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Current Situation on the Czech Electricity Market: with an Emphasis on the Fourth Regulatory Period of the Czech Energy Regulatory Office

Master Thesis

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Abstract

This thesis examines the current situation on the electricity market in the Czech Republic. A particular emphasis is put on the regulation of distribution system operators (DSOs). The Czech regulator applies only general efficiency factors for all incumbents, and the efficiency of the incumbents is not taken into account in the regulatory formula. In many countries, the regulators apply benchmarking methods to assess the efficiency of operators. This thesis analyses the current regulatory formula in international comparison and considers the application of benchmarking methods to the regulation of DSOs. The first part provides a description of the theoretical approach to the regulation of network industries, relevant legal norms, the current situation on the Czech electricity market and practices of the regulatory bodies in selected European states. The second, empirical, part presents an international benchmarking study based on data of 15 regional DSOs including two Czech operators. The study examines the application of yardstick methods using data envelopment analysis (DEA) and stochastic frontier analysis (SFA). Based on our results, we find that the cost efficiency of each of the Czech DSOs is different. This suggests that introducing individual efficiency factors in the fourth regulatory period is a suitable action.

JEL Classification	K23, L43, L49, L94
Keywords	Regulation, benchmarking, electricity distribution, utilities

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Abstrakt

Tato práce zkoumá situaci na trhu s elektřinou v České republice. Speciální důraz je kladen na regulaci distribučních společností. Energetický regulační úřad aplikuje pouze obecný faktor efektivity a v rámci regulačního vzorce tak není zohledněna efektivita jednotlivých společností. Mnoho regulačních úřadů využívá metody benchmarkingu ke stanovení efektivity jednotlivých firem. Práce analyzuje současný regulační vzorec v mezinárodním srovnání a posuzuje využití benchmarkingu pro regulaci distribučních společností. První část práce se věnuje teorii regulace síťových odvětví, legislativě, současné situaci na českém energetickém trhu a praxi regulátorů ve vybraných evropských státech. Druhá, empirická, část je věnována benchmarkingové studii 15 mezinárodních distribučních společností včetně dvou českých společností. Analýza je provedena pomocí benchmarkingových metod, data envelopment analysis a stochastic frontier analysis. Naše výsledky ukázaly, že nákladová efektivita českých společností se významně liší, což indikuje vhodnost začlenění individuálních faktorů efektivity v nadcházejícím čtvrtém regulačním období.

Klasifikace JEL K23, L43, L49, L94
Klíčová slova Regulace, benchmarking, distribuce elektřiny, síťová odvětví

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Proposed Topic:

Current Situation on the Czech Electricity Market – with an Emphasis on the Fourth Regulatory Period of the Czech Energy Regulatory Office

Topic Characteristics:

Situation on the Czech energy market was changed by an implementation of two systems of legislative norms of the European Union (EU) - the EU climate and energy package together with the third legislative package for an internal EU gas and electricity market. The position of national regulatory offices was redefined and their authority reinforced.

The distribution and transmission of electricity belong to the sectors that are typical natural monopolies because a construction of a competing infrastructure is not economic. Therefore the operation must be regulated by a regulatory body, in the Czech Republic represented by the Czech Energy Regulatory Office, which regulates monopolies to prevent incontrollable fluctuations of energy prices.

The final price of the supplied energy, which is equal for all customers, consists of five basic components. The components are a price of the commodity (energy), costs of transportation (transmission, distribution), providing the technical stability of the grid (systemic services), ensuring the trade stability of the grid (costs of deviation) and the contribution to support renewable sources, combined heat and power generation and secondary energy sources.

The aim of the diploma thesis is to consider and evaluate alternatives to the revenue-cap scheme that was used by the Czech Energy Regulatory Office in the third regulatory period and to assess the alternatives for the forthcoming fourth regulatory period (2015-2020). The aim of this work is also to evaluate whether the price-cap regulation should replace revenue-cap scheme and whether the benchmarking methods should be included in the forthcoming period. The thesis will also look at whether the incentive-based regulation facilitates deployment of new technologies and brings policy recommendations.

Hypotheses:

1. The current legal environment does not offer sufficient incentives for the distribution operators to invest in new technologies.
2. The promotion of the smart grids is not profitable for distributors.
3. The revenue-cap regulation should be adjusted in the fourth regulatory period.
4. The lack of data constraints effective adoption of benchmarking methods.

Methodology:

Concerning the literature covering the incentive regulation, I will analyze the policies of the Czech and foreign regulators and compare them.
The empirical part will be based on the available data on the distribution companies. I will analyze the effectiveness of the incentive mechanisms and the selection of parameters for incentive regulation.

To evaluate the possibility of application of benchmarking methods, frontier and non-frontier methods will be considered. Namely, I will focus on non-parametrical (DEA) and statistical techniques (e.g., COLS), and total factor productivity method (TFP) respectively. The applicability of the benchmarking in the Czech energy sector will be evaluated.

Outline:

1. Introduction
2. Theoretical approach to the regulation of network industries
3. Legal norms of the Czech Republic and the European Union
4. Current situation on the Czech energy market
5. Practices of the regulatory bodies in the Czech Republic and other states of the EU
6. Empirical part
7. Results
8. Conclusion

Core Bibliography:

1. Cambini, C. and Rondi, L. (2010). Incentive regulation and investment: Evidence from European energy utilities. *Journal of Regulatory Economics* [online]. **38**, p. 1-26. Available from: <http://link.springer.com/article/10.1007/s11149-009-9111-6>. [Accessed 26 January 2013].

2. Cullmann, A. (2012). Benchmarking and firm heterogeneity: A latent class analysis for German electricity distribution companies. *Empirical Economics* [online]. **42**, p. 147-169. Available from: <http://link.springer.com/article/10.1007/s00181-010-0413-4>. [Accessed 26 January 2013].

3. Energy Regulatory Office (2009). *Závěrečná zpráva ERÚ o metodice regulace III. regulačního období*. Prague: Energy Regulatory Office. Available from: <http://www.eru.cz/user_data/files/prezentace_III_RO/Zaverecna_zprava_o_metodice_III_RO.pdf>. [Accessed 26 January 2013].

4. Growitsch, C. et al (2010). Social cost-efficient service quality - Integrating customer valuation in incentive regulation: Evidence from the case of Norway. *Energy Policy* [online]. **38**, p. 2536-2544. Available from: <http://www.sciencedirect.com/science/article/pii/S0301421510000042>. [Accessed 26 January 2013].

5. Jamasb, T. and Pollitt, M. (2003). International benchmarking and regulation: an application to European electricity distribution utilities. *Energy Policy* [online]. **31**, p.1609–1622. Available from: <http://www.sciencedirect.com/science/article/pii/S0301421502002264>. [Accessed 1 November 2013].

6. Nagel, T. and Rammerstorfer, M. (2008). Price Cap Regulation and Investment Behavior - How Real Options Can Explain Underinvestment. *Journal of Energy Markets* [online]. **14**. Available from: <http://ssrn.com/abstract=1029578>. [Accessed 26 January 2013].

7. Nykamp, S.; Andor, M. and Hurink, J. L. (2012). ‘Standard’ incentive regulation hinders the integration of renewable energy generation. *Energy Policy* [online]. **47**, p. 222–237. Available from: <http://www.sciencedirect.com/science/article/pii/S0301421512003667>. [Accessed 26 January 2013].

8. Prüggler, N. and Bremberger, C. (2011). Grid regulation in Austria: Smart grids incentives or disincentives? *e & i Elektrotechnik und Informationstechnik* [online]. **128**, p. 336-341. Available from: <http://link.springer.com/article/10.1007/s00502-011-0042-4>. [Accessed 26 January 2013].

9. Shuttleworth, G. (2005). Benchmarking of electricity networks: Practical problems with its use for regulation. *Utilities Policy* [online]. **13**, p. 310–317. Available from: <http://www.sciencedirect.com/science/article/pii/S0957178705000135>. [Accessed 26 January 2013].

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Acronyms

ČEPS Čeps, a.s (Czech transmission system operator)

CAPEX Capital expenditures

COLS Corrected ordinary least squares

CRS Constant returns to scale

DEA Data envelopment analysis

DMU Decision making unit

DSO Distribution system operator

EEX The European Energy Exchange

EMV Energiamarkkinavirasto (Finnish regulatory office)

ERU Energetický regulační úřad (Czech regulatory office)

EU The European Union

ISO Independent system operator

ITO Independent transmission operator

MOLS Modified ordinary least squares

NIRS Non-increasing returns to scale

Ofgem Office of Gas and Electricity Markets (British regulatory office)

OLS Ordinary least squares

OPEX Operating expenditures

OTE Operátor trhu s elektřinou, a.s. (Czech electricity market operator)

PXE The Power Exchange Central Europe

RAB Regulatory asset base

RIA Regulatory impact assessment

SAIDI System Average Interruption Duration Index

SAIFI System Average Interruption Frequency Index

SFA	Stochastic frontier analysis
TFT	Total factor productivity
TOTEX	Total expenditures
TSO	Transmission system operator
URE	Urzad Regulacji Energetyki (Polish regulatory office)
URSO	Úrad pre reguláciu sieťových odvetví (Slovak regulatory office)
VRS	Variable returns to scale
WACC	Weighted average cost of capital

1 Introduction

The energy market in the Czech Republic has undergone significant changes in the last two decades. The structure of the market was reformed to introduce competition and improve the operation of natural monopoly activities. The unbundling of the electricity sector was completed and the position of national regulatory authority was reinforced. Despite the changes in the market environment, there are still sectors within the market where the competition is restrained; therefore, there is a need for them to be regulated. In the energy sector, electricity transmission and distribution services are natural local monopolies that are subject to some kind of regulation.

