ORIGINAL ARTICLE

Optimal WACC in tariff regulation under uncertainty

Ward Romeijnders[1] [ID] · **Machiel Mulder[2]**

Abstract

In the regulation of network tariffs, the compensation for the opportunity costs of capital through the Weighted Average Costs of Capital (WACC) plays a crucial role. Determining the appropriate level for the WACC is, though, problematic because of the uncertainty about the future conditions in capital markets. When the WACC is set above the future opportunity costs of capital, consumers will pay too much, while when the WACC is below that level, network operators may be unable to finance investments affecting quality of network services. In this paper, we explicitly take this uncertainty into account when we determine the optimal WACC for the tariff regulation of an electricity network. By trading off consumer surplus and expected disruption costs in the electricity grid, we conclude that from a social-welfare perspective in most cases the optimal WACC in tariff regulation is above the historical mean costs of capital. Only in case of high uncertainty about the true costs of capital while network operators are able to quickly increase investment levels, the optimal WACC is below the historical mean because then it is less likely that the WACC is constantly insufficient to cover actual costs of capital. However, when network operators cannot quickly increase investment levels the optimal WACC is always above the historical mean cost of capital.

Keywords Tariff regulation · Weighted average cost of capital · Electricity grid

JEL Classification D25 · D42 · Q48 · L51 · L94

✉ Ward Romeijnders
 w.romeijnders@rug.nl

 Machiel Mulder
 machiel.mulder@rug.nl

[1] Department of Operations, Faculty of Economics and Business, University of Groningen, Nettelbosje 2, 9747 AE Groningen, The Netherlands

[2] Department of Economics, Econometrics & Finance, Faculty of Economics and Business, University of Groningen, Nettelbosje 2, 9747 AE Groningen, The Netherlands

1 Introduction

Operators of networks for the transport of electricity, gas and heat are generally subject to regulation because of the presence of natural monopolies which make it impossible to realize competition. The objectives of this regulation are directed at both the tariffs these network operators are allowed to charge and the quality of the performance of the networks (Viscusi et al. 2005; Mulder 2021). Hence, users of these networks should not pay more than needed to compensate for the required costs while the quality of the network services should be sufficiently high. In energy-policy terms, the first objective refers to the affordability of energy, while the latter refers to the reliability. The third policy objective of the so-called Energy Trilemma refers to the sustainability, but this objective is more realized through measures regarding the production and consumption of energy than through regulation of the network operators (World Energy Council 2018). Nevertheless, investments in networks may be required to facilitate, for instance, investments in renewable production.

To realize the affordability and the reliability objectives regarding energy transport, the regulator faces a fundamental trade-off. This trade-off results from the impact of the regulated tariffs on the financeability of investments. Because of the affordability of network use, the network tariffs should be reduced as far as possible, but every reduction in tariffs reduces the revenues of the network operator which may make it difficult to finance investments in order to maintain or improve the reliability of network services (Mulder 2021). The presence of this trade-off implies that the value of grid reliability has to be weighed against the value of having low tariffs for network users. The societal importance of grid reliability follows from literature on the value of loss load, which gives estimates in the range of 10,000 to 25,000 euro per MWh (Schröder and Kuckshinrichs 2015). The societal importance of having low tariffs follows directly from the impact of these tariffs on the financial position of grid users.

The contribution of this paper is that we determine for a key variable in the tariff setting how to deal with the trade-off between these policy objectives. This key variable in the tariff regulation is the so-called Weighted Average Costs of Capital (WACC). The importance of the WACC for the ability of network operators to invest follows from the fact that external financial means play a crucial role in these investments. The Dutch high-voltage grid operator TenneT, for instance, reports that it invested about 3.5 billion euro in 2020, which was financed through 2.75 billion (net) new loans and 0.4 billion net new contribution by equity and hybrid providers (TenneT 2021), and the remaining through internal sources. The challenge here is to find the optimal level of the WACC. If the WACC is set at a level that is lower than what is required by investors, grid operators may face difficulties in financing their investment, while when the WACC exceeds that level, grid users pay more than what is needed.

Finding the appropriate WACC level is problematic because of the uncertainty about the future conditions of capital markets, while a regulator has to set the WACC in advance of a regulatory period. This holds in particular in the case of a tariff regulation which is based on a price-cap scheme in which allowed revenues are set for all future years of the new regulatory period of about three to five years. The WACC depends on many variables, such as the risk-free interest, the market-risk premium, the equity beta and the debt premium, which may fluctuate strongly (Dimson et al. 2000; Oxera

2015). Hence, the WACC is a stochastic variable. Generally, however, regulators use a deterministic approach in setting the WACC for the future regulatory period of 3 to 5 years (Council of European Energy Regulators 2019). They typically use historical data in order to set the value of the various parameters of the WACC. These values are generally determined on the basis of the mean values of historical distributions. Hence, implicitly, regulators assume symmetric economic consequences of deviations between the actual WACC during a regulatory period and the level that is assumed in the tariff regulation at the start of a regulatory period. After all, by setting the future WACC on the basis of the historical mean, the impact of a too high WACC for network users (i.e. they pay too much) are (implicitly) equally valued as the impact of a too low WACC (e.g. a higher probability of disturbances in network services).

A few authors have addressed the impact of uncertainty regarding the WACC. Dobbs (2011) applies a Monte-Carlo model of a network operator which investment' decisions depend on the actual cost of capital versus the rate set by the regulator. For sunk investments, the optimal WACC appears to be about equal to the mean of the distribution, but for new investments, the optimal WACC appears to be significantly larger. Schober et al. (2014) analyze the spread in the risks among regulated companies subject to the same regulatory scheme. This variation in risks among these companies are related to the failure probabilities of assets which result in different cash flows for the regulated companies. When a regulator takes these individual circumstances into account, the WACC can be significantly higher for some regulated companies.

Our paper differentiates from these papers since we explicitly include the impact of investments on the reliability of network services. In this paper, we analyze to what extent the optimal WACC in tariff regulation deviates from the distribution mean if we control for the impact of the allowed return on capital on grid investments and consequently on the quality of network services. We develop a stylized model of a network operator subject to price-cap regulation. This network operator has as objective to maintain the quality of its services. In order to realize that objective, it regularly replaces a part of the network infrastructure because of aging. It is assumed that the likelihood of network disturbances quadratically increases with the average age of the infrastructure. The ability to realize these investments depends on the allowed level of revenues, in particular the level of the WACC. The regulator determines the allowed level of revenues for every regulatory period, pursuing the objective to maximize consumer welfare. The latter objective, which does not include firm profits, is generally chosen by regulators of natural monopolies. Afterall, a general objective of tariff regulation is to redistribute welfare from the monopolistic grid operators to grid users (see Viscusi et al. (2005); Mulder (2021)). This welfare depends on two components: the consumer surplus resulting from the actual usage of the network in relation to the tariffs which consumers have to pay as well as the value of lost load resulting from network disturbances. The optimum level of allowed revenues depends not only on the expected values for the costs of capital, but also on its standard deviations. This optimum level is determined by maximizing a Monte Carlo approximation of consumers' expected welfare.

