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Energy Economics: The Insurance Effect of Distributed Energy Resources Under System Reliability

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ABSTRACT

This paper presents a comprehensive analysis of the insurance effect associated with distributed energy resources (DERs) within the context of system reliability. Drawing from the field of energy economics, we investigate the relationship between the failure risk of DER systems and the investment decisions made by consumers. By developing the certainty equivalent based on expected utility, we consider the choices made by both risk-neutral and risk-averse individuals. Our findings highlight the significance of risk aversion and system reliability in determining optimal investment levels in renewable DERs. This research contributes to the understanding of factors influencing investment behavior in DERs systems, offering valuable insights for policymakers and energy practitioners seeking to promote sustainable energy transitions.

1. INTRODUCTION

Distributed energy resources (DERs) are an important part of the energy transition, which aims to shift away from centralized, fossil-fuel-based power generation and towards a more decentralized and renewable energy system. Numerous studies have investigated the economic aspects of DERs, considering factors such as installation costs, operation and maintenance expenses, revenue streams, and grid integration costs. For example, Guo and Xiang [1] conducted a cost-benefit analysis of photovoltaic-battery energy storage systems and found that these distributed resources can provide substantial economic benefits over their lifespan, which provides us insight on the latest developments of DERs technology. Xiao et al. [2] analyzed the cost assumptions for solar and wind technologies in different energy scenario studies, highlighting their cost competitiveness compared to conventional centralized power generation. While DERs offer many benefits, such as improved energy efficiency, increased energy security, and reduced greenhouse gas emissions, they are not without their challenges and potential for failure. Building on the cost-competitiveness identified by Xiao et al. [2], our study examines how this influences individual investment decisions under uncertainty.

The reliability of a DERs (Distributed energy resources) system refers to its ability to consistently and dependably deliver electricity to meet the energy demands of the connected loads. This includes the performance of individual DERs components, such as solar panels, wind turbines, battery storage systems, and inverters, as well as the overall integration and coordination of the system. Factors that can affect the reliability of a DERs system include weather conditions, system design and configuration, maintenance and upkeep of the components, and the control and management systems used to regulate and balance energy supply and demand. The reliability of a power system has always been an important issue and the focus of different studies, see e.g., Muhtadi et al. [3] and references therein. In particular, Vahedipour-Dahraie et al. [4] pointed out that the uncertainty in renewable energy resources has created additional difficulties in constructing restructured power systems. The uncertainty is due to the intermittent nature, such as weather conditions and time of day, of power generation from renewable energy resources. The inability of DERs to maintain a steady and reliable energy supply also keeps households dependent on the network and lowers their welfare in the event that the DER is unable to generate power as expected [5].

While the existing literature has investigated the economic aspects of DERs, such as installation costs, operation and maintenance expenses, and grid integration costs, there is a notable research gap regarding the impact of reliability on investment decisions. Specifically, while previous studies has focused on the cost-benefit analyses of DERs, the insurance effect of system reliability on consumer investment decisions remains underexplored. Understanding how the reliability of DER systems influences consumer choices to invest in renewable energy resources is crucial for a comprehensive analysis of their feasibility and long-term sustainability.

This study aims to bridge this gap by examining how the investment in renewable DERs is affected when the reliability of the system cannot be guaranteed and the DER fails to generate the expected level of electricity. By investigating the relationship between system reliability and consumer investment decisions, the research contributes to a more holistic understanding of the factors that influence the adoption and success of DERs in the energy transition.

Our findings suggest policy incentives for DERs investment should consider the differing risk profiles of consumers. This recognition of diverse risk profiles can facilitate the development of tailored financial products that cater to the specific needs and preferences of different consumer segments.

2. MODEL DEVELOPMENT

Electricity price risk

In order to assess the impact of uncertain electricity prices on the DER system investment decision of an individual, we introduce a model that assumes a non-negative random variable X to represent the market price of electricity. Let $\mu_X \geq 0$ and $\sigma_X^2 \geq 0$ denote the mean and the variance of the electricity price, respectively. Stochastic modeling of electricity prices has been widely used in the literature. For example, Fridgen et al. [6] investigated the insurance effect of distributed energy resources against uncertain electricity price developments. Cartea et al. [7] assumed a stochastic log-price process to model electricity prices. The electricity price risk will affect the decisions on electricity consumption and on their investments in renewable energy which allow them to reduce their reliance on electricity from the external market. Note that even though we assume non-negative electricity prices in our model, negative electricity prices can occur in certain electricity markets under specific conditions. This usually occurs to the wholesale price of electricity. Negative electricity prices introduce a level of uncertainty into the market. If negative prices become more frequent, it may impact the financial returns on DER investments. The impact of negative prices can be further investigated in future work.

