Economic viability of investments in electricity capacity: Design of a simulation-based decision rule

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Abstract:

Simulation methods are often used in a forward-looking evaluation of a country's security of supply of electricity. The framework includes simulating the investors' decision to invest in new capacity. For this, a simulation-based investment decision rule is needed. This discussion paper first presents an overview of several potential investment rules. Based on this overview, we recommend modelling the investment decision using the simulation-based expected return and hurdle rates that are set equal to the cost of capital plus a hurdle premium. The latter is an important cushion to compensate for the project downside risk and model and policy risk. The discussion paper also presents a baseline simulation setup and a proof of concept.

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1. Introduction

Will there be sufficient investment in electricity capacity in Belgium to ensure security of supply ("keep the lights on") over the next decade? To answer this question, Elia publishes every two years a detailed ten-year adequacy and flexibility analysis for the Belgian electricity system.[2] Also at European level, similar analyses are done. In particular, the European Network of Transmission System Operators (ENTSO-E) is mandated by European legislation to make a European Resource and Adequacy analysis.

The adequacy and flexibility analysis typically uses simulation methods to determine the extent of capacity needed to maintain security of supply. If a capacity need is identified, an economic viability check should be performed on existing and new capacity for different technologies to see whether they would be viable in the market with the current market design and under the given hypotheses.

Within the simulation analysis, the investment decision needs to be translated into a rule that mimics a real-world decision maker who, just like a company, wants to maximize rewards and minimize costs. For investors, the reward is expressed in terms of expected return, while the cost is the investment risk. This cost is important for all rational investors, since one of the most basic tenets of modern finance is that investors are risk averse. They demand a risk premium in the sense that investments that increase the risk of their portfolio should also increase the expected return of the portfolio. If this were not the case, then the investment leads to an inefficient portfolio choice, as, by not doing the investment, it is possible to simultaneously increase the portfolio expected return and decrease the portfolio risk (Markowitz, 1952).

From a probabilistic viewpoint, the characterization of the expected return and risk of investing in electricity capacity in Belgium is highly complex due to the high variability and non-normal shape of the investment return distribution and the model uncertainty. The non-normality is partly caused by the occurrence of extreme price peaks during the investment period, while model risk is present due to omitting or misspecifying the impact of the many factors that drive the distribution of inframarginal rents. Scenarios need to be defined to quantify the impact on the return of changes in market parameters compared to the base case scenario. A key concern for some investors may be the risk of unmodelled regulatory and/or political intervention on the electricity market affecting the market design and prices. The anticipation of such intervention affects the decision to invest and thus the economic viability of the needed electricity capacity investment in Belgium.

The rule used in the economic viability study needs to be flexible and accommodate for the dynamic nature of the electricity market. Besides technology and regulation, also investment behaviour changes due to time-varying interest rates and risk premia, as well as changes in market share of different types of investors (e.g. utility incumbents, institutional investors and private investors) in electricity generation capacity (Helms et al., 2020).

The goal of this document is to present an overview of investment decision rules that are feasible in the context of an adequacy analysis, such as the one performed by Elia, while accounting for real-word investor risk/return preferences.

The remainder of the document is organized as follows. Section 2 first describes the naïve (risk-neutral) decision-maker who invests when the expected return is positive. We then switch to decision-making by the risk averse investor under expected utility theory and prospect theory. The practical version of these theories is to decide based on expected returns and hurdle rates, where hurdle rates reflect the perceived total project risk (combination of risk estimated assuming correct model

[2] See https://www.elia.be/en/electricity-market-and-system/adequacy/adequacy-studies

specification, and a cushion to account for real-world deviations from the assumed model). Section 3 describes a high-level implementation of the proposed decision rule under the framework of estimating the distribution of investment returns under assumptions on the costs, distribution of yearly inframarginal rents and lifetime of the investment. Section 4 applies the framework in a proof of concept investment evaluation for four types of electricity capacity investments, namely existing CCGT, new CCGT, new OCGT and DSM300. In the appendix, we provide more details regarding the effect of higher order moments on the expected utility theory.

2. Overview of rules for investment decision making under uncertainty

The problem to solve is an asset valuation problem since by investing in the capacity the investor incurs an immediate cost that is to be balanced with the uncertain cashflows that the project will yield. The investment decision would be straightforward if all project cashflows were predetermined. In practice, only the fixed costs in terms of capital expenditures and operations and maintenance costs are known. The revenues, called inframarginal rents (i.e. the revenues remaining after subtracting the variable costs such as fuel and variable operations and maintenance costs), have a large variability and depend on many parameters, whereby some of them are impossible to be known in advance.

The framework of analysis is thus the one of economic decision making under uncertainty. Investors are assumed to make optimal decisions according to a criterion. Below we describe the use of expected investment value, expected utility, cost of capital modelling and prospect theory. Each approach can be seen as an aggregation of random outcomes. We therefore start with setting up notation that allows us to describe the different approaches.

2.1. Notation

For simplicity in exposition, we assume that the project return is a discrete random variable. This is also consistent with the simulation setup described in Sections 3 and 4, where the randomness of the project return is driven by the simulated sequence of inframarginal rents drawn from a discrete distribution with M possible values .

Let R be the project return and assume it can take n possible values, namely $R_1, R_2, \dots, R_n$ with probability $p_1, p_2, \dots, p_n$. For each euro invested, the investor has thus a payoff equal to 1+R_i euro with probability p_i.[3]

2.2. Expected investment value

A first possible decision criterion is to evaluate the investment based on the expected value of the investment payoff:

$$1 + E[R] = 1 + \sum_{i=1}^{n} p_i R_i,$$

where $E[\cdot]$ is the expectation operator yielding the best possible prediction of the random variable in its argument.

The use of the expected return as the only decision criterion totally ignores the risk of the investment. It is a criterion used by risk-neutral investors. This is not a suitable stand-alone decision criterion for the typical investor who is risk averse. This conclusion is known as the St. Petersburg paradox in which a naive decision criterion who takes only the expected value into account predicts an investment decision that no reasonable person would take.[4]

[3] This value can be interpreted as both a present value or a future value depending on the approach used. See the next section for a more in-depth modelling of the probabilistic outcomes of the multi-period investment.

[4] The St. Petersburg paradox is derived from the St. Petersburg game, proposed by Nicolaus Bernoulli. In this game, a fair coin is flipped until it comes up heads the first time. The player pays a fixed amount initially, and then receives 2^k dollars if the coin comes up heads on the *k*th toss. The expected value of such a game is $\frac{1}{2}2 + \frac{1}{4}2^2 + \frac{1}{8}2^3 + \cdots = \infty$. The St. Petersburg paradox is the discrepancy between what people seem willing to pay to enter the game and the infinite expected value of participating in the game.

2.3. Expected utility theory

Economic theory makes use of utility functions to evaluate the welfare of the investor as a function of the project value achieved thanks to the investment. As is common, we set the initial project value as a numeraire. It is not the project final value $1 + R$ that matters, but the utility of that project: $U(1 + R)$, where $U(\cdot)$ is the utility function. The uncertain utility outcomes are aggregated by computing the expected utility, which is given by:

$$E[U(1+R)] = \sum_{i=1}^{n} p_i U(1+R_i).$$

The investment with the highest expected utility is preferred.

Risk averse investors have a utility function that is monotone increasing (more is better) and concave:

$$U\big((1-p)x + py\big) \geq (1-p)U(x) + pU(y).$$

It follows from this inequality that the expected utility of receiving $(1-p)x + py$ with probability 100% (certainty) is always higher than the expected utility of receiving x with probability $(1-p)$ and y with probability p. The two projects have the same expected net cashflow (namely $(1-p)x + py$), but the concave curvature in the utility function penalizes the risky outcome. The penalty for the variability increases as the function becomes more curved. The concavity also implies one additional euro has a higher utility impact at low levels of wealth than at high levels of wealth.

Figure 1 illustrates two common choices of the utility function, namely the CARA and the CRRA utility functions with risk aversion coefficients a for CARA and γ for CRRA. The CARA utility function is

$$U_a(x) = \frac{1 - e^{-ax}}{a}$$

where $a \neq 0 \geq 0$ is the risk aversion parameter.[5] The CRRA utility function with risk aversion parameter γ is

$$U_\gamma(x) = \frac{x^{1-\gamma} - 1}{1-\gamma}$$

for $\gamma \neq 1 \geq 0$ and, for $\gamma = 1$, $U(x) = \log(x)$.[6]

Table 1 provides an overview of various risk aversion parameters used in the literature. Based on this overview, a reasonable choice is to follow Oum et al. (2006) by setting $a = 1.5$ for CARA, and Willems and Morbee (2010) by setting $\gamma = 4$ for CRRA. A sensitivity analysis is always recommended.

[5] The corresponding coefficient of absolute risk aversion is $-\frac{U_a''(x)}{U_a'(x)} = a$. Note that this is constant, hence the name Constant Absolute Risk Aversion. For $a = 0$, $U(x) = x$ we have the special case of a risk-neutral investor.