We find that the optimum level of the WACC, which is the level that maximizes the expected social welfare, is higher than the WACC which is determined as the mean of the historical data. Only in case of high uncertainty about the true costs of capital while

grid operators are able to quickly increase investment levels, the optimal WACC is below the historical mean. The explanation for that is that in such cases it is less likely that the WACC is constantly insufficient to cover actual costs of capital. Of course, the results are sensitive to the assumption regarding the value of lost load. In particular, we find that the optimal level of the WACC exceeds the historical average WACC if the value of lost load exceeds 7,500 euro per MWh. In general, the higher the value of lost load, the more the optimal WACC exceeds the historical average WACC.

The outline of this paper is as follows. Section 2 briefly discusses literature about tariff regulation, investments and quality of network services. Section 3 presents our stochastic regulatory model, while Sect. 4 describes the data and assumption. The findings are discussed in Sect. 5, while Sect. 6 concludes.

2 Literature review

As the relationship between tariff regulation, investments and reliability of network services has been debated since the introduction of incentive regulation, it has also been analyzed extensively from various angles. These studies are directed at the impact of the design of tariff regulation, in particular the level of the WACC, on investments, the relationship between investments and service quality, and the measurement and evaluation of the performance of network operators.

In an empirical analysis regarding various European countries, Cambini and Rondi (2010) analyse the impact of the design of tariff regulation on investments in energy infrastructure. They find that tariff regulation based on an incentive scheme results in more investments than tariff regulation that is based on rate-of-return regulation. Regarding the influence of the WACC, they find that a higher WACC raises the level of investments by energy utilities.

As the WACC refers to the future regulatory period, regulators have to estimate the future costs of capital. Applying a Monte Carlo analysis to determine the optimal WACC, Dobbs (2011) finds that the WACC on new investments should be set at a significantly higher level than the mean of the historical distribution, while the WACC for already realized (sunk) investments should be set around the mean. Regulators not only have to deal with the uncertain future value of the various parameters of the WACC, they are also subject to information asymmetry regarding the precise characteristics of the regulated firms. Schober et al. (2014) find that controlling for more detailed information on firm specific risks, the WACC can increase up to 3% points.

The intensity of investments in the grid appears to be important for the quality of the network. Although the quality of network services has many dimensions, it is generally measured through the average duration of disturbances, which is expressed through the System Average Interruption Duration Index (SAIDI). Cambini et al. (2016) find a relationship between investments in grid assets and the quality of grid services. They also find that financial incentives fostering these investments have a positive effect on grid service quality. On the basis of a panel analysis of electricity distribution grid operators in nine European countries, Arcos-Vargas et al. (2017) find that a 1% higher level of regulated revenues per customer reduces the average annual duration per customer also with 1%. The authors explain this mechanism through the impact

of higher revenues on the ability to install a larger asset base per unit of load, which gives a network a higher redundancy.

Also Ter-Martirosyan and Kwoka (2010) find a relationship between the design of tariff regulation and quality of network services. Measuring the latter through the SAIDI, they find that operators facing high-powered incentives for cost reductions, realize a lower quality of services. These authors also find, however, that this negative effect of incentive regulation can be offset by imposing service quality standards.

In order to determine the optimal level of the WACC, one needs also to determine the economic value of disturbances of network services. The relevant economic metric is the Value of Lost Load (VoLL). Several authors have estimated the value of lost load (VOLL) and the results vary strongly. These differences can be partly attributed to the dimensions of lost load, such as time and duration of disruption, that have been taken into account (Ovaere et al. 2019). The difference can, however, largely be attributed to the methods used. Generally, the results of macroeconomic studies, which estimate the damage of power interruption to economic activities, are in the range of 10,000 to 25,000 euro per MWh, while stated-preference methods, based on surveys among consumers, give as result a VoLL of about 10,000 euro per MWh (Schröder and Kuckshinrichs 2015).

From this literature review, it appears that tariff regulation affects the investments of network operators in their assets and that these investments affect the reliability of network services. We also conclude that the allowed return on capital, i.e. the WACC, is a crucial regulatory parameter to determine the level of allowed revenues. In the literature up to now, scarce attention has been paid to the stochastic nature of the costs of capital. In addition, in order to determine the optimal WACC and the consequences of tariff regulation on reliability, attention has to be paid to the fact that the true value of lost load is uncertain. The contribution of this paper is that we depart from the facts that true costs of capital are subject to stochastic processes, while the welfare effects of the regulatory decisions regarding the compensation for these costs can be non-systematic.

3 Model

We consider a stylized model with only a single grid operator maintaining and operating an electricity network. The grid operator is subject to tariff regulation: the regulator sets a cap on the prices the operator may charge and, as a result, this limits the total revenues of the operator (i.e., the price cap). This price cap is determined before the start of each regulatory review period, and is fixed throughout each period. In this stylized model, we discretize time in T time periods, and we assume that every review period lasts five periods.

Traditionally, under a price-cap regime, the regulator determines caps $\bar{R}_t$ on the total revenue of the grid operator during periods t in a regulatory review period, such that $\bar{R}_t$ is sufficient to compensate for the efficient level of the total costs of the grid operator during period t. These total costs constitute of capital costs and operational costs. We let C_t, C_t^c, and C_t^o denote these total, capital, and operational costs in period t, respectively. Then,

$$C_t = C_t^c + C_t^o.$$

The total costs depend on the WACC on the capital market, since the capital costs C_t^c are given by

$$C_t^c = D_t + w_t^c \times RAB_t,$$

where D_t represents the depreciation, determined by a linear depreciation rate γ, RAB_t the value of the regulated asset base, and w_t^c the opportunity costs of capital based on the actual costs of equity and debt on the capital market in period t. Assuming that the operational costs, depreciation, and regulated asset base in each time period can be accurately estimated by the regulator, the price caps $\bar{R}_t$ are completely determined by the regulator's expectation of the opportunity costs of capital and its translation in a return for these costs, the so-called WACC in tariff regulation, denoted w^r. When the regulator sets the price caps for each year of the next regulatory period such that it perfectly compensates for the actual efficient costs, then we obtain:

$$\bar{R}_t = C_t = D_t + w^r \times RAB_t + C_t^o.$$

In practice, however, the grid operator may not operate at efficient costs, but at an efficiency level ES below 100%. This score is determined by the regulator based on an external benchmark, see Mulder (2012). This efficiency analysis is typically done through Data Envelopment Analysis or Stochastic Frontier Analysis, determining the gap in the productivity of the regulated firm and the best practice. This gap, the so-called technical inefficiency, has to be closed by the regulated firm. This process of catching up takes some time, and regulators generally give regulated companies a number of years (N) to do this. This means that price caps $\bar{R}_t$ are relatively large at the start of the time period and decrease over time. See (6.34)–(6.37) in Mulder (2021) for how the efficiency score impacts the price caps, and thus the tariffs of consumers and consumers surplus.