The liberalisation of the network industries was accompanied with transformation of regulatory arrangements that shifted from cost of service and rate of return methods to incentive-based schemes. The Czech regulator, the Energy Regulatory Office (hereafter ERU), has been applying the incentive regulation in the form of a revenue cap since its establishment in 2001. The incentive regulation is designed to mitigate regulatory constraints and motivate firms to improve their operation. The setting of parameters of the regulatory formula determines the prices the consumers are bearing and the profitability and performance of the incumbents. That is the reason why it is important to examine the operation of particular companies.

There are three regional distribution companies and one transmission operator dominating the market. In this thesis, we focus on the regional distribution system operators. Their operation is tightly regulated by ERU, which regulates their activities to control their natural monopolistic operation. In contrast to regulatory practices in other states of the European Union (e.g. Austria, Germany, Great Britain, Finland, Netherlands), the benchmarking of electricity distribution operators has not been incorporated in the Czech regulation yet. The application is constrained by a lack of data and a low number of incumbents. In the third regulatory period, ERU (2009) sought to determine individual efficiency factors using benchmarking techniques to reflect the efficiency of operation of the incumbents. The efficiency factor should have penalised the least efficient companies; however, ERU abandoned the idea and justified it by the lack of data on comparable firms. The parameters of the forthcoming 2015-2019 fourth regulatory period for the regulation of electricity companies have not been defined yet.

The benchmarking analysis of the Czech regional electricity distribution system operators in an international comparison has not been conducted yet, according to our knowledge. For our thesis, we were inspired by the work of Pollitt and his colleagues (e.g. Jamasb and Pollitt, 2003; Haney and Pollitt, 2009; Haney and Pollitt, 2013), Kuosmanen et al.

(2013), and Joskow (2013). These authors studied the use of benchmarking methods for regulation of electricity networks and examined the application of incentive regulation. For the theory of benchmarking methods and computation programmes, we generally follow studies and works of Coelli (Coelli, 1996a; Coelli, 1996b; Coelli et al., 2005).

The aim of our thesis is thereby to analyse the methods of ERU and examine the adoption of international benchmarking for regulation of Czech distribution system operators. The applicability of benchmarking methods is evaluated considering the limitations stemming from international comparison and confidentiality of data. Furthermore, the appropriateness of the regulatory framework is examined. The differences in efficiency of incumbents would indicate an unsuitable setting of only the general X factor in the regulatory formula. The current regulatory scheme is analysed to find out whether the companies are incentivised sufficiently to invest in new technologies.

In the empirical analysis, the data envelopment and stochastic frontier analyses are applied. Our study is based on data of the regional electricity distribution system operators with more than 100,000 customers. The selection is based on the legal regulatory requirements. The Czech operators are complemented with companies from other European states. For the assessment, both cost and technical data are used. The data were obtained from published financial statements, annual reports and online resources of the companies. Due to the fact that most of the data necessary for the analysis are considered confidential, these had to be complemented with data obtained directly from the individual companies. The provision of data was conditional on contracts and declarations on oath that we had to sign with multiple companies. As we are bound by contractual obligations, we are not allowed to disclose names of the companies with the exception of the Czech firms, which have the data publicly accessible.

The thesis is organised as follows. Chapter 2 provides a description of the theoretical approach to the regulation of network industries. Within the chapter, basic models of regulation of utilities, incentive regulation and benchmarking are defined. The derivation of X factor for incentive regulation is described based on a model introduced by Bernstein and Sappington (1999). Chapter 3 is devoted to the legal norms of the Czech Republic and European Union. The legislature of the European Union significantly affected the Czech energy market and initiated liberalisation of the energy market. Chapter 4 provides a summarising review of the current situation on the Czech electricity market. Chapter 5 describes methods of ERU and other regulatory bodies in selected states of the European Union. The empirical part is commenced by Chapter 6, which provides details about methodology, data and estimated models. Chapter 7 presents the results and policy implication. Last Chapter 8 concludes.

2 Theoretical approach to regulation of network industries

The network industries are traditionally subject to some kind of regulation. Given their typical market structure, natural monopoly, they are naturally inclining to, they were gradually transformed from state owned and private regulated monopolies. So called network industries comprise mostly telecommunications, energetics, railroads and water management. These utilities are characteristic by economies of scale and high level of sunk costs that prevent other competitors to enter the market.

The electric utilities were able to operate de facto exclusively on the market and therefore they did not face competition. A typical feature of the electric utilities was vertical integration. The companies were engaged in the whole chain covering generation, transmission and distribution to the end customers. It was generally believed that if these utilities were to be able to freely set the profit maximising prices, they would have been able to charge the customers prices high above the regulated rates (Joskow and Schmalensee, 1986). Even though we can assume possible substitutes for the electricity (e.g. solid fuels for heating), the demand for electricity can be hardly considered as highly elastic due to limited self-generating options and absence of perfect substitutes for most of the appliances.

The transformation of traditional regulatory regimes was not the only change that took place. The shift of regulatory practices was supplemented by other institutional changes of the network industries that evolved as either state-owned or privately held vertically integrated monopolies (Joskow, 2013). They were privatised, restructured, separated, and deregulated. The reform programmes typically encompassed the process of unbundling (vertical separation of ownership or functional separation) of potentially competitive branches of incumbent monopolist. The segments were gradually deregulated, but remained subject to price regulation, regulations ensuring the network services, quality requirements and general efficiency of the successors. The incentive regulation was expected to mitigate regulatory constraints (there are three general regulatory constraints: informational, transactional, and administrative and political; refer to Laffont and Tirole, 1993) and to motivate the regulated firms to reduce costs and improve services, stimulate them to invest in new technologies and in development of network infrastructure. The overall process is often called liberalisation.

Hand in hand with the reform of the public utility sectors, the independent regulators were established. Especially the European utilities were mainly dominated by state monopolies that were during the last two decades privatised and there was a difficult task for the independent regulators to choose and implement suitable forms of regulation. Although most of the electric utilities were unbundled and individual services were separated, the transmission system operators (TSOs) and the distribution system operators (DSOs) remained natural monopolies at least at a regional level and they have been at the centre of the regulatory policies. The competition was mostly introduced in the sectors of electricity production, trading and retail services. The unbundled distribution and transmission operators still form the natural monopolies and require regulation. Jointly with the change of the structure of the regulated companies, a demand for new non-monetary factors has been increasing. Environmental and security issues have gained an importance and have raised claims for new grid investments. The regulator seeks to secure a certain level of security of supply while ensuring the supply to be affordable for customers at a reasonable price.

2.1 Policy implementation issues

During the late 1980s and the early 1990s the liberalisation methods developed and were applied in Europe, North America, Latin America, Australia and New Zealand. Despite the seemingly straightforward incentive methods and theoretical deductions, the efficient implementation is more complex and complicated. Similarly to the rate of return regulation, the implementation of incentive schemes depends on quality and scope of acquired information, accounting and auditing methods. It is also necessary to precisely define the quality requirements. In contrast with the theory, the regulators never have perfect information; moreover, the regulated firms are generally deemed to possess more information about related activities than any other third party. The firm might be able to use the information dominance to maximise its profits at consumers' expenses (Laffont and Tirole, 1993). The effect might be further endorsed if the company is able to induce the regulator to follow directly its interests and capture the regulator (so called regulatory capture). The discretion power of regulators was reinforced over the years to mitigate the information asymmetry. They have access to accounting of the regulated firms, they have right to request additional information, and many transparency requirements were set up. The regulation is a repeated game and the regulatory methods are constantly evolving. The asymmetry of information between the regulator and the regulated firm will, however, always remain.

According to Joskow (2013), there are a few issues the regulator should address:

(i) The regulator should have consistent mechanisms to measure the firm's actual costs consisting of both operating costs and cost of capital investment. The operating costs were often neglected in the theoretical literature and the regulators should adopt transparent accounting rules, auditing techniques and reporting standards to curb the information asymmetry; moreover, the quality measurements to control the firm's performance should be introduced.

(ii) The regulator should choose whether the regulated firm will be offered a specific contract with a single set of values or a menu of contracts. The author emphasised the fact that if the firm is offered a menu of contracts, it reveals its type and allows for a better balance of the regulatory measures. The author also notes that in the reality most of the contracts are based on negotiations and are in form of a specific contract, but we see only the final outcome of the negotiations.

(iii) A type of benchmark the regulator is using. The regulators often use the yardstick methods to evaluate efficiency of the incumbents. Where there is not a comparator available, the regulators may use international data or a comparison with non-identical but similar firms.

