Comparative Investment Analysis of Wind and Nuclear Energy: Assessing the Impact of Changes in the Electricity Mix and Required Government Support for Investment Parity

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Highlights

Comparative Investment Analysis of Wind and Nuclear Energy: Assessing the Impact of Changes in the Electricity Mix and Required Government Support for Investment Parity

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- Investment analysis framework for comparing wind and nuclear projects under various market conditions, with and without government financial support.
- An increase in wind share decreases and increases the return on investment of wind and nuclear projects, respectively.
- An increase in the average market price benefits the modular nuclear project more than the remaining projects.
- Current French energy policies highly favor the offshore wind project.
- Modular nuclear power plants could become highly competitive to wind projects if offered a feed-in premium similar to that currently offered to offshore wind producers.

Comparative Investment Analysis of Wind and Nuclear Energy: Assessing the Impact of Changes in the Electricity Mix and Required Government Support for Investment Parity

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ABSTRACT

Nuclear energy is once again in the spotlight in Europe, due to recent technological advancements and geopolitical challenges. Our study presents an investment analysis framework that compares the prospects of onshore and offshore wind projects, as well as traditional and modular nuclear projects. We evaluate the investment potential of each option, both with and without government financial support, similar to the system in place in France. Our study also includes an investment parity analysis, which determines the level of government financial support required to make modular nuclear power plants as attractive as wind projects under various circumstances. Our results show that, without government support, onshore wind projects are the most attractive investment option, followed by offshore wind projects. However, in certain circumstances and based on specific metrics, modular nuclear projects can be more appealing. Interestingly, our findings indicate that with French government support, offshore wind projects offer better investment prospects than onshore wind projects. To achieve investment parity with the most attractive wind project, modular nuclear power plants, which have a relevant advantage in terms of shorter construction times than wind projects, would require a feed-in premium similar to that offered to offshore wind projects.

1. Introduction

Europe has been transitioning towards cleaner energy sources since the 1960s (IEA, 2023). Nuclear and natural gas were initially considered potential pillars of this transition, but safety concerns and dependence on fuel imports led to implementation of alternative strategies to meet demand (Ayodeji, Amidu, Olatubosun, Addad and Ahmed, 2022; Schöbel, Silla, Teperi, Gustafsson, Piirto, Rollenhagen and Wahlström, 2022). Starting in 2005, Europe shifted its focus towards renewable energy (IEA, 2023). However, the production of renewable energy requires significant amounts of metals, which are not produced in sufficient quantities in Europe (IEA, 2022; Qu and Bang, 2022; MineralsUK, 2022). This creates a risk of energy insecurity due to reliance on imports, which has gained increasing attention within the EU following the Russian invasion of Ukraine, and increasing geopolitical tension between the West and the East. Moreover, several renewable energy technologies are characterized by volatile production and contribute to unstable supply and fluctuating prices (hong Zhu, Ren, Gu, Zhang and Sun, 2023; Maniatis and Milonas, 2022). In contrast, nuclear energy has undergone significant technological advancements in recent years, particularly with the development of modular nuclear power plants, which may come with reduced construction cost and increased safety when compared to traditional nuclear power plants (Ingersoll and Carelli, 2020a). In contrast to renewable energy, nuclear technology requires fewer metals (IEA, 2022), which reduces the risk of energy insecurity caused by metal imports. Moreover, nuclear energy sources may provide more stable energy supply compared to renewable energy sources. As a result, nuclear energy has regained interest in Europe (Bohdanowicz, Łopaciuk Gonczaryk, Gajda and Rajewski, 2023).

Considering the growing role of renewable energy in the electricity mix and the renewed interest in nuclear energy, this research aims to provide comparative insights into the profitability and feasibility of renewable and nuclear energy projects in Europe. To achieve this aim, a flexible investment analysis framework is developed. The framework considers four energy technologies, namely onshore and offshore wind energy, as well as traditional and modular nuclear energy. Further, the framework takes into account various factors that impact the investment performance of energy projects. These factors include the on-grid average electricity price, the energy mix and government financial support. Using the framework, we analyze the performance of the technologies under different market scenarios. Additionally, the paper investigates how governments can influence the competitiveness of nuclear energy in the investment market through the adjustment of investment aid, feed-in premiums, and tax credits.

Existing research has investigated the profitability and prospects of onshore and offshore wind projects, as well as traditional and modular nuclear power plant projects, in isolated contexts. For example, Niesten, Jolink and Chappin (2018), Belkin (2008), Santa Catarina (2022) and bin Li, shu Lu and Wu (2013) indicate that onshore wind projects

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are generally profitable but policy-related risks can change investors' return expectations. While onshore wind investment analysis focus on the level of profitability, existing papers analyzing the investment prospects of offshore wind focus more on whether the projects can be profitable. Ziemba (2022), Liu, Sun and Wu (2021). Jåstad and Bolkesjø (2023) indicate that the outcomes of investing in offshore wind projects are heterogeneous depending on the time to market, the extent of the plant network, and related policies. The existing literature is not optimistic about the performance of traditional nuclear energy projects in the investment market (Wealer, Bauer, Hirschhausen, Kemfert and Göke, 2021; Terlikowski, Paska, Pawlak, Kaliński and Urbanek, 2019). However, modular nuclear power plants, the most recent and promising nuclear technology, have also been investigated and found to have higher chances of becoming profitable (Locatelli, Bingham and Mancini, 2014; Mignacca and Locatelli, 2020; Zimmermann and Keles, 2023). Other relevant studies have pointed to the ongoing security concerns related to renewable energy and metal import requirements (Islam, Sohag, Hammoudeh, Mariev and Samargandi, 2022; Tokimatsu, Höök, McLellan, Wachtmeister, Murakami, Yasuoka and Nishio, 2018), as well as the volatility and instability of certain renewable energy technologies (Ciarreta, Pizarro-Irizar and Zarraga, 2020; Abrell, Rausch and Streitberger, 2019; Maniatis and Milonas, 2022).

Although many studies have examined the prospects of wind and nuclear power investments, none have conducted a full comparative study, at least to the best of our knowledge. A pure survey of existing research could offer valuable insights into their economic competitiveness, but making perfect ceteris paribus comparisons would be challenging due to different assumptions used in the various studies. By developing a new framework, we can more fairly evaluate these projects under diverse market conditions, while also comparing our findings with those found in the literature. Moreover, by including aspects such as endogenous price dynamics and variable wind shares, we can offer insight that is highly relevant in a quickly changing energy system. Also, since there are no comparative studies on the topic, there are no studies that investigate what government support is needed to achieve investment parity for these different types of projects under various circumstances. This could be particularly relevant for governments interested in promoting private investments in modular nuclear power plants to increase power supply stability and energy security. Overall, our framework and analysis can contribute to the existing knowledge on clean energy and energy security, areas that warrant simultaneous examination due to the confluence of challenges posed by climate change and geopolitical instability. Our efforts also answer a call from Royston, Foulds, Pasqualino and Jones (2023) for new and alternative energy model frameworks, which can contribute to unbiased perspectives on energy policy and the transition to sustainable energy sources.