The problem with fixed price caps, however, is that in practice the costs of capital on the capital market is uncertain and fluctuates over time. This implies that, *even with an accurate estimate of* $E[w_t^c]$, the actual opportunity costs of a grid operator w_t^c may exceed the regulator's WACC w^r. In this case, the grid operator receives too little compensation for the invested capital in the grid, which may be reason to postpone replacement investments as financing such investments may be impossible, reducing the quality of the grid and, e.g., raising the risk of grid disruptions. On the other hand, if the regulator's WACC exceeds w_t^c, then consumers are too heavily charged for using the grid. Since the economic value of both effects are not necessarily symmetric, our goal is to determine the optimal regulator's WACC *taking uncertainty regarding the costs of equity and debt on the capital market into account.*

To do so, we assume that the regulator's objective is to maximize the *expected discounted social welfare*, where the expected social welfare in each time period is determined as the difference between consumer surplus and the expected costs of disruptions in the network. We estimate the latter as the product of the value of lost load (VoLL) and the expected kWh lost in the network. The most important assumption that we make is that the operator only invests in period t when the regulator's WACC w^r is equal to or exceeds the actual costs of equity and debt on the capital market w_t^c.

If this is the case, then we assume that investments are such that part of the network with age exceeding J^* becomes as good as new. In particular, because of other type of restrictions (such as in the labour market), we assume that each period the network operator can only replace a limited fraction β of the total assets. Note, that our analysis focuses solely on the distribution grids, which means that we assume that there is no impact of lack of investments in power plants on grid reliability.

To estimate the disruption costs in the network, we calculate the fraction of assets a_{jt} of age $j = 1, \ldots, J$ in time period t. If the opportunity costs of capital on the capital market are high ($w_t^c > w^r$), so that the grid operator is not able to invest in the network in period t, then all assets age and thus $a_{1t} = 0$, and for every $j = 2, \ldots, J$,

$$a_{j,t} = a_{j-1,t-1}.$$

On the other hand, if the opportunity costs of capital on the capital market are low ($w_t^c \leq w^r$), so that the grid operator can invest in the network in period t, then also all assets age, but the assets of age $j > J^*$ are made as good as new. However, if there are too many assets of age exceeding J^*, then we only maintain a fraction β of the total assets. To be precise, then we maintain the fraction β of total assets with the highest age. The reason for this is that as a result of other constraints, such as in the labour market, the operator may not be able to quickly renew a significant amount of its assets in a short period of time.

We let π_j denote the expected percentage of total load lost *if all assets were of age* j, and we compute the expected percentage of lost load Π_t in period t as

$$\Pi_t = \sum_{j=1}^{J} a_{jt} \pi_j.$$

Typically, the expected percentage of total load lost π_j is larger if the age j of the assets is larger. In fact, we estimate these percentages based on disruption data from the high-voltage networks in the Netherlands and Greece, respectively. Since the first is maintained more regularly than the latter, we assume $\Pi_1 = \Pi_{NL}$ and $\Pi_K = \Pi_{GR}$, where K is the number of periods Greece has not invested in their electricity network, and we use different types of interpolation, i.e., linear, quadratic, and exponential, to estimate the π_j's.

The expected disruption costs DC_t in period t are given by

$$DC_t = \text{VoLL} \times Q_t \times \Pi_t,$$

where VoLL is the value of lost load (euro/kWh), and Q_t is the expected quantity (in kWh) transported in the network.

To estimate the *expected* disruption costs in the network, we use Monte Carlo sampling with $S = 10,000$ samples. That is, we generate S scenarios for how the future costs of capital on the capital market w_t^c may evolve over time $t = 1, \ldots, T$. In each scenario s, we calculate the fraction of assets a_{jt}^s of age $j = 1, \ldots, J$ in time period $t = 1, \ldots, T$, we compute the expected percentage of lost load Π_t in period t for scenario s as

$$\Pi_t^s = \sum_{j=1}^{J} \alpha_{jt}^s \pi_j,$$

and determine the expected disruption costs DC_t^s in period t for scenario s as

$$DC_t^s = \text{VoLL} \times Q_t \times \Pi_t^s.$$

The estimated expected disruption costs DC_t in period t are obtained by averaging DC_t^s over all scenarios $s = 1, \dots, S$.

To calculate the consumer surplus, we assume that the demand curve is fully inelastic, which is realistic for the short term. As a result, we can use a change in the regulated level of revenues as proxy for the change in consumer surplus in period t, i.e. an increase of the price cap with x euros results in change of consumer welfare of $-x$ euro. Given two price caps $\bar{R}_t$ and $\bar{R}_t'$, determined by using two alternative values for the regulator's WACC w^r and $w^{r'}$, the difference $\Delta CS_t = \bar{R}_t - \bar{R}_t'$ represents a good proxy of the actual difference in consumer surplus. In our numerical experiments, we thus only report differences in CS with respect to a base case, and not the actual CS. In other words, letting Tar_t denote the tariffs induced by $\text{Tar}_t * Q_t = \bar{R}_t$, the difference ΔCS_t may be obtained using $\Delta CS_t = (\text{Tar}_t - \text{Tar}_t') * Q_t = \bar{R}_t - \bar{R}_t'$.

For the expected discounted social welfare ΔCW, we also only measure the difference with the base case. It is given by

$$\Delta CW = \sum_{t=1}^{T} \left(\frac{1}{1+\delta} \right)^t \left(\Delta CS_t - \Delta DC_t \right),$$

where δ represents the social discount factor.

4 Data

Our case study is based on the network operator of the Dutch high-voltage electricity grid. Therefore, parameter values are selected as accurately as possible, based on, e.g., ACM (2012, 2019a, b); TenneT (2019). The parameter values presented in this section represent the base case of our numerical experiments. For example, the discount rate that we use is $\delta = 0.03$. Using sensitivity analysis, we will investigate the effect of changing some of the parameter values one by one.