(iv) The regulator should decide about the level of the power of the incentive schemes. The slope and the height of the contracts should be defined. The regulator may supplement the caps with the floors. The floors are used as a trigger for the renegotiation of the parameters.

(v) The question is whether the incentive schemes should be comprehensive or only partial. From the definition of the costs, it may be convenient to assess differently the operating and capital costs. In contrast with the capital costs, the operating costs can be adjusted relatively quickly. Ideally, the comprehensive approach that takes into account all the factors would be applied; however, the shortage of information will always make it difficult.

2.2 Rate of return regulation

The network industries have undergone significant changes over the last thirty years in the developed world. The traditional forms of regulation were the rate of return or the cost of service regulations that essentially consist of setting a mark-up allowed on costs or allowing rate of return on firm's assets, respectively. Considering the application of both types, they share the similar fundamentals. The rate of return (as well as the cost of service) regulation followed a fundamental premise that the costs of the utility as a whole should equal its overall revenues. In theory, the marginal costs should determine the prices, but it is almost impossible to determine all the costs when many of the inputs are in addition shared.

The rate of return regulation of electric utilities in the United States was used since the early 1900s and was historically performed as price regulation putting an emphasis on allowed rate of return of the utility on invested capital (Joskow and Schmalensee, 1986). The incumbents were subject to the regulation of services and they had to maintain a particular level of services; however, the problem was that the principal concern was not aimed at the oversight of the costs. The regulation was intrinsically retrospective and did not pay attention to the performance and the efficiency in electricity production and distribution. The rate of return regulation was implemented in two steps. Firstly, the revenue requirement of the utility was set up and, secondly, such rates were designed that earned revenues should not have exceeded the revenue requirements. There was no unified approach how to arrive at the desired rate of return and the commissions had full discretion to select it according to the entity's characteristics.

As was shown, a problem is that both the rate of return and the cost of service regulations may discourage the extraordinary incumbents, because they do not reward them for the exceptional performance (Baumol and Klevorick, 1970). They may also motivate the utilities to adjust their capital/labour ratio to raise the profits. The monopoly under the rate of return regulation then may be prone to over-invest in asset base while neglect its productive efficiency. A model that illustrates that the rate of return regulation creates an incentive for the incumbent to invest in tangible assets instead of labour is known as Averch-Johnson Effect named after Harvey Averch and Leland L. Johnson (Averch and Johnson, 1962). Both the rate of return and the cost of service (cost plus) regulations are in present considered as suboptimal, because they do not force the companies to increase the operational efficiency (ERU, 2009).

2.3 Price cap regulation vs. rate of return regulation

In this section, the principal differences between the rate of return and the incentive regulation are described. We compare the rate of return regulation with the most frequent example of the incentive regulation - price cap regulation. We are aware of other general methods of the incentive regulation (predominantly the revenue cap regulation), but the price-cap regulation is in literature used as a typical example and shares most of the patterns with the revenue cap regulation. The yardstick regulation is mostly applied as a complement to the price cap or the revenue cap regulation and it is not used separately. Individual methods of the incentive regulation are described in the following section.

The incentive regulation, or its combination with traditional methods, is at present used by most of the regulators in developed world. It was pioneered and introduced by utility commission in the United States in the late 1970s and the early 1980s when the regulation of natural monopolies and oligopolies awoke broad and revived interest of policy makers (Berg and Jeong, 1991). The attention was focused on quality, price and performance of the regulated firms. The incentive regulation schemes are comprised of both financial rewards and penalties set according to the utility's performance. By the middle of the 1980s, the incentive regulation of electric utilities was widely used by the utility commissions in the United States (Joskow and Schmalensee, 1986).

The incentive regulation was not typical only for the United States. It was also introduced in the United Kingdom in a form of the price cap regulation of utilities in 1984 (Parker, 1997). As well as the rate of return and the cost of service regulation, the incentive regulation has to deal with a multiple parameters that influence and determine the costs consisting of operating and capital costs. These are depreciation, fair return the utilities are entitled to, taxes, definition of asset base and inflation. The problem is that in practice it is generally possible to observe only the accounting of the firm and thus a limited scope of data.

The fundamental assumption of the price cap regulation is that the regulated firms know more about their costs and technological opportunities than the regulators do (Braeutigam and Panzar, 1993). According to Armstrong and Porter (2007), the regulatory policies are to be sorted on four dimensions: (i) the price flexibility granted to the regulated firm, (ii) the way the policy is implemented and revised over time, (iii) the degree to which the prices reflect the realised costs, and (iv) the level of discretion the regulators have while formulating the policies. The incentive regulation (namely the price cap regulation) differs from the rate of return regulation along these four dimensions.

Under the price cap regulation, the prices are permitted to change on average at a specified rate granted for a particular period of time. The price change (increase) is often linked to the rate of inflation and is not influenced by the firm-specific factors - it does not reflect the changes of cost or revenue structure of the firm. An important characteristic is that the only price that is controlled under the price cap regulation is the average price and the firm is free to choose the selection within the basket of regulated services. In contrast, the rate of return regulation focuses on the reasonable rate of return on the company's investment and the regulator sets the prices. The firm has therefore a limited discretion to influence these prices.

The parameters of the rate of return regulation have to be systematically adjusted to provide the firm with reasonable rate of return while ensuring that it will not deviate substantially from the target. The rates for the price cap regulation are to be fixed for several years to motivate the firms to mitigate their costs. It is worth mentioning that the crucial assumption for the price cap regulation is the stability of the environment. The external instability caused for example by rapid technological changes would enable the incumbent to gain windfall profits under the price cap regulation.

The prices at the rate of return regulation are to be set in line with significant changes in costs and revenues to maintain desirable level of return for the firm. Because the firm is entitled to gain reasonable profits on its investment, it might intentionally underestimate and have limited concern about the expropriation of sunk costs by the future regulatory policy. Under the price cap regulation, the current prices do not have to be necessarily in line with the current costs. The regulator has significant discretion over the setting of future policies. Since the prices under the price cap regulation are not linked to the revenues and this status can hold for longer periods, the firms can be heavily prone to reduce their operating expenses.

Both types of regulation produce externalities, which have different effects on the investment behaviour of the firms. The rate of return regulation can promote significant investments in the grid, because the prices are directly linked to the costs; however, the management of the firm might be prone to neglect the riskiness of the particular investment. In contrast, price cap regulation may lead to the significant unobserved reductions of the cost (that would be further augmented if the regulatory period is long), which could lead to the underinvestment.

Nagel and Rammerstorfer (2008) investigated price cap regulation in the EU and they confirmed that the price cap regulation has negative effect on the investments. In contrast, Cambini and Rondi (2010) showed that this does not have to be necessarily true and drew a different conclusion. They investigated the relationship between investment and regulatory regimes of the EU energy utilities and showed that the investment was surprisingly higher under the incentive regulation.

The current state of performance of the utility is crucial for the selection of the suitable form of regulation. If the industry is stable and there is an assumed scope for cost reductions, the price cap regulation would be more suitable. In case of premature underdeveloped industry, the rate of return regulation is theoretically more appropriate. Since the electricity networks are well developed, the incentive schemes have been taking over the rate of return regulation for past 25 years.

2.4 Price cap and revenue cap regulation

There are three general models of the incentive regulation - price cap, revenue cap and yardstick regulation (alternatively called benchmarking). Especially for the electric utilities, the yardstick (benchmarking) techniques are often used to improve and complement the price cap and the revenue cap models. The sliding scale methods were used for the gas utilities in the USA in the 19th and the early 20th century. The dividend payments were dependent on the changes in prices. These methods were, however, not used for the electric utilities and have not much in common with current regulatory practices (for more details, refer to Joskow, 2013; or Joskow and Schmalensee, 1986).

As is obvious from the denotation of both methods, they are both referring to a setting of the upper limit of price or revenue that is allowed for the provision of certain services. The most commonly used methods of the incentive regulation are based on variations of the price cap or the revenue cap methods. The revenue cap regulation is similar to the price cap regulation; except that instead of the prices the attention is focused on the revenues. Both methods are based on an identical formula

$$RPI - X, \tag{2.1}$$

where RPI is a retail or a price index and takes note of inflation; and X represents the desired efficiency gains by the operating firm. The basic formula (2.1) can be for lucidity expanded and is set out

$$R_t = R_{t-1}(1 + RPI_t - X), \tag{2.2}$$

where the R_t is the allowed level of price, or revenue; and t is the index of the year. Sometimes another term is added to the right hand side of the equation to account for the costs that the regulated firm is allowed to transfer to the costumers, usually because it cannot affect these costs (Petrov et al., 2010). It is obvious from the formula that the prices in the current year are capped to the prices of the previous one adjusted for the inflation and a desired increase in efficiency through the variable X. The R_{t-1} is typically set according to some form of cost-based regulation (Joskow and Schmalensee, 1986). A pure price cap is not likely to be optimal system because of the dynamics of the industry and asymmetry of information. At the end of each regulatory period, the R_{t-1} and a new X factor are set up after another review of the firm's efficiency and costs for the regulator to have a ratchet included in the system.