The remainder of this paper is organized as follows. Section 2 presents the new framework developed for this study. Section 3 outlines the results from the private investment analysis and the investigation of required financial support from energy policies for investment parity. Section 4 conducts a sensitivity analysis. Section 5 provides a discussion and suggests avenues for the future research, and Section 6 concludes and indicates the policy implications.

2. Materials and methods

The investment analysis framework developed for this study consists of five modules: a project module, revenue module, cost module, policy module, and an assessment metrics module, as illustrated in Figure 1. The project module describes the basic characteristics of four energy projects, including their construction times, production capacities, and lifetime. The revenue module estimates the volume-weighted electricity price obtained by wind and nuclear projects by using the average market electricity price and electricity mix, which is then multiplied by production volume to determine project revenue. The cost module considers construction and operational cost, while the policy module consider three types of energy policies that can financially support wind and nuclear projects. Lastly, the assessment metrics module calculates the internal rate of return and benefit-cost ratio of the projects. In the following, we outline the details in each module. The model is available for download through a GitHub repository.

2.1. Project module

The project module considers four clean energy projects: two types of wind farms (onshore and offshore) and two variations of nuclear power plants (traditional and modular). Table 1 summarizes the projects' typical features, which we will use in our analyses.

Europe is experiencing a notable increase in renewable energy adoption, with wind energy representing the fastest-growing segment, as reported by Eurostat (Eurostat, 2023). This indicates that wind energy has been an attractive investment option, also making it a compelling option to consider for those interested in clean energy investments. Currently, onshore wind farms are the mainstay of the European wind energy sector, while offshore wind projects are still in their nascent stages (Eurostat, 2023). An average onshore wind farm has a capacity of around 450MW. In contrast, offshore wind technologies utilize larger turbines, leading to offshore wind farms having a more substantial scale and capacity (John, Jan, Til, Arno, Peter, Mattias, Stephan, Paul and Nicolaos, 2020). A typical offshore wind farm possesses a capacity of 740MW. The construction duration for onshore wind farms averages 6 years, while offshore wind farms require a longer construction period, averaging 9 years. However, the life cycles of both onshore and offshore wind farms are comparable, with each lasting approximately 20 years.

The majority of nuclear power plants operating worldwide are traditional, government-funded facilities, as noted by Hussein (2020). These plants typically possess a capacity of up to 1GW. The construction period for traditional nuclear

Table 1
Basic settings of the four typical energy projects

	Onshore wind	Offshore wind	Traditional nuclear	Modular nuclear
Typical numbers of turbines/reactors	150	100	1	1
Average turbine/reactor capacity (MW)	3	7.4	1000	300
Typical capacity of power plants (MW): $Capacity_p$	450	740	1000	300
Construction time (years): CT_p	6	9	14	4
Lifecycle of turbines/reactors (years)	20	20	40	30

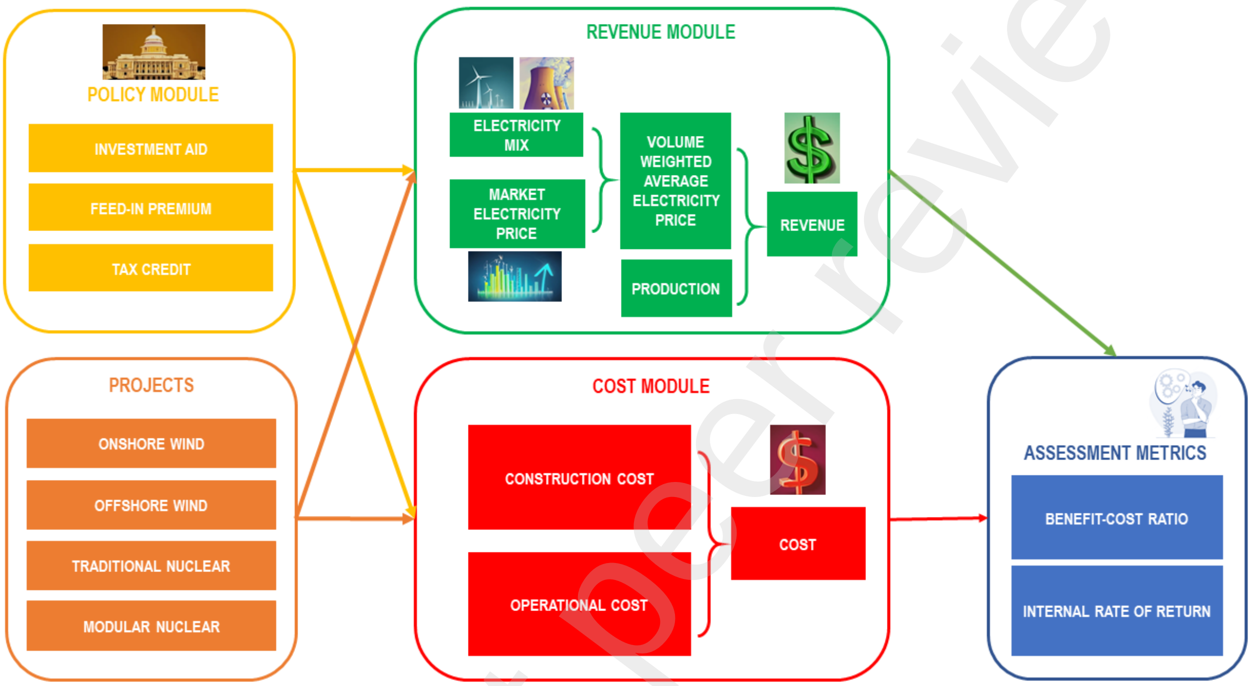

Figure 1: Investment analysis framework

power plants can extend up to 14 years, which highlights their nature as a long-term investment. But at the same time, the life cycle of large reactors in traditional nuclear power plants averages up to 40 years. In contrast, modular nuclear power plants exemplify a cutting-edge approach to nuclear energy generation. According to Ingersoll and Carelli (2020b), these plants are designed with a capacity not exceeding 300 MW, substantially smaller than their traditional counterparts. The construction time for modular nuclear power plants is estimated at 4 years, which is considerably shorter than that of traditional plants, thus significantly accelerating the time to operation, which can be a great advantage from an investment perspective, especially for investors with a high discount rate. The lifetime of small reactors in modular nuclear power plants is 10 years shorter than that of large reactors in traditional nuclear power plants, that is, about 30 years.

2.2. Revenue module

To determine a project's revenue, the framework utilizes a simple basis for calculation. It multiplies the electricity price obtained by the project with its total electricity production and then deducts any relevant income taxes for a given time period t, as shown in Equation 1. This revenue calculation does not take into account any energy policies that may offer financial assistance to clean energy projects. In Section 2.4, we will explore various types of financial support policies and how they can impact the revenue equation, i.e., explain how the policy module feeds into the revenue module of our framework.

$$R_{p,i,t}^{\text{Without-energy-policies}} = P_{p,i,t}^{\text{WV}} \times Q_{p,t} \times (1 - Tax_i^{\text{inc}}) \quad (1)$$

In this notation, $R_{p,i,t}^{\text{Without-energy-policies}}$ represents the revenue for project p in country i through time period t, without considering any energy-related policies that have influence on the revenue of a project. p can take on the values of onshore wind (onw), offshore wind (ofw), traditional nuclear power (tnp), or modular nuclear reactor (mnr). i can take on the values of Germany (DE), France (FR), Belgium (BE), Spain (ES), and Finland (FI). $P^{WV}_{p,i,t}$ represents the volume-weighted average electricity price obtained by project p in country i in time period t, and $Q_{p,t}$ is the production of project p through time period t, which is the same regardless of country. Tax^{inc}_i represents the income tax rate, which can vary from country to country.