In our case study, we assume that each period t represents one year, with time horizon $T = 30$. Thus, our time horizon contains six regulatory review periods. We assume that the regulator's WACC in these review periods is based on accurate estimates of the average yearly mean WACC on the capital market during these regulatory periods, and thus the regulator's WACC may differ over the regulatory periods if these estimates differ. However, we do not assume that the regulator's WACC equals the mean WACC, but we add the same markup (which can be both positive and negative) to all WACC levels in each regulatory period.

4.1 Operational parameters

We assume that the operational costs C_t^o are constant over time and equal 39 million euros per year (ACM 2019b). Moreover, the initial value of the regulated asset base (RAB) at $t = 0$ equals 2.86 billion euros (ACM 2019b). The initial annual revenues R_0 are estimated to be 259 million euros. For the constant depreciation rate, we use $\gamma = 1/30$. This value is based on the assumption that the lifetime of new assets is approximately $J^* = 30$ years (ACM 2012). Furthermore, we assume that we are dealing with an ideal complex so that for each $j = 1, \ldots, 30$, there is an equal fraction $\alpha_{j1} = 1/30$ of the assets in the network with age j at time $t = 1$. We assume that $\beta = 1/10$. That is, the maximum percentage of total assets that can be replaced per year is 10%. The reason for this maximum is the fact that network operators may face other constraints, such as in labour or input markets, which hinder a full replacement in a short period of time. Since $\alpha_{j1} = 1/30$, this is equivalent to performing all regular maintenance actions of three sequential years in one year. This implies that a few years of actual costs of capital being above the WACC does not result in under investment over a longer period of time, as the resulting delay in investments will be compensated in the years with more favourable capital market circumstances.

Finally, referring to the actual benchmark analysis of the Dutch regulator ACM, we assume that the current efficiency score ES of the operator is $ES = 92.5\%$, and will reach full efficiency after $N = 9$ years, after which the operator should operate at efficient cost level (ACM 2019b).

With respect to the electricity network, we assume that the expected quantity of yearly transported MWh throughout the electricity network is constant and equals $Q_t = 120$ million (TenneT 2019). With respect to the size of the VoLL, the results vary strongly among the various studies, but in general, the outcomes of the macroeconomic studies are in the range of 10,000 to 25,000 euro per MWh (Schröder and Kuckshinrichs 2015). Based on this, we use a VoLL of 17,500 euro per MWh. Finally we use the fact that the average number of disruptions in the network is currently 25 minutes per year, leading to a percentage of the yearly load lost equal to 0.005%. Assuming that this percentage increases to 0.05% if the network is not maintained for 20 years (situation in Greece), we can estimate percentage of load lost if all assets in the network have age j. These percentages are obtained using quadratic interpolation, assuming that $\pi_j \geq 0$ for all $j = 1, \ldots, J$, and are given in Figure 1. In this figure, we also show the result of a linear and exponential interpolation which we use in the sensitivity analysis in Sect. 5. Note that we do not necessarily assume a bathtub curve for these probabilities in line with Nemati et al. (2015).

In Table 1 below we summarize the values of all operational parameters.

4.2 Uncertain WACC on the capital market

We assume that the WACC on the capital market follows an AR(1) process over the time horizon with autocorrelation $\rho = 0.92$ (AR regression result based on data derived from ACM (2021)). We use an AR(1) process to model persistency on the capital market, meaning that the WACC on the capital market typically tends to be a
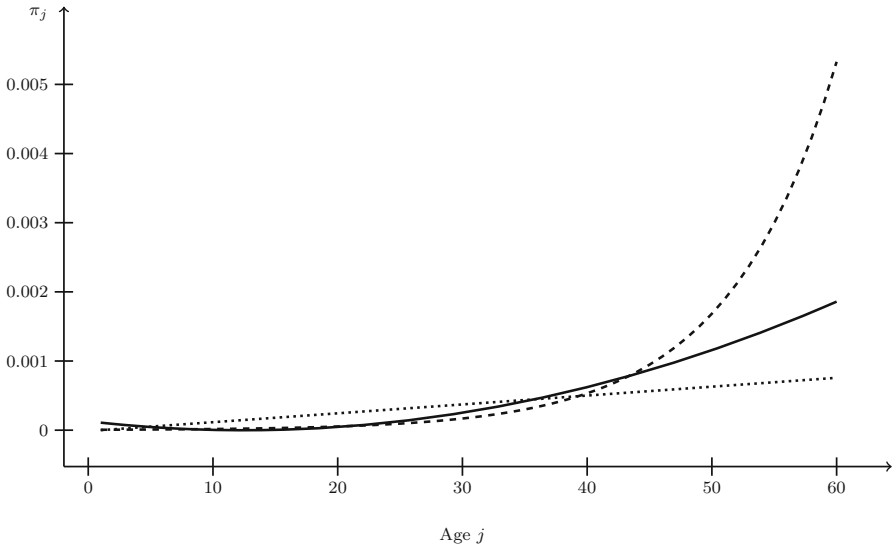
Fig. 1 The expected percentage of lost load π_j as a function of age $j = 1, \ldots, J$ for the quadratic (solid), linear (dotted), and exponential (dashed) interpolation

Table 1 Operational parameter values . sources: ACM (2012), ACM (2019b), Schröder and Kuckshinrichs (2015), Nemati et al. (2015)

Parameter	Symbol	Value
Operational costs	C_t^o	39 million euro
Initial value Regulated Asset Base	RAB_0	2.86 billion euro
Initial revenues	R_0	259 million euro
Depreciation rate per year	γ	1/30
Lifetime of assets	J^*	30 years
Initial fraction of assets of age j	α_{j1}	1/30, $j = 1, \ldots, 30$
Maximum maintainable fraction of assets per year	β	1/10
Efficiency	ES	92.5%
Years until full efficiency	N	9 years
Expected quantity MWh transported	Q_t	120 million MWh
VoLL	$VoLL$	17,500 euro per MWh

high/low for several time periods in a row. In particular, we assume for the WACC on the capital market, w_t^C, in time period t, that

$$w_t^C = \mu_{WACC} + \rho(w_{t-1}^C - \mu_{WACC}) + \epsilon_t,$$

where the ϵ_t are independently and normally distributed with mean zero and variance σ_{WACC}^2. Here, the mean and standard deviation of the WACC are based on the gearing g of the grid operator which we assume to be 0.5 (ACM 2019a), and the costs of debt

Table 2 Capital market WACC parameter values . Sources: ACM (2019a), ACM (2021)

Parameter	Symbol	Value
Mean costs of equity	μ_E	5%
Standard deviation costs of equity	σ_E	2.5%
Mean costs of debt	μ_D	1.5%
Standard deviation costs of debt	σ_D	1%
Gearing	g	0.5
Mean WACC	μ_{WACC}	3.3%
Standard deviation WACC	σ_{WACC}	1.3%
Persistency level in the WACC on the capital market	ρ	0.92

r_D and the cost of equity r_E. Based on data of a 10-year Dutch government bond from 2010 to 2018, we assume that r_D is normally distributed with mean $\mu_D = 1.5\%$ and standard deviation $\sigma_D = 1\%$. Moreover, we assume that the cost of equity is normally distributed with mean $\mu_E = 5\%$ and standard deviation $\sigma_E = 2.5\%$ (Dimson et al. 2000). The mean value and standard deviation for the WACC are then calculated using:

$$\mu_{WACC} = g * \mu_D + (1 - g)\mu_E,$$

and

$$\sigma_{WACC} = \sqrt{g^2\sigma_D^2 + (1 - g)^2\sigma_E^2}.$$

The resulting mean and standard deviation of the WACC are given in Table 2, along with the other parameter values of this section.