Reliability of the DER system

If the individual chooses to install the DER system, they are exposed to the risk of system failures and outages. The failure risk is inevitable due to the intermittent nature of renewable energy resources like solar and wind. In order to assess how the reliability of DER system will affect the investment decisions of the DER system, we introduce the risk of system failure into the model. We consider an indicator random variable, Y, which takes values 0 or 1. Y is equal to 1 when the DER system is successful in supplying the expected amount of electricity with probability $0 \leq q \leq 1$, and equal to 0 otherwise. That is,

$$Y = \begin{cases} 1, & prob.\, q \\ 0, & prob.\, 1-q \end{cases}$$

While we assume a binary outcome for DER system reliability, real-world systems may experience partial failures, which could be modeled in future work. The specific value of q would depend on various factors, such as environmental conditions and maintenance practices. It may change over time due to climate change [8], system upgrades, or improvements in technology. The estimation of q would require a detailed analysis of the specific DER system and its operational characteristics, which is beyond the scope of the current study and is left for future research. Here, we would take the probability q as given. By definition, the expected value and the variance of Y are, respectively, given by

$$E[Y] = q, \qquad Var(Y) = q - q^2$$

The indicator random variable Y is assumed to be independent of the electricity price X.

The reliability assessment of renewable and distributed resources has been approached using various methods. One such method, proposed by Xiao et al. [9], involves utilizing Monte Carlo simulation. They explored the stochastic nature of renewable and distributed resources such as solar energy and battery energy storage. They conducted assessments under different scenarios to examine the reliability of these resources. For more detailed information, interested readers may refer to the case study therein which provides valuable insights into the assessment of reliability for renewable and distributed resources using empirical data.

Preference function

The concept of certainty equivalent origins [10], which laid the groundwork for expected utility theory. The concept of certainty equivalent has been widely applied in different areas such as portfolio selection [11, 12], asset pricing [13-15], and pollution and greening issues [16-18]. In this paper, the following certainty equivalent is applied to study the investor's risk preferences:

$$\Phi(\mu, \sigma) = \mu - \frac{\alpha}{2}\sigma^2, \tag{1}$$

where, μ and σ^2 represent the expected value and the variance of a risky investment, respectively. The parameter α is the coefficient of constant absolute risk aversion. The certainty equivalent is based on the assumption of exponential utility for the investor. Fridgen et al. [6] applied the certainty equivalent while assuming exponential utility and a normal distribution for the electricity price. In our paper, we assume a point mass for the failure probability of the DER system. The assumption of normality does not hold in this case. In practice, many financial and economic applications involve non-normal distributions of returns, such as skewed or heavy-tailed distributions. In such cases, the certainty equivalent formula is often used as an approximation (see e.g., study of Markowitz [19]). In our context, we assume that the electricity price is random and acknowledge the potential for the failure of the DER system. In this framework, we interpret the parameter μ as the expected cash flow. To capture the uncertainty and variability associated with the DER investment, we also consider the parameter σ^2. This parameter represents the deviation of the cash flow from its expected value. The parameters μ and σ^2 are two measures of the individual's preference for the DER investment. In the subsequent section, we will provide a detailed analysis that explores the parameters' impact on the investment decision for DERs.

3. DECISION ANALYSIS BY CONSIDERING THE RELIABILITY OF DERS SYSTEM

Consider an individual with a priori electricity demand represented by a constant $d_0 \geq 0$. Let $I \geq 0$ be the installed capacity of the DERs system. The individual can choose to invest in the DERs system to reduce its electricity demand from the external grid. The primary benefit of investing in the DERs system is the energy cost savings by offsetting grid purchases with on-site generation. Let $v \in (0,1]$ be the efficiency of the renewable energy system. By assuming a linear reduction in energy demand from the external grid with increasing investment in the DER system, the posteriori demand can be represented by

$$d_1(I) = d_0 - vI. \tag{2}$$

By increasing one unit of capacity in the DERs system, the marginal reduction in energy demand is given by the parameter k. The posteriori demand $d_1(I)$ is allowed to be negative. Negative demand, or sometimes called the reverse power flow, occurs when electricity supply exceeds total demand. This is often associated with the prosumer phenomenon, where the individual transforms from a pure consumer to a prosumer on the electricity grid. In this case, the individual transforms from pure consumer to prosumer on the electricity grid. This is becoming increasingly common with the more cost-effective distributed energy resources and more widespread renewable energy technologies, which allow individuals to generate their own electricity and feed excess power back into the grid.

