebi, 2021). Hence, this study applies the ROA and compares different sustainable energy projects considering the value of flexibility to postpone the implementation of the project based on various sources of uncertainties in energy investment.

This research applies the dynamic optimization method to evaluate the optimal timing of shifting energy sources from coal to various renewable and nuclear energy sources. To describe a more realistic situation where investors, policy makers, and people are skeptical about investing in nuclear energy due to its risks, this study poses a scenario of the possibility of having a nuclear accident. The negative externality of using various types of energy is also incorporated in the ROA model to reflect national energy security and environmental concerns such as water and air pollution, greenhouse gas emission, and ecosystem and biodiversity loss. Finally, the proposed model is applied in the case of the Philippines to verify the model.

2.1 Real Options Model

This study takes the perspective of an investor who is planning to maximize his investment in the energy sector. He has three options: continue using coal for electricity generation, invest in any sustainable energy sources, or postpone the investment and implement the decision at a later period.

For the first option, the value of using coal annually is given by Equation (1)

$$PV_{F,t} = \frac{P_{e,t}Q_e - P_{F,t}Q_F - OM_F - E_F}{(1+r)^t} \quad (1)$$

where: PV is the annual present value using coal for electricity generation, P_e is the electricity price, Q_e is the quantity of electricity produced, t is the time period, r is the discount rate, P_F is the price of coal, Q_F is the quantity of coal input to produce Q_e, OM is the operations and maintenance cost, and E is the negative externality cost for using fossil fuels.

For the second option, the value of the project can be calculated using the Net Present Value (NPV) as shown in Equation (2)

$$NPV_{SE} = \sum_{t=0}^{T_{SE}} \frac{B_{SE} - C_{SE}}{(1+r)^t} \quad (2)$$

where: NPV is the net present value of the investment in a sustainable energy project $SE = \{solar, wind, hydropower, geothermal, ocean, nuclear\}$, T_{SE} is the lifetime of the SE project, t is period, r is the discount rate, the benefit of the project is $B = P_{e,t}Q_e$ while the costs of the project $C = P_{SEf,t}Q_{SEf} - OM_{SE} - I_{SE}$ with I is the capital investment cost.

Since renewable energy RE sources use no input fuel, Equation (2) can be expanded for nuclear energy NE and renewables RE (solar PV, wind, hydropower, geothermal, and ocean) as described in Equation (3).

$$\begin{cases} NPV_{NE} = \sum_{t=0}^{T_{NE}} \frac{P_{e,t}Q_e - P_{NEf,t}Q_{NEf} - OM_{NE} - DC - I_{NE}}{(1+r)^t} \\ NPV_{RE} = \sum_{t=0}^{T_{SE}} \frac{P_{e,t}Q_e - OM_{RE} - I_{RE}}{(1+r)^t} \end{cases} \quad (3)$$

For the third option, the dynamic optimization is adopted from (Agaton, 2018; Guno *et al.*, 2021) which maximizes the value of either investing in sustainable energy sources at any given period or continuing coal-based energy generation, as presented in Equation (4)

$$\max_{0\le\tau<T+1} \mathbb{E}\{\textstyle\sum_0^{\tau} PV_{F,t} + \sum_{\tau}^{T_F} PV_{F,t}\,(1+\mathbb{I}_{\tau\le T}) + NPV_{SE}(\mathbb{I}_{\tau\le T}) \big| P_{F,t}\} \quad (4)$$

where: $\mathbb{I}_{\tau<T}$ is an indicator function equal to 1 when $\tau \le T$ or when investment in sustainable energy is done at period $t = \tau$, otherwise zero when the investor continues coal-based electricity generation.

To solve this problem, the optimization identifies the option value OV_{SE} at each price node of coal $P_{F,t}$ that maximizes the value of either investing in a sustainable energy source with $\mathbb{E}\{NPV_{SE}\}$ or continue using coal with $\mathbb{E}\{NPV_F\}$ as shown in Equation (5).

$$OV_{SE,t} = \max\left(\mathbb{E}\{NPV_{SE}\}, \mathbb{E}\{NPV_F\}\middle|P_{F,t}\right) \quad (5)$$

Applying dynamic optimization, option values are calculated from the terminal valuation period $t = T$ to the initial valuation period $t = 0$ using backward induction. The optimal timing of shifting to a sustainable energy source is evaluated as the minimum period that maximizes the value of the investment as described in Equation (6). This is also defined in this study as the trigger price of coal when shifting to sustainable energy sources is optimum.

$$\tau^* = \min\left\{\tau\middle|OV_{SE,0}(P_{F,0}) = OV_{SE,T}(P_{F,0})\right\} \quad (6)$$

Finally, the optimal investment strategy is characterized by the decision to invest in a sustainable energy source, continue using coal (not invest), or postpone the investment as shown in Equation (7).

$$\mathbb{S}_{SE} = \begin{cases} OV_{SE,\tau^*} < OV_{SE,0}, \mathbb{E}\{NPV_{SE}\} \geq 0 & invest\ now \\ OV_{SE,\tau^*} < OV_{SE,0}, \mathbb{E}\{NPV_{SE}\} < 0 & not\ invest \\ OV_{SE,\tau^*} \geq OV_{SE,0}, \mathbb{E}\{NPV_{SE}\} \geq 0 & postpone \end{cases} \quad (7)$$

The decision is to invest now if there is no value in waiting or the value of waiting OV_{SE,τ^*} is less than the value of investing now $OV_{SE,0}$ provided that investing in a sustainable energy source has a positive expected net present value, $\mathbb{E}\{NPV_{SE}\}$. Otherwise, do not invest (continue using coal) if there is no value in waiting and investment in a sustainable energy source is a loss or $\mathbb{E}\{NPV_{SE}\}$ is negative. Last, postpone the investment if the value of investing at a later stage OV_{SE,τ^*} is greater than the value of shifting energy sources now. Note that the third decision will only take place with a profitable investment in a sustainable energy source that $\mathbb{E}\{NPV_{SE}\}$ is positive.

2.2 Uncertainties and Monte Carlo Simulation

This study identifies the major sources of uncertainties, including the coal price, electricity price, extreme prices, and the probability of a nuclear accident.

