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The insurance effect of renewable distributed energy resources against uncertain electricity price developments

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ABSTRACT

To combat climate change, many countries all around the world currently foster the development of renewable energy sources (RES). However, in contrast to traditional energy systems that relied on few central power plants, RES are typically highly decentral and spread all over a country. Against this backdrop, the promotion of a decentralization of the energy system by fostering a regional balance of energy demand and supply with a corresponding increase in energy democracy is seen as a promising approach. However, energy democracy driven by an increasing involvement of consumers requires adequate investments of consumers in their own local RES in order to become active players, usually called prosumers. Risk associated with uncertain long-term electricity price developments is generally seen as a barrier to investments. In contrast, we describe that an investment in distributed energy resources (DERs) may actually serve as a consumer's insurance against price risk. Our results set out that the consideration of risk-aversion may actually positively shift an investment decision in renewable DERs. This is due to the prosumer becoming more self-sufficient and less dependent on uncertain price developments. To analyze such an insurance effect, we create a formal decision model considering the prosumer's risk-aversion and derive the prosumer's optimal investment in renewable DERs. However, our results also indicate that under some circumstances the insurance effect disappears: When a prosumer turns into a predominant producer, the prosumer is again exposed to risk in terms of uncertain revenues. Ultimately, our work highlights the importance of a consideration of the insurance effect when assessing an investment in renewable DERs.

1. Introduction

The energy transition challenges existing energy systems worldwide. In particular, renewable energy sources, playing the most important role in the energy transition, are characterized by high fluctuations and hard predictabilities of their generation. In addition, renewable energies are typically highly regionally distributed over a country (Reiche and Bechberger, 2004; Moriarty and Honnery, 2016; Trepper et al., 2015; DeForest et al., 2014; Qiu et al., 2017). Due to these characteristics, the integration of an increasing share of renewable energies fundamentally challenges and changes the existing grid infrastructure with extreme peak situations, voltage stability issues, and an increased threat of power outages (Alarcon-Rodriguez et al., 2010; Rodrigues et al., 2016; Beraldi et al., 2018; Mengelkamp et al., 2018; Quadri et al., 2018). Consequently, a successful energy transition will require a grid architecture substantially different from the existing one (Bullich-Massagué et al., 2018; Mengelkamp et al., 2018; Battaglini et al., 2012).

Fostering a transformation of the existing centralized energy system towards a decentralized one appears as an important option other than large-scale grid expansion projects to tackle the challenges of the energy transition (Bundesverband der Energie- und Wasserwirtschaft, 2016; Quadri et al., 2018). As highlighted above, the renewables-driven decentralization of the energy system leads to a change in the supply structure. While the traditional, centralized energy system used few large conventional power plants, a decentralized energy system consists of a large number of smaller renewable distributed energy resources (DERs) meeting power demand close to load centers (Quadri et al., 2018). These renewable DERs include photovoltaic systems as well as wind turbines (Akorede et al., 2010; Jiayi et al., 2008). A transformation towards a decentralized energy system may lead to a relief of the existing electricity grid and lower the need for large-scale public grid expansions (Bullich-Massagué et al., 2018; Quadri et al., 2018). Though, the latter is typically related to new investments in renewable DERs that are required to set up such a more decentralized energy system (Bullich-Massagué et al., 2018). Against this need of adequate investments, there must be sufficient economic incentives for potential

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consumers to decide on the installation of new renewable DERs and in this way to turn into a prosumer (Kitzing and Weber, 2015).

Evaluating an investment in renewable DERs, by now consumers consider possible reductions in their electricity demand from the external market through a corresponding investment in a DER. As for a given investment renewable DERs can generate electricity at almost zero marginal costs (Callaway et al., 2018), the consumer may ultimately be able to realize energy cost savings over the considered planning horizon. However, a profitable investment requires that these energy cost savings exceed the necessary amount of investment. As future cost savings are typically highly uncertain, such uncertainties may pose severe barriers to the highly needed investments (Ländner et al., 2019). In times of the energy transition with a growing share of intermittent renewable energy production and unknown future regulatory changes, energy systems are exposed to an uncertain development of long-term electricity prices, which directly translates into a severe price risk for consumers (Wickart and Madlener, 2007; Zangiabadi et al., 2011; Dietrich and Weber, 2018). Accordingly, high uncertainty in future electricity prices directly leads to an uncertain level of energy costs for energy consumers. Consequently, in addition to the absolute energy savings potential, risk management and the consideration of a consumer's risk attitude gain increasing attention (Cano et al., 2016) when evaluating new investments in renewable DERs. In this context we refer to risk as the quantifiable consequence resulting from uncertain electricity price developments (Dow and Serfio, 1992). Gaining increasing attention, such price risk together with a consumer's risk attitude must be considered in an adequate evaluation of an investment in renewable DERs.

There is already a vast literature on approaches investigating the economics of renewable DERs (Helm and Mier, 2019; Ellabban et al., 2014; Deichmann et al., 2011; Lin and Chen, 2019; Mai et al., 2018; Steffen, 2018; Polzin et al., 2019; Zhang et al., 2019). In particular, there are different approaches to take uncertainty in the economics of renewable DERs into account. One approach addresses the possibility to hedge against possible uncertainties. In literature, there are various possibilities for hedging against uncertainties, e.g., resulting from uncertain future electricity price developments, such as financial hedging strategies or an investment in a conventional diesel generator (Roques et al., 2008). Another approach focuses on the consideration of uncertainties in the assessment of investments in renewable DERs. In this paper we focus on the latter approach. Even though, some of the approaches existing in literature include uncertainties in the assessment of an investment decision in renewable DERs, many of these consider uncertainties in terms of weather volatilities that lead to an uncertain level of production (Mavromatidis et al., 2018; Coniglio et al., 2019). Apparently, such an analysis of renewable DERs leads to a relatively conservative assessment of investments (Akbari et al., 2014; Cardoso et al., 2013; Coniglio et al., 2019). However, basing on a mere electricity producer perspective, the latter approaches neglect the prosumer perspective: Investing in a renewable DER, a consumer may cover a share of its energy consumption by the installed renewable DERs and turn into a prosumer (European Commission, 2015; Parag and Sovacool, 2016) that interacts bidirectionally with the main grid. Especially in times of low renewable production, the prosumer may cover a larger share of its current energy consumption by the external grid, while in times of an overproduction of the DERs the prosumer may sell parts of the electricity generated by the DERs to the external grid. Evaluating an investment in renewable DERs, a consumer should not only consider total energy cost savings, but also the effect of price risk stemming from uncertain electricity prices.

Thus, in this paper we raise the following research question (RQ):

RQ: What effect does long-term risk stemming from uncertain electricity prices have on individual consumers' investment decisions in renewable DERs?

To answer our research question, we apply a quantitative approach that formalizes the problem at hand. In the following we introduce our research methodology before we apply it and develop our formal model.

2. Methodology

Our methodology builds on a formal analysis of the decision-making behavior of a consumer that may turn into a prosumer by investing in DERs. For this purpose, we refer to a principle that is founded in normative decision theory, namely the Bernoulli principle (Bernoulli, 1738, 1954). Using expectation utility theory, we describe the utility function of the prosumer as well as its risk preferences (Markowitz, 1952; von Neumann and Morgenstern, 1947). For the modelling of the risk preference, we assume the Arrow-Pratt characterization of absolute risk aversion (Arrow, 1970). In particular, we use an economic investment model grounded on these theories to generally analyze the effect of risk consideration on optimal investments in a DER. While alternative research approaches may use statistical methods to derive corresponding research insights on the basis of real-world data sets, such long-term effects are difficult to measure with data available today. Especially given the relatively short history of renewable DERs, an analysis of the effect of risk-aversion on optimal long-term investment decisions is naturally restricted by the limited data availability. In contrast, by applying our analytical approach, we aim at taking a first step towards a general analysis of the main implications of risk on optimal investments in DERs independent of a specific data set.