As mentioned above, both methods are sharing principal assumptions. The regulator usually specifies regulatory periods and sets allowed tariffs for these periods based on expected inflation and efficiency improvements. The division into the clearly defined periods is important to maintain a stable business environment for the incumbents. The main idea is that due to stability and specification of the parameters in advance, the firm has incentives to improve its efficiency and maximise the wedge between the tariff and its own performance to increase the profits; moreover, due to the expected efficiency gains, the customers are benefiting from the price decreases (at least in nominal terms). The methods, however, require a precise specification of the parameters to improve the efficiency of the operations of the incumbents.

The crucial question for both types of regulation is how to define the X factor. In comparison of the price cap and the rate of return regulation, the effects of oversetting or undersetting of the X factor were discussed. They can lead to excessive profits for the firm or underinvestment. In the initial stages, indexing and econometric methods were used to set the X factor (Liston, 1993). The indexing was conducted to compare outputs and inputs and their aggregate growth. The econometric methods focused on estimation of parameters of the firm's production and production functions to gain information about the structure of the production process. The X factor does not represent only the technological progress. There are other factors the regulation has to be adjusted for. As Liston (1993) notes, the increase in demand hand in hand with the economies of scale may call for another adjustments. Because of the natural monopoly structure the transmission and the distribution companies are inclining to, this factor seems still legitimate.

The benchmarking methods (see the following chapter) are mostly used to assess the firm's relative efficiency in comparison with its peers. Efficiency frontier is modelled and the firm should be ideally moved to the frontier based on the X factor. Other factors accounting for the quality of the service should be also included. These are for example parameters accounting for electricity outages and quality standards.

There are multiple forms of regulations using either the price or the revenue caps. The adjustments to the RPI may be for example based on a basket of goods or services, or separately for each good and service (Estache et al., 2003). Regulatory periods usually range between three and five years. The tariffs should be designed to redistribute cost savings/efficiency gains to the customers and tariff adjustments should be exogenous on the firm's behaviour. The regulation is a repeated game and therefore each period is often preceded by a consultation period where the incumbents may challenge the proposal and lodge objections. The final scheme should be based on the consultation procedure and should be subject to minor adjustments throughout the regulatory period.

2.5 Modelling the X factor in price cap regulation

In this section, we outline a theoretical model introduced by Bernstein and Sappington (1999), which defines a framework how to determine the X factor. The model is in line with the general formula (2.1) that defines the inflation-adjusted ratio at which the prices should decrease. The idea behind the X factor is quite straightforward, but we believe that the theoretical guidance is noteworthy. We decided to use this model, because the evidence shows that the regulators are favouring the price cap over the revenue cap schemes (refer to Chapter 5). ERU (2013b) also announced shift from the revenue cap to the price cap for the fourth regulatory period for the gas sector and therefore we consider the model to be more appropriate; however, there was no additional information about the regulation in the oncoming fourth regulatory period for the electricity sector during writing of the thesis.

The X factor defines a level of surplus that is transferred from producers to customers. For the sake of simplicity, we assume that all of the services of the firm are subject to the price cap regulation, the output price inflation is independent from the prices of the regulated industry, and we do not anticipate any significant structural change in the regulated industry.

The price cap regulation is designed to replicate the competitive environment. The competition is pushing the prices down. In a perfectly competitive industry, there is no opportunity for the firm to attain a positive profit in the long run and the firm covers its costs. A profit of the firm (Π) is defined as the difference between revenues (R) from its sales and costs (C). The firm buys m inputs and produces n outputs for prices p and w respectively. Assume the prices of the outputs (costs or services) to be regulated. The profit function is defined

$$\Pi = R - C = \sum_{i=1}^{n} p_i q_i - \sum_{j=1}^{m} w_j v_j, \tag{2.3}$$

where the p_i is the price for the i-th regulated output; q_i is the quantity of the regulated output; w_j is the price of the j-th input; and v_j is the quantity of the j-th input.

Taking differentials of the equation (2.3), we determine how the profit changes with respect to changes in all variables. We denote the differentials as "d" for the sake of lucidity and further notation. So we have

$$\Pi\frac{\mathrm{d}\Pi}{\Pi}=\sum_{i=1}^{n}p_iq_i\frac{\mathrm{d}q_i}{q_i}+\sum_{i=1}^{n}p_iq_i\frac{\mathrm{d}pi}{p_i}-\sum_{j=1}^{m}w_jv_j\frac{\mathrm{d}v_j}{v_j}-\sum_{j=1}^{m}w_jv_j\frac{\mathrm{d}w_j}{w_j}. \tag{2.4}$$

In the next step, we divide the equation (2.4) by revenue R, or equivalently, by $C+\Pi$ and after some rearrangements, we get

$$\sum_{i=1}^{n}r_i\dot{p_i}=\frac{C}{C+\Pi}\left(\sum_{j=1}^{m}s_j\dot{w_j}-\sum_{i=i}^{n}r_i\dot{q_i}+\sum_{j=1}^{m}s_j\dot{v_j}+\frac{\Pi}{C}\dot{\Pi}-\frac{\Pi}{C}\sum_{i=1}^{n}r_i\dot{q_i}\right), \tag{2.5}$$

where $r_i\equiv\frac{p_iq_i}{R}$ is a share of revenue generated from a sale of the i-th output; $s_j\equiv\frac{w_jv_j}{C}$ represents a share of total costs for a purchase of the j-th input; and $x\equiv\frac{\mathrm{dx}}{x}$ is the rate of change of the variable x, for $x=\{p_i,q_i,w_j,v_j\}$.

Further, we adjust the formula (2.5) letting $\dot{P}=\sum_{i=1}^{n}r_i\dot{p_i}$, $\dot{W}=\sum_{j=1}^{m}s_j\dot{w_j}$, $\dot{Q}=\sum_{i=i}^{n}r_i\dot{q_i}$, and $\dot{V}=\sum_{j=1}^{m}s_j\dot{v_j}$. We have

$$\dot{P}=\left(\frac{C}{C+\Pi}\right)\left[\dot{W}-\left(\dot{Q}-\dot{V}\right)+\frac{\Pi}{C}\left(\dot{\Pi}-\dot{Q}\right)\right]. \tag{2.6}$$

The formula $\left(\dot{\Pi}-\dot{Q}\right)$ is the difference between the growth rate of the firm's outputs and inputs, which is basically the total factor productivity (we denote it $\dot{T}$). If we aggregate the growth rates for individual revenue shares (r_i), we get the already defined output growth rate $\dot{Q}=\sum_{i=i}^{n}r_i\dot{q_i}$. Similarly, we obtain the input growth rate $\dot{V}=\sum_{j=1}^{m}s_j\dot{v_j}$, and we can adjust the formula (2.6)

$$\dot{P}=\left(\frac{C}{C+\Pi}\right)\left[\dot{W}-\dot{T}+\frac{\Pi}{C}\left(\dot{\Pi}-\dot{Q}\right)\right]. \tag{2.7}$$

The formula (2.7) defines a growth rate of prices for the regulated firm's output ensuring a profit growth rate $\dot{\Pi}$ for costs C, profit Π, growth rate of the input prices $\dot{W}$, growth rate of the output $\dot{Q}$, and growth rate of the total factor productivity $\dot{T}$. Assume that for the positive level of profit ($\Pi>0$), a higher price of the output is necessary, ceteris paribus, to maintain a strictly positive growth rate of the profit ($\dot{\Pi}>0$). In a theoretical setting of perfect competition, the firm is not able to attain a positive profit in the long run and keep the competitive advantage. Letting the profit equal to zero as well as its growth rate, the formula (2.7) is

$$\dot{P} = \dot{W} - \dot{T}. \tag{2.8}$$

The derived formulas are crucial for the definition of the price cap regulation. From the formula (2.8) modelling the perfect competition, we see that the regulated firm will get a zero profit if the growth rate of the prices for its goods and/or services is equal to the difference between the growth rate of the input prices and its productivity growth rate. The regulator should price as the condition is met and the situation is similar to the perfect competition scenario.

If the prices are set after a detailed analysis of the input prices and productivity, the price cap regulation would be similar to the rate of return regulation (Bernstein and Sappington, 1999). The problem of this scenario is that there would not be any motivation for the firm to improve its productivity, because the gains would be immediately offset by an adjustment of the cap. There should be defined some industry-wide measure that would reflect the average productivity of the firm and its peers. The projected "standard" productivity should motivate the firms to invest and increase their efficiency and gain extranormal profits, and on the other hand to punish the firms with lower productivity; therefore, there are usually price caps defined for longer period to form a stable business environment. Within the period, the firms should be provided with incentives to mitigate production costs and increase productivity. Too prudent setting may, however, drain all profits or adversely too generous setting may provide a firm with high profits. The firms should adjust their strategies according to the projected values and not according to the actual setting, but the longer the period the greater deviations can arise.

A problem that should be carefully handled is how to calculate output inflation of the economy. We extend the model considering a few assumptions. For simplicity, assume that (1) all the output prices in the sector are regulated, (2) the producers have similar operating conditions that allow us to treat them symmetrically, and (3) the prices in other sectors are not affected by the prices in the regulated sector. The symmetrical treatment is preferred, because using only the firm's historic value, the current performance is strongly linked to the future performance. Also in energy sector the firms are compared to their peers and to industry to assess their productivity.