5 Numerical results

5.1 Base case

First we determine the optimal regulator's WACC in the base case with all data as given in Sect. 4. To do so, we estimate the total discounted consumer surplus, the total expected discounted disruption costs in the network, and the total expected discounted social welfare for different choices of the regulator's WACC. In Fig. 2 these estimates are depicted as differences with respect to the situation where we use zero markup for the regulator's WACC on top of the mean WACC on the capital market μ_{WACC}. For convenience, we define ΔCWD, as the negative value of the difference in expected discounted disruption costs (DC) in order to have a clear relation with consumer welfare (i.e. disruption costs are negatively related to consumer welfare). As a consequence, $\Delta CW = \Delta CS + \Delta CWD$, where ΔCW represents the difference in expected discounted social welfare, and ΔCS the difference in consumer surplus
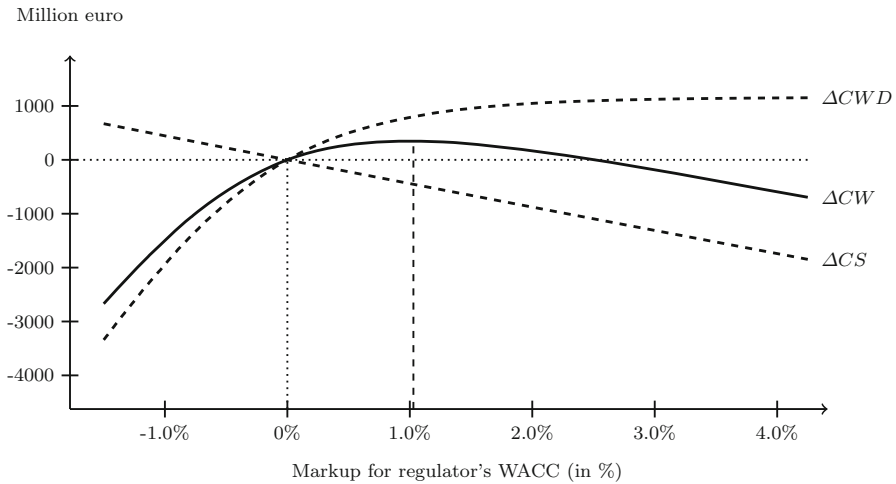
Million euro

Fig. 2 The impact on welfare (total and components) of alternative markup levels for the regulator's WACC in comparison to a zero markup (which is represented by a dotted vertical line in the graph). The markup for the regulator's WACC maximizing the Welfare, represented by the dashed vertical line, is 1.0%

resulting from changing in grid tariffs. We do not report confidence intervals for our estimates, since they are extremely small when using $S = 10,000$.

From Fig. 2, we observe that the consumer surplus is negatively related and the consumer welfare resulting from disruption cost is positively related to the markup level used by the regulator. This is because a lower markup level, for instance, leads to less investments in the network, and thus more disruptions on the one hand, but also lower prices for network usage, and thus larger consumer surplus on the other hand. This reasoning also explains why consumer welfare resulting from expected discounted disruption costs increases when the markup increases, while the consumer surplus resulting from tariffs decreases when the regulator uses a positive markup. As can be seen in Fig. 2, it turns out, however, that the decrease in consumer welfare resulting from the disruption costs is much larger for negative markups for the regulator's WACC than the increase in consumer surplus. As a result, the optimal markup level for the regulator's WACC, maximizing total expected discounted social welfare, is +1.0%, which means that the optimal level of the regulator's WACC is above the historical mean WACC.

In Table 3, we show several quantiles of the distribution of the network disturbances over time for three different levels of the markup for the regulator's WACC (−1%, 0%, +1%). In particular, we show the hours per year of network disruptions, averaged over five-year regulatory periods. Since these values depend on whether there have been investments in the electricity grid, and thus on the expected future values of the WACC on the capital market, we show median values in Table 3, as well as the 25% and 75% quantiles. We observe that for a negative markup level of −1%, the hours of disruptions in the electricity network per year during the first regulatory period remain small, between 0.61 and 0.81. However, these numbers gradually increases over the time horizon, and in the last regulatory period the median value is 1.55 hours per year

Table 3 Quantiles of the distribution of the hours of network disruptions per year averaged over five-year regulatory periods for several values of the markup of the regulator's WACC. The markup of +1.0% corresponds to the optimal markup level for the regulator

Markup WACC	Quantile	Regulatory period					
		1	2	3	4	5	6
−1.0%	25%	0.61	0.67	0.71	0.77	0.82	0.86
	Median	0.77	0.88	1.05	1.23	1.35	1.55
	75%	0.81	1.26	1.62	1.96	2.34	2.68
0%	25%	0.60	0.60	0.60	0.60	0.60	0.60
	Median	0.65	0.65	0.71	0.72	0.72	0.72
	75%	0.79	0.88	0.96	1.00	1.03	1.08
+1.0%	25%	0.60	0.60	0.60	0.60	0.60	0.60
	Median	0.60	0.60	0.60	0.60	0.60	0.60
	75%	0.66	0.68	0.69	0.69	0.69	0.69

and 75% quantile equals 2.68 hours per year. Also observe that the uncertainty in the hours of network disruptions per year increases over the time horizon. This is explained by the fact that over a longer time horizon, it is possible that the electricity network is not maintained for a longer period, leading to longer and larger disruptions in the network. The quantiles, however, also depend on the probability that the electricity network will be maintained, and thus on the markup level for the regulator's WACC. This explains why we see the same effects for the zero markup case, but to a lesser extent. For the optimal markup level of +1.0%, however, the hours of disruption in the electricy network do not seem to increase over time, suggesting that for this markup level the network operator is able to maintain a high quality of the electricty grid with high probability.