In the following section we first describe the underlying decision problem. To obtain a benchmark for the assessment of the effects of risk-aversion, we then formalize the described decision problem in an investment model of a risk-neutral prosumer in Section 4 and formally determine the optimal level of investment in renewable DERs. Then, in Section 5 we formalize the model of a risk-averse prosumer and determine the corresponding optimal level of investment. To assess the overall effect of risk-aversion on an optimal investment, in Section 6 we compare the results from Section 4 with those from Section 5.

3. Decision problem

We consider a prosumer who faces an investment decision regarding renewable DERs. When deciding on an investment in renewable DERs, the considered prosumer faces risk that stems from uncertain electricity prices. Modelling such an electricity price risk, we introduce a set of discrete and independent scenarios $S = \{1, \ldots, |S|\}$ that relate to possible long-term electricity price developments. We assume that the chosen set of scenarios represents a random sample of all possible future electricity price developments. As we consider a long-term planning horizon we neglect daily volatility in renewable generation. Furthermore, striving for a theoretical knowledge gain with respect to investment behavior, we only assume a single time period.[1] Inspired by the 'wisdom of crowds' principle (Galton, 1907), we assume that all possible electricity price developments are normally distributed. Consequently, the prosumer faces electricity prices p_s which depend on the electricity price scenario s.

Depending on the revealed electricity price scenario, the prosumer may realize different electricity cost savings, resulting from the investment in DERs and the corresponding reduction in electricity demand from the external grid. In particular, as post-investment electricity costs are a product of electricity prices and the possible demand reduction, the electricity cost savings over all scenarios will also be normally distributed. Consequently, in our case we can use the utility mean-variance, as returns (energy cost savings) are distributed normally (Roques et al., 2008). Accounting for the corresponding price risk, the prosumer may ultimately calculate the mean of all possible electricity

[1] Note that our single-period model can easily be extended to the case of a multi-period model. As this does not change our main results, we decided in favour of a simple model presentation.

price developments as the next best guess of the expected value of the electricity cost savings μ.

However, as the use of the expected value ignores the risk of unlikely but possible extreme price scenarios, a risk-averse prosumer will additionally consider the deviation of possible electricity cost savings from the expected value. Therefore, when modelling a risk-averse prosumer, we also take the volatility σ^2 of possible electricity cost savings into account. As a prosumer's attitude towards the occurrence of extreme price scenarios may differ depending on personal characteristics and the decision situation at hand, we also include a prosumer-specific risk attitude α in the model. Integrating these measures, we apply the security equivalent as an evaluation measure considering the expected value and volatility of the electricity cost savings as well as the prosumer's risk attitude (Buhl et al., 2018). In this context, the security equivalent for normally distributed random variables and an exponential utility function has been widely used for decisions in a techno-economic context, e.g. in Beer et al. (2015), Beer et al. (2013) and Fridgen and Müller (2011). It represents the risk adjusted value of the prosumer's utility, i.e., the net electricity cost savings resulting from the investment in renewable DERs. This approach is based on the Bernoulli principle itself and has established as a standard in decision theory (Bernoulli, 1738, 1954).

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

Note that the above risk-aversion parameter α is a linear transformation of the Arrow-Pratt characterization of absolute risk-aversion (Arrow, 1970; Borch, 1969; Buhl et al., 2018; Feldstein, 1969; Fridgen and Müller, 2011). Consequently, the higher the value of α, the more risk-averse is the prosumer and the less the prosumer tolerates uncertainties in terms of deviations from an expected value of electricity cost savings. Finally, applying the above security equivalent, we model the investment problem considering expected electricity cost savings as well as the risk associated with them.

4. Optimal investment in DERs of a risk-neutral prosumer

We consider a consumer with a corresponding consumption unit that may represent, e.g., a private household or an industrial consumer. The consumer meets its electricity demand by purchasing electricity from the external grid at electricity prices whose future development is uncertain. Consequently, the purchase of electricity results in electricity procurement costs at an uncertain level. Investing in renewable DERs, the consumer is able to satisfy a share of its electricity demand through its own production and in this way turns into a prosumer. As DERs typically produce at marginal costs approximating zero, the prosumer may reduce the amount of electricity purchased from the grid and in consequence decrease electricity procurement costs. However, choosing an optimal investment, the consumer, who will turn into a prosumer, must consider both the described electricity procurement cost savings and the necessary investments.

In this section we consider a risk-neutral prosumer that accounts for the mean of all possible electricity price developments, the so-called expected value of the net electricity cost savings μ. In the following, we formalize the problem at hand and determine the optimal investment, which maximizes the prosumer's net cost savings.

4.1. Formalization of the investment problem

We describe the ex-ante given and deterministic electricity demand of the prosumer by the non-negative parameter $d^{\text{ante}} \geq 0$. As our prosumer is a former pure consumer, we assume an electricity demand greater than zero, i.e., $d^{\text{ante}} > 0$. Satisfying this demand, the prosumer purchases the required electricity from the external grid at an electricity price $p_s \geq 0$. Considering uncertain electricity prices, we additionally make the realistic assumption of a positive price variance $\sigma^2 = \frac{1}{|S|-1}\sum_{s=1}^{|S|}\left(p_s - \frac{1}{|S|}\sum_{i=1}^{|S|} p_s\right)^2 > 0$. Note that this modelling choice does not include sudden changes in grid tariffs or other regulatory measures. We denote the product of electricity demand and electricity prices as the prosumer's uncertain electricity procurement costs EC_s^{ante}, i.e., $EC_s^{\text{ante}} = d^{\text{ante}}\ p_s$.

By investing in renewable DERs, the prosumer can reduce its ex-ante given electricity demand d^{ante}, whereas the extent of the possible demand reduction is affected by the endogenous, non-negative level of investment $I \geq 0$. In particular, we introduce $d^{\text{post}}(I)$ as the post-investment electricity demand function that depends on the chosen level of investment I in renewable DERs. In the remainder of this paper, for the sake of simplicity, we will assume that $d^{\text{post}}(I)$ is an affine-linear function $d^{\text{post}}(I) = d^{\text{ante}} - vI$. The parameter $v \geq 0$ describes linear relationship between the possible electricity demand reduction and the level of investment I, i.e., an increase in the level of investment of one unit will result in v units of electricity demand reduction. We will restrict v to values in the range of [0,1], which may, e.g., describe the relative availability of sun or wind. Again, uncertain electricity procurement costs are the product of the electricity demand and the respective uncertain electricity price. As post-investment demand is a function of I, also the post-investment procurement costs will depend on the respective investment: $EC_s^{\text{post}}(I) = d^{\text{post}}(I)p_s$. Note that with a growing size of the renewable DERs, i.e., with an increasing level of investment, the renewable DERs may generate more electricity than needed by the prosumer. Consequently, we explicitly allow for a negative electricity demand of the prosumer, which corresponds to a sale of the surplus electricity to the external grid. As future feed-in prices are hard to predict, we assume that the prosumer sells and purchases electricity at the same price. In such cases, our prosumer actually acts as a producer.