[6] The corresponding coefficient of relative risk aversion is $-\frac{U''(x)x}{U'(x)} = \gamma$. Note that this is constant, hence the name Constant Relative Risk Aversion. For $\gamma = 0$, $U(x) = x - 1$ we have the special case of a risk-neutral investor.

Table 1 Overview of CARA and CRRA risk aversion coefficients

Authors	Application	Value
CARA utility function		
Biais et al. (2010)	Portfolio choice	$a = 1.735$
Jondeau and Rockinger (2006)	Equity portfolio optimization	$a = 1$, $a = 2$, $a = 5$, $a = 10$, $a = 15$ and $a = 20$
Oum et al. (2006)	Managing quantity risk in the electricity market	$a = 1.5$
CRRA utility function		
Ang and Bekaert (2002)	Equity portfolio optimization	$\gamma = 5$
Conine et al. (2017)	Asset pricing model for stocks	Average value for γ of 2.
Martellini and Ziemann (2010)	Equity portfolio optimization	$\gamma = 10$ as reference case and $\gamma = 1$, $\gamma = 5$ and $\gamma = 15$ as alternatives.
Willems and Morbee (2010)	Hedging and investments in the electricity sector	$\gamma = 4$ as it is "in the middle of the typical 2-6 range"

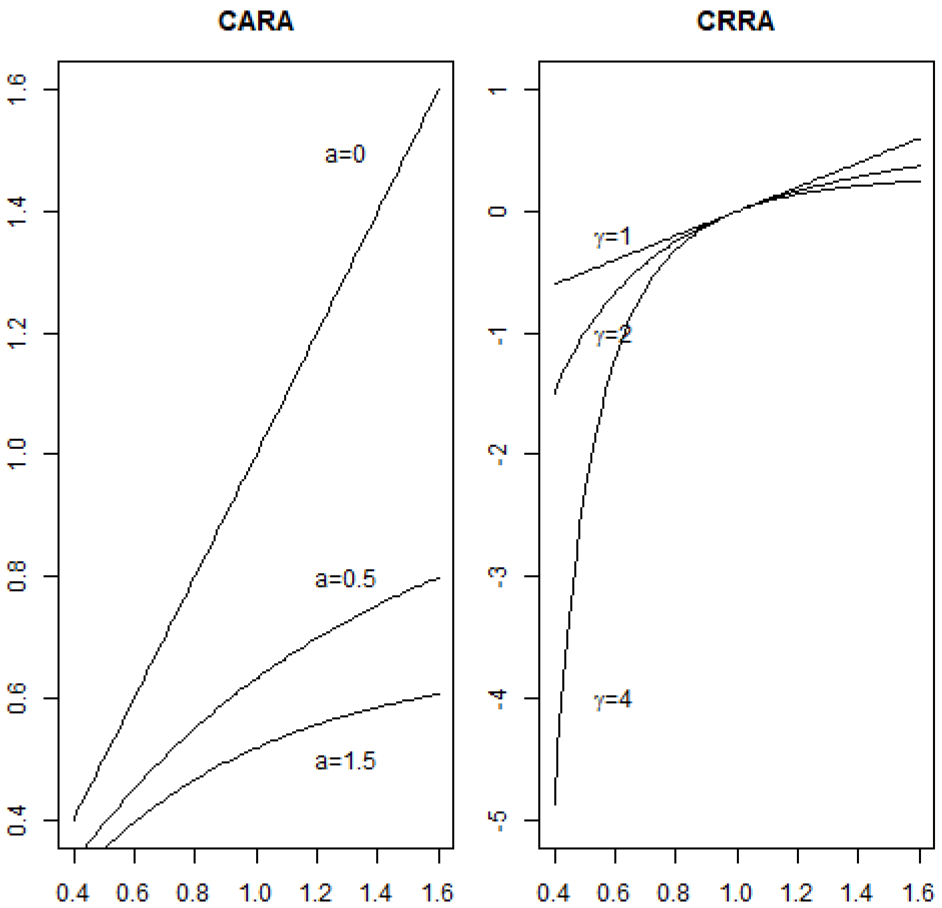

Figure 1 CARA and CRRA utility functions with risk aversion coefficients a for CARA and γ for CRRA. When $a = 0$ and $\gamma = 1$ the utility function is linear, which is the special case of a risk-neutral investor who only considers the expected cashflows and ignores the associated investment risk.

2.4. Impact of higher project return moments on the investor's expected utility

The higher is the expected utility obtained from the investment project, the better. But how do the stochastic properties of the project return contribute to the expected utility? The decomposition of expected utility in the contribution by the following four moments aids in the interpretation:

- the expected return $\mu = E[R] = \sum_{i=1}^{n} p_i R_i$
  [equals the best possible prediction of the investment return]
- the variance of the return $\sigma^2 = E[(R-\mu)^2] = \sum_{i=1}^{n} p_i (R_i - \mu)^2$
  [quantifies total variability of the return]
- the (unstandardized) skewness of the return $\zeta = E[(R-\mu)^3] = \sum_{i=1}^{n} p_i (R_i - \mu)^3$
  [quantifies the asymmetry in the distribution. Reference value of zero is achieved when positive and negative deviations cancel each other out (symmetry). Positive skewness results from a higher probability of large positive returns than large negative returns]
- the (unstandardized) kurtosis of the return $\kappa = E[(R-\mu)^4] = \sum_{i=1}^{n} p_i (R_i - \mu)^4$
  [quantifies the total variability in the return distribution, but compared to the variance, it gives more weight to the variability of the tails in the distribution]

Scott and Horvath (1980) show that the typical risk averse investor has positive preferences for the odd moments (mean and skewness: the higher, the better) and negative preferences for the even moments (variance and kurtosis: the lower, the better). Note that these are preferences with respect to the unstandardized moments. In the case of a return distribution with a fat right tail (high likelihood of extreme positive returns) all moments (even and odd) are inflated. The net effect depends on the utility function considered and the exact shape of the distribution.

It is common to use Taylor expansion to quantify the effect of each of these variability measures on the expected utility. In the appendix, we show that the CARA and CRRA utility functions can be approximated as follows using the first four moments:

$$EU_a \approx \frac{e^{-a(1+\mu)}}{a}\left(e^{a(1+\mu)} - 1 - \frac{a^2}{2}\sigma^2 + \frac{a^3}{6}\zeta - \frac{a^4}{24}\kappa\right)$$

$$EU_\gamma \approx U(1+\mu) - \frac{\gamma}{2}(1+\mu)^{-(\gamma+1)}\sigma^2 + \frac{\gamma(\gamma+1)}{6}(1+\mu)^{-(\gamma+2)}\zeta - \frac{\gamma(\gamma+1)(\gamma+2)}{24}(1+\mu)^{-(\gamma+3)}\kappa.$$

Consistent with the general result of Scott and Horvath (1980) we find that for CARA and CRRA utility function, a risk averse investor has positive preferences for the mean and skewness and negative preferences for the variance and kurtosis.[7] The higher order expansion of the expected utility function is important since the returns on investing in electricity capacity are non-normal. Price spikes in the electricity markets inflate all moments, and especially the higher moments because of the power transformation.

While the different utility functions agree on the sign of the effect of the moments, they differ in terms of the respective impact on the expected utility function. Assuming one specific utility function (and risk aversion parameter) for all investors may therefore be considered as restrictive.

[7] In the simulation study one can check the accuracy of the approximation using the first four moments. The interpretation of moments greater than four is a subject for further research.

2.5. Prospect theory

Expected utility theory makes heroic assumptions about the rationality of investors. Behavioral finance describes decision making under uncertainty by normal people. The main framework in this literature is the prospect theory of Kahneman and Tsversky (1979) that explicitly models the loss aversion preferences of an investor. There are two key elements of this theory. First, individuals do not make choices based on a utility function but on a value function in which outcomes are compared to a reference point, called anchor. The value function is concave for gains (outcomes higher than the anchor; risk-aversion), convex for losses (risk-seeking), and steeper for losses than for gains. Experiments show that the impact of a loss tends to be twice as large as the impact of a gain of the same magnitude.

A second key element is that investors use decision weights for each outcome that are a nonlinear transformation of the true probability. The probability transformation is such that the decision maker tends to overweight small probabilities and underweight high probabilities. Tsversky and Kahneman (1992) propose the following probability transformation function:

$$\pi(p) = \frac{p^{\delta}}{(p^{\delta} + (1-p)^{\delta})^{1/\delta}}.$$

For the electricity capacity investment, the low probability event of interest is that over the long investment cycle there will be no price spikes. This is a concern as the occurrence of a price spike is a main driver of the expected investment return. From the viewpoint of the investor, a loss scenario thus occurs when there is no price spike over the investment horizon. Under prospect theory, (s)he will tend to overweight this low-probability scenario leading to a lower perceived return than the actual expected return.