First, the price of coal is assumed to be stochastic (Chi *et al.*, 2021; Wang & Zhang, 2018) that follows a Geometric Brownian motion (GBM), a continuous-time stochastic process, which the logarithm of randomly varying quantity follows the Wiener process or Brownian motion with a drift. Future prices of coal can be described in Equation (8)

$$P_{F,t+1} = P_{F,t}exp\left[\left(\mu_F - \frac{1}{2}\sigma_F^2\right)\Delta t + \sigma_F\sqrt{\Delta t}\varepsilon_{F,t}\right] \quad (8)$$

where: $P_{F,t+1}$ and $P_{F,t+1}$ are the future and current prices of coal, μ_F and σ_F are the percentage drift and volatility of coal prices and $\sqrt{\Delta t}\varepsilon_{F,t}$ is a Wiener process such that $\varepsilon \sim N(0,1)$.

The estimated prices of coal are substituted in Equation (1) to calculate the present value of using coal for electricity generation. Using Monte Carlo simulation, the expected NPV of using coal can be calculated by getting the average value of $NPV_{F,j}$ estimations repeated several J times at each initial coal price node $P_{F,0}$ as described in Equation (9)

$$\mathbb{E}\left\{NPV_{F,j}\middle|P_{F,0}\right\} \approx \frac{1}{J}\sum_{j=1}^{J} NPV_{F,j} \approx \mathbb{E}\left\{NPV_F\middle|P_{F,0}\right\} \quad (9)$$

Second, the uncertainty with extreme prices of coal, also known as price jumps, is added to the original model. In real life, there are "unpredictable unknowns" that characterize jump-type stochastic abrupt perturbations, such as financial crisis, earthquakes, hurricanes, and other man-made and natural disasters (Ilalan, 2016; Li, 2022). These fluctuations can be modelled with a Poisson jump or process, where the average time between events is known, but the exact timing of events is random and independent of the event (Volk-Makarewicz *et al.*, 2022). Extending Equation 8, stochastic future prices following GBM with Poisson jumps can be described in Equation (10)

$$P_{F,t+1} = P_{F,t}exp\left[\left(\mu_F - \frac{1}{2}\sigma_F^2 - \lambda k\right)\Delta t + \sigma_F\sqrt{\Delta t}\varepsilon_{F,t} + \sum_{1}^{N_t} lny_i\right] \quad (10)$$

where: the jump size y_i is a nonnegative random variable that has a log-normal distribution and has an expected value of k, N_t is a compound Poisson process with jump frequency λ equal to the mean number of jumps per unit time. In this integrated model, it is assumed that the Wiener process, the Poisson process, and the jump size are independent. Same with the case of GBM, future prices are then substituted to Equation (1) and Monte Carlo simulation is done to calculate the expected NPV of coal-based energy generation in Equation (9).

Third, in line with previous studies (Feng *et al.*, 2022; Guno *et al.*, 2021; Wang *et al.*, 2020), electricity prices are also assumed to follow GBM. Future electricity prices can be calculated using Equation (11).

$$P_{e,t+1} = P_{e,t}exp\left[\left(\mu_e - \frac{1}{2}\sigma_e^2\right)\Delta t + \sigma_e\sqrt{\Delta t}\varepsilon_{e,t}\right] \quad (11)$$

Since this study focuses on oil-importing countries, we can assume that electricity generation is primarily based on fossil fuels, hence, electricity prices are affected by the changes in coal prices. Then, the Wiener processes are correlated such that $\mathbb{E}(dW_{F,t}dW_{e,t}) = \rho_{F,e}dt$, where $\rho_{F,e} = 1$. The calculated future electricity prices will be substituted in Equation (3) and Monte Carlo simulation will be employed to calculate the expected NPV of investment in sustainable energy sources.

Lastly, the risk of an accident is considered in nuclear energy investment. Recent studies discuss the probability of nuclear accident using a classical probabilistic and simple empirical approach such as severe accident management guidelines, severe nuclear accident program, Bayesian networks, and so on (Cho *et al.*, 2022; Kim, 2022; Ulimoen *et al.*, 2022). However, none of them fit with our ROA model, where the decision to invest in nuclear energy is evaluated in discrete time and so is the probability of a nuclear accident.

This study assumes that an accident may happen only once, at most, in the entire lifetime of nuclear energy generation, and the plant terminates once the accident occurs. Hence, an accident cannot be repeated. Consider an independent and identically distributed (i.i.d.) random variable $x_i \sim Bernoulli$ with $i = \tau, \tau+1, \tau+2, \ldots, \tau+T_N$ as shown in Equation (12).

$$x_i = \begin{cases} 0, with\ probability\ q(\hat{t}) & no\ disaster \\ 1, with\ probability\ 1-q(\hat{t}) & with\ disaster \end{cases} \quad (12)$$

The probability of having no accident in the lifetime of nuclear energy generation is described as $Pr(\hat{t} > T_N) = 1 - Pr(\hat{t} \leq \tau + T_N)$ (see (Agaton, 2017) for a more detailed mathematical explanation). Hence, the probability of having no accident decreases over time, or the risk of an accident increases as the nuclear power plant gets older, especially during a continued operation beyond the end of its useful years, T_N. Then, the NPV calculation in Equation (3) can be expanded as shown in Equation (13)

$$NPV_{NE} = \mathbb{E}\left\{\sum_{\tau}^{\hat{t}} PV_{NE,t}\left(\mathbb{D}_{\hat{t}\leq T_N}\right) + \sum_{\hat{t}}^{T_N} PV_{NE,t}\left(1 - \mathbb{D}_{\hat{t}\leq T_N}\right)\right\} \quad (13)$$

$$PV_{NE,t} = \frac{P_{e,t}Q_e - P_{NE,t}Q_{NE} - OM_{NE} - E_{NE} - ND - DC}{(1+r)^t} \quad (14)$$

where: $\hat{t}$ is the period when an accident may happen, $\mathbb{D}_{\hat{t}\leq T_N}$ is an indicator equal to 1 if a nuclear accident occurs and zero if not, and ND is the damage cost of a nuclear disaster.

2.3 Case Study Background

The Philippines is a developing country in Southeast Asia with a 5-year average gross domestic product (GDP) growth rate of 5.6% before the pandemic. Its economy is driven by the service sector, with a 61% share followed by the industry sector at 29%, and agriculture and fisheries at a 10% share of GDP (Cueto *et al.*, 2022). The rapid industrialization and economic development result in increasing demand for energy from the utilities, industry, and transportation sectors.