Based on the above notations, we can now formally define the difference between the electricity costs ex-post and ex-ante, resulting in the electricity cost savings $\Delta EC(I)$ associated with a level of investment I. As we model a risk-neutral prosumer, we will use the mean of electricity procurement cost savings over all electricity price scenarios:

$$\Delta EC(I) = \frac{1}{|S|}\sum_{s=1}^{|S|} I v_s p_s \tag{2}$$

Considering the investment that the prosumer has to pay initially for the renewable DERs, we introduce a quadratic investment function $F(I) = -aI^2 - bI + c$. The investment function consist of three parts. First, the parameter $b > 0$ describes a linear increase of the per MW investment. Second, we additionally assume that there is also a disproportional growth in investments with an increasing size of the DER. In particular, we consider the case where with an increasing DER size, the prosumer needs to purchase land or larger technical facilities, e.g., a larger transformer capacity, whose costs grow disproportionally. Against this backdrop, we make the realistic assumption that the prosumer preferably uses the cheapest alternative for the installation of the renewable DER, however, with an increasing I, more expensive technical facilities may be needed. The respective disproportional increase is determined by the coefficient $a > 0$. Finally, we introduce the constant investment cost $c > -\infty$ which may account for either additional fixed installation costs ($c < 0$) or for granted subsidies for the installation of renewable energies ($c > 0$). Both fixed installation cost and subsidies are independent of the size of the invested DERs.

The model's objective refers to a maximization of the difference between the ex-ante and ex-post energy costs $\Delta EC(I)$ taking the corresponding investment function $F(I)$ into account. Ultimately, we have:

$$H(I) = \Delta EC(I) + F(I) \ =$$

$$= -aI^2 - bI + \frac{1}{|S|}\sum_{s=1}^{|S|} vp_s I + c \tag{3}$$

4.2. Determination of the optimal investment

For a risk-neutral prosumer, the optimal level of investment is given by

$$I_N^* = \frac{d-b}{2a} \tag{4}$$

with

$$d := \frac{1}{|S|}\sum_{s=1}^{|S|} vp_s$$

(for details refer to Appendix A.1). As the coefficient a represents the scaling factor of the assumed quadratic cost function with $a > 0$, the denominator of Eq. (4) will always be positive. However, depending on the input parameter constellation, the optimal investment of a risk-neutral consumer will either be zero or strictly larger than zero. Fig. 1 illustrates the shape of the objective function for the two relevant cases of the investment decision of a risk-neutral consumer. In Eq. (4), we directly see that for an input parameter constellation where $b - d \geq 0$ holds for a given $b > 0$, the optimal level of investment of a risk-neutral consumer will be zero given the assumed non-negativity of the investment. In this case, the aggregated mean per unit of energy cost savings is lower than the linear per MW investments, i.e., the average costs per unit of renewable DER are too expensive for a risk-neutral investor. For an input parameter constellation where $d - b > 0$ holds for a given $b > 0$, there is an optimal level of investment of a risk-neutral consumer strictly larger than zero. In this case, up to the optimal investment, the aggregated mean per unit of energy cost savings is larger than the linear per MW investments, i.e., a risk-neutral investor would choose an optimal investment in renewable DERs taking into account that for investments beyond this optimal investment the energy cost savings per invested unit cannot justify any further investment.

5. Optimal investment in DERs of a risk-averse prosumer

Only using the expected value of cost savings, the risk-neutral prosumer in Section 4 ignores the risk of unlikely but possible extreme price scenarios. When considering a risk-averse prosumer, we now additionally account for the deviation of possible electricity cost savings from the expected value. Therefore, we model a risk-averse prosumer taking the volatility σ^2 of possible electricity cost savings into account. In the following, we formalize the corresponding decision problem and determine the optimal investment of the risk-averse prosumer.

5.1. Formalization of the investment problem

In Section 3 we already introduced the security equivalent (Eq. (1)) as an evaluation measure which considers both the expected value and the volatility of electricity procurement cost savings for a given prosumer's risk attitude. As the risk-neutral prosumer in Section 3 already includes the expected value in form of a mean over all possible electricity procurement cost savings, we add a risk-adjusting term to Objective (3) in order to account for the corresponding risk-aversion. This risk-adjusting term $R(I)$ considers the change in variance resulting from a given level of investment I, i.e., the difference between the ex-ante variance without investment σ^{ante2} and the ex-post variance $\sigma^{post}(I)^2$ after an investment in renewable DERs, and adjusts it by the prosumer's risk-aversion α.

$$R(I) = \alpha\sigma^2\left[d^{ante\,2} - \left(d^{ante} - vI\right)^2\right] \tag{5}$$

As the model's objective is to maximize the beneficial effect of the investment in renewable DERs for a risk-averse prosumer, we compare the security equivalent of a prosumer that may decide to make an investment $\Phi^{post}(I)$ to the security equivalent for the case without an investment Φ^{ante}. Therefore, the resulting objective function maximizes the difference between the two security equivalents with respect to the corresponding investment function $F(I)$:

$$\Delta\Phi(\mu,\sigma) = -aI^2 - bI + I\frac{1}{|S|}\sum_{s=1}^{|S|} vp_s + c + \alpha\left[d^{ante^2} - \left(d^{ante} - vI\right)^2\right]\sigma^2 \tag{6}$$

5.2. Determination of the optimal investment

For a risk-averse prosumer, we can derive the following optimal level of investment (for details refer to Appendix A.2):

$$I_{AV}^* = \frac{d-b+e}{2a+2f} \tag{7}$$

In the above equation, for notational convenience we use the substitutions $e := \alpha 2 d^{ante} v\sigma^2$ and $f := \alpha v^2\sigma^2$. Since the risk-aversion parameter for a risk-averse prosumer is $\alpha > 0$ and we assume an aggregated demand $d^{ante} > 0$ as well as $v > 0$, the parameters e and f describe a positive term. Consequently, the denominator of Eq. (7) will always be positive. However, similar to the case of a risk-neutral investor, the optimal investment of a risk-averse consumer will also be either zero or larger than zero depending on the respective input parameter constellation. Fig. 2 illustrates the shape of the objective function for the two relevant cases of the investment decision of a risk-averse consumer. In Eq. (7), we see that for an input parameter constellation where $b - d \geq e$

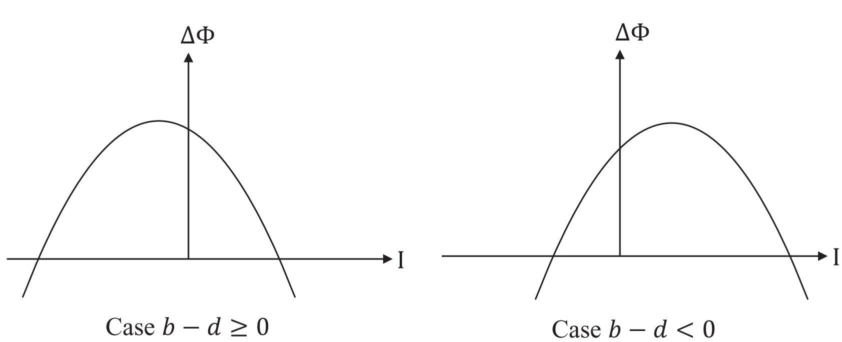

Fig. 1. Shapes of the objective function for the two input parameter constellations for the risk-neutral prosumer.