The objective function under prospect theory is the perceived weighted value of the different outcomes:

$$\sum_{i=1}^{n} \pi(p_i)V(1 + R_i - A),$$

where A is the anchor and $V(\cdot)$ is the function that expresses the perceived value. The value function is increasing (the more the better), with the absolute impact of a loss roughly equal to two times the impact of a gain of the same magnitude: $|V(0) - V(-d)| \approx 2(V(0) + V(d))$ (loss aversion: effect of loss is twice the one of a gain). The value function $V(\cdot)$ is concave (resp. convex) for gains (resp. losses).

Figure 2 illustrates a hypothetical value function and probability transformation function. The anchor is 1. Values of $1 + R_i$ above one are considered as gains and valued using a concave increasing function, values below one are considered as losses and therefore valued using a convex increasing function. In the probability transformation plot we see that low probabilities receive a higher decision weight than their actual probability.

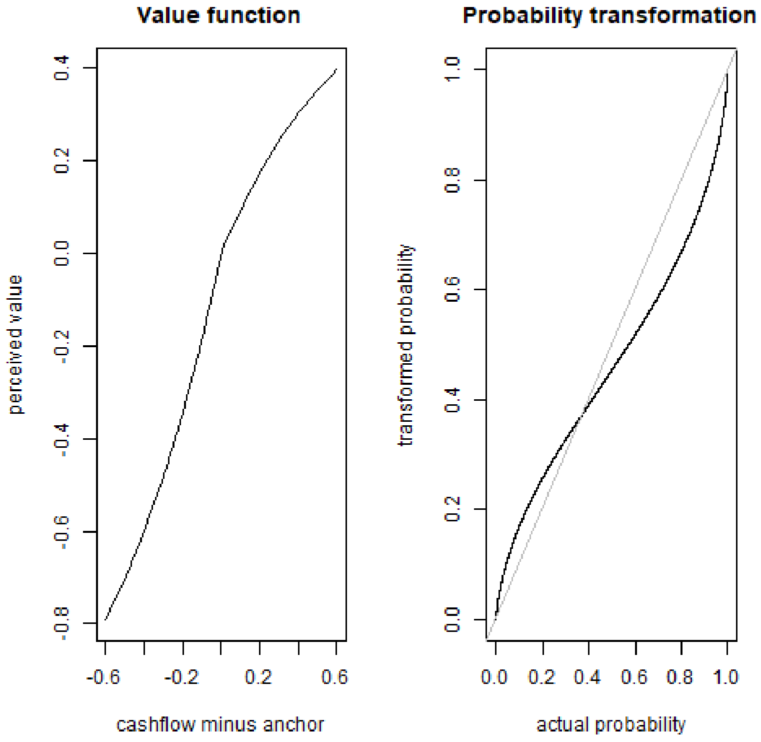

Figure 2 Hypothetical value function and probability transformation function used in prospect theory

2.6. Internal rate of return, hurdle rate determinants and cost of capital modelling

The expected utility theory and prospect theory are popular frameworks in economic theory, but they are less often used in practice. The standard textbook solution for capital budgeting is to compute the project's net present value as the sum of discounted expected cashflows, where the discount factor assumes a Weighted Average Cost of Capital (WACC) of debt and equity.

An equivalent approach is to compute the internal rate of return and decide to invest when the expected internal rate of return exceeds the so-called hurdle rate (Helms et al., 2020). The hurdle rate is thus the threshold τ that the expected internal rate of return of the project needs to exceed for the project to be economically viable.

Economic viability: $E[R] \geq \tau$

We can directly estimate the expected return from the simulation used in the adequacy and flexibility analysis. The analysis should be dynamic, as both expected returns and hurdle rate are time-varying.

Setting the hurdle rate requires a combination of qualitative and quantitative approaches. The qualitative approach relies on surveys of investors and market experts. Such surveys have been conducted by Meier and Tarhan (2007) and Graham and Harvey (2018), among others. They can be complemented by an analysis of recent investment opportunities in similar projects.[8]

The quantitative approach supports the qualitative approach:

[8] A data-driven approach could be to compute the largest expected returns of the investments for which there has not been an investment and the lowest expected return for which there has been an investment in recent times. The hurdle rate is in between these two numbers. In the ideal case where one has a large number of observed returns, regression techniques can be used to quantify the compensation for the risk taken.

- by providing numbers on the project risk,
- and by aggregating the hurdle rates suggested by several experts into a single consensus number.

2.6.1. Hurdle rate and risk factors

For simplicity of exposition, we will discuss here only the base case scenario that the project is fully equity funded and we ignore the presence of taxes and inflation in the discussion.[9] The cost of equity has two components: (i) the risk-free rate (expressing the opportunity cost of investing at no risk) and (ii) the risk premium (expressing the compensation for the risk taken). Financial theories like the modern portfolio theory of Markowitz (1952), the Capital Asset Pricing Model (CAPM) of Sharpe (1964) and the Arbitrage Pricing Theory (APT) of Ross (1974) formalize the central paradigm of finance that rational investors optimize their portfolio by maximizing expected returns and minimizing risk. If two portfolios have the same expected return, the rational risk-averse investor chooses the portfolio with the lowest risk. Since risk is multidimensional, there are many plausible candidates to be used as risk measure. A general view is therefore to include several risk factors in the cost of capital equation, each having their compensation for risk. Suppose there are K risk factors f_i, then the cost of equity capital equals:

$$k = r + \sum_{i=1}^{K} \zeta_i f_i,$$

where ζ_i is the compensation in terms of expected excess return per unit of exposure to risk factor f_i taken.

Markowitz (1952) uses the portfolio return variance as risk measure. His modern portfolio theory states that mean-variance efficient investors only invest in portfolios that offer the highest expected return for a given level of risk. The collection of all these portfolios is called the efficient frontier.

Sharpe (1964) extends the framework to asset pricing and uses the stock's beta as the relevant risk measure in determining the value of an asset. Under the proposed Capital Asset Pricing Model (CAPM) the expected return of an investment in excess of the risk free rate equals the investment's beta multiplied with the market expected return (μ_{MKT}) in excess of the risk free rate:

$$k_{CAPM} = r + \beta(\mu_{MKT} - r).$$

The investment's beta is the covariation of the investment return with the market portfolio return, divided by the variance of the market return. Extensions to the CAPM include the three-factor and four-factor models of Fama and French (1993) and Carhart (1997).

The above models assume that the return distribution is symmetric. In practice, investment returns for energy projects tend to be skewed and heavy-tailed. From the above discussion about the utility functions, it is clear that risk-averse investors care about the non-normal character of this distribution.

Markowitz (1959) recommends using semivariance as a measure of downside risk. Modern investors heavily rely on value-at-risk and expected shortfall as measures of downside risk.[10] Boudt et al. (2008)

[9] The investor's cost for financing the investment in the electricity capacity project depends on the financing mix, and is referred to as the investor's WACC (Weighted Average Cost of Capital), *i.e.* the cost for the investor to obtain capital from its shareholders and creditors in order to invest in the project. We refer to ACER (2020) for details on the (pre-tax and real) WACC calculation. Brealy et al. (2020) recommend separating the investment decision from the financing decision by viewing the project "*as if it were all-equity-financed, treating all cash outflows required for the project as coming from stockholders and all cash inflows as going to them.*" This leads to a base-case investment analysis that can then be adjusted based on the gearing ratios of the potential investors.

[10] Popular downside risk measures are the Value at Risk and Expected Shortfall at loss probability α (typically 5%). Let Q_α be the α −quantile of R, then: $VaR_\alpha = -Q_\alpha$ and $ES_\alpha = -E[R|R \leq Q_\alpha]$.

show how downside risk measures like value-at-risk and expected shortfall can be estimated for non-normal distributions.

Kraus and Litzenberger (1976), among others, extend the CAPM to account for the higher moments of the return distribution. They conclude that investors not only care about the covariance between the project return and the market return, but also the coskewness. Bawa and Lindenberg (1977) define the downside beta as the covariance between the stock return and the market return, conditional on the market return being below its average, divided by the corresponding conditional variance of the market return. Irrespective of the downside risk measure used, there is the consensus that agents who are averse to losses demand greater compensation, in the form of higher expected returns, for investing in projects with high downside risk (Ang et al., 2006). The disadvantage of these alternative risk measures is that there is no readily available number to express the return compensation per unit of risk taken.

2.6.2. Decomposition of the hurdle rate into model-based cost of capital and hurdle premium

Once the hurdle rate and a model-predicted cost of capital are determined, it is useful to decompose the hurdle rate into the explained component (the model-based cost of capital) and an unexplained component (called the hurdle premium).

$$\text{hurdle rate } \tau = \text{model-based cost of capital } k + \text{hurdle premium } \pi$$

Even if the model-based based cost of capital is a correct representation of the actual cost of capital, there may still be a positive hurdle premium due to the irreversibility of the investment or when investors are cautious (Driver and Temple, 2010). Brealy et al. (2020) note he approach of adding a (relative) project adjustment to a reference cost of capital is easier than estimating each project's cost of capital from scratch. They make the following music analogy: "Most of us, lacking perfect pitch, need a well-defined reference point, like middle C, before we can sing on key. But anyone who can carry a tune gets relative pitches right."