Using the assumptions, we can use economy outside of the regulated sector as a benchmark. Assume that outside of the regulated sector the linkage between the prices and other variables is similar to our setting in formula (2.7). Marking the outside sector with superscript "E", we have

$$\dot{P^E} = \left(\frac{C^E}{C^E + \Pi^E}\right)\left[\dot{W^E} - \dot{T^E} + \frac{\Pi^E}{C^E}\left(\dot{\Pi^E} - \dot{Q^E}\right)\right]. \tag{2.9}$$

In the next step, we subtract formula (2.9) from the expression for the regulated sector (2.7) and after rearrangement of particular terms, we get

$$\begin{aligned}\dot{P} = \dot{P^E} &- \left[\left(\frac{C}{C+\Pi}\right)\dot{T} - \left(\frac{C^E}{C^E+\Pi^E}\right)\dot{T^E}\right]\\ &- \left[\left(\frac{C^E}{C^E+\Pi^E}\right)\dot{W^E} - \left(\frac{C}{C+\Pi}\right)\dot{W}\right]\\ &- \left[\left(\frac{\Pi^E}{C^E+\Pi^E}\right)\dot{\Pi^E} - \left(\frac{\Pi}{C+\Pi}\right)\dot{\Pi}\right]\\ &- \left[\left(\frac{\Pi}{C+\Pi}\right)\dot{Q} - \left(\frac{\Pi^E}{C^E+\Pi^E}\right)\dot{Q^E}\right].\end{aligned} \tag{2.10}$$

Now, we can define the X factor X_1

$$\begin{aligned}X_1 = &\left[\left(\frac{C}{C+\Pi}\right)\dot{T} - \left(\frac{C^E}{C^E+\Pi^E}\right)\dot{T^E}\right]\\ &+ \left[\left(\frac{C^E}{C^E+\Pi^E}\right)\dot{W^E} - \left(\frac{C}{C+\Pi}\right)\dot{W}\right]\\ &+ \left[\left(\frac{\Pi^E}{C^E+\Pi^E}\right)\dot{\Pi^E} - \left(\frac{\Pi}{C+\Pi}\right)\dot{\Pi}\right]\\ &+ \left[\left(\frac{\Pi}{C+\Pi}\right)\dot{Q} - \left(\frac{\Pi^E}{C^E+\Pi^E}\right)\dot{Q^E}\right].\end{aligned} \tag{2.11}$$

Now, if we combine formulas (2.10) and (2.11), we arrive at

$$\dot{P} = \dot{P^E} - X_1, \tag{2.12}$$

which is exactly the expression for the price cap regulation similar to the expression (2.2) defining that the output prices should rise equally to the prices in economy ($\dot{P^E}$) less the X factor corresponding to the productivity gains.

To interpret the role of the basic X factor, suppose that outside of the regulated sector the economy is perfectly competitive with a zero profit. Further assume that the regulator seeks to impose a zero profit in the regulated sector. Rearranging formula (2.11) using the assumptions, we get expression for the X factor

$$X_0 = \left(\dot{T} - \dot{T^E}\right) + (\dot{W^E} - \dot{W}), \tag{2.13}$$

and substituting in formula (2.12)

$$\dot{P} = \dot{P^E} - \left[\left(\dot{T} - \dot{T^E}\right) + (\dot{W^E} - \dot{W})\right]. \tag{2.14}$$

Formula (2.14) extends the expression (2.12). The regulator is setting price for the regulated industry such as the firms are generating a zero profit. To do that, the regulator could allow the price to rise on average by the same rate as in the industry (economy output inflation $\dot{P^E}$) less the X factor (X_0). The X factor is comprised of a sum of the (1) difference in the total factor productivity in the regulated sector and the rest of the economy ($\dot{T} - \dot{T^E}$), and the (2) difference in the growth rates of input prices between the industry and the rest of the economy ($\dot{W^E} - \dot{W}$). Formula (2.14) basically implies that if the firm faces the same inflation rate of input prices and the same productivity as the rest of the economy, it could be reasonably assumed that keeping these rates generates the firm a zero profit. If there are differences between the industry and the economy, these rates should be adjusted.

The theoretical model is using strong assumptions, but it well describes the setting of the price caps and comes up with a few important implications for the regulators. It is important to cautiously handle the inflation rate included in the model, because the inflation rate of input prices may differ among industries. Similarly, the productivity rate must be carefully set to reflect the industry and its potential. For the incentive regulation to be efficient over time, there should be a stable framework over the particular period that would motivate the firms to invest, increase productivity and mitigate costs. The positive profit should not be immediately drained, because it would disincentivise the firms. Inaccurate setting of the incentive regulation may lead to windfall profits for the firms or, on the other hand, to unsustainable conditions for the incumbents.

It is complicated to set the parameters of the price cap and the revenue cap regulations. That is the reason why these methods are usually supplemented with other techniques to better fit the particular regulated sector. In the energy sector, the benchmarking techniques are used as another tool to compare the firms within the field. These are described in the following chapter.

2.6 Yardstick methods

There is a wide range of studies covering the application of the benchmarking methods to the electric utilities. These were repeatedly examined by Pollitt and his colleagues (e.g. Jamasb and Pollitt, 2003; Jamasb et al., 2004; Haney and Pollitt, 2011; and Haney and Pollitt, 2013), who focused on the use of the benchmarking methods in the regulation of energy utilities. The benchmarking methods were also subject to the research of other authors (e.g. Shuttleworth, 2005; Farsi et al., 2006; Farsi et al., 2007; and Kuosmanen et al., 2013) and advisory companies (e.g. Frontier Economics, 2010).

The substantial interest in the benchmarking methods is also enhanced by the fact that the benchmarking methods are widely used and have been implemented by many utility regulators in the EU, for example in Austria, Belgium, Denmark, Finland, Germany, Great Britain, Ireland, Italy, Latvia, the Netherlands, Poland, Portugal and Spain (ERU, 2009). The Czech Energy Regulatory Office does not publicly use the benchmarking methods for regulation. ERU noted that the methods were considered for the third regulatory period, but it was impossible to obtain reliable data (ERU, 2009).

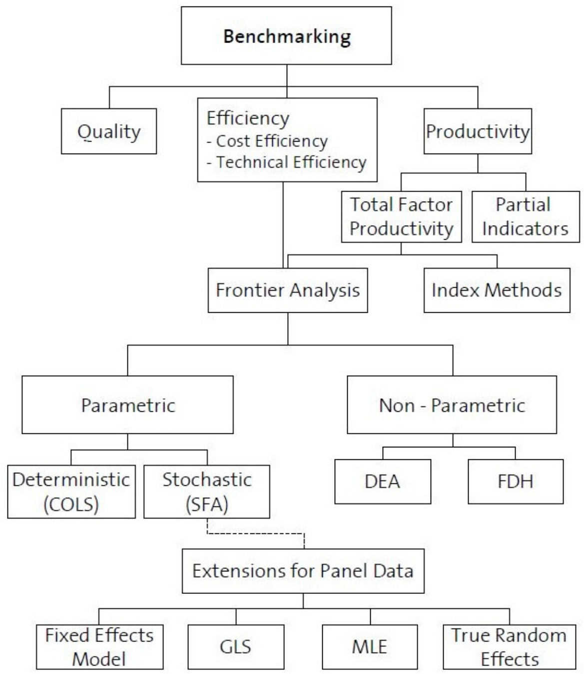
In the electricity sector, the benchmarking methods are in principle used as a complement to the incentive regulation. The yardstick methods are usually used to benchmark the costs of the firms. The regulation based on "caps" leaves a central question how the address the X factor. The benchmarking methods are identifying the most efficient firms in the sector and measuring relative performance of their peers. The individual X factors are then assigned to the firms according to their efficiency to provide them with incentives to adjust their performance. The aim is to curtail the efficiency gap among the firms in the industry (Jamasb and Pollitt, 2003).

The utilisation of the benchmarking techniques can be restricted by a shortage of data within the industry, especially in the electricity transmission and distribution sectors that were originally monopolised. There are often too few companies and in spite of recent liberalisation and privatisation it is often complicated to acquire longer time series of data. These problems can be overcome by a use of international data; moreover, the cross-country comparisons can be acquired. The international benchmarking must be, however, carefully applied and the country specific features should be taken into account.

There are several methods of benchmarking to be used for the regulation of electric utilities. Generally, they can be divided in two categories - frontier and non-frontier methods. The frontier methods are broadly used for benchmarking. They consist of parametric (stochastic frontier analysis and deterministic methods based on ordinary least squares regressions) and non-parametric methods (data envelopment analysis).

The yardstick methods are mostly used by the regulators to benchmark costs of the regulated firms. The most frequently used methods are frontier, non-frontier (total factor productivity method) and their combinations. They are described in the following subsections in detail. For the schematic description of the benchmarking methods, see the attached Figure 1.