Negative demand offers economic benefits for prosumers, who can earn revenue from selling surplus electricity. It reinforces the economic viability of DERs and accelerates the adoption of renewable energy technologies. Prosumers capitalize on the opportunity to generate and sell excess electricity during times of negative demand, offsetting their energy costs and even turning them into net revenue generators. Overall, negative demand provides insights into the evolving energy landscape and the potential for a decentralized and flexible energy system.

The investment cost for a level of I is denoted by a quadratic function $c_2I^2 + c_1I + c_0$. The coefficient $c_2 > 0$ represents the economies of scale. As the size of a DER system increases, it can become more efficient and cost-effective due to economies of scale. However, there is a point where further increases in size may result in diminishing returns, as the costs of maintaining and integrating the larger system may outweigh the benefits. For instance, a larger DER system may require more complex interconnections with the grid, which can lead to higher costs for advanced control systems and equipment. The coefficient $c_1 > 0$ represents the cost per unit of installed capacity for the DERs system. The constant c_0 represents the fixed costs associated with installing renewable energy technology ($c_0 > 0$) or subsidies and incentives provided by the government to promote the installation of renewable energies ($c_0 < 0$). The assumptions of a linear reduction in energy demand from external grid and the quadratic investment function are consistent with those used in study of Fridgen et al. [6], which facilitates a comparison of the results between the two papers.

The choice of a quadratic investment cost function can be justified analytically due to its closed-form representation. A quadratic investment function is also a common assumption in the literature on green production, for example in study of Wang et al. [20] and Jin et al. [21]. The quadratic form approximates the concept of economies of scale, where larger-scale installations of distributed energy resources (DERs) benefit from cost reductions. Different cost function assumptions can lead to varying model outcomes. Alternative cost functions, such as linear, exponential, or piecewise functions, can be considered in future work as they reflect different cost dynamics and assumptions.

The linear relationship assumption in (2) aligns with the model considered in the study of Fridgen et al. [6]. However, the special case where $v = 0$ was not considered separately in their work. We propose to fill this gap with a more general model which gives a point mass to the special case. That is, there is a probability that the DERs system will fail. The general model explicitly addresses how the individual will factor in the reliability of DERs system when making investment decisions.

Let C_0 and C_1 be the cash flows before and after the installation of the DER system, respectively. Then, we got

$$C_0 = -d_0X.$$

The expected value and the variance of C_0, are given by

$$E[C_0] = -d_0\mu_X,$$

and

$$Var(C_0) = d_0^2\sigma_X^2,$$

respectively. For the cash flow after the installation of the DERs system, we have

$$C_1 = \begin{cases} -(d_0 - vI)X - (c_2I^2 + c_1I + c_0), with\ prob.\ q \\ -d_0X - (c_2I^2 + c_1I + c_0), with\ prob.\ 1-q \end{cases}$$
$$= -(d_0 - vIY)X - (c_2I^2 + c_1I + c_0).$$

The expected value of C_1 is given by

$$E[C_1] = -d_0\mu_X + vIq\mu_X - (c_2I^2 + c_1I + c_0),$$

While the variance of C_1 is given by

$$\begin{aligned} Var(C_1) &= Var\{(d_0 - vIY)X\} \\ &= (vI)^2(q - q^2)(\sigma_X^2 + \mu_X^2) \\ &\quad + (d_0 - vIq)^2\sigma_X^2. \end{aligned}$$

The difference in certainty equivalents after the installation of the DER system is given by

$$\begin{aligned} \Delta\Phi &= E[C_1] - \frac{\alpha}{2}Var(C_1) - \left[E[C_0] - \frac{\alpha}{2}Var(C_0)\right] \\ &= vIq\mu_X - (c_2I^2 + c_1I + c_0) \\ &\quad + \frac{\alpha}{2}\{[d_0^2 - (d_0 - vIq)^2]\sigma_X^2 \\ &\quad - (vI)^2(q - q^2)(\sigma_X^2 + \mu_X^2)\}. \end{aligned} \tag{3}$$

Let $\hat{I}_R$ be the level of investment that maximizes (3), it yields the first-order condition

$$\begin{aligned} &vq\mu_X - 2c_2\hat{I}_R - c_1 \\ &\quad + \frac{\alpha}{2}\left[2\left(d_0 - v\hat{I}_Rq\right)vq\sigma_X^2 \right. \\ &\quad \left. - 2v^2\hat{I}_R(q - q^2)(\sigma_X^2 + \mu_X^2)\right] = 0 \end{aligned}$$