For long-term investments in electricity capacity in which simulations are used to compute the expected return and risk, there is an inevitable model risk. Elimination of model risk is impossible due to the non-linear dependence between decisions of various market players (modelled as an iterative process), the long horizon of the investment, the international context of the electricity market, the uncertainty about economic policy, and the risk of regulatory and political intervention in case of a sustained period of extreme high prices.

When using the CAPM cost of capital, the hurdle premium may also be used to account for the impact of the non-normality of the return series on the investor's evaluation of the project. This result follows directly from the observation that ignoring non-normality leads to an omitted variable bias in the standard CAPM cost of capital calculation versus the higher order moment CAPM cost of capital models (see e.g. Kraus and Litzenberger (1976) and Jurczenko and Maillet (2006)).

The presence of a hurdle premium accommodates the investor's requirement for a cushion to offset the model risk that the project cashflow distribution is framed in a too optimistic way (Helms et al., 2020) and/or the failure of the model-based capital cost calculation to take the non-normality of the project return distribution into account.

The model risk is related to the scenario used, as well as possible price intervention affecting the value of the inframarginal rents. Policy makers or regulators may intervene in market prices by setting price caps (Jamasb and Pollitt, 2000). When this intervention is not modelled in the simulation design, then investors will ask additional return compensation for the risk that price caps lead to lower actual inframarginal rents than the simulation would predict. Besides explicit price caps imposed by governments to safeguard the customers against extreme electricity prices, there can also be implicit price caps when owners of the electricity generation capacity sell at lower prices than market price because of the threat of a regulatory investigation of market abuse.

To quantify the sensitivity to model risk it is recommended to conduct sensitivity analysis of the expected return to the potential presence of a price cap κ. We refer for this to the robust statistics literature (see e.g. Maronna et al., 2019) in which the observed return data coming from the Tukey-Huber contamination model

$$(1-\delta)R+\delta\tilde{R},$$

where δ is a 0/1 random contamination indicator, $\tilde{R}$ is the project return in case of contamination in the sense that the distribution model is different than the reference one (e.g. due to unmodelled price caps). The potential presence of outlier contamination justifies the use of higher hurdle rates or more robust estimates of the expected project return (e.g. by winsorizing extreme returns). The specific challenge of outlier contamination is of course that the contamination is unknown (otherwise we would have included it in the model). The (possibly subjective) interpretation of the difference in distribution between R and $\tilde{R}$ and its likelihood affects the hurdle premium.

2.6.3. Conclusion

The overview of methods confirms the quote "*all models are wrong, but some are useful*" by George Box. Any proposed method is subject to criticism since we are simplifying human behavior in a context of high uncertainty.

The economic viability rule may thus lead to erroneous decisions. Based on the confusion matrix in Table 2, two mistakes are possible:

- False positive mistake: Simulation-based rule classifies the investment project as economically viable while it is not
- False negative mistake: Simulation-based rule classifies the investment project as economically unviable while it is

From the viewpoint of guaranteeing security of supply ("keep the lights on") the false positive mistake is the most damaging one. This implies that the hurdle premium can be set in a conservative way, but not in an excessive way as to avoid also inefficient use of available resources.

Table 2 Confusion matrix when algorithms needs to predict actual investment. The null hypothesis is that there is no investment. The simulation-based decision maker seeks for sufficient data evidence to reject that null and thus conclude that there will be an investment[11]

		Actual investor's decision	
		Investment (null hypothesis is false)	No investment (null hypothesis is true)
Simulation-based decision to invest	Economically viable (reject the null, positive)	Correct inference (true positive)	Error of type I (false positive)
	Economically not viable (do not reject the null, negative)	Error of type II (false negative)	Correct inference (true negative)

[11] The analogy can be made with judicial decision: someone is innocent until proven guilty. Here the project is not economically viable until proven viable.

2.7. Overall recommendation

The overview paper by Helms et al. (2019) describes the use of expected returns and hurdle rates to decide on investing in electricity capacity. We recommend using this approach in economic viability assessment. The corresponding decision algorithm is described below.

1. Use qualitative and quantitative research methods to set the hurdle premium π with respect to the CAPM-based cost of capital. If these are not available, based on Helms et al. (2019), a rule of thumb could be to set π such that the pre-tax nominal hurdle premium equals at least 5%.[12]
2. Use simulation techniques to estimate the distribution of the internal rate of return of the project in the most likely scenario:
- Plot the distribution
- Compute all relevant summary statistics, such as expected return, volatility, beta, semideviation, skewness, kurtosis, value-at-risk, expected shortfall
- Compute the CAPM-based cost of capital k_{CAPM}
- Study sensitivity to price caps
3. Verify that the postulated hurdle rate $\tau = k_{CAPM} + \pi$ is reasonable given the various risk statistics computed in the previous step.
4. Invest when the expected return exceeds the hurdle rate.

[12] The use of a fixed rule of thumb is a poor man's approach. Helms et al. (2019) note that "an additional hurdle premium of 5% or more on the WACC" is common in many industries. NERA (2015) provides an overview of ranges of pre-tax real hurdle rates for the various energy generation technologies, as well as a description of the impact of the considered macro uncertainty scenario. In the proof of concept, we consider two scenarios that differ in terms of the price cap used. In one scenario, the price cap is at cap at 3k€/kW, while in the second scenario there is a price cap at 20k€/kW. It would be natural to have a different hurdle premium in the two scenarios, since the differences in price cap affect the skewness and kurtosis of the return distribution. If the investor considers that the actual price cap is less than 20k€/kW, then there is more price cap model risk under scenario 2 than under scenario 1.

3. Implementation in a simulation setup

Here we discuss how the investment decision that compares expected returns with hurdle rates can be implemented in a simulation setup. We first list the assumptions on the costs and revenues of the investment projects. These assumptions are made to set a framework. It is up to the reader to modify the assumptions as (s)he sees fit. We then discuss a potential calibration of the hurdle rate. Next we describe the simulation approach to compute expected return and risk of the project.

3.1. Assumptions on revenues and costs

The viability assessment is part of a simulation analysis. A hypothetical investor is considered who needs to make an investment decision. To formalize this decision we need assumptions on revenues and costs that determine the cashflows for the investor.[13] All values are in real terms.

General assumptions:

1. The investment has a lifetime of K years (including the construction period).
2. The terminal value of the project is zero.
3. The beta of the company that undertakes the project equals $\bar{\beta}$.

Assumption on revenues:

1. The distribution of annual inframarginal rents takes M equally likely positive values (annual values denoted by IR_1 , IR_2 , … , IR_M . All amounts are in real terms and net of taxes.
2. The annual inframarginal rents are independently and identically distributed.

Assumption on costs:

1. At the start of the investment, there is a one-time cost of the initial capital expenditures (total amount is denoted by $CAPEX$). This amount is predetermined. The initial $CAPEX$ investment is completely irreversible.
2. There are fixed operation and maintenance costs that need to be paid each year (annual amount is denoted by FOM). This amount is predetermined and the same every year. The amount is paid at the beginning of each year.
3. The initial investment (outflow of cashflows at time 0) equals all the cashflow needed to cover all costs foreseen over the lifetime of the investment:

$$I = CAPEX + \sum_{t=1}^{K} \frac{FOM}{(1+r)^{t-1}}$$

with $r \geq 0$ the (risk-free) interest rate and $t = 0,1,\dots,K$ is the time index, with $t = 0$ the start date.[14]

[13] The illustration here is in the case of a pure play investor who takes all the merchant risk and does not engage in financial contracts (insurance contract, forward agreements).

[14] Assumption 11 guarantees that the project vehicle has under all scenarios enough cashflow to complete. The base-case scenario is that project is fully equity funded. In practice, the cost of capital can be reduced by considering a financing mix of debt (D) and equity (E). The optimal gearing ratio $g = D/(D+E)$ is such that the Weighted Average Cost of Capital (WACC) is minimized and financiers consider the amount of equity as a sufficiently high buffer to protect them in case of insolvency.

3.2. Simulation of sequence of cashflows and calculation of return

Under the above assumptions, we have M possible values for each year and thus M^K different sequences for a project with lifetime equal to K years.

For each sequence, we can compute the internal rate of return and hence estimate the distribution. Let $IR(t)$ be the inframarginal rents in year t. The internal rate of return for a sequence of cashflows is the rate R for which the net present value equals 0:

$$NPV = -I + \sum_{t=1}^{K} \frac{IR(t)}{(1+R)^t} = 0.$$

The investment risk is due to the differences in return between these different sequences. See Artelys (2015, p. 28) for a similar approach.