The country is archipelagic, composed of 7,641 islands. The national energy transmission is divided into three grids: Luzon, Visayas, and Mindanao grids, while most of the smaller islands are not connected to the national grid. The power industry in the Philippines is divided into four different segments: (1) the generation consists of private and distribution unit-owned companies as well as the unsold assets of the National Power Corporation; (2) the transmission is handled by the private-owned National Grid Corporation of the Philippines; (3) the distribution consists of electric cooperatives as well as private and local government-owned distribution utilities; and (4) retail electricity consists of electricity aggregators for the contestable end-users (Gulagi *et al.*, 2021). Currently, the country's energy generation is based on 50% coal; 11% oil, 17% natural gas, and 22% renewable energy dominated by geothermal (11%) and hydropower (8%) wind (1%), solar (1%), and biomass (1%). Despite the country's vast resources, it imports the majority of its coal and oil, resulting in an unstable energy security and sustainability (Guno & Agaton, 2022).

To address this problem, the government started its nuclear program during the world oil crisis in 1973, but the succeeding administration discontinued the program due to numerous protests related to nuclear disasters, controversies, and nuclear safety issues (Beaver, 1994; Yap, 2020). In recent years, the government has been considering the rehabilitation of the mothballed power plant and the construction of four new nuclear power plants as a long-term option for an energy source in the country (Collera & Agaton, 2021).

Another sustainable energy alternatives are renewables. According to the National Renewable Energy Laboratory report, the Philippines has a huge renewable energy opportunity capacity of 58GW solar, 94 GW wind, 365 MW geothermal, 655 GW hydropower, and 374 MW biomass (Lee e*t al.*, 2020). The country's Philippine Energy Plan aims to increase the renewable energy generation to 35% and 50% share in the power generation mix by 2030 and 2040, by developing and optimizing the use of these renewable energy sources as an important part of the country's low emissions development strategy to addressing the challenges of climate change, energy security, and access to energy (DOE, 2021).

2.4 Data, Parameter Estimation, and Scenarios

The proposed ROA model for sustainable energy investments is applied in the case of the Philippines. For estimation of the parameters used in the real options valuation, we gather the data from the Philippines' Department of Energy (DOE, 2021), Philippines Power Statistics, and the National Renewable Energy Laboratory report on Renewable Energy in the Philippines (Lee *et al.*, 2020), and the National Economic Development Authority. All parameters used in the study are summarized in Tables 1 and 2.

For the valuation of sustainable energy projects, the electricity production is set to 1 TWh per year and calculated the investment costs and fixed O&M costs for solar PV, wind, geothermal, hydropower, and nuclear as shown in Tables 2. The estimated investment costs are USD 1091/MWh for geothermal, USD 1433/MWh for hydropower, USD 1138/MWh for solar PV, USD 1125/MWh for wind, and USD 732/MWh for nuclear. These costs include the technology cost, installation, grid connection, and other administrative and government fees. The estimated fixed O&M costs are USD 3.63/MWh/yr for geothermal, USD 10.94/MWh/yr hydropower, USD 11.27/MWh/yr solar PV, USD 10.92/MWh/yr wind, and USD 14.74/MWh/yr nuclear. These include the labor, management, operations, maintenance, and annual taxes and fees. For nuclear energy, the fixed O&M cost also includes the decommissioning cost that is accumulated towards the end life of the nuclear energy generation. The USD 2.37/MWh/yr variable O&M cost for nuclear includes the fuel and all other associated costs for operations not included in the fixed O&M cost. The lifetime of all energy sources is set to 30 years for comparison of valuation results.

Table 1
Parameters for dynamic optimization

Parameter	Unit	Value
Electricity price	USD/MWh	174
Electricity drift	%	4.053
Electricity volatility	%	3.033
Electricity-coal covolatility	%	1.90
Quantity of Electricity Generation	TWh	1
Coal price drift	%	3.47
Coal price volatility	%	26.87
Quantity of coal	kton	332
Fixed O&M cost for coal	USD/MWh/yr	16.2
Lifetime of energy generation	Years	30
Discount rate	%	5
Decision period	years	20

Sources: Philippines Power Statistics, National Economic Development Authority, World Bank- World Development Indicators, Philippine Department of Energy (DOE, 2021)

Table 2
Sustainable energy sources investment parameters

	Investment Cost	Fixed O&M Cost	Variable O&M Cost
	USD/ MWh	USD/ MWh/yr	USD/ MWh/yr
Renewables			
Geothermal	1091	3.63	
Hydropower	1433	10.94	
Solar PV	1138	11.27	
Wind	1125	10.92	
Nuclear	732	14.74	2.37

Sources: Philippine Department of Energy (DOE, 2021), National Renewable Energy Laboratory report (Lee et al., 2020)

The dynamic optimization is set to 20 years for the life of the option, which represents the period when an investor has the option to implement the project or wait up to the end of the life of the option. All benefits and costs are calculated to their present value using a discount rate of 5%. The benefits of producing electricity are based on electricity production with an average feed-in-tariff rate of USD 174/MWh for renewables. Using a 10-year historical price of electricity, we run an Augmented Dickey-Fuller (ADF) unit root test to determine whether electricity prices are stochastic. The ADF result shows that the null hypothesis that electricity price has a unit root at all significant levels cannot be rejected and therefore, it follows GBM with a drift of μ=4.053%, volatility of σ=3.033%, and co-volatility with coal prices of $\boldsymbol{\rho_{F,e}} = \mathbf{1.90\%}$, which are used to generate future prices of electricity.

The cost of using coal for electricity generation includes the fixed O&M cost of USD 16.2/MWh/year and the 332kton quantity of coal needed to produce 1 TWh of electricity per year at 56% efficiency of a coal power plant. To calculate the variable O&M cost, the quantity of coal is multiplied by the prices of coal. Similar to electricity prices, we used the ADF test, and the result shows that coal prices follow GBM with a drift of μ =3.47% and volatility σ=26.87%. These parameters are used to estimate the price of coal for each node (i,t), which is the future price based on the initial price I for every period t. These price nodes result in a matrix of prices. Using Monte Carlo simulation, the value of using coal is calculated at each price node by getting the average of all estimations run J=10000 times.

To evaluate the robustness of the investment decision, four investment scenarios are analyzed: extreme prices, electricity price, negative externality, and nuclear disaster. For the extreme price scenario, the GBM model for coal prices is combined with a Poisson process, which accounts for the extreme prices, described here as "jumps". The parameter estimation result identified a coal price frequency of λ =3.9 at k=1.37% jump size. For the electricity prices scenario, three FIT rates are used: current, 1% higher, and 1% lower than the current rate. The negative externality scenario only accounted for the CO_2 emissions from the combustion of coal. Hence, three levels of CO_2 prices are considered: USD 50/ton, USD 100/ton, and USD 150/ton. Lastly, the probability of having a nuclear accident is simulated assuming that it can happen at most once in the lifetime of power generation. When this happens, nuclear energy generation will cease to operate, and pay a huge damage cost equal to USD 1651/MWh. Here, the "Baseline Scenario" is defined as an investment environment without integrating any of the conditions mentioned in all the scenarios analyzed.