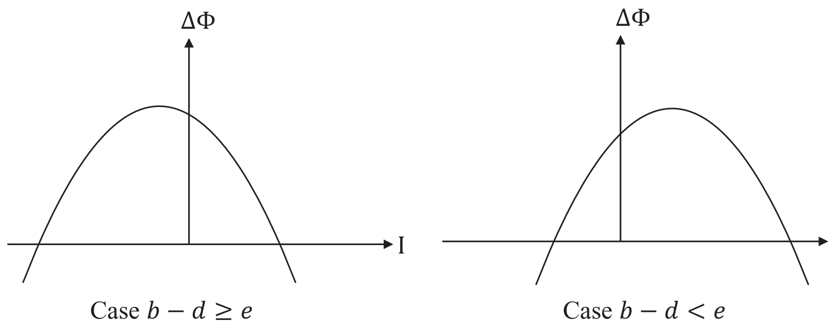

Fig. 2. Shapes of the objective function for the two input parameter constellations for the risk-averse prosumer.

holds for a given $b > 0$, the optimal investment of a risk-averse consumer will be zero given the assumed non-negativity of the investment. In this case, the aggregated mean per unit of energy cost savings is lower than the linear per MW investments, i.e., the average costs per unit of renewable DER are too expensive for a risk-neutral investor. However, in contrast to a risk-neutral consumer's optimal investment (Fig. 1), the parameter e accounting for risk additionally influences the investment decision of a risk-averse consumer. For an input parameter constellation where $b-d<e$ holds for a given $b > 0$, similar to the case of a risk-neutral consumer, the optimal level of investment of a risk-averse consumer is larger than zero. Though, in contrast to a risk-neutral investor (see Fig. 1), again, the parameter e affects the investment decision of a risk-averse consumer. In the present case, up to the optimal investment the aggregated mean per unit of energy cost savings plus a risk-adjusting term are larger than the linear per MW investments.

6. On the insurance effect of renewable DERs

To determine the effect that risk-aversion can have on an optimal investment in renewable DERs, we formally compare the optimal investments of Sections 4 and 5 before we discuss the economic implications of the identified mathematical results.

For a comparison of the optimal investment of a risk-neutral and a risk-averse prosumer, we take their two cases of a positive and a zero investment (see also Sections 4.2 and 5.2) into account, respectively. In total, we have to make three different comparisons (a) to (c) as summarized in Table 1. In particular, in each of the three comparisons we calculate the difference between the optimal levels of investments $\Delta I = I_{AV}^{*} - I_{N}^{*}$ and determine the positivity/negativity of the respective difference.

Overall, Table 1 indicates that in at least two out of three parameter constellations, the consideration of risk-aversion results in an equal or even higher optimal level of investment.

In case (a), neither a risk-neutral nor a risk-averse prosumer invests in renewable DERs. In this case, the initial investment for the renewable DER exceeds the mean of energy cost savings over the whole planning horizon. At the same time, also a reduction in energy cost savings volatility does not justify an investment due to the high initial investment.

Table 1
Difference in optimal investments between risk-neutral and risk-averse prosumer for three different input parameter constellations.

	Case (a): $b-d \geq e$	Case (b): $0 \leq b-d < e$	Case (c): $b-d<0$
I_N^*	0	0	$\frac{d-b}{2a}$
I_{AV}^*	0	$\frac{d-b+e}{2(a+f)}$	$\frac{d-b+e}{2(a+f)}$
ΔI	0	$\frac{d-b+e}{2(a+f)}$	$2\alpha v\sigma^2\left(d^{ante} - v\frac{d-b}{2a}\right)$

Accordingly, the consideration of risk does not affect a prosumer's decision on an investment in renewable DERs for this input parameter constellation.

In case (b), a risk-neutral prosumer does not invest in renewable DERs, while a risk-averse prosumer invests a strictly positive amount. Consequently, for the second input parameter constellation, risk-aversion positively shifts a prosumer's decision on an investment in renewable DERs, i.e., the prosumer's optimal level of investment increases.

By considering not only the mean cost savings but also the price risk that the prosumer is exposed to, the risk-averse prosumer in case (b) also assesses the extent to which the cost savings of the individual scenarios differ from each other, i.e., how much the prosumer is still exposed to uncertain electricity prices due to external purchases from the grid. Reducing the electricity demand from the grid by an investment in renewable DERs, in case (b) the risk-averse prosumer is less exposed to uncertain developments in electricity prices. Thus, the investment in renewable DERs functions as an insurance against uncertain electricity price developments. Consequently, for a risk-averse prosumer as in case (b), the protection against the risk stemming from uncertain electricity procurement costs represents an additional value given the investment in renewable DERs. In the following, we refer to this effect as the insurance effect of renewable DERs against uncertain electricity price developments. Contrary to current literature that identified uncertainty and ultimately risk consideration to result in a decreasing/weaker investment (Coniglio et al., 2019; Mavromatidis et al., 2018), it is actually the risk consideration and more precisely the insurance effect that shifts the optimal level of investment in the upward direction in case (b).

Finally, in case (c), both the risk-neutral and the risk-averse prosumer invest a strictly positive amount. However, the sign of the corresponding investment difference is ex-ante unclear. Therefore, in the following we will analyze, under which conditions the risk-averse prosumer of case (c) will invest (c-i) more, (c-ii) less, or (c-iii) the same amount as the risk-neutral prosumer. To this end, we first start with subcase (c-i) where risk-aversion increases the investment amount, i.e., $I_{AV}^{*} > I_{N}^{*}$. Reformulating the latter inequality, we arrive at a condition on the corresponding input parameters, where the term for the investment difference is greater than zero:

$$0 < v\sigma^2\left(d^{ante} - v\frac{d-b}{2a}\right) \quad (8)$$

We can see that as the ex-ante electricity demand d^{ante} ceteris paribus increases, not only the optimal level of investment of the risk-averse prosumer but also the corresponding difference to the optimal level of investment of the risk-neutral prosumer increases.

For the subcases (c-ii) and (c-iii), we get similar conditions by replacing greater with “lower than” or “equal to” zero in the condition above.

The respective condition specifies the possible parameter constellations of case (c), under which the risk-averse prosumer invests more than the risk-neutral prosumer, i.e., subcase (c-i). In particular, for constellations, where $d^{\text{ante}} - v\frac{d-b}{2a}$ is positive, which can be interpreted as the ex-ante electricity demand being sufficiently high to justify the risk-neutral investment (similar to case (b)), the risk-averse investment is actually greater than the risk-neutral one.

In subcase (c-ii) the consideration of risk-aversion actually results in a lower optimal level of investment as compared to the optimal investment of the risk-neutral prosumer. In order to understand this parameter constellation, we again consider the risk-adjusting term in Eq. (5).

For a given ex-ante electricity demand of the former consumer d^{ante}, an increasing investment in renewable DERs I, as stated above, first results in an increasing insurance effect as the dependency on uncertain electricity prices decreases. The risk-adjusting term $R(I)$ positively shifts the optimal level of investment and thereby confirms an investment decision in renewable DERs. Though, with an increasing level of investment, the prosumer reduces the ex-ante electricity demand completely (self-supply exceeds the own demand) and sells an increasing amount of electricity to the grid. At this point the prosumer turns into a producer. Consequently, a consumer, investing in renewable DERs, first turns into a prosumer with a predominant share of consumption, while with an increasing level of investment, the former consumer turns into a prosumer with a predominant share of production. In the following, we will denote these two types of prosumers as the 'consuming prosumer' and the 'producing prosumer'. In Eq. (5) we recognize this shift from the 'consuming' to the 'producing prosumer' when the investment in DERs I becomes so large that the term $d^{\text{ante}2} - (d^{\text{ante}} - vI)^2$ takes a negative value and the risk-adjusting term $R(I)$ lowers the objective function value, i.e., the investment increases risk. The change in sign (from positive to negative) of the risk-adjusting term clarifies that for the consuming prosumer a consideration of risk-aversion results in a higher investment, as a reduced variance in electricity costs appears as an additional value – the insurance effect of renewable DERs confirms the investment decision. For the producing prosumer, however, risk stemming from uncertain electricity price developments leads to a decreasing benefit of the investment in renewable DERs as they indicate uncertain revenues of the corresponding sales.

The risk-neutral prosumer, however, only considers the mean of the energy costs savings and obviously the initial investment. Consequently, as the risk-adjusting term does not affect the risk-neutral prosumer's investment decision, for subcase (c-ii) the risk-neutral investment is higher than the risk-averse one.