3.3. The distribution of returns and simulation-based estimates of average return and risk

The simulation study with N (e.g. 10000) runs, leads to N simulated returns: R_1 , R_2 , ..., R_N . A picture is worth a thousand words. The analysis should start with a graphical inspection of the histogram. Next summary quantities are to be computed. We get the simulated mean, standard deviation, skewness and kurtosis as follows:

$$\mu = \frac{1}{N}\sum_{i=1}^{N} R_i$$

$$\sigma = \sqrt{\frac{1}{N}\sum\nolimits_{i=1}^{N}(R_i - \mu)^2}$$

$\zeta = \frac{1}{N}\sum_{i=1}^{N}(R_i - \mu)^3$ and standardized skewness = $\frac{\zeta}{\sigma^3}$

$\kappa = \frac{1}{N}\sum_{i=1}^{N}(R_i - \mu)^4$ and standardized kurtosis = $\frac{\kappa}{\sigma^4}$

In a similar fashion we can compute downside risk estimates, such as the semideviation, value-at-risk and expected shortfall at loss probability α:

$$SemiDev = \sqrt{\frac{1}{N}\sum\nolimits_{i=1}^{N}(\min\{R_i - \mu, 0\})^2}$$

$$VaR = R_{(\lceil \alpha N \rceil)}$$

$$ES = \frac{1}{\lceil \alpha N \rceil}\sum_{i=1}^{\lceil \alpha N \rceil} R_{(i)}$$

where $R_{(1)}, R_{(2)}, \ldots, R_{(N)}$ are the ordered simulated return observations such that $R_{(i)} \leq R_{(i+1)}$. Popular choices for α are 1%, 2.5% and 5%.

Under the CAPM, the cost of equity depends on the project's beta. For investments in electricity capacity, the project beta cannot be directly computed as the simulation approach only yields a marginal distribution of the project return. A crude estimate could be to take the beta of publicly listed firms in the electricity sector. In practice, the project beta differs because of differences in both correlations between project returns and market returns, and standard deviation of the project. One ad hoc solution is to proxy the project β by using the the company beta $\bar{\beta}$ and standard deviation $\bar{\sigma}$. Under the simplifying assumption that the correlation between the project return and the market return is equal to the correlation between the company return and the market return, we have that:

$$\beta = \frac{cov(R,R_{MKT})}{\sigma_{MKT}^2} = \frac{corr(R,R_{MKT})\sigma\sigma_{MKT}}{\sigma_{MKT}^2}\frac{\bar{\sigma}}{\bar{\sigma}} = \bar{\beta}\frac{\sigma}{\bar{\sigma}}.$$

The right-hand side can thus be a seen as a simulation-augmented project beta, since we use the simulation based project σ to estimate the project β.[15]

3.4. Sensitivity analysis

The above analysis is sensitive to the risk of using the wrong model to characterize the project investment return distribution.

Several scenarios can be conducted. A straightforward additional analysis is to compute the returns in a scenario where all inframarginal rents exceeding an amount κ (e.g. 100 €/kW/y) are replaced with that upper bound κ. The corresponding investment return in the case of price limits is then the rate $\tilde{R}$ for which the NPV is zero:

$$\widetilde{NPV} = -I + \sum_{t=1}^{K} \frac{\min\{IR(t), \kappa\}}{(1+\tilde{R}_\kappa\ )^t} = 0.$$

Clearly $\tilde{R}_\kappa \ \leq R$ for each generated sequence.

3.5. Certainty equivalent break-even analysis under CARA and CRRA utility functions

A further interesting statistic is the number of euro's to invest in a risk free deposit per euro invested in the project to obtain the same level of expected utility. In order to compute the break-even cash position we make the additional assumption that the utility function of the financial decision maker depends on the gross return of the project investment, which equals the final value per euro invested.[16] All intermediate revenues are reinvested at the risk-free rate such that the end capital (per euro invested) equals:

$$FV = \frac{1}{I}\sum_{t=1}^{K} IR(t)(1+r)^{K-t}$$

In order to invest, the expected utility of the investment needs to be at least the utility of the capital accumulated by the initial investment on a risk-free account. We determine the risk free investment C needed in order to be indifferent with investing in the risky project. If C exceeds 1, the project is more interesting than putting the money in a risk-free deposit. If C is less than 1, then the decision maker needs an investment subsidy to be indifferent. Formally, we compute the cash amount C needed to be indifferent by solving the equation:

$$\sum_{i=1}^{N} p_i\, U_a(FV_i) = U_a(C(1+r)^K\ ).$$

The value C can be interpreted as the certainty equivalent as is expressed the risk-free end-of-period cashflow which the investor considers as equivalent to the risky project cashflow.

[15] For simplicity in exposition, we make here abstraction of taxes and leverage. The formula assumes that the project standard deviation is the investor's equity return standard deviation.

[16] We use the gross return and not the values themselves for numeric reasons linked to the exponential function. The approach is standard and corresponds to setting the initial investment value as numeraire.

4. Proof of concept

This section provides a proof of concept of the methodology outlined in the previous sections. We use a set of hypothetical distributions of inframarginal rents that are not necessarily representative of a current investment case.[17] Results are thus presented to illustrate the two decision methods:

- Invest when expected returns exceed the hurdle rate.
- Invest when the certainty equivalent of 1 euro invested in the project is higher than 1 euro.

The results are descriptive about the methodology only and should not be interpreted as indicative of any currently considered investment opportunity.

4.1. Design

4.1.1. Assumptions about investment project

We now illustrate the simulation-based decision analysis for four investment cases that differ in terms of technology used and yield a different distribution of inframarginal rents. They also differ in terms of lifetime (that we denote by K years) and costs (both the initial $CAPEX$ and the yearly FOM cost). The four technologies (their lifetime and related fixed costs used to illustrate the outcome) are as follows

- New CCGT (*K=20* years, CAPEX = 600 €/kW, FOM = 15 €/kW/y)
- New OCGT (*K=20* years, CAPEX = 400 €/kW, FOM = 5 €/kW/y)
- DSM300 (*K=10* years, CAPEX = 10 €/kW, FOM = 5 €/kW/y)
- Existing CCGT (*K=15* years, CAPEX = 90 €/kW, FOM = 15 €/kW/y)

The cost related to the time to construct is assumed to be in the CAPEX calculation.[18]

As in Elia (2019), we use simulated rents obtained under a model in which there is a maximum energy price at which the modelled market can clear. We consider two scenarios for the price cap design. In the first scenario, there is a price cap at 3k€/kW, while in the second scenario there is a price cap at 20k€/kW. The first price can be considered as the reference price cap, as it "corresponds to the European harmonized maximum clearing price for the Day-Ahead market in Belgium and all other modelled markets as set according to a decision from ACER upon the proposal by the NEMOs (i.e. the power exchanges) following Art. 41 of the CACM guidelines" (Elia, 2019). We consider also the second scenario, since, according to Elia (2019), "the rules governing this price cap also foresee that it could increase over time via an automatic adjustment mechanism. In particular, when a price of 60% of the prevailing price cap is reached in one of the concerned markets, the price cap increases by 1 000 €/MWh. In theory, the price cap could increase over time until it is high enough to cover the Value of Lost Load (VoLL). Estimations on the VoLL vary greatly but could easily reach ranges of 10000 or 20000 €/MWh (or even go beyond, depending on the estimate and the methodology used)."

We choose the scenarios with different price cap to document the sensitivity of the distribution of investment returns to the price cap. The value of the price cap can also alter the investment decision.

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[17] The illustration here is in the case of a pure play investor who takes all the merchant risk and does not engage in financial contracts (insurance contract, forward agreements). The specification of the best possible distribution reflecting the relevant income distribution of the investor is beyond the scope of this study.

[18] An alternative approach is to increase the lifetime variable *K* and let the specification of revenues and cost depend on the time elapsed since the initial investment.

Figures 3-4 show the corresponding histograms of the inframarginal rents under the two scenarios.[19] Summary statistics are shown below each figure.

The inframarginal rents are right-skewed and the price cap is clearly a binding constraint that will be influential for the investment analysis. The occurrence or not of a price peak will lead to different modes in the distribution of returns. Suppose that the yearly probability of a price peak leading to inframarginal rents higher than 100 €/kW is 2/33. Then the probability of not observing a price peak over $K = 10,15,20$ periods is $(\frac{31}{33})^K$, namely 53.5%, 39.1% and 28.6%, respectively.[20]

As a consequence of the price peaks, the distribution of inframarginal rents is right skewed in all scenarios: mean inframarginal rents exceeds the median inframarginal rent, and the standardized skewness statistic is positive.

In case of price peaks, all capacities are used. This explains why the right side of the distribution (percentage inframarginal rents higher than 100 €/kW and maximum values) are so similar across technologies.