3. Results

3.1 Real Options Valuation Using Historical Data

Figure 1 shows the results of dynamic optimization of the real option value for shifting energy sources from coal to various sustainable energy sources. Each point on the curves represents the maximized value of an option at every initial price of coal. The bold curves represent the option values at the initial decision period t=0 (implement the investment now) while the dotted curves at the terminal decision period t=20 (wait until the option expires). Note that between bold and dotted curves are option values between initial and terminal decision periods. Therefore, the distance between the bold and dotted curves is equal to the value of waiting to invest. Each sustainable energy source is represented by colors: violet for geothermal, red for nuclear, green for wind, yellow for solar PV, and blue for hydropower.

The first point of interest in the figure is the shape of the curves. It can be observed that the values decrease with coal price. The leftmost side of the curves shows the maximized value of the options which selected coal over other energy sources. Hence, the lower the price of coal, the higher the economic value of using coal for energy generation, and the higher the option value. On the other side is a straight line, which represents the value of a sustainable energy source. With higher coal prices, variable operational expenditure using coal increases, and therefore, the maximization problem selected sustainable energy sources over coal. Among the sustainable energy source analyzed, geothermal energy showed the highest option value at USD 3545/MWh, followed by USD 3481/MWh nuclear, USD 3400/MWh wind, USD 3381/MWh solar PV, and USD 3092/MWh hydropower. This implies that geothermal energy is the most economically viable option among the other sustainable energy alternatives.

At almost free initial coal price, the option value at the initial period is USD 3907/MWh, while USD 3629/MWh at the terminal period for all types of sustainable energy. Subtracting the option value of the initial period from the terminal period gives a negative value of waiting, for instance, negative USD 278/MWh at an initial USD 1/ton coal. This means that while waiting to implement the project, its option value decreases, hence postponing the investment incurs losses from the opportunity to produce cleaner sources of energy. Moreover, the negative waiting value decreases with increasing the initial coal price.

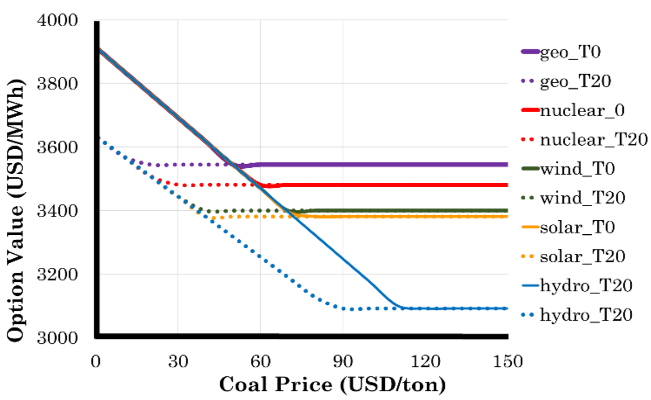

Fig. 1. Option values of shifting various sustainable energy sources at different decision periods. T0: initial decision period at t=0, T20: terminal decision period at t=20.

The intersection between the bold and dotted curves represents the trigger price of coal, where the option value at the terminal period is equal to the initial period, and when the value of waiting is zero. This means that at this initial price of coal upwards, the optimal strategy is to invest in sustainable energy as there is no additional value gained even at higher initial prices of coal. Based on the optimization results, the trigger price for geothermal is USD 49.95/ton, followed by USD 58.55/ton for nuclear, USD 69.48/ton for wind, USD 72.04/ton for solar PV, and USD 111.14/ton for hydropower. With the 2021 average coal price of USD 150/ton, the trigger prices imply that all sustainable energy projects are economically viable, considering their implementation in the selected case country. Furthermore, geothermal energy and hydropower with the lowest and highest trigger prices support the previous claim that the two or the most and least viable options for sustainable energy generation in the case country.

3.2 Extreme Coal Price Scenario

In the previous subsection, the development of prices of coal in the future periods is based on historical data on coal prices. This is referred to the "baseline scenario", where coal prices are assumed to be traded freely in the market, hence the price behavior follows GBM and is assumed to mimic that of other financial assets having two components: (upward) drift and a random walk. However, there are several events that change the behavior of the prices such as changes in policies, market crashes, wars, and natural disasters. This study tries to capture this (jump) behavior by combining the GBM with the Poisson jump process in the extreme coal price scenario. The result of dynamic optimization is presented in Table 3.

The table compares the trigger prices of coal for shifting energy sources using the Baseline and Extreme Prices Scenarios. It can be observed that the trigger prices decrease from USD 49.95/ton to USD 45.87/ton for geothermal, USD 111.14/ton to USD 102.06/ton for hydropower, USD 69.48/ton USD 63.81/ton for wind, USD 72.04/ton to USD 66.16/ton for solar PV, and USD 58.55/ton to USD 52.77/ton for nuclear energy. The main reason behind this is the movement of option value curves to the left while extending the straight path leftwards at the same level, as shown in Figure 2.

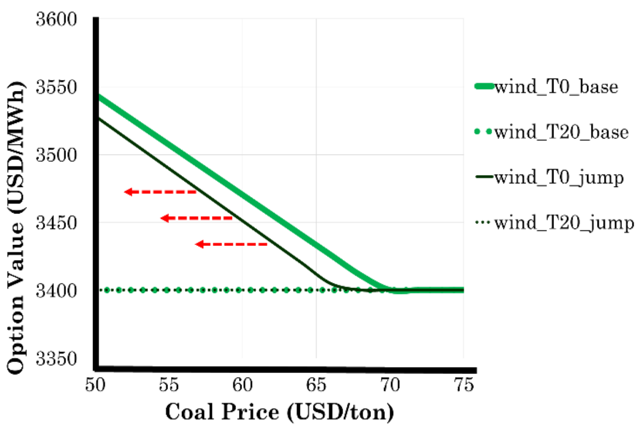

Fig. 2. Option values for shifting to wind energy at coal prices with jumps. Base: baseline values using historical prices of coal, jump: coal prices with jumps

Table 3
Trigger prices of coal for shifting to various sustainable energy sources at extreme coal price scenario

Sustainable EnergySources	Trigger Price of Coal (USD/ton)	
	Baseline	Extreme Prices
Renewables		
Geothermal	49.95	45.87
Hydropower	111.14	102.06
Wind	69.48	63.81
Solar PV	72.04	66.16
Nuclear	58.55	53.77

Note: The baseline scenario is based on the historical prices of coal

Accounting for the presence of extreme prices increases the variable operational costs of using coal for energy generation, resulting in a decrease in option values (wind_T0_jump) on the left side of the curves. On the other hand, the value of the investment in sustainable energy sources is not affected by these changes, hence, it remains constant at the same level. Therefore, the results imply that the presence of extreme events that suddenly increase the prices of fossil fuels provides a more favorable investment environment for sustainable energy projects.