The parameter constellation of subcase (c-iii) is a special case that only holds when due to a given ex-ante demand d^{ante} of the former consumer and a given efficiency in demand reduction v, the insurance effect formally does not exist. In this case, the risk-adjusting term $R(I)$ assumes a value of zero and both objective functions are equal.

7. Exemplary case study

In this section we use an academic example to illustrate the identified insurance effect of renewable DERs. In order to keep the example as simple as possible, we assume two scenarios $S = \{1,2\}$ that correspond to a high price and a low price scenario, respectively. The given consumer requires 40 units of electricity to satisfy the ex-ante demand. Corresponding prices under the two scenarios are 30 and 50 with a price volatility of $\sigma^2 = 200$. Finally, we assume the following investment function, where $v = 1$ holds:

$$F(I) = -I^2 - 4I$$

Note that assuming $v = 1$, mean cost savings per invested unit equal the mean of the electricity prices, i.e., $G(I) = 40I$.

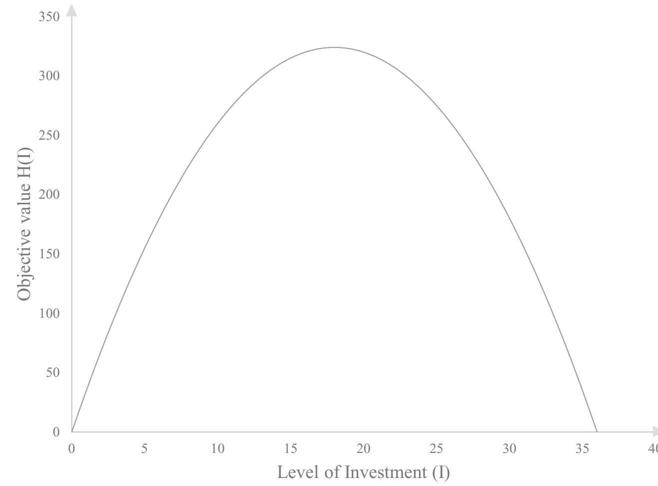

Fig. 3. Objective function of a risk-neutral prosumer.

For the given parameter setting, the objective function for the risk-neutral prosumer writes:

$$H(I) = F(I) + EC(I) = -I^2 + 36I.$$

Fig. 3 shows the corresponding optimal investment of $I_N^* = 18$. As can directly be seen, by investing in a DER, the risk-neutral prosumer purchases only purchases 22 units from the external market at uncertain prices.

Modelling a risk-averse prosumer with a risk-aversion parameter of $\alpha = 1$, we first calculate the corresponding risk-adjusting term:

$$R(I) = \alpha\sigma^2\left[d^{\text{ante}^2} - \left(d^{\text{ante}} - vI\right)^2\right] = -200I^2 + 16000I$$

Adding the risk-adjusting term to the objective function of the risk-neutral prosumer, we get the objective function of the risk-averse prosumer:

$$\Delta\Phi(I) = F(I) + EC(I) + R(I) = -201I^2 + 16036I$$

Finally, we determine the optimal level of investment for the risk-averse prosumer[2]:

$$I_{AV}^* = \frac{\frac{1}{|S|}\sum_{s=1}^{|S|} vp_s - b + e}{2a + 2f} = \frac{40 - 4 + 16000}{2 \cdot 1 + 2 \cdot 200} = 39.89$$

The results from this simple example indicate that the optimal level of investment of the risk-averse prosumer is indeed higher than the one of the risk-neutral prosumer. Accordingly, condition (18) is satisfied. In our case, the risk-averse prosumer invests 21.89 units more than the risk-neutral one, as this additional investment results in a reduction in external purchases and ultimately in a reduction of volatility, i.e., risks for the risk-averse prosumer. The insurance effect of the renewable DER, assessed by the risk-averse prosumer, consequently, positively shifts the investment decision.

We now can determine the reduction of volatility resulting from the risk-neutral and the risk-averse optimal investment. In particular, the risk-averse prosumer is able to reduce the ex-ante investment volatility in energy costs by 100%, while the risk-neutral prosumer only reduces the volatility by 69.75%.

[2] Note that for a sufficiently large α, the formula will take a value of $\frac{d^{\text{ante}}}{v}$, i.e., 40 for our case.

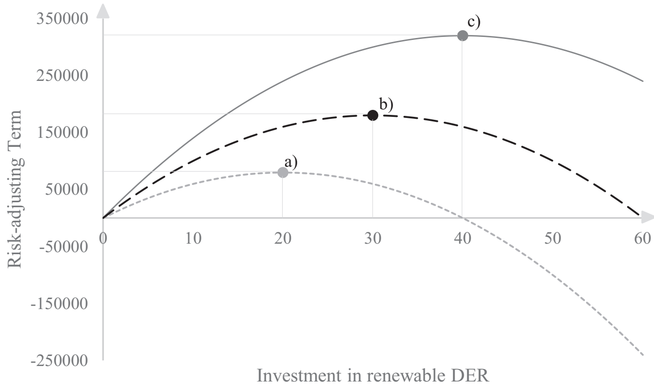

Fig. 4. Risk-adjusting term for different ex-ante electricity demands The figure illustrates former consumers with a maximum risk-adjusting term of an ex-ante demand of (a) 20 units, (b) 30 units, and (c) 40 units. The solid function describes the risk-adjusted term for the case of 40 units, the dashed function for the case of 30 units, the dotted function 20 units.

However, as our results from Section 6 already indicate, the optimal level of investment of a risk-averse prosumer especially depends on the given ex-ante electricity demand of the former consumer d^{ante}. In the following, we therefore illustrate the shift from a consuming prosumer to a producing prosumer using our academic example. As pointed out above, the objective function of the risk-averse prosumer takes the risk-adjusting term $R(I)$ into account, which ultimately affects the corresponding investment. Fig. 4 therefore illustrates the risk-adjusting term for three different ex-ante electricity demands of 20, 30, and 40 units. We clearly see that with an increasing ex-ante demand, the maximum of the risk-adjusting term shifts to higher investments.

Additionally, Fig. 4 also illustrates the level of investment at which the shift from a consuming prosumer to a producing prosumer appears, namely the corresponding maximum of the function.

Next, we draw the objective function of a risk-averse prosumer for the three given ex-ante electricity demands.

Fig. 5 illustrates the increasing optimal level of investment for a risk-averse prosumer with an increasing ex-ante electricity demand. This effect results from the increasing risk-adjusting term, illustrated in Fig. 4. Note that in our case the maxima of the functions in Fig. 4 match the corresponding maxima in Fig. 5, as we assume a risk-aversion parameter $\alpha = 1$ and a demand reduction efficiency $v = 1$. Consequently, the optimal investment of the risk-averse prosumer equals the prosumer's ex-ante electricity demand as a former consumer.