Figure 1: Benchmarking methods



Source: Farsi et al. (2005, p. 8)

2.6.1 Total factor productivity indices

The non-frontier methods are not so common and are usually represented by total factor productivity (TFP) indices. TFP is an approach to measure the productivity while considering all factors of production (Frontier Economics, 2010). Another definition is that TFP "is a productivity measure involving all factors of production" (Coelli et al., 2005, p. 3) while under productivity the ratio of outputs over inputs is defined. The TFP indices can be combined with the frontier methods and they focus on the rate of change of the explanatory factors and outputs relatively to the rate of change of inputs. To compute TFP, various price indices (e.g. Laspeyres and Paasche indices) or distance functions are often used. The most commonly used indices are Malmquist and Törnqvist indices.

The Törnqvist index is based on price aggregation. A significant advantage of the Törnqvist index is that it can be calculated using only two data points, however, it requires information about prices and it implicitly assumes that the firms are fully efficient.

The Malmquist index is based on a distance function. A complex dataset is needed as well as the estimation of the efficient frontier is necessary to compute the index. The frontier methods need to be used to compute the index, which restricts its applicability. It does not require information about prices and does not assume the firms to be efficient. It also allows for decomposition of the index into various components, such as technical, technical efficiency and scale changes (Coelli et al., 2005).

2.6.2 Data envelopment analysis

The Data Envelopment Analysis (DEA) is a non-parametric deterministic method. The method uses linear programming to construct a frontier over the data (to calculate the efficient frontier over the sample). The efficient firms are placed on the frontier that envelopes the less efficient firms. DEA has an important advantage that it does not require the algebraic form of the relationship between outputs and inputs (Coelli et al., 2005). Using the variations and extensions of DEA (i.e. input or output oriented DEA; DEA assuming constant, variable and non-increasing returns to scale), the allocative and technical efficiencies can be measured. DEA can be also decomposed into scale, congestion and pure technical efficiency. The efficiency is calculated in terms of efficiency scores on 0-1 scale. The firms lying on the frontier have a score of one.

An advantage of DEA is that the firms are mutually compared and not set against some artificial statistical measure. DEA also does not require a specification of the cost or the production function, which simplifies its usage. In addition, DEA can be more easily used for smaller samples than parametric methods, which require bigger samples. There are some limitations and possible problems related to DEA (Coelli et al., 2005). DEA does not consider the stochastic factors of measurement error; furthermore, not accounting for exogenous variables (e.g. environment) may give misleading results.

2.6.3 Ordinary least squares methods

Econometric ordinary least squares methods (OLS) can be also used for benchmarking. The techniques use adjusted regression analysis to find the relationship between independent and dependent variables (e.g. cost drivers and total costs). Similarly to DEA, the efficiency scores on 0-1 scale are estimated. There are two common variations of OLS, corrected OLS (COLS method) and modified OLS (MOLS method).

COLS technique is derived from OLS. The equation is estimated using the regression analysis and then shifted to the efficient frontier. The regression line is moved to match the best performing firm in the sample by adding the value of the largest residual to the intercept. In other words, the production function is shifted upwards until all residuals, except the one we consider as the most efficient, are negative (Greene, 2007).

MOLS requires a parametric distribution of residuals of OLS. MOLS is less restrictive, because it is unlikely to lead to a full set of negative residuals (Greene, 2007). The method similarly to COLS shifts the efficient frontier. The efficient frontier is for MOLS shifted by the expected value of the error term and adjusting regression to get a consistent estimate.

Both methods require a specification of the cost or the production function. It implies that it is necessary to make assumptions about the firm's technology and production processes. The problem is that the methods do not account for stochastic errors and rely on the position of the frontier firm (Jamasb and Pollitt, 2003). In comparison with DEA, the methods account for noise and they can be used for the standard testing of hypotheses.

2.6.4 Stochastic frontier analysis

Stochastic frontier analysis (SFA) is a statistical parametric method. The deficiency of both DEA and OLS methods is that they do not take into account measurement errors and other sources of statistical noise caused by omission of explanatory variables (Coelli et al., 2005). The possible deviations from the frontier are under the DEA and the OLS methods assigned to inefficiency and therefore a precise specification is necessary. This problem is overcome by SFA.

An advantage over DEA is that SFA allows for conventional testing of hypotheses. A disadvantage of SFA is that it, similarly to the OLS methods, requires a specification of the production or the cost function (and implicitly the assumptions about technology). SFA accounts for stochastic errors and therefore their probability function has to be defined.

2.6.5 Comparison of methods

The Malmquist index requires the use of frontier methods, which significantly restricts the benefits of the method. If we have a suitable panel of data, the frontier methods are better and they generate more information about the data than the TFP methods while demanding fewer assumptions (Coelli et al., 2005). If we have only a limited scope of data, the Törnqvist approach might be beneficial, because it is easy to calculate and it can be calculated using only two data points. The most significant limitation of the Törnqvist index is that it requires complex price and quantity information and assumes firms to be efficient.

To sum the frontier methods up, the advantage of DEA over OLS and SFA is that it does not require a functional form of the production and the cost function, and a distribution of the stochastic errors. In comparison to DEA, SFA and the OLS methods allow for conventional testing of hypotheses and they account for noise. The frontier methods do not assume the firms to be efficient and do not require price information, however, they require larger datasets in comparison with TFP. DEA is less data demanding than the OLS and SFA methods.

According to Coelli et al. (2005), there are some problems, which should be cautiously handled and for which the frontier methods ought to be controlled. The inputs/outputs should be treated correctly as heterogeneous/homogeneous, because the misspecification may bias the results. The possible measurement error should be considered as it can affect the shape and the position of the frontier. All methods are very sensitive to the selection of variables and omission of an important input or output can lead to biased results. The omission of environmental differences can lead to misleading outcomes. Most methods do not take into consideration managerial methods like risk management procedures or multi-period optimisation. Further, the methods cannot be used for a comparison of different samples, because the efficiency scores belong to particular samples. In addition, the outliers may also significantly influence the results.

3 Legal norms of the Czech Republic and the European Union

The process of liberalisation of the energy markets in the EU states has spontaneously started at the beginning of the 1990s. The liberalisation and privatisation of the markets required a transformation of the regulatory regimes. These changes also affected new member states of the EU. Therefore, the Czech Republic had to comply with the EU legislation and thus implement directives of the European Commission which codified a transition of the structure of the electricity and gas markets.

The electricity and gas utilities were traditionally operated by monopolies. The incumbents were in most cases state-owned or subject to a strict state supervision. The codified and enforced privatisation and separation of these companies introduced a competition into the formerly monopolistic markets, but the transformation raised doubts about the quality and security of supplied services. In addition, there was a demand for new regulatory approaches, because the traditional methods were not suitable for the liberalised markets.

In the first part, legal norms of the EU covering the electric and gas markets are introduced. In the second part, the legislation of the Czech Republic is described.

3.1 Directives and regulations of the EU

The liberalisation of electricity and gas markets started in the Europe at the beginning of the 1990s when first states pioneered to open their energy markets. The liberalisation was conducted by command and control regulation to introduce competitive and integrated markets (Bohne, 2011). The command and control regulation as a traditional form of regulation basically defines what is prohibited or permitted while the infringement is enforceable by law using multiple fines or physical coercion (Bohne, 2011). The term refers also to the set of standards or objectives, and possible punishments.

The reforms were initiated at the EU level by the first directive introducing the market liberalisation for electricity in 1996. The principal idea behind the liberalisation efforts was to enhance the internal market. The creation of competitive energy market was another step to complete the internal energy market in the EU. The directives of the EU have to be implemented by member states and transposed into national law. The liberalisation of the EU energy markets can be divided into three phases. In the first regulatory phase, a first two directives (from years 1996 and 1998) laid down general principles. In the second and third phase, the sets of 2003 and 2009 directives further extended and amended the existing legislation. Each stage further widened the unbundling processes.

In the first phase, the set of directives 1996/1998 of the European Commission can be considered as a milestone for the EU energy liberalisation and privatisation reforms. The first document was Directive 96/92/EC of the European Parliament and of the Council of 19 December 1996 concerning common rules for the internal market in electricity; two years later supplemented by Directive 98/30/EC of the European Parliament and of the Council of 22 June 1998 concerning common rules for the internal market in natural gas. The directives established general definitions of limited competition, unbundling and laid down principles for the third party access to the market (of transmission and distribution services). The directives aimed at the elimination of obstacles to the creation of the internal market. The electricity undertakings were obliged to separate the accounting for generation, transmission and distribution subdivisions. The member states were supposed to establish competent and independent regulatory authorities. The first phase initiated the informational and accounting unbundling.

In the second phase, the European Commission came up with a new set of directives, which replaced the 1996/1998 directives. The Commission legislated Directive 2003/54/EC of the European Parliament and of the Council of 26 June 2003 concerning common rules for the internal market in electricity and repealing Directive 96/92/EC; and Directive 2003/55/EC of the European Parliament and of the Council of 26 June 2003 concerning common rules for the internal market in natural gas and repealing Directive 98/30/EC. For the electricity, the second package aimed at generation, transmission and distribution. The new directives brought more detailed regulation and contained definitions of the third party access and legal unbundling. The importance of competent independent regulatory authorities was further stressed and EU member states were charged to designate them. The paramount importance was given to the elimination of barriers to entry to the network and elimination of monopolistic structure of transmission and distribution system operators. The Directives stressed the importance of the legal and managerial separation of the vertically integrated undertakings (legal and functional unbundling) and therefore a need to create independent managements of the generation, transmission, distribution and supply. The legal unbundling, however, was not meant to result in ownership separation.