In contrast, when electricity prices are high, first the capacity of CCGT is used, then OCGT and only as a last resort DSM300. This explains why the inframarginal rents of CCGT never reach the lower bound of zero, while for new OCGT and DSM300 there is each year 9.1% and 51.5% probability to have zero inframarginal rents.[21]

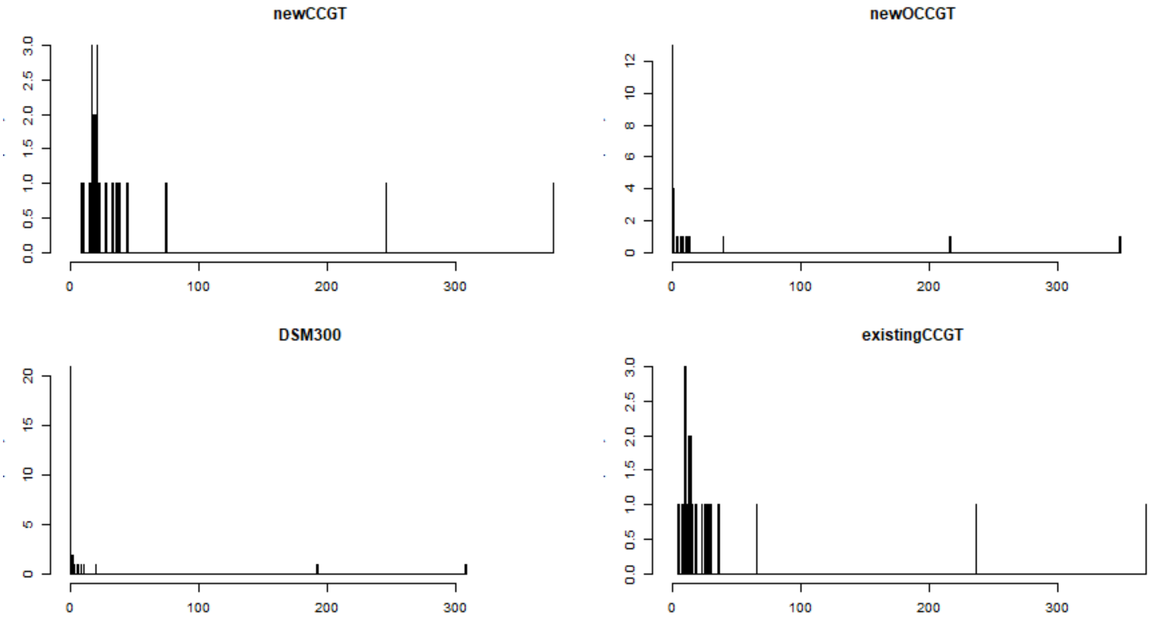

Figure 3 Histogram of yearly inframarginal rents under scenario 1

[19] There are *M=33* equiprobable values, but when they are similar they are binned in the histogram visualization
[20] Calculation based on the binomial distribution: pbinom(q=0, prob=2/33, size=20) yields 0.2863882.
[21] Note that there is time diversification. Under the assumption of independently and identically distributed inframarginal rents, we thus have each year a probability of 51.5% that the inframarginal rent of a DSM300 investment equals 0. A DSM300 investment has a lifetime of 10 years. The probability of observing a zero inframarginal rent equal to zero in each of those 10 years equals $(51.5\%)^{10} = 0.13\%$. The probability of observing at least one year with a non-zero inframarginal rent is 1-0.13% = 99.87%.

Table 3 Summary statistics of inframarginal rents under scenario 1

	newCCGT	newOCGT	DSM300	existingCCGT
Percentage equal to 0	0.000	0.091	0.515	0.000
Percentage higher than 100	0.061	0.061	0.061	0.061
min	9.208	0.000	0.000	4.423
median	21.323	0.831	0.000	14.189
mean	42.024	20.934	16.955	34.599
max	376.217	348.007	307.551	368.580
sd	72.312	69.762	61.910	72.021
std skewness	3.815	3.948	3.984	3.843
std kurtosis	16.733	17.554	17.711	16.912

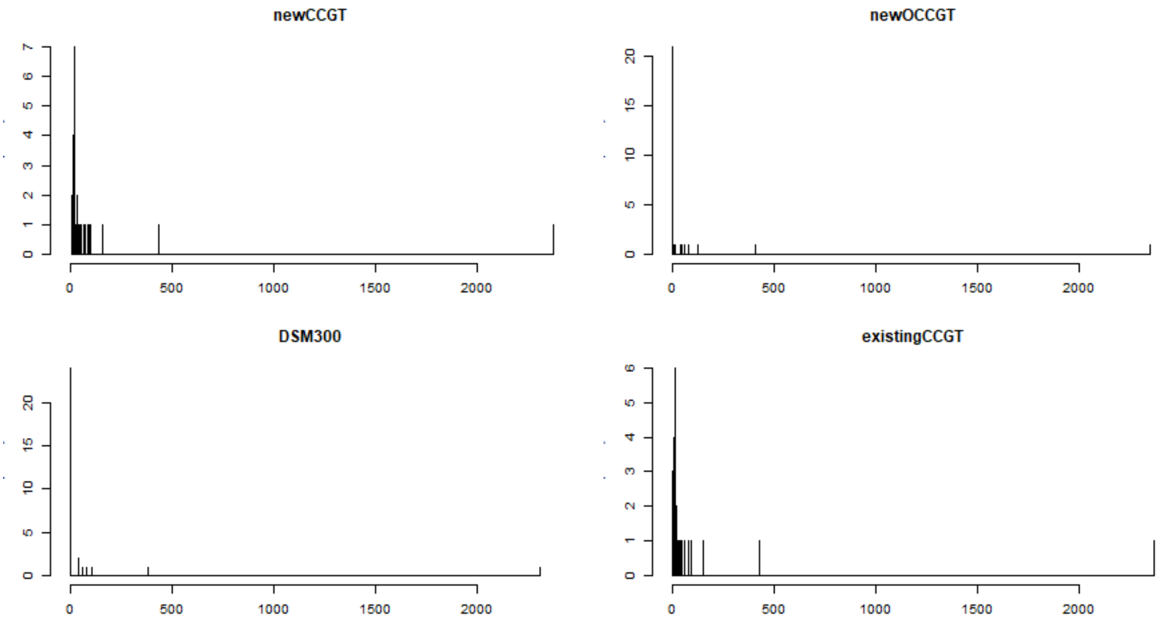

Figure 4 Histogram of yearly inframarginal rents under scenario 2

Table 4 Summary statistics of inframarginal rents under scenario 2

	newCCGT	newOCGT	DSM300	existingCCGT
Percentage equal to 0	0.000	0.091	0.515	0.000
Percentage higher than 100	0.121	0.091	0.091	0.091
min	9.208	0.000	0.000	4.423
median	21.474	0.831	0.000	14.189
mean	116.516	95.426	91.472	109.090
max	2372.069	2343.863	2304.235	2364.432
sd	412.098	410.345	403.247	411.983
std skewness	5.208	5.225	5.246	5.211
std kurtosis	28.936	29.063	29.230	28.957

4.1.2. Assumptions about investor views and preferences

We use the following market variables:

- We take an expected inflation rate of 1.6%
- We set the expected excess real return on the market portfolio based on the suggested 10-year calibration from the Research Affiliates website as of July 2020, namely 4.2%.[22] The corresponding nominal value is (1+0.042)(1+0.016)-1 ≈ 5.9%.
- We set the risk free rate of return at 0%.
- We set the nominal and pre-tax hurdle premium (compared to the required return following from the CAPM model) at 5% and assume a corporate tax rate of 25%.[23]

All these values are set for illustrative purposes. The assumption of setting the hurdle premium to the same value irrespective of the price cap being at 3k€/kW versus 20k€/kW is not realistic, since the price cap affects the (non-normal) shape of the return distribution and impacts also the severity of the model risk that actual price caps may be lower than the one assumed.

We calibrate the project beta based on the corporate beta of two companies active as investors in energy capacity namely Engie and Eni. We downloaded their adjusted close price series for the 5-year period October 2015-September 2020. We then use monthly returns to compute their (adjusted) beta with respect to Euro Stoxx 50 as well the annualized volatility (obtained using the square root of time rule).[24] We find that the beta is 1.07 and 0.97 for Engie and Eni, respectively. Based on this, we set $\bar{\beta} = 1$. It follows that the pre-tax company cost of equity in real terms is 6.1%.[25] To obtain the hurdle rate, we add a hurdle premium of 5% (nominal and pre-tax), which is 3.3% in real terms. Hence the (pre-tax and real) hurdle rate is set at 9.5%. In practice, this needs to be further adjusted based on the risk of each project, as discussed in NERA (2015).

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[22] This number is based on the conditional 10-year estimates published in July 2020 by Research Affiliates at https://interactive.researchaffiliates.com/asset-allocation#!/?currency=EUR&model=ER&scale=LINEAR&terms=REAL . Alternatively one could also do a time series analysis based on the historic values of the equity risk premium published at https://www.credit-suisse.com/about-us-news/en/articles/media-releases/credit-suisse-global-investment-returns-yearbook-2020-202002.html.