Thus, the optimal level of investment is given by

$$\hat{I}_R = \frac{-c_1 + vq\mu_X + \alpha d_0vq\sigma_X^2}{2c_2 + \alpha v^2q\sigma_X^2 + \alpha v^2(q - q^2)\mu_X^2}. \tag{4}$$

By definition of the parameters, the denominator of (4) is positive. Therefore, whether the optimal level of investment is positive or equal to zero depends on the numerator. If $vq(\mu_X + \alpha d_0\sigma_X^2) > c_1$, then there will be a positive level of investment, that is when the marginal benefit is greater than the marginal cost. Otherwise, the individual will not invest in the DER system, i.e. the level of investment will be equal to zero.

For a risk-neutral individual, with $\alpha = 0$, the optimal level of investment reduces to

$$\hat{I}_{R,0} = \frac{-c_1 + vq\mu_X}{2c_2}. \quad (5)$$

The risk-neutral individual will have a positive level of investment if $vq\mu_X > c_1$, and there will be no investment otherwise.

To study how DER investment acts as insurance against an increase in electricity price, we compare the result of a risk-averse individual to that of a risk-neutral individual. There are three possible cases shown as follows.

Case (i): $vq(\mu_X + \alpha d_0 \sigma_X^2) < c_1$ for $\alpha \geq 0$

In this scenario, both $\hat{I}_R$ and $\hat{I}_{R,0}$ are zero due to the significantly higher unit cost of the DERs investment compared to the expected unit energy cost savings. Several factors can influence the financial viability of DERs investments, such as the cost of technology, system reliability, and electricity market conditions. However, the high unit cost of the DERs investment is prohibitive, leading to a situation where even risk-averse individuals, who consider electricity price volatility, are unwilling to invest in the DERs system. Similarly, risk-averse individuals who do not consider electricity price volatility also find the investment unappealing.

Case (ii): $vq\mu_X < c_1 < vq(\mu_X + \alpha d_0 \sigma_X^2)$ for $\alpha > 0$

In this scenario, $\hat{I}_R > 0$ and $\hat{I}_{R,0} = 0$, indicating that a risk-averse individual chooses to invest in the DERs system, while a risk-neutral individual does not. Taking into account the electricity price risk σ_X^2, the risk-averse individual, with a positive α adjusts their investment decision in the DERs system and decides to increase their level of investment. Moreover, the increase is even larger if the demand for electricity d_0 is higher. Investing in the DERs system allows the risk-averse individual to hedge against electricity price risk and reduce reliance on the grid. The investment can be seen as an insurance mechanism against electricity price fluctuations, with the reliability of the DERs system q acting as a factor influencing the "insurance loading." If the DERs system is more reliable, i.e., with a smaller loading, the individual is more inclined to invest in the DERs system.

Case (iii): $vq\mu_X > c_1$

In this scenario, both $\hat{I}_R$ and $\hat{I}_{R,0}$ are positive, which means that both the risk-neutral and the risk-averse individuals choose to invest in the DER system. For the risk-neutral individual, the optimal solution (5) can be interpreted as follows. The numerator $-c_1 + vq\mu_X$ represents the net benefit or savings obtained from the DER system. It takes into account the initial investment cost c_1 and the expected energy cost savings achieved by the DERs system based on its efficiency and the mean electricity price. The denominator represents the scaling factor due to economies of scale. It reflects the cost reduction achieved as the DERs system scales up and benefits from economies of scale.

For the risk-averse individual, the optimal investment is given by (4) and it provides a more comprehensive model for assessing the net benefit obtained from investing in a DER system. By comparing the optimal investment between the risk-neutral and the risk-averse individuals, we found the following major differences. The optimal solution for the risk-averse individual captures the impact of the individual's aversion to risk on their investment decision. It considers the interaction between risk factors, such as the variance of electricity price (σ_X^2), the reliability of the DER system (q), and the electricity demand (d_0). The risk adjustment factors are incorporated in both the numerator and denominator. By considering these risk adjustments, the equation provides a more comprehensive evaluation of the net benefit or savings obtained from the DER system, incorporating both the expected returns and the individual's risk perception.

The analysis of the results also reveals that a higher v, which represents a higher efficiency of the renewable energy system, has a positive impact on the expected unit energy cost savings. As the efficiency of the system increases, more energy is generated from the same amount of input, leading to greater cost savings. The increased efficiency of the renewable energy system translates into higher energy production per unit of resource input. The expected unit energy cost savings is one of the key factors driving the individual's incentive to install the DERs system. When the renewable energy system is more efficient, the cost savings achieved per unit of energy consumed or generated are higher. This creates a stronger financial incentive for individuals to invest in DERs, as they can anticipate greater reductions in their energy bills. The results under the three scenarios are summarized in Table 1.