The third regulatory phase further tightened the regulation. The second phase was not found sufficient to form efficient electricity and gas markets. The European Commission inquired the energy sector and concluded that the customers and businesses were still suffering from the imperfect competition and inefficiencies (EC, 2007). The third regulatory package consisted of a set of two directives and three regulations:

- Directive 2009/72/EC 13 July 2009 concerning common rules for the internal market in electricity and repealing Directive 2003/54/EC,
- Directive 2009/73/EC of 13 July 2009 concerning common rules for the internal market in natural gas and repealing Directive 2003/55/EC,
- Regulation (EC) No 713/2009 of 13 July 2009 establishing an Agency for the Co-operation of Energy Regulators,
- Regulation (EC) No 714/2009 of 13 July 2009 on conditions for access to the network for cross-border exchanges in electricity and repealing Regulation (EC) No 1228/2003,
- Regulation (EC) No 715/2009 of 13 July 2009 on conditions for access to the natural gas transmission networks and repealing Regulation (EC) No 1775/2005.

The third legislative package entered into force in September 2009 and the member states had 18 months to transpose it into the national laws. The third package further aimed at generation, transmission and distribution of electricity, but it also focused on the supply of electricity. There were three underlining aspects of the package - enhancing the competition in the energy market, strengthening the competences of independent national energy regulators and widening the customer protection. The new legislature introduced legal unbundling of DSOs in vertically integrated utilities, non-discriminatory third party access to the transmission and distribution, creation of single national regulatory authority and each state was obliged ensure its impartial and transparent operation. It introduced establishment of the European Networks of Transmission System Operators (ENTSO) to enhance the cooperation among TSOs, and created the European Agency for the Cooperation of Energy Regulators to improve and supervise the operation of national regulatory offices.

The new law prescribed unbundling of electricity generation and transmission with predefined exceptions. The exceptions were the Independent System Operator model (ISO) and the Independent Transmission Operator model (ITO), last alternative was a case of existence of national more efficient arrangements. The ISO model assumes creation of ISO (with unbundled ownership) operating the energy transmission but not owning the grid. The ITO model assumes unbundling of transmission and production of energy by establishment of ITO. Therefore both models enable the companies to possess the grid.

The regulation has profoundly changed over the years. The first package relied more on the market forces while over the years the legislature brought commands, prohibitions and other tools for the national authorities, which were presumed to impose competition. The regulation evolved towards to the classical command and control type (Bohne, 2011). The regulatory model of the EU is often compared with the British model of liberalisation of energy markets (Alexander et al., 2003; Bohne, 2011).

The creation of genuine market for electricity (and energy) was among the priorities of the EU. The EU customers were given a possibility to choose a supplier. The generation, transmission, distribution and supply services were unbundled and the market entry was significantly simplified for new suppliers. The inclusion of more RESs was facilitated. The energy packages were also created to enable the carbon dioxide emission trading. The liberalisation directives, however, increased the regulatory burden and the principal belief in the market forces has faded.

3.2 Legal norms of the Czech Republic

The structure of the energy system in the Czech Republic in the early 1990s was inherited from the command economy. After the Velvet Revolution, the central task for the first governments was to transform the system towards the market economy. The electricity market was highly monopolised with ČEZ controlled and owned by the state that was as a dominant player on the market. The liberalisation was at the end of 1990s triggered when the Czech Republic was intensifying efforts to prepare for the EU accession and to adapt the economy to comply with the community legislative corpus.

The Czech Republic became a member of the EU on 1 May 2004. As a member of the EU, the Czech Republic has to comply with the EU norms. The legislature had to be adjusted prior to the accession. The first set of directives did not have a direct impact on the energy market in the Czech Republic, but the 2003 directives from the second energy package influenced the Czech energy market by their transposition into national law.

The adoption of the Act No. 458/2000 on Conditions of Business and State Administration in the Energy Industries and Changes to Certain Laws (the Energy Act) in 2001 was a key step towards the liberalisation of the electricity market. The Energy Act laid down principles of consumers' protection, energy security and competition in the market, efficient operation of the incumbents and price stability for customers. The Energy Act established legislative conditions for the liberalisation of the market and the regulation was assigned to the independent regulatory office - ERU (Bachanova, 2006). ERU was commissioned to maintain competition and protection of consumer interests in the energy sectors with limited competition (where the natural competition is not possible).

The Energy Act brought more changes. In 2001, the market operator was created and its role was stipulated in the Energy Act. The company Operátor trhu s elektřinou, a.s. (hereafter OTE) was founded by the state as another component necessary for opening the electricity market. OTE has been operating the information system for short-term electricity market and settlement of imbalances for subjects of settlement (OTE, 2003). The operation of OTE started the process of opening the electricity market for different types of customers.

In line with the Energy Act, the only company licensed for transmission of electricity has been Čeps, a.s (hereafter ČEPS). ČEPS is the sole TSO in the Czech Republic. The company had been owned by the ČEZ, however, during the years of 2003 and 2004 it was separated (CEPS, 2004). The company can be regarded as independent through its ownership unbundling from other activities (production, distribution and sales). ČEPS was fully unbundled from electrical energy producers and distributors as at 3 September 2009 (ERU, 2013d).

The Energy Act was amended several times over the years to comply with the EU legislation and changes on the market. The directives from second energy package were transposed into the Czech legislature by amendment of the Energy Act No. 670/2004 that entered into force in 2005. In this act, managerial, legal, information and accounting unbundling of the electricity and gas transmission and distribution operators were defined in detail. The principal task was to separate operators from production and trade activities. Since there was sole electricity TSO in the market, the paramount importance was aimed at the unbundling of DSOs dominating the market. It was scheduled as at 1 January 2007 at latest. With respect to the EU legislation, subject to unbundling were DSOs with more than 100,000 customers. In the Czech Republic, they have been represented by three companies dominating the market and controlling certain areas of the country - E.On, ČEZ and PRE. The process was less complicated than expected and the separation was completed in 2005.

The last stage of the liberalisation of electricity markets was carried out in 2006. Since 1 January 2006, all end customers including the households have had the right to choose supplier (all clients became eligible customers).

The third energy package was transposed by the amendment No. 211/2011 of the Energy Act. It entered into force in August 2011. As mentioned above, the main task was to further promote liberalised market and to put an emphasis on customer protection. The amendment reinforced customer rights, extended powers of national regulators, demanded completion of unbundling and enabled better control over development of the renewable energy sources (RES).

The energy market is further regulated by other laws and subordinate legislation. These are for example environmental regulation, energy management laws aiming at rational and efficient utilisation of electricity, and legislation controlling business activities in energy sector and generally the subject of enterprise. Especially the environmental regulation introduced by the EU has significantly altered the Czech energy market (for details refer to e.g. Strielkowski et al., 2013) in the last ten years, however, thorough listing and description of relevant legislation is beyond the scope of this thesis.

4 Current situation on the Czech energy market

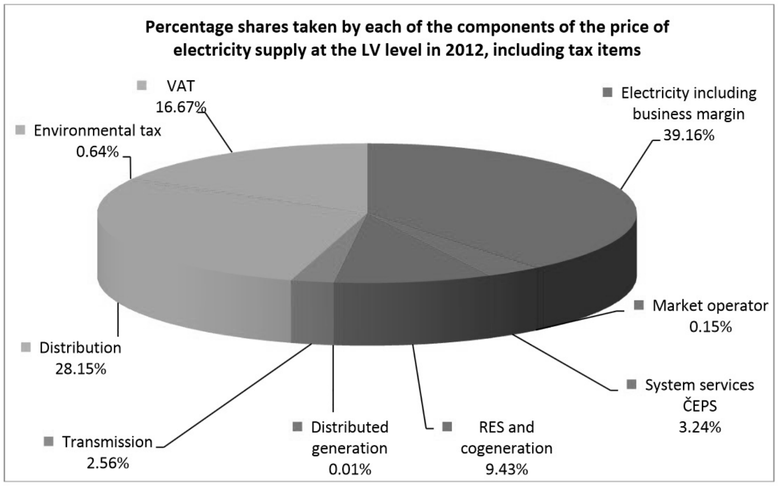
The energy sector in the Czech Republic was tailored to carry out needs of industrialised economy. The industrialisation began in the second half of the 19th century. The electrification was on larger scale conducted during the First Czechoslovak Republic. The process was designed to meet industrial requirements. After the Second World War, the economy was further industrialised to be in line with plans of the Soviet Union focusing on heavy industry. The high share of the heavy industry formed excessive demand for energy that was mostly met by electricity generated from solid fossil sources. Despite a nuclear power plant Dukovany finished in the middle of the 1980s, the biggest share of electricity was produced in coal-fired power plants.