Relating to the prices and revenue, we hypothesize that nuclear energy, with its high degree of stability, may command a price premium, particularly when wind energy represents a large share of the on-grid electricity mix, due to its inherent variability. To capture the hypothesized price dynamics, which is confirmed through regression analysis, the framework incorporates volume-weighted average prices of wind projects calculated based on assumptions regarding the average price observed over time and assumptions regarding the on-grid electricity mix, as shown in Equation 2.

$$\mathrm{P}^{\mathrm{WV}}_{p=\mathrm{onw,ofw},i,t} = \alpha + \beta_1 \bar{\mathrm{P}}_{i,t} + \beta_2 \mathrm{S}_{i,t} + \gamma_i + \mu_{i,t} \quad (2)$$

In this notation, $\mathrm{P}^{\mathrm{WV}}_{p=\mathrm{onw,ofw},i,t}$ is the volume-weighted average electricity price obtained by wind projects in country i through time period t, where $\bar{\mathrm{P}}_{i,t}$ is the market average electricity price in country i through time period t, and $\mathrm{S}_{i,t}$ is the average real wind share in country i during time period t. The real wind share refers to the proportion of wind energy actual power generation in the total actual power generation, rather than the installed capacity of wind power plants as a percentage of the total installed capacity of all types of power plants. The coefficients α, β_1, and β_2 are estimated through regression, and represent the intercept and slopes for the independent variables. The individual effect γ_i is a time-invariant effect specific to each country, and $\mu_{i,t}$ is the error term.

We use Equations 3 and 4 to estimate the volume weighted average electricity price of nuclear projects.

$$\mathrm{P}^{\mathrm{WV}}_{p=tnp,mnr,i,t} = \mathrm{P}^{\mathrm{WV}}_{p=\mathrm{onw,ofw},i,t} + \mathrm{Diff}^{\mathrm{WV}}_{p=tnp,mnr,i,t} \quad (3)$$

$$\mathrm{Diff}^{\mathrm{WV}}_{p=tnp,mnr,i,t} = \theta + \rho_1 \bar{\mathrm{P}}_{i,t} + \rho_2 \mathrm{S}_{i,t} + \epsilon_i + \vartheta_{i,t} \quad (4)$$

where $\mathrm{P}^{\mathrm{WV}}_{p=tnp,mnr,i,t}$ is the volume weighted average electricity price of nuclear projects. As before, $\mathrm{P}^{\mathrm{WV}}_{p=\mathrm{onw,ofw},i,t}$ is the volume-weighted prices obtained by the wind projects, while $\mathrm{Diff}^{\mathrm{WV}}_{p=tnp,mnr,i,t}$ represent the volume-weighted price premium obtained by nuclear producers. ϵ_i is the time-invariant individual effect, $\vartheta_{i,t}$ is the error term. θ, ρ_1 and ρ_2 are coefficients estimated through regression.

To test our hypothesis regarding price dynamics and estimate the coefficients in Equations 2-4, we conduct a robust fixed effect panel data regression using STATA. For this purpose, we utilize NordPool (2023) data on hourly electricity prices and hourly energy production by source from January 2015 to December 2022 in the selected five countries. The data is converted from hourly to monthly, calculating the volume-weighted monthly average prices by source in the process. In line with standard practice, we deflate all price data to remove the influence of inflation on our results.

Table 2
Results for Equation 2

Variable	Coefficient	P-value
Average electricity price: $\bar{\mathrm{P}}_{i,t}$	β_1: 0.90	0.000
Real Wind Share: $S_{i,t}$	β_2: -41.3	0.022
cons	α: 6.08	0.025

Table 3
Results for Equation 4

Variable	Coefficient	P-value
Average electricity price: $\bar{\mathrm{P}}_{i,t}$	ρ_1: 0.1	0.013
Real Wind Share: $S_{i,t}$	ρ_2: 43.51	0.017
cons	θ: -6.28	0.014

The results of the regression analyses are presented in Tables 2-3. Our regression and estimation outcomes clearly support the hypothesis that increasing the share of wind energy in the electricity mix reduces the unit revenue of wind power generation. Moreover, our results suggest a positive relationship between the market average electricity price and the volume-weighted average electricity price of wind, which is intuitive. If it wasn't for intra-monthly fluctuations in production by source and price, one would expect the volume-weighted prices to be fully explained by the average price observed over time, i.e., for Equation 2, the constant would equal zero, the coefficient for wind share would equal zero, the coefficient for average price would equal one, while for Equation 4, all coefficients would be zero, leading to both volume weighted average prices equaling the average price observed over time. All estimated coefficients in Equations 2 and 4 are statistically significant different from zero in the expected direction, validating their use in our framework. The incorporation of these price dynamics and estimated coefficients allow a more precise estimation of revenue and profitability for wind and nuclear power generation projects.

After estimating $P^{WV}_{p,i,t}$, we need to calculate the $Q_{p,t}$ as well for Equation 1. According to Table 1, the typical capacity of different power plants is in a unit of MW, but the unit of the volume weighted electricity price obtained in this way is euros/MWh. So we need to unify the units before multiplying them by Equation 5. The capacity factors used in the unit conversion process are shown in the Table 4 (IRENA, 2019; WNA, 2022).

$$\mathrm{Q}_{p,t} = \mathrm{Capacity}_p \times \mathrm{CF}_p \times \mathrm{Complete}_{p,t} \times \mathrm{Active}_{p,t} \quad (5)$$

Where, $Capacity_p$ is the typical production capacity of project p, for which we apply the values found in Table 1. CF_p is the conversion factor of project p, for which we apply the values found in Table 4. $\mathrm{Complete}_{p,t}$ is a binary variable,

Table 4
Unit conversion factor from MW to MWh for different energy sources

Factors	Onshore Wind	Offshore Wind	Traditional Nuclear	Modular Nuclear
Capacity factor	0.25	0.51	0.92	0.94
Conversion factor: CF_p	2190	4467.6	8059.2	8234.4

taking the value of 1 if the construction of project p is completed at time t, and the value of 0 otherwise, following the specifications given in Table 1. Similarly, $\text{Active}_{p,t}$ is a binary variable, taking the value of 1 if the project is operating within its lifetime, and 0 otherwise, following the specifications given in Table 1.