3.3 Electricity Price Scenario

The Baseline scenario used the current feed-in-tariff (FIT) rates for sustainable energy sources. For instance, the FIT rate in the case country is at USD 117/MWh for hydropower, USD 148/MWh for wind, and USD 174/MWh for solar PV (DOE, 2021). The Electricity Price Scenario evaluated the sensitivity of trigger prices to the changes in FIT rates, as presented in Table 4.

The table compares the trigger prices of coal for shifting to sustainable energy sources by increasing and decreasing the FIT rates by 1%. The results show an increase in trigger prices with lower tariffs from USD 49.95/ton to USD 56.29/ton for geothermal, USD 111.14/ton to USD 117.48/ton for hydropower, USD 69.48/ton to USD 75.82/ton for wind, USD72.04/ton to USD 78.38/ton for solar PV, and USD 58.55/ton to USD 64.89/ton for nuclear energy. On the other hand, trigger prices decrease to USD 43.61/ton for geothermal, USD 104.80/ton for hydropower, USD 63.14/ton for wind, USD 65.70/ton for solar PV, and USD 52.21/ton for nuclear. The reason behind these is the movement of the curves downwards at lower FIT rates while upwards at higher FIT rates, as shown in Figure 3.

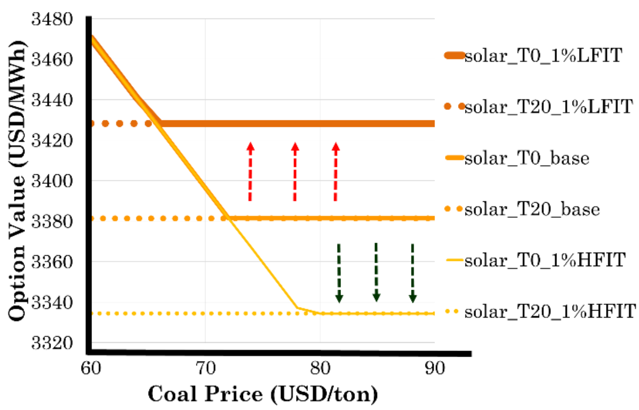

Fig 3. Option values for shifting to solar PV at different feed-in-tariff (FIT) rates. Base: current FIT rates, 1%LFIT: 1% lower than the current FIT rates, 1%HFIT: 1% higher than the current FIT rates.

Table 4
Trigger prices of coal for shifting to various sustainable energy sources at different feed-in-tariff (FIT)

Sustainable Energy Sources	Trigger Price of Coal (USD/ton)		
	1% lower FIT rate	Baseline	1% higher FIT rate
Renewables			
Geothermal	56.29	49.95	43.61
Hydropower	117.48	111.14	104.80
Wind	75.82	69.48	63.14
Solar PV	78.38	72.04	65.70
Nuclear	64.89	58.55	52.21

Note: The baseline scenario refers to the current FIT.

A lower FIT rate decreases the benefit (revenue) of energy generation from a sustainable source, resulting in lower option values (green arrows). On the other hand, a higher FIT rate increases the revenue of sustainable energy generation resulting in a higher option value (red arrows) and lower trigger price of coal for shifting energy sources. Note that the values of energy generation from coal are not sensitive to changes in FIT rates for renewables. These results imply that governments should improve the FIT rates to make sustainable energy projects more economically attractive to investors, as well as to power generation firms to shift to more sustainable sources of energy.

3.4 Negative Externality Scenario

A negative externality occurs when the social cost is greater than the private cost of energy production. The externalities described in this research are the emissions of GHG and air pollutants from burning fossil fuels that are harmful to both the environment and public health. Since the case country does not account for these externalities in accounting for the costs of a project, the Baseline Scenario has zero externality cost. Assuming that the carbon cost of burning fossil fuels will be accounted for in the near future, this study evaluates the sensitivity of trigger prices when carbon cost is added to energy generation from fossil fuels, as shown in Table 5.

The table compares the trigger prices of coal for shifting to sustainable energy sources by imposing an externality cost, carbon cost, to energy generation from coal. The results show that the trigger prices decrease with higher carbon costs. For instance, trigger prices for the geothermal decrease from USD 49.95/ton to USD 45.69/ton at USD 50/ton carbon price, USD 41.45/ton at USD 100/ton, and USD 37.20/ton at USD 150/ton carbon price. This is because of the shifts of the option value curves to the left (red arrows) as shown in Figure 4.

Table 5
Trigger prices of coal for shifting to various sustainable energy sources at different negative externality costs

Sustainable Energy Sources	Trigger Price of Coal (USD/ton)			
	Baseline	USD 50/ton	USD 100/ton	USD 150/ton
Renewables				
Geothermal	49.95	45.69	41.45	37.20
Hydropower	111.14	106.88	1102.64	98.39
Wind	69.48	65.23	60.98	56.74
Solar PV	72.04	67.78	63.54	59.30
Nuclear	58.55	54.29	50.05	45.81

Note: The baseline scenario has no externality cost.

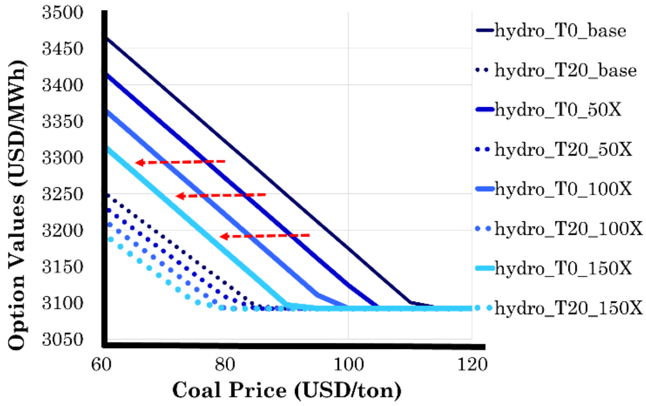

Fig. 4. Option values for shifting to hydropower at different CO_2 price. Base: baseline scenario without negative externalities, 50X, 100X, 150X: negative externality at USD 50/ton CO_2, USD 100/ton CO_2, and USD 150/ton CO_2.