Considering the three objective functions in Fig. 5, we can divide them into three intervals: For levels of investment smaller than the

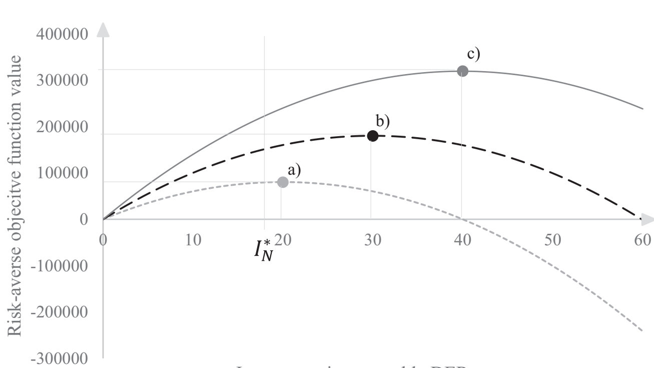

Fig. 5. Risk-averse objective function for different ex-ante electricity demands The figure illustrates former consumers with the optimal level of investment of an ex-ante demand of (a) 20 units, (b) 30 units, and (c) 40 units. The solid function describes the optimal investment for the case of 40 units, the dashed function for the case of 30 units, the dotted function for the case of 20 units.

maxima (a), (b) and (c), both the expected value of electricity cost savings and the reduction in variance increase with an increasing level of investment I. For levels of investment beyond the maxima for which the objective function value takes a positive sign the expected electricity cost savings increase further, but the reduction in variance decreases from here on. Finally, for levels of investment for which the objective function value takes a negative sign the expected electricity cost savings increase further, however, the level of the ex-post variance by now dominates the electricity cost savings.

8. Conclusion

This paper analyzes the effect that risk stemming from uncertain electricity prices can have on individual consumer's investment decisions in renewable DERs. To do so, we propose an economic investment model grounded on decision- and expectation utility theory. As a benchmark for the assessment of the effect of risk-aversion on an investment decision in renewable DERs, we first formulate the investment model for a risk-neutral prosumer. Next, we extend our model by a risk-adjusting term that accounts for the risk-aversion of a prosumer as well as by the variance of the energy cost savings after the investment decision. Comparing the optimal investment of the two models, we can analyze, which effect the consideration of risk-aversion has on an investment decision in renewable DERs. Finally, we apply both models to an exemplary case in order to illustrate our main findings.

Our results indicate that the consideration of risk-aversion affects an investment decision in renewable DERs. In fact, we point out that in the case of a prosumer with a low share of electricity sale to the grid, the integration of risk-aversion increases the level of an optimal investment in renewable DERs. We attribute these results to the insurance effect of renewable DERs. In particular, we conclude that for such a risk-averse consuming prosumer, a reduction in demand resulting from an investment in DERs leads to a reduction in the risk stemming from uncertain electricity prices. Thus, the investment can be interpreted as an insurance premium. Furthermore, our results indicate that for an increasing level of investment in renewable DERs, the consuming prosumer at some point turns into a producing prosumer whose production share is predominant in comparison to the prosumer's share of consumption. We point out that for such a producing prosumer, an increasing investment results in an increasing volatility in revenues from the DERs' production.

Even though our research can be seen as a valuable starting point for the analysis of the described insurance effect of DERs, our research still has some limitations, which actually demonstrate the potential for future work in this field of research: Our model is based on the security equivalent. Thus, we assume the decision maker to have an exponential utility function. At the same time, the model assumes a rational decision-maker acting based on risk-aversion, which is only defined by a risk-aversion parameter. Obviously, this constitutes main simplifications of real-word-decision making. Nevertheless, the security equivalent may in general be seen as an established model in research and therefore suitable for our context. Also, there may be other sources of risk, e.g., the threat of a blackout that may encourage an investment in renewable DERs that we do not model explicitly. Furthermore, our approach currently does not take into account alternative hedging possibilities, e.g., financial hedging strategies in terms of one year contracts. An investment other than in a DER, e.g., in a conventional diesel generator, may additionally represent a scalable generation resource to partially cover an ex-ante demand (Roques et al., 2008). However, the use of a non-renewable energy resource results in an additional dependency on external price risks that, e.g., need to be addressed by fuel mix diversification (Awerbuch, 2000; Awerbuch and Berger, 2003; Bar-Lev and Katz, 1976; Humphreys and McClain, 1998; Roques et al., 2008). An integrated approach considering alternative investment options for hedging against uncertain electricity prices could therefore be investigated in future research. Another limitation of our work is our modelling of electricity prices. We consider wholesale prices, whose long-term price level is normally distributed. Moreover, we assume that the prosumer sells and purchases electricity at the same price. In fact, the used wholesale price does only represent a part of the final end-consumer price. In reality, for instance grid tariffs make up a large part of final end-consumer prices, which, however, are typically determined by complex future regulation being hard to anticipate and quantify. An analysis of such factors therefore constitutes part of further research. Also, a rebound effect leading to an increasing demand of consumers after investing in renewable DERs may have implications for expected electricity cost savings and therefore on the insurance effect itself (Havas et al., 2015; Qui et al., 2019; Toroghi and Matthew, 2019). We consider a proper modelling and analysis of such effect to be relevant for future research.

Despite these limitations, our results have important theoretical implications. Our work provides an extension of the existing literature that up to now mainly considers uncertainties, for instance in form of a hard predictability of weather developments, which ultimately result in a more conservative assessment of the economic potential of DERs. Against this backdrop, we have developed a model that takes risk in terms of uncertain price developments and the risk-aversion of the prosumer into account when deciding on investments in DERs. In addition, we were able to expand the known applications for DERs by illustrating that DERs can be used as an insurance against uncertain electricity prices. In this respect, there are obviously also major implications for practice. For example, our results demonstrate that a pure consideration of energy cost savings is not sufficient to assess the full potential of DERs. Practitioners should also consider the insurance effect of DERs as an additional incentive for consumers to make their investment decision in renewable DERs. In fact, an appropriate consideration of the insurance effect might increase consumers' involvement as active players in energy systems and ultimately lead to an increasing decentralization and energy democracy.

However, if, due to the insurance effect an increasing number of consumers were to invest in renewable DERs, total market demand would tend to decrease and in direct consequence average market prices will decrease as well. At the same time, a reduced market demand would also lead to a loss of financial resources available for maintenance and development of the public grid infrastructure due to a reduced overall amount of paid grid fees. Ultimately, this may result in an increase in the level of grid fees that must be paid by the (remaining) consumers that buy from the market, and thus increasing end-consumer prices. Such price increase in turn implies a higher importance of the insurance effect. Overall, politics and regulation play an important role in responding to such self-reinforcing promotion of renewable energies. In particular, it will be the task of policymakers to pursue a consistent energy market policy that takes such developments together with possible distributional effects into account. The latter may for instance stem from the fact that not all consumers may be able to invest in DERs and would ultimately have to bear higher energy costs. Overall, the corresponding incentives for appropriate investments in DERs may contribute to a further development of renewable energy sources, a corresponding reduction in CO_2 emissions, and ultimately to a successful energy transition.

Declarations of interest:

none

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Appendix A. Appendix

A.1. Determination of the optimal investment of a risk-neutral prosumer

As Objective (3) is a strictly concave function with $\frac{\partial^2 H}{\partial I^2} = -2a < 0$, we can directly take its first derivative and set it to zero in order to derive the optimal level of investment for a risk neutral prosumer:

$$\frac{\partial H}{\partial I} = -2aI - b + \frac{1}{|S|}\sum_{s=1}^{|S|} vp_s = 0 \tag{A.1}$$

Solving Eq. (A.1) for I, we obtain the following optimal level of investment for a risk-neutral prosumer.

$$I_N^* = \frac{\frac{1}{|S|}\sum_{s=1}^{|S|} vp_s - b}{2a} \tag{A.2}$$

For notational convenience and improved readability, throughout the main part of the paper we use the following notation:

$$d := \frac{1}{|S|}\sum_{s=1}^{|S|} vp_s \tag{A.3}$$

Note that the parameter d refers to the mean of electricity procurement cost savings per invested unit over all electricity price scenarios.