2.3. Cost module

The cost of a typical power plant consists of two main components, construction cost and operating cost (includes decommissioning cost). The cost of a project can be obtained by multiplying the unit construction cost and operating cost by the MW capacity in period t, with consideration of the construction and life time of the project (Equation 6). In this module, like in the revenue module, we calculate the cost of the projects per period t without considering any energy-related support polices that can help decrease the cost of clean energy projects. We will outline how governmental financial support can impact the cost equation in Section 2.4.

$$\begin{aligned} \mathrm{C}_{p,t}^{\text{Without-energy-policies}} &= \frac{\mathrm{UCC}_p \times \mathrm{Capacity}_p}{CT_p} \\ &\times(1-\mathrm{Complete}_{p,t}) + \mathrm{UOC}_p \times \mathrm{Capacity}_p \\ &\times \mathrm{Complete}_{p,t} \times \mathrm{Active}_{p,t} \end{aligned} \tag{6}$$

Where $\mathrm{C}_{p,t}^{\text{Without-energy-policies}}$ is the total cost of project p through time period t, without considering any energy-related policies that can affect the cost of a project. UCC_p and UOC_p are the unit construction cost per MW capacity and unit annual operational cost per MW capacity of project p. We assume the constructions cost is evenly spread out over the project's construction time. Further, we assume no operational cost during the construction time. After the project is put into production until the end of the lifetime of the engine or reactor, the annual cost will only include the operating cost.

The relevant data for onshore wind farms comes from EnergyFacts (2022), and the cost data for offshore wind farms comes from a report by BVG Consulting (BVG, 2019). Cost-related data for traditional nuclear power plants come from a joint report published by IEA and NEA (2020). The cost data of modular nuclear power plants comes from an open-source platform for the construction and financing of nuclear power plants which is named OPEN100 (2020). Table 5 gives an overview of the applied data.

2.4. Policy module

For clean energy projects, European governments generally have different energy policies for financial support. Among them, feed-in premium, tax credit and investment aid are the three most common measures. Table 6 presents the current government financial support policies for renewable energy including wind energy and nuclear energy projects. The data comes from the websites of the Ministry of Energy and the Ministry of Finance of each country and the European Commission. It shows that the current European energy policies for renewable are extensive. In comparison, the financial support for nuclear energy appears scarce.

Feed-in tariffs are a financial support mechanism that provides a fixed price for electricity generated from clean energy sources. The feed-in premium is the difference between the auction price and the market price for electricity. Tax credit refers to the percentage of income tax that can be reduced for clean energy producers (EuropeanCommission, 2020). Both of these two policies affect investment analysis in terms of revenue (Equation 7).

$$\begin{aligned} R_{p,i,t}^{\text{with FIP\&TC}} &= (P_{p,i,t}^{\text{WV}} + FIP_{p,i}) \times Q_{p,t} \\ &\times (1 - Tax_i^{\text{inc}} \times (1 - TC_{p,i})) \end{aligned} \tag{7}$$

Where $R_{p,i,t}^{\text{with FIP\&TC}}$ is the revenue for project p at time period t after considering the feed-in premium policy and tax credit policy. $FIP_{p,i}$ and $TC_{p,i}$ are the feed-in premium and tax credit of project p in country i, respectively.

Investment aid refers to the percentage of construction cost that the government is able to subsidize for a project (EuropeanCommission, 2020). This policy is to affect the investment return in terms of cost (Equation 8).

$$\begin{aligned} \mathrm{C}_{p,t}^{\text{with IA}} &= \frac{(\mathrm{UCC}_p \times \mathrm{Capacity}_p)(1 - IA_{p,i})}{CT_p} \\ &\times(1-\mathrm{Complete}_{p,t}) + \mathrm{UOC}_p \times \mathrm{Capacity}_p \\ &\times \mathrm{Complete}_{p,t} \times \mathrm{Active}_{p,t} \end{aligned} \tag{8}$$

Where, $\mathrm{C}_{p,t}^{\text{with IA}}$ is the total cost of project p at time period t after considering the investment aid policy. $IA_{p,i}$ is the investment aid for project p in country i.

2.5. Assessment metrics module

This paper uses two indicators to analyze investment attractiveness, benefit-cost ratio (BCR) and internal rate of return (IRR).

The BCR (Equation 9) shows the relative relationship between the present value of benefit and cost of a project (Shively, 2012). If a project has a BCR higher than 1, it indicates that the project can generate a positive net present value.

Table 5
Cost comparison of four types of power plants (euros/MW)

Cost	Onshore wind	Offshore wind	Traditional Nuclear	Modular Nuclear
Construction cost: UCC_p	**1213000**	**2701800**	**5654000**	**2276000**
Turbine/Reactor	928000	1140000	1209000	642000
Foundation and installation	80000	114000	718000	424000
Electric system	142000	458280	328000	328000
Land	48000	225720	132000	13000
Financial cost	15000	136800	755000	111000
O&M cost: UOC_p	**42000**	**85500**	**3281600**	**1117010**
Operations	19000	28500	614600	583000
Maintenance & services	23000	57000	2667000	534000

Table 6
Current government financial support from energy policies for clean energy in different countries

Country	Renewable energy(including wind energy)			Nuclear energy		
	Feed in premium (euros/MWh):$FIP_{p,i}$	Investment aid:$IA_{p,i}$	Tax credit:$TC_{p,i}$	Feed in premium (euros/MWh):$FIP_{p,i}$	Investment aid:$IA_{p,i}$	Tax credit:$TC_{p,i}$
Finland	53	up to 30%	up to 50%	no	up to 30%	up to 25%
Germany	0 for projects over 50MW capacity	up to 40%	no	no	no	no
France	40-72 for onshore, 150-200 for offshore	up to 40%	up to 40%	no	up to 33%	up to 50%
Spain	75-84 for onshore, 140-174 for offshore	up to 30%	up to 25%	no	up to 7.5%	no
Belgium	74-96	up to 30%	no	no	no	no

$$BCR_{p,i} = \frac{PVR_{p,i}}{PVC_p} = \frac{\sum_{t=0}^{T} R_{p,i,t}/(1+\delta)^t}{\sum_{t=0}^{T} C_{p,t}/(1+\delta)^t} \tag{9}$$

Where, $PVR_{p,i}$ is the total present value of revenues of project p in country i and PVC_p is the total present value of cost for project p. T is the life cycle of the project from construction to expiration. δ is the discount rate.

The IRR (Equation 10) is the discount rate that can make the net present value of a project equal to zero (Magni, 2010). When comparing investment options, the one that has higher IRR would be considered the better.

$$\mathrm{NPV_{p,i}} = \sum_{t=0}^{T} \frac{(\mathrm{R}_{p,i,t} - \mathrm{C}_{p,t})}{(1+\mathrm{IRR})^t} = 0 \tag{10}$$

Where $NPV_{p,i}$ is the net present value of project p in country i.

3. Results

To emphasize our framework's capabilities and accomplish the study's objectives, we conduct three distinct analyses. We first run the model to evaluate the attractiveness of the four investment options without considering energy-related government financial support. Then, we integrate French energy-related government financial support into the model and run it again. Finally, we examine the required level of government financial support to achieve investment parity between wind and nuclear projects in terms of IRR. In each analysis, we compute the BCR and IRR for the four projects across market electricity prices ranging from 100 to 370 euros/MWh and energy mixes with real wind shares ranging from 0 to 100%. For context, the average annual electricity price in the EU was 126 euros/MWh in 2021 and 198 euros/MWh in 2022 (Eurostat, 2023). In the following, we present the results. The outcomes from the private investment analysis without financial support hold relevance for all EU countries, while the results from the analysis with energy-related financial support and the investment parity assessment mainly apply to France. For those interested in performing similar analyses for other countries and what-if policy-scenarios, our framework can be accessed through GitHub.