Next, we carry out a sensitivity analysis to see how the optimal markup level for the regulator's WACC behaves under changes in the standard deviation of the WACC on the capital market (Sect. 5.2), the value of lost load (Sect. 5.3), the social discount factor (Sect. 5.4), and the persistency level of the WACC on the capital market (Sect. 5.5).

5.2 Optimal markup for the regulator's WACC as a function of the standard deviation

Above we found that the socially-optimal markup level for the regulator's WACC is positive, but this result may be related to the assumed uncertainty. Therefore, we conduct a sensitivity analysis. Figure 3 shows the optimal markup for the regulator's WACC as a function of the standard deviation of the WACC on the capital market and the annual replacement rate (β). As can be observed, when $\beta = 0.1$, the optimal markup value for the WACC is positive unless the standard deviation is large and exceeds 3.5%. In that case, it is optimal to choose a negative markup level, and thus a WACC which is below the historical average.
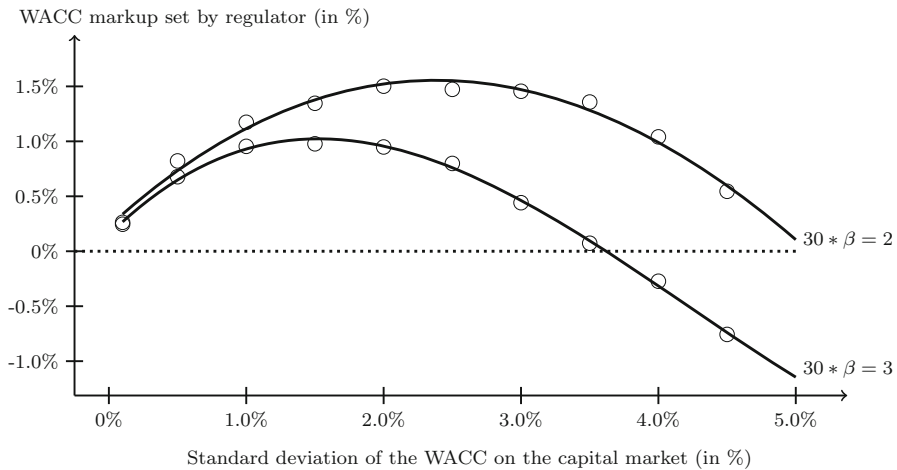
WACC markup set by regulator (in %)

Fig. 3 The optimal markup for the regulator's WACC as a function of the standard deviation of the cost of capital on the capital market for both $\beta = 1/15$ and $\beta = 1/10$. All other parameters are the same as in the base case. The points are the calculated values. The lines represent quadratic regressions through these points

For $\beta = 0.1$, the optimal markup level for the WACC turns out to be largest for medium values of the standard deviation between 1.0% and 2.5%. This can be explained as follows. For small values of the standard deviation, the value of the costs of capital on the capital market is almost deterministic and equal to the mean value of the WACC. By setting the WACC slightly above its mean level, the regulator makes sure that the network operator will be able to invest in the network in almost every period. This significantly reduces the total expected discounted disruption costs in the network at the expense of only a small increase in the total consumer surplus. For large values of the standard deviation, however, a small increase in the WACC does not lead to a large reduction in the expected total discounted costs. In fact, an opposite effect takes place. The reason for this is that in case of high uncertainty around the true costs of capital, there are likely also more situations in which the regulated WACC is sufficiently high to compensate for the actual costs, and, consequently, the firm will be able to finance and maintain the network quality. Since the effect on the expected total discounted costs is small, it pays off to lower the value of the WACC so that consumer surplus increases. We thus observe a counterintuitive effect from increased uncertainty in the WACC: there is a significant probability that the WACC on the capital market is low and investments can be financed, even if the markup for the regulator's WACC is negative, so that the WACC is below its mean value, which means that under high uncertainty, the WACC can be set below the historical average level. In all other cases, however, the regulator's WACC should be set above the historical average level.

The latter observation depends significantly on the ability of the network operator to replace a sufficiently large fraction of its assets in a single period. When $\beta = 1/15$, and thus lower than in the base case, then we observe from Fig. 3 that the regulator should always set a positive markup level for the WACC, and always higher than in the case $\beta = 0.1$. This is because expected disruption costs will be higher if less

assets can be renewed in a single period. To avoid large expected disruption costs, it is optimal for the regulator to set a higher WACC.

5.3 Relation between optimal WACC markup, VoLL, and the expected percentage of lost load

As expected, the optimal markup for the regulator's WACC increases if the value of lost load increases. This is because disruptions in the network hurt social welfare more when the VoLL is higher. To compensate for that, the regulator should typically set the WACC higher. This is confirmed in Fig. 4 for both $\beta = 1/15$ and $\beta = 1/10$. There we also observe that the optimal markup for the WACC does not seem to increase linearly in the VoLL but increases slower for larger values of the VoLL. This can be explained by the fact that for these higher values the optimal markup for the WACC is already quite high, meaning that there are already investments in the network in most of the time periods. A large further increase in the markup, and thus the WACC, will reduce the consumer surplus more than it will increase the total expected discounted disruption costs in the network. Finally, we note that it is almost always optimal for the regulator to set a positive markup level for the regulator's WACC unless the VoLL is small and below 7,000 euro per MWh. Thus, for realistic values of the VoLL between 10,000 and 25,000 euro per MWh, the regulator should set the WACC above its mean value.