A.2. Determination of the optimal level of investment for a risk-averse prosumer

In order to determine the optimal investment for a risk-averse prosumer, we again take the first and second derivative of the objective function (6) with respect to I:

$$\frac{\partial \Delta\Phi}{\partial I} = -2aI - b + \frac{1}{|S|}\sum_{s=1}^{|S|} vp_s + \alpha\ 2d^{ante} v\sigma^2 - 2\alpha\ I\ v^2\sigma^2 \tag{B.1}$$

$$\frac{\partial^2 \Delta\Phi}{\partial I^2} = -2a - 2\alpha v^2\sigma^2 \tag{B.2}$$

As we consider a risk-averse prosumer ($\alpha > 0$), we infer for Objective (6) to be a strictly concave function with $\frac{\partial^2 \Delta\Phi}{\partial I^2} < 0$ and directly take its first derivative that we set to zero in order to derive the optimal investment amount:

$$\frac{\partial \Delta\Phi}{\partial I} = -2aI - b + \frac{1}{|S|}\sum_{s=1}^{|S|} v\ p_s + \alpha\ 2d^{ante} v\sigma^2 - 2\ \alpha\ I\ v^2\sigma^2 = 0 \tag{B.3}$$

Solving Eq. (B.1) for I, we obtain the following optimal investment amount for a risk-averse prosumer:

$$I_{AV}^* = \frac{-b + \frac{1}{|S|}\sum_{s=1}^{|S|} vp_s + \alpha 2d^{ante} v\sigma^2}{2a + 2\alpha v^2\sigma^2} \tag{B.4}$$

Again, for notational convenience and improved readability, in the main part of the paper we will make use of two notations simplifying Eq. (B.1):

$$e \coloneqq \alpha\ 2\ d^{\text{ante}} v \sigma^2,\ \ f \coloneqq \alpha\ v^2 \sigma^2 \tag{B.5}$$

Using this notation, we can rewrite the optimal level of investment for a risk-averse prosumer (Eq. (B.1)) as:

$$I^*_{AV} = \frac{d-b\ +\ e}{2a\ +\ 2f} \tag{B.6}$$

References

Akbari, Kaveh, Nasiri, Mohammad M., Jolai, Fariborz, Ghaderi, Seyed F., 2014. Optimal investment and unit sizing of distributed energy systems under uncertainty: a robust optimization approach. Energy Build 85, 275–286. https://doi.org/10.1016/j.enbuild.2014.09.009.

Akorede, Mudathir Funsho, Hizam, Hashim, Pouresmaeil, Edris, 2010. Distributed energy resources and benefits to the environment. Renew. Sust. Energ. Rev. 14 (2), 724–734. https://doi.org/10.1016/j.rser.2009.10.025.

Alarcon-Rodriguez, Arturo, Ault, Graham, Galloway, Stuart, 2010. Multi-objective planning of distributed energy resources: a review of the state-of-the-art. Renew. Sust. Energ. Rev. 14 (5), 1353–1366. https://doi.org/10.1016/j.rser.2010.01.006.

Arrow, Kenneth J., 1970. Essays in the Theory of Risk Bearing. 7. Markham Publishing, Chicago (4).

Awerbuch, Shimon, 2000. Investing in photovoltaics: risk, accounting and the value of new technology. Energy Policy 28 (14), 1023–1035.

Awerbuch, Shimon, Berger, Martin, 2003. Energy security and diversity in the EU: a mean-variance portfolio approach. IEA Research Paper.

Bar-Lev, Dan, Katz, Steven, 1976. A portfolio approach to fossil fuel procurement in electric utility industry. J. Financ. 31 (3), 933–947.

Battaglini, Antonella, Komendantova, Nadejda, Brtnik, Patricia, Patt, Anthony, 2012. Perception of barriers for expansion of electricity grids in the European Union. Energy Policy 47, 254–259. https://doi.org/10.1016/j.enpol.2012.04.065.

Beer, Martina, Fridgen, Gilbert, Müller, Hanna V., Wolf, Thomas, 2013. Benefits quantification in IT projects. Wirtschaftsinformatik 45.

Beer, Martina; Wolf, Thomas; Zare Garizy, Tirazheh (2015): Systemic risk in IT portfolios - an integrated quantification approach. Proceedings in International Conference on Information Systems 2015 Forth worth, USA.

Beraldi, Patrizia, Violi, Antonio, Carrozzino, Gianluca, Bruni, Maria E., 2018. A stochastic programming approach for the optimal management of aggregated distributed energy resources. Computers & Operations Research 96, 200–212. https://doi.org/10.1016/j.cor.2017.12.018.

Bernoulli, Daniel, 1738. Specimen theoriae novae de mensura sortis. Commentarii Academiae Scentarum Imperialis Petropolitanae 5, 175–192.

Bernoulli, Daniel, 1954. Exposition of anew theory on the measurement of risk. Econometrica 22, 22–36. https://doi.org/10.1142/9789814293501_0002.

Borch, Karl, 1969. A note on uncertainty and indifference curves. Rev. Econ. Stud. 36 (1), 1–4.

Buhl, Hans Ulrich, Gaugler, Tobias, Mette, Philipp, 2018. The "insurance effect": how to increase the investment amount in green buildings - a model-based approach to reduce the energy efficiency gap. Environ. Eng. Manag. J. 17 (7), 1599–1611.

Bullich-Massagué, Eduard, Díaz-González, Francisco, Aragüés-Peñalba, Mònica, Girbau-Llistuella, Francesc, Olivella-Rosell, Pol, Sumper, Andreas, 2018. Microgrid clustering architectures. Appl. Energy 212, 340–361. https://doi.org/10.1016/j.apenergy.2017.12.048.

Bundesverband der Energie- und Wasserwirtschaft, 2016. Rollenmodell für die Marktkommunikation im deutschen Energiemarkt. Strom und Gas. Anwendungshilfen. Bundesverband der Energie- und Wasserwirtschaft. Berlin.Available online at. https://www.bdew.de/media/documents/Awh_20160823_Anwendungshilfe-Rollenmodell-MAK-v1.1.pdf checked on 6/29/2019.

Callaway, Duncan S., Fowlie, Meredith, McCormick, Gavin, 2018. Location, location, location: the variable value of renewable energy and demand-side efficiency resources. J. Assoc. Environ. Resour. Econ. 5 (1), 39–75.

Cano, Emilio L., Moguerza, Javier M., Alonso-Ayuso, Antonio, 2016. A multi-stage stochastic optimization model for energy systems planning and risk management. Energy Build. 110, 49–56. https://doi.org/10.1016/j.enbuild.2015.10.020.

Cardoso, Goncalo, Stadler, Michael, Siddiqui, Afzal, Marnay, Chris, DeForest, Nicholas, Barbosa-Póvoa, Anna, Ferrão, Paulo, 2013. Microgrid reliability modeling and battery scheduling using stochastic linear programming. Electr. Power Syst. Res. 103, 61–69. https://doi.org/10.1016/j.epsr.2013.05.005.

Coniglio, Stefano, Märtz, Alexandra, Weibelzahl, Martin, 2019. The Flexibility Puzzle in Liberalized Electricity Markets: How to Choose the Right Flexibility Options under Uncertainty? Working Paper

DeForest, Nicholas, Stadler, Michael, Cardose, Goncalo, Brandt, Tobias, Narayanan, Sankar, 2014. Enabling broad adoption of distributed pv-storage systems via supervisory planning & control. ACEEE Summer Study on Energy Efficiency in Buildings Asilomar Conference Center Pacific Grove, USA.

Deichmann, Uwe, Meisner, Craig, Murray, Siobhan, Wheeler, David, 2011. The economics of renewable energy expansion in rural sub-Saharan Africa. Energy Policy 39 (1), 215–227. https://doi.org/10.1016/j.enpol.2010.09.034.

Dietrich, Andreas, Weber, Christoph, 2018. What drives profitability of grid-connected residential PV storage systems? A closer look with focus on Germany. Energy Econ. 74, 399–416. https://doi.org/10.1016/j.eneco.2018.06.014.