3.1. Private investment results without government financial support

Figure 2 presents the relevant BCR results from the analysis without government financial support. The BCR results provide three interesting insights. First, when the market electricity price rises, the BCR of wind and nuclear projects both show an increase. However, the BCR of the four projects are all less than 1 when the average electricity price is as low as 100 euros/MWh. This means that without any government financial support, neither wind nor nuclear projects can generate a positive return on investment when market electricity prices are low.

Second, under the condition that the market electricity price remains constant, increasing the proportion of wind energy in the existing electricity mix will significantly decrease the BCR of onshore and offshore wind projects, while slightly increasing the BCR of the two nuclear projects.

Third, the comparison of the four projects across the price range demonstrates that the BCR for the two wind projects consistently surpasses that of the two nuclear projects regardless of price and wind share. The primary reason for this disparity is the substantially lower construction cost associated with wind projects compared to nuclear projects. Although the BCR for the modular nuclear project can attain a positive return when the average electricity price lies at the upper end of the examined price range, the traditional nuclear energy project is unable to achieve a positive return within the assessed price range. But this conclusion regarding the failure of traditional nuclear projects to achieve profitability does not imply that we advocate for the phase-out of existing traditional nuclear power plants.

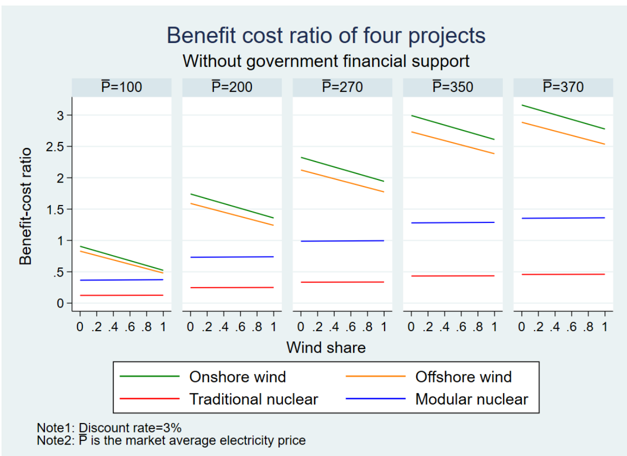

Figure 2: Benefit cost ratio of four projects without considering government financial support

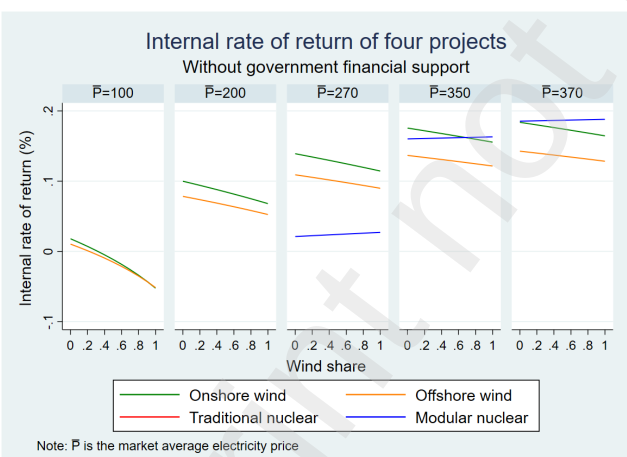

Figure 3: Internal rate of return of four projects without considering government financial support

Figure 3 showcases the relevant IRR findings, which, in contrast to the BCR outcomes, suggest that under certain conditions, the modular nuclear project may be more appealing to certain investors than wind projects. Although wind projects exhibit higher BCR values than nuclear projects across all price levels and wind shares, the IRR of the modular nuclear project surpasses that of the wind projects in particular scenarios. For example, at an average electricity price of 370, the BCR of both wind projects is greater than that of the modular nuclear project; however, the modular nuclear project outperforms the wind projects in terms of IRR for all wind shares. This discrepancy is attributable to the role of the discount rate and the construction times of the projects. While our BCR calculation applies a fixed time preference in terms of a discount rate of 3%, the IRR calculation determines the discount rate that can be employed without resulting in negative return on investment, which could be an interesting metric to investors with time preferences deviating from those corresponding to a discount rate of 3%. The modular nuclear project can be constructed in four years, which is two and five years shorter than construction times of onshore and offshore wind, respectively, as shown in Table 1. As a result, the modular nuclear project starts generating revenue at a significantly earlier point in time than the wind projects, which represents an advantage that becomes increasingly attractive the higher the employed discount rate. These insights imply that, under favorable price conditions, the modular nuclear project may be a more attractive investment option for impatient investors operating with a high discount rate than wind projects.

3.2. Private investment analysis with current government financial support

The previous section outlined the results from the analysis without consideration of energy-related financial support. In this section, we present the results from the analysis which integrates three current energy-related policies, as in place in France, and compare them to those obtained in the previous section.

Figure 4 compares the BCR results obtained from model runs with and without financial support. The figure shows that current French clean energy policies, including investment aid, feed-in premiums, and tax credits, significantly increase the BCR of both wind projects, while, in comparison, only leading to a modest increase in the BCR of the two nuclear projects. In other words, the results indicate that the energy policies in place in France favor wind energy more than nuclear, and increase the disparity between the BCR of wind and nuclear projects observed in the results from the analysis without any energy-related policies.

Figure 4 also reveals an intriguing finding when comparing the two wind projects. After factoring in the current financial support, the BCR rankings of the wind projects are reversed. In contrast to the findings without energy-related policies, the BCR of the offshore wind project now exceeds the onshore wind project across the examined price and wind share ranges, making it the most profitable option in the investment market given the discount rate of 3%. This shift is attributed to government energy policies, particularly the feed-in premium, which subsidizes offshore wind energy far more than onshore wind energy.

One last observation from Figure 4 pertains to nuclear projects. The figure demonstrates that, despite receiving government financial support, the traditional nuclear project remains an unattractive option for private investors.