Imposing carbon costs for energy generation from coal increases the variable operational expenditures resulting in a lower value of cash flows. Hence, the option value also decreases (red arrows) until a certain period when the dynamic optimization selects a sustainable energy source to maximize the investment. Note in the figure that sustainable energy sources are not affected by the carbon prices due to our assumption that power generation from these sources is carbon-free and releases no GHG emissions. Therefore, considering the negative externality, such as carbon pricing, in project valuation may accelerate the transition towards a more sustainable energy system in the developing countries.

3.5 Nuclear Disaster Scenario

The probability of having a nuclear disaster once in the lifetime is considered in nuclear energy generation. The world has experienced several nuclear disasters such as the Three Mile Accident in 1979, the Chernobyl disaster in 1986, and the Fukushima nuclear disaster in 2011, which incurred billions of dollars in damage costs and nuclear radiation. Table 6 presents the result of the dynamic optimization considering a USD 200 billion damage cost if a nuclear accident occurs.

The table shows the sensitivity of trigger prices for shifting to sustainable energy sources with respect to the probability of having a nuclear disaster. It can be observed that the trigger prices for the renewables are not sensitive to this variable. On the other hand, the trigger price for nuclear increased by almost five-fold from USD 58.55/ton to USD 281.65/ton. This is due to the shift of option value curves downwards (green arrows) as shown in Figure 5.

Table 6
Trigger prices of coal for shifting to various sustainable energy sources considering the risk of a nuclear disaster

Sustainable Energy Sources	Trigger Price of Coal (USD/ton)	
	Baseline	Nuclear Disaster
Renewables		
Geothermal	49.95	49.95
Hydropower	111.14	111.14
Wind	69.48	69.48
Solar PV	72.04	72.04
Nuclear	58.55	281,65

Note: The baseline scenario assumes no nuclear accident.

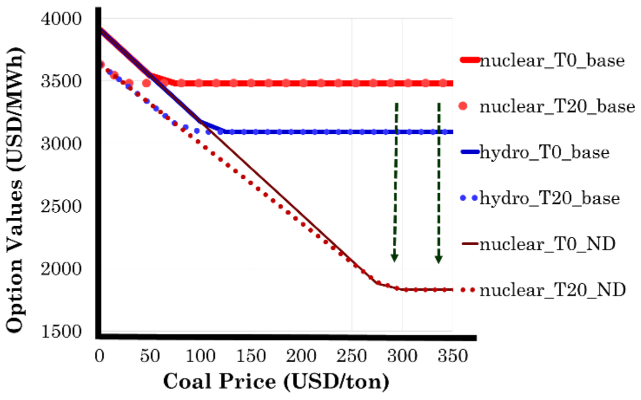

Fig. 5. Option values of shifting to nuclear and hydropower considering the risk of nuclear accident. Base: baseline scenario without nuclear disaster, ND: scenario with nuclear disaster.

While the probability of having a nuclear accident is very low, considering the huge damage cost significantly decreases the value of nuclear energy generation, as the power plant can no longer operate once the accident occurs. Meanwhile, the value of the project is still positive, which indicates that it is still a viable investment. However, the maximization problem selects the operation that gives the highest value of investment, which favors the use of coal over nuclear for energy generation. Otherwise, the maximization favors nuclear only after the coal reaches a price above USD 281.65/ton.

Lastly, compared with renewable energy sources, the trigger price for nuclear is the highest in this scenario. As shown in Figure 5, option curves for nuclear even went down below hydropower. Therefore, considering the risk of a nuclear accident in a project valuation favors investment in renewable energy sources than nuclear energy generation.

4. Discussion

4.1 Summary of Findings and Existing Studies

This research developed a valuation framework that can support investment decisions in sustainable energy projects. Applying the real options approach under uncertainties, we identified trigger prices of coal and electricity that make shifting to sustainable energy sources a better decision than continuing to use coal for electricity generation. Our estimation results highlight three key findings.

First, the result found that delaying investments results in a decrease in a real option value, which implies that waiting or postponing the implementation of the sustainable energy project incurs losses. This result contradicts previous studies, for instance, in the cases of Ireland (Assereto & Byrne, 2021), Ghana (Ofori *et al.*, 2021), and Colombia (Isaza Cuervo *et al.*, 2021) that, in the absence of comprehensive policy support, large-scale investment in renewable energy is not commercially viable and since the real option has value, the optimal strategy is to defer investment. By delaying the investment, investors obtain new and valuable information that minimizes the uncertainties, while improving the levels of technology maturity that provide reductions in technology risks (Ofori *et al.*, 2021). Similar results are also expected from the investment in nuclear energy under uncertainty in electricity prices, that the higher drift rate in selling electricity prices increases the value of the option to defer as this limits the risk and leads to a higher probability of accumulative profits (Najafi & Talebi, 2021). In this study, the value of real options is based on the flexibility to delay the shift of a power system from fossils to more sustainable energy sources. Since the case country is very dependent on imported fossil fuels, delaying the transition implies more imports. With the current trend of volatile and increasing prices of fuels in the world market, postponing the investment incurs losses from paying high fuel prices instead of producing fuel-free and more sustainable sources of energy.

Second, comparing the sustainable energy options, the result found that, except for geothermal, nuclear is a more viable option than renewable sources. This result is consistent with previous studies in India (Danish *et al.*, 2021) and China (Xie *et al.*, 2017) that nuclear energy is more suitable for replacing fossil energy than renewable energy in terms of costs and reducing GHG emissions. Despite its huge capital cost, nuclear energy, once installed has low operating costs with less fuel needed than fossil fuels to generate comparable wattage. Also, its marginal cost of power generation shows a declining trend due to the improvement of energy use technology and safety facilities, compared to renewables with unstable power generation due to the impact of climate change and other sources of uncertainties (Xie *et al.*, 2017).