This observation also holds when we perform a sensitivity analysis on the expected percentage of lost load π_j in Fig. 5. Using the values from Fig. 1, we observe that the regulator has to set the WACC highest in the linear case, and higher in the quadratic than in the exponential case. This result is counterintuitive, since the expected percentage
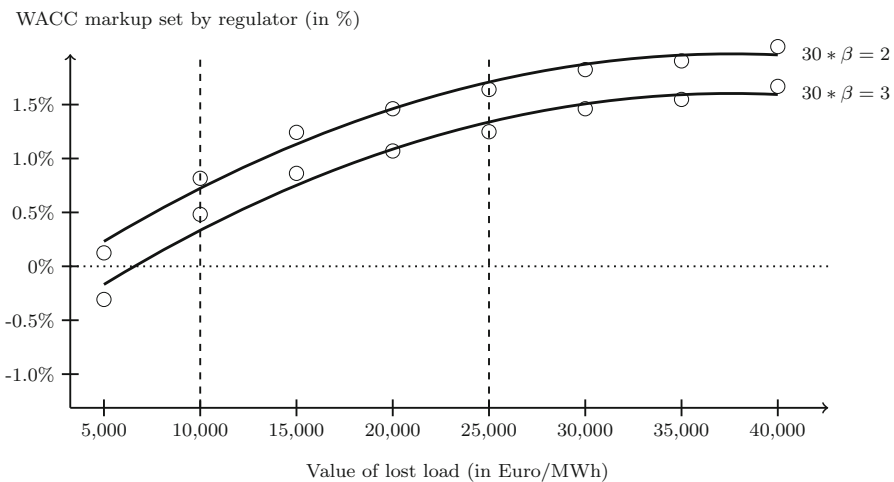
Fig. 4 The optimal markup for the regulator's WACC as a function of the value of lost load for $\beta = 1/15$ and $\beta = 1/10$. All other parameters are the same as in the base case. The dotted line represents zero markup for the regulator's WACC. The points represented the computed optimal values of the markup for the regulator's WACC. The solid lines are quadratic regressions through these points
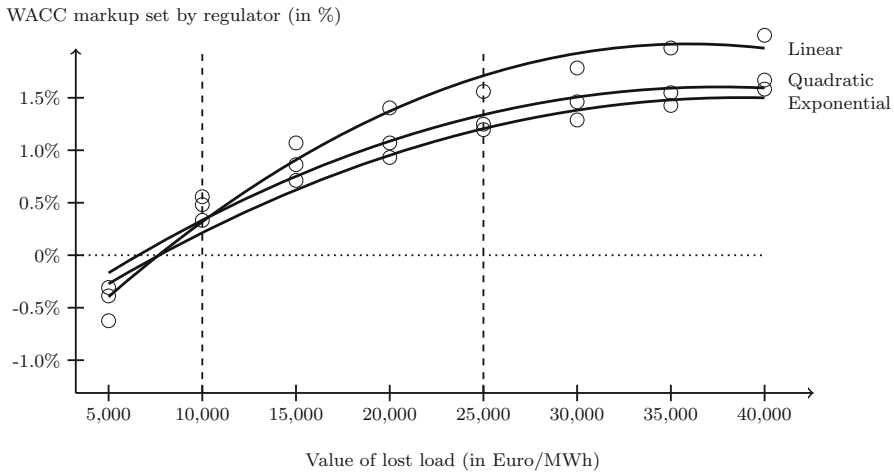
WACC markup set by regulator (in %)

Fig. 5 The optimal markup for the regulator's WACC as a function of the value of lost load using expected percentages of lost load π_j determined by linear, quadratic, and exponential interpolation, see Fig. 1. All other parameters are the same as in the base case. The dotted line represents zero markup for the regulator's WACC. The points represented the computed optimal values of the markup. The solid lines are quadratic regressions through these points

of lost load is highest in the exponential case for high age levels, and thus we expect the WACC highest in the exponential case to avoid this high loss of load. It turns out, however, that the optimal markup for the WACC is selected such that large periods of underinvestment are avoided anyway. It is therefore, much more relevant what the expected percentage of lost load is for smaller age values j. Since for the linear model this expected percentage is larger compared to the quadratic and exponential model, there are more benefits from increasing the WACC set by the regulator so that on average, say every 2 instead of 3 periods, replacement investments can be made. In the quadratic and exponential model, this effect is smaller, and thus the regulator can set the WACC at a lower level. The same argument explains why the regulator has to set the WACC slightly higher in the quadratic case than in the exponential case.

5.4 Relation between optimal markup for the regulator's WACC and social discount rate

It appears, however, that the social discount rate does not have a large impact on the optimal markup level for the WACC. As can be seen in Fig. 6, the differences are small even for extreme values of the discount factor. This also holds when using different values for β, e.g., $\beta = 1/15$.

5.5 Persistency on the capital market

In our analysis so far, we have assumed that there is a high persistency in the WACC on the capital market, meaning that the correlation ρ between consecutive observations of the WACC on the capital market is large. As expected, the optimal markup level
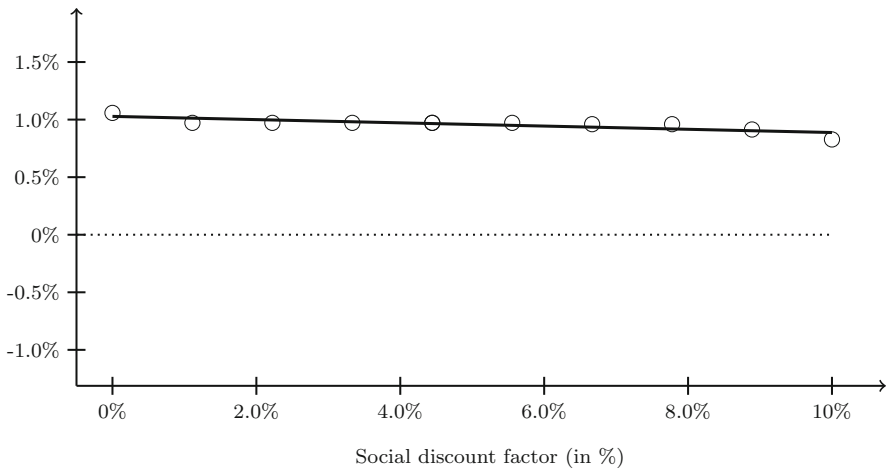
WACC markup set by regulator (in %)

Fig. 6 The optimal markup for the regulator's WACC as a function of the social discount factor. All other parameters are the same as in the base case. The points are the values computed and the line represents a linear interpolation through these points
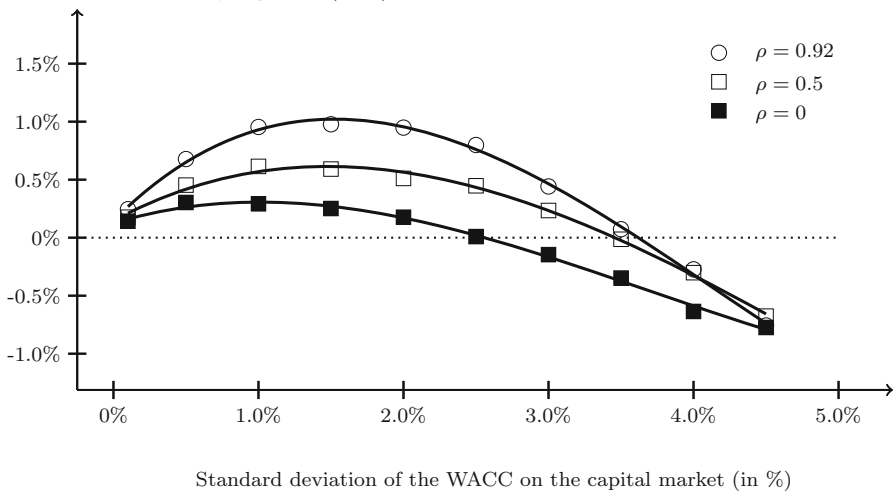
WACC markup set by regulator (in %)

Standard deviation of the WACC on the capital market (in %)

Fig. 7 The optimal markup for the regulator's WACC as a function of the as a function of the standard deviation of the cost of capital on the capital market for several values of the autocorrelation ρ of the WACC on the capital market. All other parameters are the same as in the base case. The lines represent quadratic regressions through these points

for the regulator's WACC decreases when this autocorrelation ρ is smaller; see Fig. 7. The optimal markup level for the regulator's WACC, however, remains positive for small-medium values of the standard deviation of the WACC on the capital market. For $\rho = 0$, the case where the observations of the WACC on the capital market are independent, the optimal markup only becomes negative for values of the standard deviation above the 2.5%.