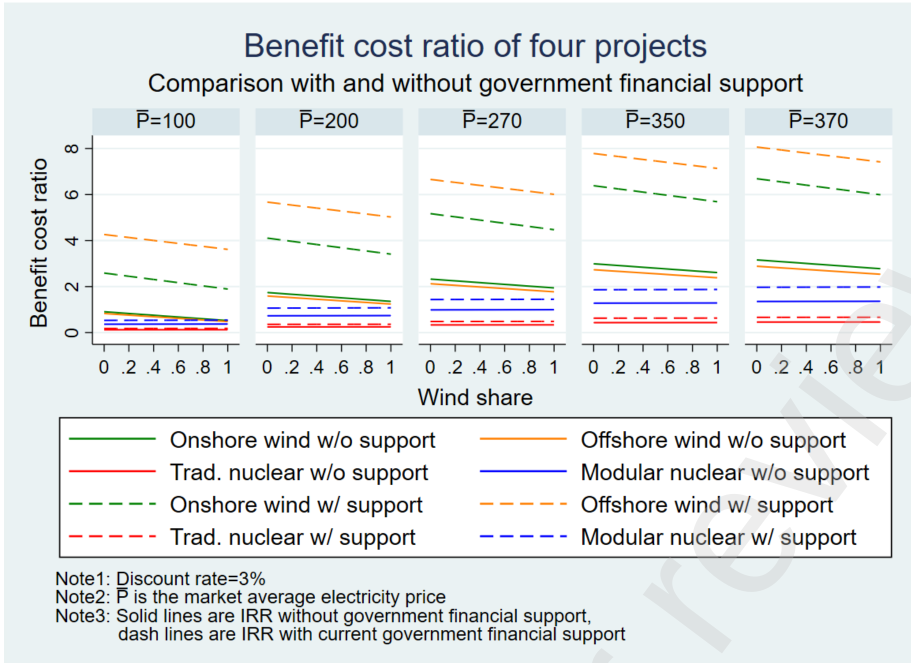

Figure 4: Comparison of BCR with and without government financial support

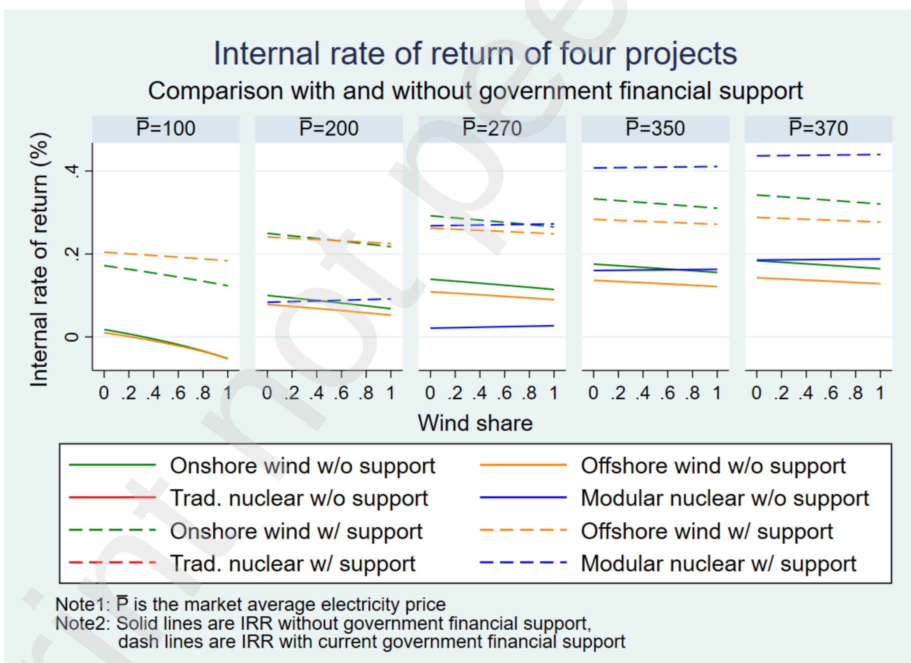

Figure 5: Comparison of IRR with and without government financial support

Figure 5 displays a comparison of the IRR results for the energy projects, considering scenarios with and without financial support, and highlights several significant observations. In contrast to the BCR outcomes, the IRR results indicate that current government financial support increase the relative competitiveness of nuclear power in comparison to wind energy. For example, at an average electricity price of 270, the IRR of the modular nuclear project is consistently lower than that of wind projects when financial support is not taken into account. However, when incorporating existing energy policies, the IRR of the modular nuclear project exceeds that of the least favorable wind project across all wind shares and even surpasses the most favorable wind project when the wind share is high.

In comparing the two wind projects, the greater feed-in premium provided to offshore wind energy relative to onshore wind energy causes the IRR of the offshore wind project to outperform that of the onshore wind project when the market electricity price is low and the wind share is high. Conversely, when the average market electricity price is elevated and/or the wind share is low, onshore wind can yield a higher IRR than offshore wind. This latter observation contrasts with the BCR results from the analysis that considers energy-related policies, where the BCR is higher for offshore wind than onshore wind across all examined prices and wind shares. The reason for the IRR of onshore wind re-surpassing that of offshore wind when the price is high can be attributed to the onshore wind's advantage in terms of a shorter construction period (Table 1), which becomes more significant for higher prices and offsets the lower government financial support when compared to offshore wind.

The insights from the comparison of IRR results, both with and without government financial support, somewhat diminish the perception that the French government strongly favors wind projects over nuclear projects, and offshore wind over onshore wind, which could be obtained from the BCR results.

3.3. Required government financial support for investment parity

Our private investment analysis reveals that the current government financial aid increase the performance of both wind and nuclear projects in the investment market. However, nuclear projects continue to lag behind in competitiveness, particularly when the average electricity market price and wind share are low (Figures 4 and 5). Assuming a scenario in which governments aim for investment parity for modular nuclear power plants, for example motivated by concerns around energy security, power supply stability and biodiversity preservation, this section investigates how this goal can be achieved by tweaking existing energy policies. This analysis could be relevant for policy-makers and stakeholders who want to understand the cost associated with realizing non-internalized benefits of modular nuclear power plants, given the existing policies in place for alternative projects.

We use IRR as the primary metric for the investment parity analysis, and investigate required increases in government financial support for modular nuclear to become equally attractive to the most attractive wind project, which vary between onshore and offshore wind depending on circumstances pertaining to prices and wind shares, as illustrated by our previous results. Further, we would like to emphasize that our analysis is premised on the assumption that only the government financial support for modular nuclear energy is increased, while the government financial support for wind energy remains constant at today's French levels.

The feed-in premium is an effective policy by which the government can influence the investment market. Figure 6 shows that even in the case of low market electricity prices or small wind share, this policy can help the IRR of the modular nuclear project to be equal to that of wind projects.

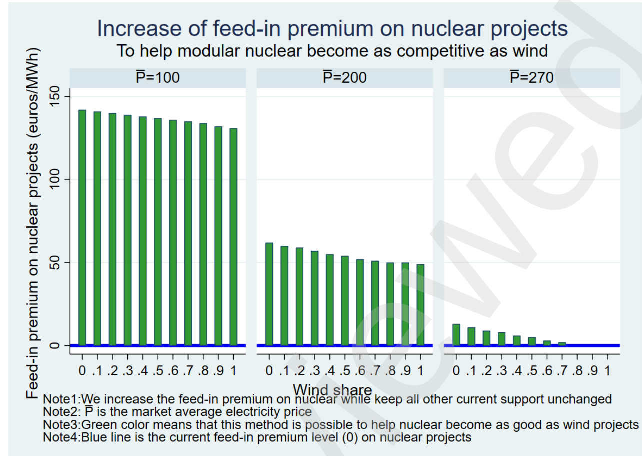

Figure 6: Increase of feed-in premium on nuclear energy to help modular nuclear become as competitive as wind projects

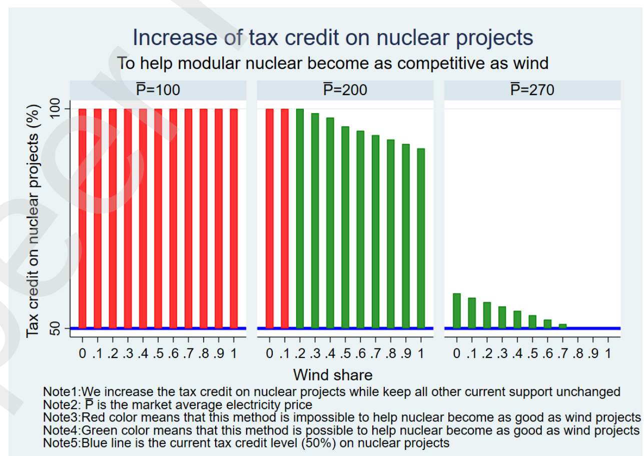

Figure 7: Increase of tax credit on nuclear energy to help modular nuclear become as competitive as wind projects

Although the feed-in premium for nuclear energy needs to be as much as 150 euros/MWh when the market electricity price is equal to 100 euros/MWh, it is not unreasonable. Because according to Table 6, the current feed-in premium for offshore wind in some countries is at such a high level.