[23] The adjustment using an additional hurdle premium of 5% or more is according to Helms et al. (2019) common in many industries.

[24] The adjusted beta equals 0.67 times the regression beta plus 0.33 times 1.

[25] The nominal equity market return pre-tax is 0.059/0.75. Using Fisher's equation, the real pre-tax one is (1+0.059/0.75)/(1+0.016)-1 ≈ 6.1%.

4.2. Results for scenario 1

We now follow the approach described in Section 3 and simulate 10000 possible investment paths. For each path, we compute the internal rate of return. This leads to a distribution of internal of returns. Based on this distribution, we then evaluate economic viability either by comparing the expected return with the hurdle rate, or by means of the certainty equivalent approach assuming a specific utility function.

4.2.1. Decision rule using expected returns and hurdle rates

Below we show the distribution of the internal rate of return obtained using 10,000 simulations. We also report a table with summary statistics.

There is a substantial probability of negative returns. The investment return also has a high a high variability and is non-normally distributed. The distribution is very different between CCGT, OCGT and DSM300. All features imply that the degree of risk aversion of the investor will have a major impact on the investment decision.

The new CCGT and OCGT have negative expected returns and are thus not economically viable, as they are dominated by a risk free investment (no risk, higher return). For the existing CCGT, the expected return exceeds the cost of capital but is below the hurdle rate. For DSM300, the expected returns exceed the hurdle rate. DSM300 is thus economically viable according to that metric under this scenario.

All distributions are positively skewed.

As predicted based on the distribution of inframarginal rents (high probability of zero inframarginal rents, low probability of price peaks) and the short lifetime of the DSM300 investment, we see that the number of price peaks determines the modes of the return distribution.

For all technologies, we see that there is a high probability of negative returns. New OCGT and DSM300 have the largest downside risk. The 5% expected shortfall for them is -19% and -53%. The minimum value of all simulated DSM300 returns is -1 indicating that there is a risk of total loss.

The hurdle premiums are calibrated here to be the same for the four technologies. Given that the downside risk differs to such great extent, this assumption does not seem realistic.

Table 5 Dashboard of expected investment returns, hurdle rate, CAPM cost of capital, and risk statistics under scenario 1

	new CCGT	new OCGT	DSM300	Existing CCGT
mean	-0.010	-0.038	0.270	0.071
hurdle rate	0.095	0.095	0.095	0.095
CAPM cost of capital	0.059	0.059	0.059	0.059
Prob R<0	0.647	0.680	0.536	0.345
median	-0.011	-0.027	-0.066	0.055
min	-0.077	-0.256	-1.000	-0.088
max	0.177	0.342	4.987	0.857
sd	0.036	0.083	0.909	0.112
std skewness	0.475	0.022	2.946	1.751
std kurtosis	2.994	2.825	12.398	8.109
semidev	0.024	0.060	0.375	0.062
5% VaR	-0.061	-0.172	-0.398	-0.048
5% ES	-0.065	-0.193	-0.527	-0.057

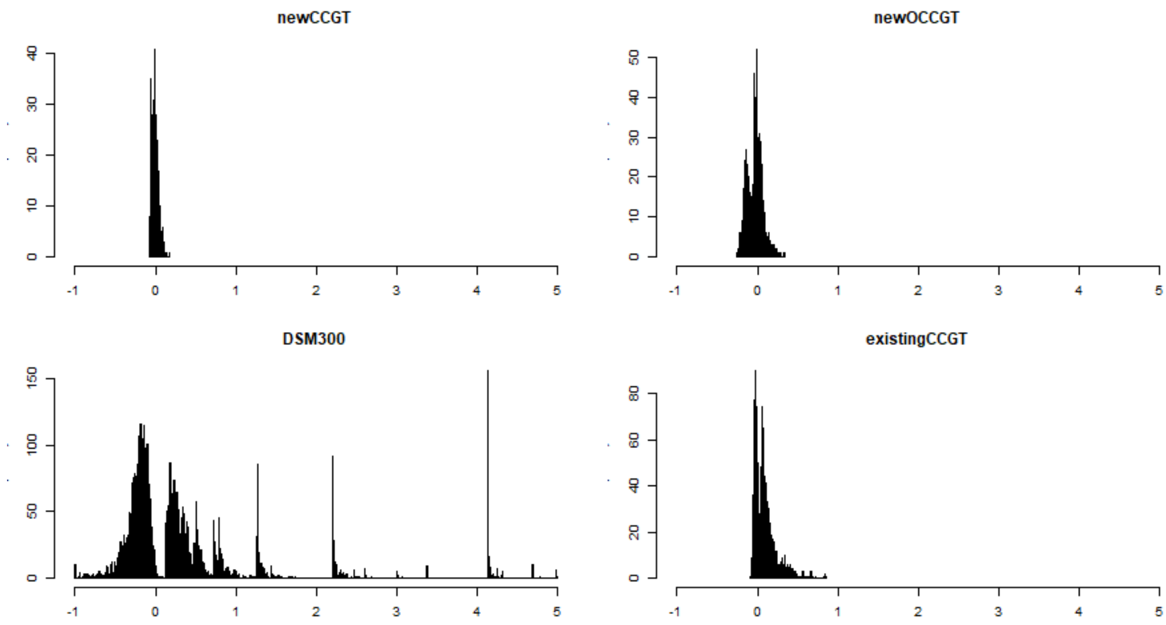

Figure 5 Histogram of internal rate of return of investments under scenario 1

4.2.2. Decision rule using CARA and CRRA certainty equivalents

Recall that we have defined the certainty equivalent as the number of euro's that the decision maker needs to have on the bank account at a risk free rate to be indifferent with respect to 1 euro invested in the risky investment project. If the certainty equivalent is less than 1 euro then the project is not interesting.

Results are shown in the table below. The higher the risk aversion, the lower the certainty equivalent. For the reference case of CARA with $a = 1.5$ and CRRA with $\gamma = 4$ we find that only the existing CCGT is economically viable.[26]

Table 6 Certainty equivalents with respect to 1 euro invested in the project under scenario 1. The higher the certainty equivalent, the more attractive the project is.

CARA	new CCGT	new OCGT	DSM300	Existing CCGT
a=0.1	0.926	0.817	2.345	1.608
a=0.5	0.902	0.750	1.361	1.480
a=1	0.876	0.678	0.895	1.354
a=1.5	0.851	0.617	0.693	1.259
a=2	0.829	0.566	0.582	1.184
a=2.5	0.809	0.523	0.512	1.126
a=3	0.791	0.486	0.462	1.078

CRRA	new CCGT	new OCGT	DSM300	Existing CCGT
gamma=0	0.932	0.835	2.791	1.645
gamma=0.5	0.900	0.713	1.847	1.537
gamma=1	0.870	0.579	0.970	1.434
gamma=1.5	0.840	0.447	0.453	1.339
gamma=2	0.812	0.339	0.225	1.253
gamma=4	0.720	0.150	0.042	1.019
gamma=5	0.686	0.113	0.030	0.951
gamma=10	0.590	0.049	0.016	0.791

[26] When the final value is 0 (total investment loss) the CRRA utility becomes minus infinity. We have winsorized all final values below 1% (of initial investment value) at 1% to ensure the monetary equivalent calculation is still feasible.

4.2.3. Sensitivity to assumption of fixed operations and maintenance (FOM) costs

The results presented above assume a rather low level of fixed operations and maintenance costs, namely 15 €/kW/y for new CCGT, 5 €/kW/y for new CCGT, 5 €/kW/y for DSM300 and 15 €/kW/y for existing CCGT. These correspond to a minimum cost assessment by Elia (2019). Several market participants have argued that these costs underestimate actual costs. To study the sensitivity of the results to the level of the costs, we now consider the alternative calibration of setting the FOM to 20 €/kW/y for new CCGT, 15 €/kW/y for new CCGT, 10 €/kW/y for DSM300 and 20 €/kW/y for existing CCGT.

We then have the below performance results. The *ceteris paribus* impact of increasing the FOM costs is of course to lower the expected returns. The impact is economically significant as the expected return for DSM300 drops from 27.0% to 3.4%, and for existing CCGT drops it drops from 7% to 3.4%. All expected returns are below the hurdle rate. A similar impact is observed for the certainty equivalents.