Among the renewable energy sources, the study found that geothermal is the most economically attractive, followed by wind, solar, and hydropower. This result is in contrast to previous studies. For instance, Assadi *et al.* (2022) ranked renewables according to technical, economic, environmental, and social criteria using the case of Iran and found that solar, wind, biomass, hydroelectric, hydrogen, geothermal, and marine resources were the first to seventh priorities in facilitating the optimal selection of electricity generation resources. In the case of Taiwan, Lee and Chang (2018) used ranked the renewables according to four criteria (efficiency, job creation, operation, and maintenance cost) and found that hydropower is the best alternative with the most mature technology and lowest cost. It can be observed here that results are country-by-country basis and depend on several factors such as maturity of technology, availability of resources, geographic location, and policy support. In the case of the Philippines, geothermal has reached its technological maturity due to a particular natural endowment and a strong deployment strategy, which made the Philippines the world's second-biggest generator of geothermal power (Agaton, 2018). On the other hand, renewables-based electricity is now the cheapest power option in most regions due to decreasing costs, particularly wind and solar, which have consolidated their dominance over time and, with the recent increase in fossil fuel prices, the economic outlook for renewables power is undeniably good (IRENA, 2022).

Third, the results identified several drivers (scenarios) to accelerate the transition toward more sustainable energy systems such as increasing electricity tariffs, accounting for the externality costs, and considering the risk of a nuclear accident. The study confirmed that increasing the feed-in-tariff makes sustainable energy sources more economically attractive than using fossil fuels. This supports previous claim, for instance in China, that FIT implementation plays an important role in promoting renewable energy development (Du & Takeuchi, 2020). Particularly for large-scale deployment, non-residential plants are generally much more profitable from high FIT fixed prices (Wen *et al*., 2021). On the other hand, Yang *et al*. (2021) clarified that FIT is particularly suitable for the early stage of the development of the renewable energy industry, and once the industry is mature, a renewable portfolio strategy can be strategically integrated with FIT to ensure healthy and sustainable development.

This study also confirmed that accounting for the negative externality of energy generation will favor the alternatives to fossil fuels. This result is nothing new as it has been discussed extensively in the literature. For instance, Azam *et al*. (2021) found that fossil fuels did not contribute to economic growth and CO_2 reduction like nuclear energy and renewable energy, hence the expansion and improvement of these alternatives are vital to avoid global warming and climate change as well as to promote economic growth. Saidi and Omri (2020) also concluded that the best option to reduce CO_2 emissions is to consider a mix of nuclear and renewable energy and the two sources of energy are complementary. Meanwhile, the negative externality of the combustion of fossil fuels includes both environmental and public health impacts such as GHG emission, air pollution, and health problems (Jorli *et al*., 2018). While this study did not account for the other types of externalities, it should be noted that renewables also have negative impacts on the environment. For instance, considering the severity of negative environmental impacts, hydroelectric power plants are found to be the most hazardous among other renewable sources in terms of biodiversity losses, hence, measures should be taken to restore the rivers to the way they were when using fossil fuels come to an end (Rahman *et al*., 2022). Meanwhile, wind turbine generators demonstrate the least adverse environmental effects compared to others, which makes them the most sustainable renewable energy source (Lee & Chang, 2018; Rahman *et al*., 2022).

Lastly, this study found that considering the risk of nuclear accidents reduced the value of the investment in nuclear energy. While this is still a viable option with a positive NPV, it became less favored compared to other renewable energy alternatives. This is because the risk perceptions of the public translate into a significant social cost, and are likely to affect the revenues, costs, and financing conditions in the nuclear power sector (Huhtala & Remes, 2017). Despite significant reforms following past disasters, Wheatley *et al*. (2016) estimated that there is a 50% chance that a Fukushima event occurs every 60–150 years, with a decreasing frequency, but increasing in severity. This necessitates governments to post-Fukushima reforms that will truly minimize extreme nuclear power risks. While improvements in reliability and safety will certainly be made, legislation alone cannot guarantee that these actions will create a culture of safety (Behling *et al*., 2019). This is because the public depends heavily on trust in authorities responsible for inspecting nuclear power plants to evaluate the value of nuclear power (Kim *et al*., 2014).

4.2 Implications

The above findings provide broader implications for socio-economic policy, energy, climate change, and nuclear safety. For developing countries with limited financial resources, the transition to sustainable energy production and utilization is only possible in a favorable policy environment. First, investment valuation should be inclusive of the societal benefits of the sustainable energy project, particularly to the community who are the end-users and direct beneficiaries of such a project. These include local employment and job opportunities, consumer choice, better health and improvement of life standards, social bonds creation, social bonds creation, and community development (Kumar, 2020). To maximize these socio-economic development opportunities, policies and projects should ensure the community benefits by localizing the value chain, utilizing the local workforce and local skills training, tapping the domestic suppliers, and realizing a job creation beyond the energy sector such as experts in legal matters and taxation, logistics and safety, and other skilled laborers.

In this research, results found the crucial role of accounting for the negative externality, such as carbon pricing and carbon tax, in using fossil fuels for energy generation. Carbon pricing is a prime example of a systemic policy that can simultaneously shift the choices of consumers, producers, investors, and innovators in all sectors to a low-carbon transformation (van den Bergh & Botzen, 2020). If policymakers can increase the CO_2 prices in percentages for several years, and if investors are certain about this increase, it will encourage investment in sustainable energy sources (Azari Marhabi *et al*., 2021). Carbon taxes are another policy lever in jurisdictions that seek to accelerate decarbonization, climate change mitigation, and energy transition goals (Abdul-Salam, 2022).

Technological advancements are essential for improving efficiency and the economics of sustainable energy systems while restricting CO_2 growth. These advancements require political coordination in building-up new infrastructure projects such as grid connections from the sustainable energy generation facility over larger geographic areas, or charging stations for electric vehicles, as well as public acceptance for the deep system transformations involved (Luderer *et al*., 2021). Hence, these advancements should also cover other sectors such as the transport and manufacturing sectors (Gielen *et al*., 2019), while requiring a broader industry and public support as well as a determined action of policymakers to seize these opportunities (Luderer *et al*., 2021).