Tax credit is a also feasible method that can affect the revenue of an investment project. However, it is not as effective as feed-in premium. For example, Figure 7 shows that when the electricity price is low and the wind share is small, tax credit is not able to help the modular nuclear project to catch up with the gap in investment attractiveness with wind projects (the red zone in Figure 7). Under these circumstances, even with tax credit for income tax up to 100%, the IRR for the modular nuclear project is still lower than that for wind projects. But when the market electricity price is higher and the wind share is larger, the modular nuclear project can become as competitive as wind projects with the help of tax credit (the green zone in Figure 7).

For example, when market electricity price is equal to 200 euros/MWh and wind share is larger than 20%, the modular nuclear project will have a same high IRR as wind projects if the government can give a tax credit for nuclear energy as higher than 90%.

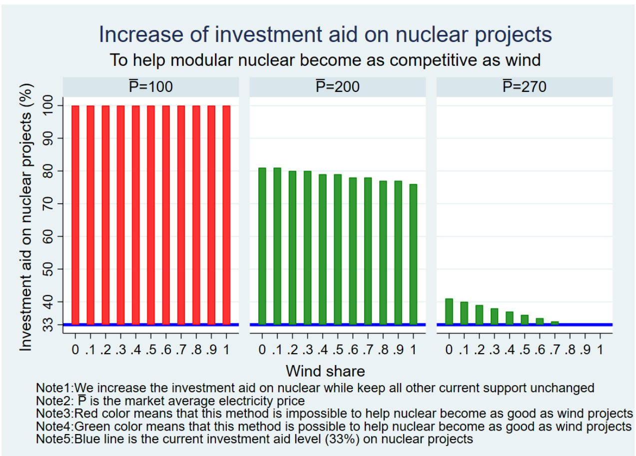

Figure 8: Increase of investment aid on nuclear energy to help modular nuclear become as competitive as wind projects

Investment aid is a measure that, like tax credit, can help but does not work in all scenarios. Figure 8 indicates that this approach is insignificant in the case of low market electricity prices or small wind share (the red zone in Figure 8).

4. Sensitivity analysis

Sensitivity analysis is essential for evaluating a model's resilience and the accuracy of its conclusions. In this study, we focus on analyzing the effects of varying construction and operational cost for modular nuclear power plants and changes in the conversion factor for offshore wind energy. We investigate cost variations in modular nuclear projects due to our reliance on data from private entities, which may present optimistic estimates. Additionally, we study alterations in the offshore wind conversion factor, as real-world projects may not reach the 0.51 factor used in our main analysis, possibly yielding a lower value. Specifically, we assess the impact of a 10% cost increase in the modular nuclear project on IRR results and a decrease in the offshore wind conversion factor from 0.51 to 0.4 on BCR outcomes, incorporating existing government financial support.

Table 7 displays the best investment option based on the IRR outcomes, factoring in current government financial support, from the main analysis and the sensitivity scenario with a 10% cost increase for all aspects of the modular nuclear project. The table shows that the cost increase of the modular nuclear project will lead to a decrease in its return on investment but will not distort our comparative conclusion between wind and nuclear projects which is that the modular nuclear project can surpass wind projects and become the most profitable project when the electricity price and wind share are large.

Table 7
The most profitable energy project with and without the increase of cost of the modular nuclear, in terms of IRR

$\bar{P}$	MNR cost baseline	MNR cost increase
100	Wind	Wind
200	Wind	Wind
270	Wind/Modular Nuclear	Wind
350	Modular Nuclear	Modular Nuclear
370	Modular Nuclear	Modular Nuclear

Table 8
The most profitable energy project with different capacity factor of offshore wind energy, in terms of BCR

$\bar{P}$	Capacity factor=0.51	Capacity factor=0.4
100	Offshore Wind	Offshore Wind
200	Offshore Wind	Offshore Wind
270	Offshore Wind	Offshore Wind
350	Offshore Wind	Onshore Wind
370	Offshore Wind	Onshore Wind

Table 8 displays the best wind investment option based on the BCR outcomes, factoring in current government financial support, from the main analysis and sensitivity scenario involving a decrease in the conversion factor for offshore wind energy. The table reveals that the BCR of the offshore wind project is no longer always greater than that of the onshore wind project even after considering the current financial support if we lower the expected conversion efficiency of the offshore wind energy. When the market average electricity price exceeds 350, the BCR of the onshore wind project will re-surpass that of the offshore wind project. This finding implies that for the offshore wind project to remain more profitable than the onshore wind project under all circumstances, investors should ensure that its capacity factor is sufficiently high, in addition to the government policies that favor offshore wind energy.

In conclusion, our sensitivity analysis demonstrates that changes in key parameters can impact the optimal investment choice to different degrees under various circumstances. Despite this, the analysis does not undermine our qualitative findings, which highlight that both modular nuclear and onshore wind possess advantages regarding shorter construction times, with modular nuclear having a more pronounced edge than wind. This advantage becomes increasingly important as prices rise, especially for investors interested in quicker returns.

5. Discussion

In the subsequent discussion, we will compare our results with those in prior studies. We will then delve into the novel aspects of our research and their implications for investors and governments. Finally, we will point to some limitations of our study and propose potential avenues for further research.

5.1. Isolated findings in our study vs. the literature

The isolated findings for the four energy projects studied in this paper are mostly aligned with those found in the literature, but with some interesting differences.

First, the literature on the investment analysis of onshore wind projects focuses on how much they can obtain on the basis of affirming the profitability of onshore wind energy (Niesten et al., 2018; Belkin, 2008; Santa Catarina, 2022; bin Li et al., 2013). The results in this paper indicate that the onshore wind project can generate a positive net present value in most but not all scenarios. Specifically, our results indicate that the onshore wind project cannot generate positive returns on investment without the financial support of government energy policies when the market electricity price is low (e.g.,$\bar{P}$=100). In addition, we find that an increase in the real wind share can also decrease the return on investment of the onshore wind project. But for higher prices and/or low wind shares, and/or with existing financial support, as in place in France, onshore wind projects appear attractive for investment.