6 Conclusion

Although regulators in practice base the WACC in tariff regulation on the average historical values, from a social-welfare perspective it may be optimal to choose a different level. We have analyzed how a regulator should select the weighted average cost of capital (WACC) over a fixed regulatory period when the actual WACC on the capital market fluctuates over the period. Trading off consumer surplus and expected total discounted disruption costs in the grid, we conclude that it is optimal for the regulator to set the WACC above the mean WACC on the capital market, provided that the uncertainty about the real cost of capital is not very large while the network operator is able to quickly increase the size of the investments. Only when these conditions do not hold, it is optimal to set the regulator's WACC below the average historical value of the actual costs of capital. However, when the network operator is limited in the speed of increasing investments, the uncertainty regarding the actual costs of capital does not matter: in such a situation it is always optimal to set the WACC above the historical average levels independent of this uncertainty. Further sensitivity analysis reveals that increasing the value of lost load increases this optimal WACC, which follows from the fact that a higher value of lost load raises the costs of under investments. The finding that a higher WACC contributes to grid investments and, hence, in grid reliability is in line with literature (see e.g. Cambini and Rondi (2010) The contribution of our paper is that we show that a higher WACC is also optimal from a consumer-welfare point of view. We have shown that the costs of a higher WACC in terms of higher tariffs for consumers are more than outweighed by the benefit of having a lower risk of disturbances. These results are based on a stylized model that simulates investments by the operator of an electricity grid which is subject to price-cap regulation and that is calibrated on the Dutch situation. These results could be tested by further researching the relationship between investments and network degradation and the impact of the level of allowed revenues and investments by regulated network operators. Despite the restricted setup of the model, the general conclusion that, in most cases, the optimal WACC is above the WACC based on historical averages appears to be consistent with findings of others (see e.g. Dobbs (2011) These conclusions may be considered by regulators when evaluating the methods for determining the WACC in tariff regulation. This conclusion does, however, not imply that raising the WACC is a sufficient measure to guarantee the reliability of the grid. The level of WACC, and other components of tariff regulation, only affect the ability of grid operators to finance the necessary investments. Next to this, other types of regulation may be necessary, such as reliability standards, to give incentives to grid operators to maintain or improve network quality.

References

ACM (2012). Regulatorische accountingsregels 2011. https://www.acm.nl/sites/default/files/old_publication/bijlagen/7179_RARRAR%20TenneT%202011.pdf.

ACM (2019a). Documentnr. ACM/UIT/505475. https://www.acm.nl/sites/default/files/documents/2019-01/herstel-bijlage-2-uitwerking-van-de-methode-voor-de-wacc.pdf.

ACM (2019b). X-factorbesluit transporttaak tennet 2017-2021. https://www.acm.nl/sites/default/files/documents/2019-01/herstel-bijlage-2-uitwerking-van-de-methode-voor-de-wacc.pdf.

ACM (2021). Advies vermogenskostenvoet drinkwaterbedrijven vanaf 2022. ACM/21/053238, The Hague, 28 September.

Arcos-Vargas, A., Núñez, F., & Ballesteros, J. A. (2017). Quality, remuneration and regulatory framework: Some evidence on the European electricity distribution. *Journal of Regulatory Economics, 51,* 98–118.

Cambini, C., Fumagalli, E., & Rondi, L. (2016). Incentives to quality and investment: Evidence from electricity distribution in Italy. *Journal of Regulatory Economics, 49,* 1–32.

Cambini, C., & Rondi, L. (2010). Incentive regulation and investment: Evidence from European energy utilities. *Journal of Regulatory Economics, 38,* 1–26.

Council of European Energy Regulators (2019). Incentive regulation and benchmarking. CEER Report C18-IRB-38-03.

Dimson, E., Marsh, P., & Staunton, M. (2000). Risk and return in the 20th and 21st centuries. *Business Strategy Reviews, 11*, 1–18.

Dobbs, I. M. (2011). Modeling welfare loss asymmetries arising from uncertainty in the regulatory cost of finance. *Journal of Regulatory Economics, 39*, 1–28.

Mulder, M. (2012). Financeability of investments and allocation of costs: An assessment of the incentive regulation of the Dutch high-voltage network. *Competition and Regulation in Network Industries, 13*, 160–186.

Mulder, M. (2021). *Regulation of Energy Markets: Economic Mechanisms and Policy Evaluation*. Springer International Publishing.

Nemati, H. M., Sant'Anna, A., & Nowaczyk, S. (2015). Reliability evaluation of underground power cables with probabilistic models. In *In DMIN'15: The 2015 International Conference on Data Mining* (pp 37–43).

Ovaere, M., Heylen, E., Proost, S., Deconinck, G., & van Hertem, D. (2019). How detailed value of lost load data impact power system reliability decisions. *Energy Policy, 132*, 1064–1075.

Oxera (2015). Which WACC When? A cost of capital puzzle. April.

Schober, D., Schaeffler, S., & Weber, C. (2014). Idiosyncratic risk and the cost of capital: The case of electricity networks. *Journal of Regulatory Economics, 46,* 123–151.

Schröder, T., & Kuckshinrichs, W. (2015). Value of lost load: An efficient economic indicator for power supply security? a literature review. *Frontiers in Energy Research, 3,* 55.

TenneT (2019). Tariefbesluit TenneT 2019. https://www.tennet.eu/fileadmin/user_upload/The_Electricity_Market/Dutch_Market/Tarievenbesluit_TenneT_2019.pdf.

TenneT (2021). Integrated annual report 2020. https://annualreport.tennet.eu/2020/downloads/qSzBp7HNbwVX/TenneT-IAR-2020.pdf.

Ter-Martirosyan, A., & Kwoka, J. (2010). Incentive regulation, service quality, and standards in U.S. electricity distribution. *Journal of Regulatory Economics, 38*, 258–273.

Viscusi, W. K., Harrington, J. E., & Vernon, J. M. (2005). *Economics of Regulation and Antitrust*. The MIT Press.

World Energy Council. (2018). *World energy trilemma index 2018*. United Kingdom.