Dow, James, Serfio, Ribeiro da Costa Werlang, 1992. Uncertainty aversion, risk aversion, and the optimal choice of portfolio. Econometrica 60 (1), 197–204. https://doi.org/10.2307/2951685.

Ellabban, Omar, Abu-Rub, Haitham, Blaabjerg, Frede, 2014. Renewable energy resources: current status, future prospects and their enabling technology. Renew. Sustain. Energy Rev. 39, 748–764. https://doi.org/10.1016/j.rser.2014.07.113.

European Commission, 2015. Regulatory Recommendations for the Deployment of Flexibility - EG3 Report Smart Grid Task Force (January 2015. In European Comission).

Feldstein, Martin S., 1969. Mean-variance analysis in the theory of liquidity preference and portfolio selectrion. Rev. Econ. Stud. 36 (1), 5–12.

Fridgen, Gilbert, Müller, Hanna V., 2011. An approach for portfolio selection in multi-vendor IT outsourcing. Proceedings in International Conference on Information Systems 2011.

Galton, Francis, 1907. Vox populi (the wisdom of crowds). Nature 75 (7), 450–451.

Havas, Lisa, Ballweg, Julie, Penna, Chris, Race, Digby, 2015. Power to change: analysis of household participation in a renewable energy and energy efficiency programme in Central Australia. Energy Policy 87.

Helm, Carsten, Mier, Mathias, 2019. On the efficient market diffusion of intermittent renewable energies. Energy Econ. 80, 812–830. https://doi.org/10.1016/j.eneco.2019.01.017.

Humphreys, H. Brett, McClain, Katherine T., 1998. Reducing the impacts of energy price volatility through dynamic portfolio selection. Energy Journal 19 (3).

Jiayi, Huang, Jiang, Chuanwen, Xu, Rong, 2008. A review on distributed energy resources and MicroGrid. Renew. Sust. Energy Rev. 12, 2472–2483. https://doi.org/10.1016/j.rser.2007.06.004.

Kitzing, Lena, Weber, Christoph, 2015. Support mechanisms for renewables: how risk exposure influences investment incentives. Int. J. Sust. Energy Plan. Manag. 7, 117–134. https://doi.org/10.2139/ssrn.2505976.

Ländner, Eva-Maria, Märtz, Alexandra, Schöpf, Michael, Weibelzahl, Martin, 2019. From energy legislation to investment determination: shaping future electricity markets with different flexibility options. Energy Policy 129, 1100–1110. https://doi.org/10.1016/j.enpol.2019.02.012.

Lin, Boqiang, Chen, Yufang, 2019. Does electricity price matter for innovation in renewable energy technologies in China? Energy Econ. 78, 259–266. https://doi.org/10.1016/j.eneco.2018.11.014.

Mai, Trieu, Bistline, John, Sun, Yinong, Cole, Wesley, Marcy, Cara, Namovicz, Chris, Young, David, 2018. The role of input assumptions and model structures in projections of variable renewable energy: a multi-model perspective of the U.S. electricity system. Energy Econ. 76, 313–324. https://doi.org/10.1016/j.eneco.2018.10.019.

Markowitz, Harry, 1952. Portfolio selectrion. J. Financ. 7 (1), 77–91.

Mavromatidis, Georgios, Orehounig, Kristina, Carmeliet, Jan, 2018. A review of uncertainty characterisation approaches for the optimal design of distributed energy systems. Renew. Sustain. Energy Rev. 88, 258–277. https://doi.org/10.1016/j.rser.2018.02.021.

Mengelkamp, Esther, Gärttner, Johannes, Rock, Kerstin, Kessler, Scott, Orsini, Lawrence, Weinhardt, Christof, 2018. Designing microgrid energy markets. A case study: the Brooklyn microgrid. Appl. Energy 210, 870–880. https://doi.org/10.1016/j.apenergy.2017.06.054.

Moriarty, Patrick, Honnery, Damon, 2016. Can renewable energy power the future? Energy Policy 93, 3–7. https://doi.org/10.1016/j.enpol.2016.02.051.

Parag, Yael, Sovacool, Benjamin K., 2016. Electricity market design for the prosumer era. Nat. Energy 1 (4), 16032. https://doi.org/10.1038/NENERGY.2016.32.

Polzin, Friedemann, Egli, Florian, Steffen, Bjarne, Schmidt, Tobias S., 2019. How do policies mobilize private finance for renewable energy?—a systematic review with an investor perspective. Appl. Energy 236, 1249–1268. https://doi.org/10.1016/j.apenergy.2018.11.098.

Qiu, Yueming, Wang, Yi David, Wang, Jianfeng, 2017. Soak up the sun: impact of solar energy systems on residential home values in Arizona. Energy Econ. 66, 328–336. https://doi.org/10.1016/j.eneco.2017.07.001.

Quadri, Imran Ahmad, Bhowmick, S., Joshi, D., 2018. A comprehensive technique for optimal allocation of distributed energy resources in radial distribution systems. Appl. Energy 211, 1245–1260. https://doi.org/10.1016/j.apenergy.2017.11.108.

Qui, Yueming L., Kahn, Matthew E., Xing, Bo, 2019. Quantifying the rebound effects of residential solar panel adoption. J. Environ. Econ. Manag. 96, 310–341.

Reiche, Danyel, Bechberger, Mischa, 2004. Policy differences in the promotion of renewable energies in the EU member states. Energy Policy 32 (7), 843–849.

Rodrigues, Sandy, Chen, Xiaju J., Torabikalaki, Roham, Mata-Lima, Herlander, Faria, Fabio, Cafofo, Nuno, et al., 2016. Economic feasibility analysis of small scale PV systems in different countries. Solar Energy 131, 81–95. https://doi.org/10.1016/j.solener.2016.02.019.

Roques, Fabien A., Newbery, David M., Nuttall, William J., 2008. Fuel mix diversification incentives in liberalized electricity markets: a mean–variance portfolio theory approach. Energy Econ. 30 (4).

Steffen, Bjarne, 2018. The importance of project finance for renewable energy projects. Energy Econ. 69, 280–294. https://doi.org/10.1016/j.eneco.2017.11.006.

Toroghi, Shahaboddin H., Matthew, Oliver E., 2019. Framework for estimation of the direct rebound effect for residential photovoltaic systems. Appl. Energy 251, 113391.

Trepper, Katrin, Bucksteeg, Michael, Weber, Christoph, 2015. Impacts of renewables generation and demand patterns on net transfer capacity: implications for effectiveness of market splitting in Germany. IET Generation Transm. Distrib. 9 (12), 1510–1518. https://doi.org/10.1049/iet-gtd.2014.1063.

von Neumann, John, Morgenstern, Oskar, 1947. The Theory of Games and Economic Behaviour. Princeton University Press, Princeton.

Wickart, Marcel, Madlener, Reinhard, 2007. Optimal technology choice and investment timing: a stochastic model of industrial cogeneration vs. heat-only production. Energy Econ. 29, 934–952. https://doi.org/10.1016/j.eneco.2006.12.003.

Zangiabadi, Mansoureh, Feuillet, Rene, Lesani, Hamid, Hadj-Said, Noouredine, Kvaloy, Jan T., 2011. Assessing the performance and benefits of customer distributed generation developers under uncertainties. Energy 36, 1703–1712. https://doi.org/10.1016/j.energy.2010.12.058.

Zhang, M. M.; Wang, Qunwei; Zhou, Dequn; Ding, H. (2019): Evaluating uncertain investment decisions in low-carbon transition toward renewable energy. Appl. Energy 240, pp. 1049–1060. DOI: https://doi.org/10.1016/j.apenergy.2019.01.205.