Second, papers in the literature on offshore wind projects are not in agreement on whether they can generate positive returns on investment (Ziemba, 2022; Liu et al., 2021; Jåstad and Bolkesjø, 2023). Our isolated findings are more positive on behalf of offshore wind. Specifically, they suggest offshore wind can be profitable even without government financial support for scenarios where prices reasonably high and the wind share reasonably low. Moreover, the government financial support in place in France makes the likelihood of positive return on investment even more significant, even with prices at the lower end of the studied range.

Third, the papers in the literature on traditional nuclear energy investment analysis indicate that it is not suitable for private investment because of its huge upfront investment and operating cost (Wealer et al., 2021; Terlikowski et al., 2019). The conclusion of this paper is the same as theirs. This paper finds that the traditional nuclear project cannot obtain positive investment returns under any of the market circumstances studied in this paper, even with the government financial support.

Finally, the investment analysis of modular nuclear energy in the literature is often compared to traditional nuclear energy (Locatelli et al., 2014; Mignacca and Locatelli, 2020; Zimmermann and Keles, 2023). They conclude that modular nuclear projects are more likely and quantitative than traditional nuclear projects to achieve a positive return on investment. The conclusion of this paper is completely consistent with the findings in this literature. Specifically, our results suggest that the lower upfront cost and shorter construction time of modular nuclear power plants represents a great advantage for investors.

5.2. Intra-study cross-project comparative insights

The existing literature often focus on a single type of project, making the comparative aspect of our study the main contribution to the literature. Our results provide two main comparative insights and some interesting implications relevant to both investors and governments.

The first key insight arises from the comparison of investment returns between wind projects and nuclear projects. According to our results, wind projects yield higher returns on investment than nuclear projects, regardless of whether there is government financial support, when the market price of electricity is low or the share of wind energy is small. However, in the scenarios where there are high market electricity prices and a large proportion of wind power generation in the electricity mix, the investment returns of the modular nuclear project may surpass those of wind projects. The current financial support can help the modular nuclear project become more attractive, but not enough to achieve parity with the wind projects when the electricity price is within close range of today's average price (no more than 200 euros/MWh).

The implication from the first key insight is that, if governments want to achieve investment parity between the modular nuclear project and wind projects in considerations of energy security and power supply stability in the future, they need to further improve the feed-in premium, tax credit, and investment aid on nuclear energy. Among them, the feed-in premium is a more applicable method. With the feed-in premium on nuclear energy at roughly the same level as offshore wind energy, the modular nuclear project can be equally attractive to wind projects in all scenarios.

The second key insight comes from the comparison between the two types of wind projects. This comparison suggests that the onshore wind project is more likely to yield higher returns on investment than the offshore wind project when we do not consider the government financial support. However, with the aid of energy policies, such as those implemented in France, the offshore wind power project is predicted to outperform the onshore wind power project and become the most profitable energy project.

The implication from the second key insight is that France's current energy policies are effective. A report from WindEurope (2023) states that the development of onshore wind energy in France has reached a bottleneck period, prompting the country to focus on expanding offshore wind energy. This intention is reflected in France's financial support policies such as feed-in premium, which is significantly higher for offshore wind energy than for onshore wind energy. Our analysis supports the efficacy of these policies, as they results in increased traction of offshore wind energy in the investment market. This also suggests that for investors, keeping their investment choices consistent with government energy support tendencies is a technique to make more profits.

5.3. Limitations and avenues for future research

This paper identifies three limitations that require further investigation through future research. First, our analysis specifically takes into account the electricity and investment markets within a country. Our pricing model acknowledges that the fluctuating nature of wind power generation within a nation may result in a negative volume-weighted price premium compared to nuclear energy (Section 2.2). However, the pricing model does not directly address the role of interconnected power grids between countries. The interconnection of power grids among different nations can potentially balance the unpredictable production of wind power within a country by facilitating the import of excess wind energy from neighboring countries. Although not directly incorporated in the regression model, some of the effects associated with this type of interconnection are likely captured through the estimated coefficient for the real wind share within the country in focus. In cases where the wind share within a country is low, but wind production is high in a neighbouring country, the upward pressure on price may be underestimated. Conversely, in circumstances where the wind share within a country is high and the wind share in a neighboring country is also high, the downward pressure on price may be overestimated. Depending on which scenario is more prevalent, we might be underestimating or overestimating the influence of an increase in the real wind share within a country on the volume-weighted average prices achieved by wind and nuclear projects. Therefore, we recommend that future research examines the impact of interconnectivity between power grids on the volume-weighted price premium to provide a more accurate understanding of this relationship. In addition, the recently popular hydrogen as a means of energy storage can also be considered to be added into the electricity mix to reduce the fluctuation of unit revenue of wind energy caused by its unstable production, as an alternative to expanding the power grid.

The second limitation is that the policy module only examines three types of financial support (Section 2.4), while other policies, such as low-interest loans from governments, may also impact investors' confidence in clean energy projects. In addition, this paper analyzes the investment parity and explores the impact of increasing financial support for a specific policy. However, it does not take into account the potential effects of changing two or three energy policies concurrently. So, future research could consider examining the potential synergies or trade-offs between various energy policies by using the new investment analysis framework of this paper.

The third limitation pertains to the feasibility of the most effective method identified in the study - feed-in premiums - to achieve investment parity between wind and nuclear projects. The paper suggests that governments need to subsidize nuclear projects as high as 150 euros/MWh to match wind energy's attractiveness under low market electricity prices (Section 3.3). This raises concerns about whether this method is financially feasible for governments, given the substantial cost implications. Therefore, future research should explore alternative policies that consider the government's budget constraints while influencing clean energy investment markets effectively.

6. Conclusion and policy implications

This paper constructs a flexible investment analysis framework to explore the investment attractiveness of four energy projects, namely onshore wind, offshore wind, traditional nuclear and modular nuclear, under different scenarios. This paper investigates the impact of electricity mix, market average electricity prices, and government financial support from energy policies, on the return on investment for private investors. The findings indicate that an increase in the share of wind energy in the electricity mix reduces the return on investment for wind projects but increases it for nuclear projects. The explanation for this is that an increase in the wind share is associated with lower unit revenues for wind and higher unit revenues for nuclear. In addition, this paper finds that the possibility of higher return on investment of wind projects is significantly greater than that of nuclear projects when the market electricity price and real wind share are low. However, the return on investment of the modular nuclear energy project may exceed that of the two wind projects when the market electricity price rises or the share of wind energy in the electricity mix increases, because the modular nuclear project has a shorter construction time, giving it an advantage of early revenue-generation when compared to the wind projects.

Moreover, this research concludes that the current financial support for clean energy projects from energy policies in European countries such as France can significantly help both wind and nuclear projects improve their performance in the investment market. The results demonstrate that the offshore wind project exceeds the onshore wind project's return on investment after considering the current energy policies, while the absence of government financial support makes the onshore wind project more attractive than the offshore wind project in the investment market. The study also reveals that current energy policies are insufficient to help the modular nuclear project achieve investment parity with wind projects based on energy security and power supply stability considerations. Therefore, the paper explores the requirements for three common energy policies, namely feed-in premium, investment aid, and tax credits, to help the modular nuclear project become competitive with two wind projects. The research findings suggest that increasing feed-in premium on nuclear energy is the most effective way, although it may require high government budgets.

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