Table 7 Investment results under scenario 1 with average level of FOM costs

	new CCGT	new OCGT	DSM300	Existing CCGT
mean	-0.020	-0.070	0.034	0.034
hurdle rate	0.095	0.095	0.095	0.095
CAPM cost of capital	0.059	0.059	0.059	0.059
Prob R<0	0.713	0.823	0.538	0.388
median	-0.021	-0.056	-0.143	0.028
min	-0.085	-0.271	-1.000	-0.110
max	0.146	0.205	2.585	0.613
sd	0.034	0.074	0.483	0.089
std skewness	0.408	-0.215	1.942	1.274
std kurtosis	2.793	2.272	8.117	6.013
semidev	0.023	0.055	0.256	0.053
5% VaR	-0.069	-0.192	-0.457	-0.070
5% ES	-0.073	-0.213	-0.581	-0.079

	new CCGT	new OCGT	DSM300	Existing CCGT
a=0.1	0.834	0.587	1.382	1.304
a=0.5	0.815	0.552	0.982	1.218
a=1	0.793	0.512	0.707	1.130
a=1.5	0.773	0.478	0.555	1.059
a=2	0.754	0.447	0.462	1.001
a=2.5	0.737	0.419	0.401	0.954
a=3	0.722	0.395	0.358	0.916

	new CCGT	new OCGT	DSM300	Existing CCGT
gamma=0	0.839	0.596	1.522	1.328
gamma=0.5	0.810	0.509	1.008	1.242
gamma=1	0.783	0.413	0.533	1.158
gamma=1.5	0.756	0.319	0.258	1.081
gamma=2	0.731	0.242	0.140	1.012
gamma=4	0.648	0.107	0.037	0.823
gamma=5	0.617	0.081	0.028	0.768
gamma=10	0.531	0.035	0.016	0.639

4.3. Results for scenario 2

4.3.1. Decision rule using expected returns and hurdle rates

Under scenario 2, we relax the price cap from 3k€/kW to 20k€/kW. In this case, the occurrence of extreme price spikes leads to extreme investment returns. These extremes inflate all moments, as they are sample averages of returns (mean) or powers of centered returns (variance, skewness, kurtosis).

The end result, as can be seen in Table 7, is that all investments have a higher expected return than the hurdle rate, but that there is also a substantial investment risk. The important caveat for this conclusion is that we have modified the distribution of inframarginal rents, but kept the same investor's appreciation about the hurdle premium to invest (namely 5%). In practice, the more pronounced non-normality and perceived risk of price interventions are likely to be higher in scenario 2, which could result in a higher hurdle premium and thus (potentially) impact the economic viability result.

Table 8 Dashboard of expected investment returns, hurdle rate, CAPM cost of capital, and risk statistics under scenario 2

	new CCGT	new OCGT	DSM300	Existing CCGT
mean	0.151	0.261	1.943	0.466
hurdle rate	0.095	0.095	0.095	0.095
CAPM cost of capital	0.059	0.059	0.059	0.059
Prob R<0	0.284	0.292	0.175	0.123
median	0.054	0.088	0.331	0.141
min	-0.077	-0.256	-1.000	-0.083
max	2.418	4.540	38.380	7.404
sd	0.326	0.693	6.666	1.180
std skewness	3.650	4.166	4.932	4.511
std kurtosis	17.410	20.791	26.299	23.192
semidev	0.117	0.217	1.561	0.326
5% VaR	-0.046	-0.111	-0.338	-0.027
5% ES	-0.054	-0.150	-0.494	-0.043

4.3.2. Decision rule using CARA and CRRA certainty equivalents

The higher price caps increase the certainty equivalents. Due to the concavity, the impact is small when the risk aversion is high. For the reference case of CARA with $a = 1.5$, all investments are economically viable. For the CRRA utility function with $\gamma = 4$ only the existing CCGT investments is economically viable.

Table 9 Certainty equivalents with respect to 1 euro invested in the project under scenario 2. The higher the certainty equivalent, the more attractive the project is.

CARA	new CCGT	new OCGT	DSM300	Existing CCGT
a=0.1	2.399	3.246	6.097	4.184
a=0.5	1.878	2.016	2.574	2.541
a=1	1.526	1.434	1.722	1.966
a=1.5	1.331	1.168	1.329	1.710
a=2	1.210	1.011	1.088	1.555
a=2.5	1.128	0.903	0.922	1.446
a=3	1.067	0.823	0.800	1.365

CRRA	new CCGT	new OCGT	DSM300	Existing CCGT
gamma=0	2.585	3.810	15.161	5.187
gamma=0.5	2.226	2.953	9.140	4.137
gamma=1	1.892	2.095	4.081	3.221
gamma=1.5	1.611	1.396	1.194	2.543
gamma=2	1.397	0.921	0.329	2.094
gamma=4	0.980	0.216	0.043	1.365
gamma=5	0.890	0.134	0.030	1.217
gamma=10	0.694	0.050	0.016	0.894

4.4. Conclusion

A simulation-based approach to evaluate the economic viability of investments in electricity capacity requires to define a decision rule that mimics as close as possible actual investment decision making. Based on the literature survey, we decided to implement two criteria in the proof concept, namely (i) the expected return and hurdle rate approach, and (ii) expected utility approach and break-even values in terms of risk free investments (certainty equivalents). The proof of concept has shown that the two methods are computationally feasible, but that a careful calibration of the simulation setup and decision rule parameters is required.

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Appendix: Taylor expansion of the expected utility function

The utility function $U(x)$ is a non-linear function. We can use Taylor expansions to describe its behavior around a fixed point such as the expected value of $x = 1 + R$, namely 1+μ with $\mu = E[R]$. The first order expansion uses the tangent line:

$$U(1 + R) \approx U(1 + \mu) + U'(1 + \mu)(R - \mu).$$

For risk-averse investor, the utility function is concave. We can take the curvature into account by computing the second-order tailor expansion:

$$U(1 + R) \approx U(1 + \mu) + U'(1 + \mu)(R - \mu) + \frac{1}{2}U''(1 + \mu)(R - \mu)^2.$$

Note that the expected value of the second-order approximation of the utility function shows the trade-off between expected return and variance:

$$EU \approx U(1 + \mu) + \frac{1}{2}U''(1 + \mu)\sigma^2,$$

where $\sigma^2 = E[(x - \mu)^2]$. We have a trade-off since, for risk-averse investors, the utility function is concave and hence $\frac{1}{2}U''(1 + \mu) \leq 0$.

The utility function is however not quadratic and project returns are skewed. We can thus improve the approximation by taking higher order terms into account. The third order approximation equals:

$$U(1 + R) \approx U(1 + \mu) + U'(1 + \mu)(R - \mu) + \frac{1}{2}U''(1 + \mu)(R - \mu)^2 + \frac{1}{6}U'''(1 + \mu)(R - \mu)^3.$$

The expected value of the third-order approximation shows the trade-off between expected return, variance and skewness:

$$EU \approx U(1 + \mu) + \frac{1}{2}U''(1 + \mu)\sigma^2 + \frac{1}{6}U'''(1 + \mu)\zeta,$$

where $\zeta = E[(R - \mu)^3]$. From Theorem 1 in Scott and Horvath (1980) it follows that $U'''(\mu) > 0$. Let's verify this in the concrete case of the CARA and CRRA utility functions.

The expected value of the fourth-order approximation shows the trade-off between expected return, variance, skewness and kurtosis:

$$EU \approx U(1 + \mu) + \frac{1}{2}U''(1 + \mu)\sigma^2 + \frac{1}{6}U'''(1 + \mu)\zeta + \frac{1}{24}U''''(1 + \mu)\kappa,$$

where $\kappa = E[(R - \mu)^4]$. The impact of the moments depends on the derivatives of the utility functions. Let's elaborate this in the concrete case of the CARA and CRRA utility functions.

- CARA : $U_a(x) = \frac{1-e^{-ax}}{a}$. Hence : $U_a'(x) = e^{-ax} \geq 0$, $U_a''(x) = -ae^{-ax} \leq 0$, $U_a'''(x) = a^2e^{-ax} \geq 0$ and , $U_a''''(x) = -a^3e^{-ax} \geq 0$. The corresponding value of the expected utility function is

$$EU_a \approx \frac{e^{-a(1+\mu)}}{a}\left(e^{a(1+\mu)} - 1 - \frac{a^2}{2}\sigma^2 + \frac{a^3}{6}\zeta - \frac{a^4}{24}\kappa\right).$$

- CRRA: $U_\gamma(x) = \frac{x^{1-\gamma}-1}{1-\gamma}$. Hence $U_\gamma'(x) = x^{-\gamma} \geq 0, U_\gamma''(x) = (-\gamma)x^{-(\gamma+1)} \leq 0$, $U_\gamma'''(x) = \gamma(\gamma + 1)x^{-(\gamma+2)} \geq 0$ and $U_\gamma''''(x) = -\gamma(\gamma + 1)(\gamma + 2)x^{-(\gamma+3)} \leq 0$. The corresponding value of the expected utility function is

$$EU_\gamma \approx U(1 + \mu) - \frac{\gamma}{2}(1 + \mu)^{-(\gamma+1)}\sigma^2 + \frac{\gamma(\gamma+1)}{6}(1 + \mu)^{-(\gamma+2)}\zeta - \frac{\gamma(\gamma+1)(\gamma+2)}{24}(1 + \mu)^{-(\gamma+3)}\kappa.$$