From all scenarios analyzed, the study found that nuclear energy is still a viable alternative to fossil fuels. However, for developing countries, specifically those that are prone to natural disasters and terrorist attacks, certain issues on safety, sustainability, waste disposal, and security should be addressed to increase public acceptance. With the new era of nuclear energy development mainly driven by developing countries, the concept of nuclear safety from a sociotechnical perspective should be clarified such as integrating social and technical elements in risk decision making, integrating the systems thinking and social mechanism as a substitute to reductionism in risk assessment, and establishing a public-centered risk communication (Wu *et al*., 2019). As nuclear fuel, such as uranium, is a scarce resource, cooperative relations and import agreements with countries abundant in uranium reserves (e.g., Australia, Russia, and Canada) should be well-established (Xie *et al*., 2017). Another concern on the radioactive waste, despite the decades of effort, has not been clearly solved yet resulting in a negative perception of nuclear energy as a solution to climate change. Research and development should be funded on reprocessing nuclear fuel, converting it into fuel again, and sending it to other countries with more mature industries to re-utilize it. Meanwhile, cooperation with international institutions such as the International Atomic Energy Agency should be established for technical and financial assistance as well as identifying suitable sites for the long-term storage of nuclear wastes. Moreover, the security of nuclear facilities both from natural disasters (e.g., earthquakes, tsunamis, super typhoons, flooding) and terrorist attacks is also an important issue for an effective nuclear policy and efficient nuclear power plant operation (Kim *et al.*, 2014). Therefore, nuclear energy development should be advanced including the installation of a cyber security system to prevent cyber nuclear attacks, the combinational preparations of both civilians and the government, as well as intensive training in preparation for the anticipated incident (Cho & Woo, 2017).

4.3 Limitations and Future Research Directions

To develop a general framework for decision support in sustainable energy decision support projects, this study made simplifying assumptions leading to various limitations in the analyses.

Firstly, several uncertainties that affect investment decisions were considered, such as coal prices, extreme prices, electricity prices, and the risk of nuclear disaster. There are also sources of uncertainties not covered in this study, such as intraday variability of renewable energy (solar irradiation, wind speed), impacts of climate change (drought, extreme weather conditions), technological advancement (decreasing technology cost, discovery of new and more efficient materials), load demand, abrupt changes in energy policies, and the combinations of several uncertainties (Adedoyin *et al.*, 2021; Borozan, 2022; Zakaria *et al.*, 2020). Future studies can account for these uncertainties and evaluate how they impact investment decisions on energy transition technologies. Several uncertainty models may also be used such as mean-reverting, technology learning, moving average, probability distributions, and other Brownian motions, depending on the case of each country, investment, and best fit model with the given data.

Secondly, the source of data is taken in consideration. At present, there is no nuclear energy facility operating in the case country, hence, all the data related to nuclear investment, operation, decommissioning, and damage costs are derived from the literature. To apply the proposed model in other developing countries, it is recommended to use the data from existing facilities to produce more realistic estimations and decision support recommendations.

Lastly, this study compared the economic attractiveness of sustainable energy options over fossil fuels. Future studies may complement an economic analysis with other aspects such as social acceptance for both private/firms and the public perception, legal and policy analysis, and environmental impact assessment. Also, the technologies were analyzed as mutually exclusive projects. In reality, investors may have a portfolio of several investment alternatives (Kuang, 2021; Zhang *et al.*, 2022). Hence, future studies may consider the combination of these technologies to further maximize the economic opportunities for investing in more sustainable sources of energy.

5. Conclusion

In the next decades, sustainable energy sources are expected to transform the energy sector from carbon-intensive to a net-zero carbon power system. While investments in these projects have been extensively discussed in the literature, this paper's contribution focused on providing decision support for shifting power generation by applying a real options-based framework that integrates several sources of uncertainties including energy and fuel prices, extreme prices, and probability of a nuclear accident. The real options valuation employed the dynamic optimization and Monte Carlo simulation to calculate the real option values and the optimal timing of investment, while the uncertainties modelled using geometric Brownian motion, Poisson process, and Bernoulli probability.

Applying the real options model using the Philippines as a case study, the optimization identified trigger prices of coal and electricity to make shifting to sustainable energy sources a better option than continue using coal for electricity generation. Among the available sustainable energy sources, geothermal is the most attractive, followed by nuclear, wind, solar, and hydropower. Results found that waiting or delaying the technology switch may lead to possible opportunity losses from generating carbon-free energy sources. The presence of extreme prices of coal accelerates this energy transition, as well as increasing the electricity tariff for sustainable energy sources and adding negative externality for using fossil fuels. Moreover, considering the probability of a nuclear accident and its corresponding huge damage cost, real options valuation favors the investment in renewable energy sources over nuclear. Hence, investment in nuclear energy only serves as a transition technology from fossil fuels to renewables, as the concerns about nuclear safety, disposal, and risks should be addressed first. Besides, renewables are now becoming more competitive with decreasing technology costs and with increasing prices of fossil fuels.

The valuation results showed that flexibility is crucial in making irreversible investment decisions. It highlights the usefulness of the real options approach as a powerful tool that can support investment decisions in sustainable energy investment projects under several uncertainties. Despite the limitations of the study, the real options framework proposed in this research could be a good benchmark for further analysis of decision support tools for investment decisions in cleaner and more sustainable sources of energy.

Nomenclature

Acronyms	
ADF	Augmented Dickey-Fuller
DOE	Philippine Department of Energy
FIT	Feed-in-Tariff
GBM	Geometric Brownian Motion
GDP	Gross Domestic Product
GHG	Greenhouse gas
NE	Nuclear Energy
NPV	Net Present Value
O&M	Operations and Maintenance

OV	Option Value
PV	Photovoltaic
RE	Renewable Energy
ROA	Real Options Approach
SE	Sustainable Energy
Symbols	
$\mathbb{E}\{NPV_{SE}\}$	Expected NPV for sustainable energy
$\mathbb{E}\{NPV_F\}$	Expected NPV for coal
$\mathbb{I}_{\tau<T}$	indicator function for shifting energy sources
I	capital investment cost
P_F	price of coal
P_e	electricity price
Q_e	quantity of electricity produced
Q_F	quantity of coal input
t	valuation period
T_{SE}	lifetime of the sustainable energy project
T_{NE}	lifetime of the nuclear energy project
T	Option valuation period
$\mathbb{S}_{SE}$	decision to invest in sustainable energy
r	discount rate
μ_e	percentage drift of energy prices
μ_F	percentage drift of coal prices
σ_e	volatility of energy prices
σ_F	volatility of coal prices
$\rho_{F,e}$	Co-volatility of electricity and coal prices
τ^*	optimal timing of shifting energy source
y_i	Poisson jumps size
N_t	compound Poisson distribution
λ	jump frequency
$\hat{t}$	period when a nuclear accident occurs
$\mathbb{D}_{\hat{t}\leq T_N}$	indicator function for nuclear accident
ND	damage cost of a nuclear disaster

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