Table 1. Optimal investments of risk-averse and risk-neutral individuals under different scenarios

	$\boldsymbol{vq(\mu_X + \alpha d_0 \sigma_X^2) < c_1}$	$\boldsymbol{vq\mu_X < c_1 < vq(\mu_X + \alpha d_0 \sigma_X^2)}$	$\boldsymbol{vq\mu_X > c_1}$
$\hat{I}_R$	0	> 0	> 0
$\hat{I}_{R,0}$	0	0	> 0

4. NUMERICAL EXAMPLE

4.1 Paper title

In this section, we study a numerical example to study the insurance effect of DERs under system reliability. Let the mean and the variance of the electricity price be $\mu_X = 40$ and $\sigma_X^2 = 200$, respectively. Assume that the priori electricity demand of the individual is $d_0 = 40$ and the efficiency of the renewable energy system is $v = 1$. Also, assume that the investment cost is denoted by $I^2 + 4I$. In the numerical example, the parameter values are chosen to align with study of Fridgen et al. [6] for easy comparison and consistency. This approach facilitates a direct evaluation of the model's performance and allows for the validation and extension of their findings. By replicating the parameter values, we build upon their work and potentially extend their findings. Furthermore, it enhances the reproducibility and transparency of the research, as future researchers can replicate and verify the results using the same parameter values. In our paper, we consider the reliability of the DERs system by assuming that $q = 0.9$. That is, there is a 0.9 probability that the system is successful. DERs systems, such as microgrids and those used in remote communities, demonstrate high reliability. These systems integrate renewable energy sources, energy storage, and advanced control technologies to ensure uninterrupted power supply, even during grid outages or in remote locations. Additionally, DER systems play a vital role in emergency preparedness and enhance reliability for industrial and commercial applications, minimizing disruptions and reducing operational risks.

For a risk-neutral individual, $\alpha = 0$, the objective function in (3) becomes

$$\Delta\Phi = (0.9)40I - I^2 - 4I = -I^2 + 32I.$$

The optimal level of investment for the risk-neutral individual is therefore given by

$$\hat{I}_{R,0} = 16,$$

which means that the individual will purchase 24 units of electricity from the external grid.

For a risk-averse individual with $\alpha = 1$, the objective function in (3) becomes

$$\begin{aligned}\Delta\Phi &= (0.9)40I - I^2 - 4I \\ &\quad + \frac{1}{2}\{[1600 - (40 - 0.9I)^2](200) \\ &\quad - 0.09(200 + 1600)I^2\} \\ &= -163I^2 + 7232I.\end{aligned}$$

The optimal level of investment of the risk-averse individual is therefore given by

$$\hat{I}_R = 22.1840,$$

which means that the individual will purchase 17.8160 units from the external grid. The results show that the risk-averse individual is less relied on the external market with volatile electricity prices when compared to the risk-neutral individual. The renewable DERs acts as an insurance to the uncertain electricity prices in the market.

5. CONCLUSION

This paper investigated how the level of failure risk influences individuals' choices regarding investments in DER systems. By developing a theoretical framework, we investigated the choices made by both risk-neutral and risk-averse individuals. Our findings reveal that risk-aversion plays a significant role in determining investment decisions in renewable DERs. Specifically, the consideration of risk-aversion leads to higher levels of optimal investment in renewable DERs, primarily due to the insurance effect they provide against the electricity price risk. This finding holds important policy implications for promoting the adoption of DER systems, particularly among risk-averse consumers. The government can consider implementing financial incentives such as subsidies to the consumers or develop insurance programs that cover potential losses associated with DER system failure.

Moreover, we established that the reliability of the DER system is a crucial factor influencing investment decisions. Individuals tend to invest less in DER systems characterized by higher failure risk. These results underscore the importance of understanding risk-aversion and system reliability in shaping investment behavior, and they highlight the need to address system reliability concerns and promote risk management strategies to encourage greater adoption of renewable DERs. While we assume a binary outcome for DER system reliability, real-world systems may frequently encounter partial failures. To enhance our understanding of DER reliability, future research can incorporate more complex models of DERs failure risks.

Our research focuses on risk-averse consumers and their adoption of DER systems. While we strive to provide comprehensive insights, individual preferences, regional variations, and market dynamics may introduce additional complexities that warrant further investigation.

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