The collapse of the communist administration brought a need for transformation of the command economy and raised requirements for environmental regulations. Altogether with a decline of the heavy industry, there was an acute need for a reform of the market with electrical energy. The dominant player on the market was a state-owned company České energetické závody, which dominated the electricity market in all sectors from production to sales. The transformation of the company started shortly after the Velvet Revolution of 1989. The process included a change of the structure of the company, separation of heating plants, distribution and other activities. In 1992, a joint stock company ČEZ, a. s. was founded by the Czech National Property Fund. Two years later a minor stake of the company was included in privatisation.

The structure of DSOs changed as at 1 January 1994. There were eight companies that demerged from the sector monopolist České energetické závody at the beginning of 1994. These were joint stock companies Jihočeská energetika, Jihomoravská energetika, Pražská energetika, Severomoravská energetika, Severočeská energetika, Středočeská energetická, Východočeská energetika and Západočeská energetika. The variety of operators shrunk in 2003 when the company E.On took control over Jihočeská energetika and Jihomoravská energetika. Pražská energetika retained its position, but in the same year ČEZ acquired the dominant stake in the five remaining companies. The market structure of DSOs was defined and has preserved up to the present time.

In the last decade of the 20th century, the electricity grid was integrated and interconnected with western states and it was decided to complete construction of the second nuclear power plant in Temelín. The measures were taken to curtail sulphur and other harmful emissions. Even though the share of industry on the country's GDP has been gradually declining since the Velvet Revolution, the share in 2010 was still 36% in comparison with 40% in 1990 (World Bank, 2014).

Figure 2: Price components at low voltage level in 2012



Source: ERU (2013a, p. 18)

The production in the second nuclear power plant Temelín started in 2003 and together with Dukovany they have formed a principal base-load source in the system. The past decade was important for adjustments made to harmonise the legislation with the acquis communautaire. The process of legislative changes related mostly to the transmission and distribution networks is described in the previous chapter.

Apart from the unbundling, the Czech Republic was obliged to comply with environmental regulation of the EU. It made a commitment to increase the share of renewable sources and take appropriate measures for further expansion. The deployment of RES was negligible and amounted to 4% in 2005 while it was mostly comprised of hydroelectric power plants (ERU, 2013d). The target adjusted for conditions on the Czech market was set to 8% share of the RES on the gross consumption of electricity in 2010 as a result of Directive 2011/77/EC. The target was met despite the primary scepticism, but the significant costs related to the expansion of RES were created. These costs will have to be borne by customers in the future (Smrcka, 2011).

The significant rise in costs of promotion of the renewable energy sources raised the regulated contribution for RES included in the electricity prices. There was an excessive growth of installations of photovoltaic power plants in the second half of the past decade and the costs are mostly related to these sources. There is still 13% target of share of RES on gross electricity consumption given by the Directive 2009/28/EC that should be fulfilled by 2020. The Czech Republic is among a few EU states with positive balance of electrical energy. The net balance in the Czech electricity grid amounted to 17 GWh in 2012 (ERU, 2013d). The components of the electricity price are depicted in Figure 2.

4.1 Significant market players

The main regulatory body in the Czech Republic is ERU founded in 2001. Its main responsibility is to regulate electricity, gas and heat supply industries in order to substitute free market and protect interests of market players in segments where the competition is not possible (ERU, 2013c). This general definition entails significant competences that are related to the electricity market. These competences are: setting prices, setting support schemes and mechanisms in line with legislation and market conditions; preparation of laws and subordinate legislation; competition protection, support and supervision; and cooperation with other public institutions. ERU is a member of the EU regulatory institutions (the Council of European Energy Regulators and the Agency for the Cooperation of Energy Regulators) where it should represent the Czech Republic and protect national interests. ERU is managed by a Chairperson who is appointed by the President of the Czech Republic for a six-year term (the Chairperson is proposed by the government).

The market operator is a joint-stock company OTE, a.s. founded in 2001. Its main competences related to the electricity market are: daily settlements of imbalances between factual deliveries and contracted values, maintenance of related data and preparation of reports, organisation of short-term electricity market (day-ahead and intra-day trades), settlement of regulating energy and settlement during emergencies (OTE, 2013). OTE organises wholesale trading on the spot market with fixed expiry dates. The company has been maintaining a trading registry for greenhouse gas emission allowances since 2004 (OTE, 2013). The sole shareholder is the state of Czech Republic.

Another important player is the Power Exchange Central Europe (hereafter PXE). PXE was established in 2007 and offers trading of standardised products of Czech, Slovak and Hungarian power (PXE, 2013). The primary electricity market in the region is Germany and the power exchange located in Leipzig (EEX). Trading at PXE and EEX is based on bilateral contracts. There are two main traded products - base load and peak load.

The electricity generation is fully unbundled. The largest market player is traditionally ČEZ (ČEZ Group). The gross production of electricity in the Czech Republic amounted in 2012 to 88 TWh, steam-cycle power plants produced 54% (including biomass), 35% was generated in nuclear plants, 5% in natural gas combustion plants, and the rest was attributable to RES (hydroelectric, wind and photovoltaic power stations). The share of RES on gross electricity consumption amounted to 11% (ERU, 2013d). The total installed power was 21 GW (ERU, 2013d). ČEZ Group companies generated 64 TWh and disposed of 13 GW of installed power capacities (CEZ, 2013). ČEZ Group operates the nuclear power plants in Dukovany and Temelín, which generated 30 TWh of gross energy in 2012;

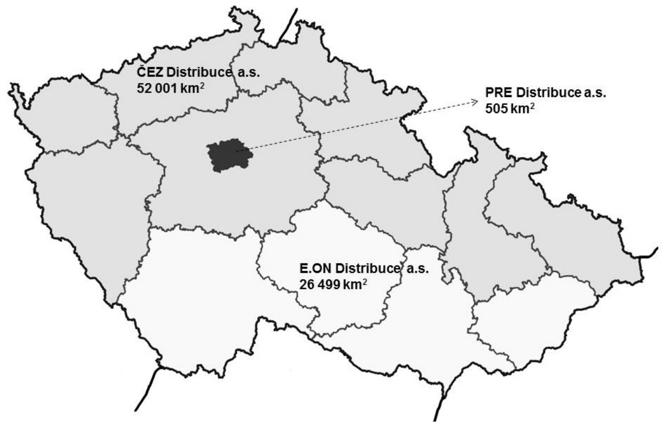
coal, gas and combined cycle power plants generated 32 TWh of gross energy in 2012, and renewable energy sources generated 2 TWh of gross energy in 2012 (CEZ, 2013).

ČEPS is a sole transmission operator in the Czech Republic. It was founded in 1998 by ČEZ and the state has been the sole shareholder since 2004. ČEPS is responsible for the grid system and ancillary services, transmission services, auctions and settlements of costs resulting from cross-border flows, and international cooperation (CEPS, 2013). ČEPS is also responsible for energy balancing. ČEPS closely cooperates with TSOs from Visegrad countries (the Czech Republic, Slovakia, Poland and Hungary). The current main task for the company is to extend the integration of the EU electricity grids. Another significant mission is to secure sufficient capacities to be able to handle energy inflows from the north and the west. Since the grids are interconnected, there arise inflows of energy predominantly from Germany, which are caused by an excessive electricity production from wind farms. These inflows are hardly predictable, because they are dependent on the current state of atmosphere. Due to the monopolistic structure of TSO, most of the activities are subject to detailed regulation of ERU. The electricity transmission network comprises 400 kV, 220 kV and 110 kV lines, which are not included in the distribution system, and other related transmission systems. The services of TSO are paid through a contribution included in the price of electricity.

The eligible customers are given a right to choose their electricity supplier and product tailored to their needs (all customers have been eligible customers since 2006); however, they cannot choose their regional DSO. The access to both transmission and distribution grid is regulated. The prices are regulated by ERU and set using revenue cap regulation. There are three licensed regional DSOs: ČEZ Distribuce, a.s., E.On Distribuce, a.s., and PREdistribuce, a.s. Particular regions of the Czech Republic are allocated to individual DSOs (see Figure 3). The energy distribution market is a typical example of natural monopoly. The grid is comprised of cable and overhead lines on 110 kV and lower voltage levels, transformers and other appliances. Power plants with lower wattage may be connected directly into the distribution network. The customers cannot change the regional distributor. The fees for electricity distribution also comprise the contribution for RES.

The sales of electricity have been fully unbundled since 2006. Both retail and wholesale markets are fully liberalised. There are more than 300 licensed entities operating on the market (ERU, 2013c). Some of them offer their services only on local basis. The licenses are granted by ERU. The customers can compare the prices online on the website of ERU. The companies operating on the market are trading electrical energy and selling the products directly to the customers. The energy is delivered to the customers using the transmission grid maintained by ČEPS and the distribution network operated by three

Figure 3: DSOs in the Czech Republic



Source: MDCR (2003), edited by author

DSOs. Since 2006, ERU has not been setting the price of electricity for customers, but it has been regulating individual components as the electrical energy is traded and marketed separately. The switching rate of the customers has been increasing since 2006. In 2011, 450,000 customers changed their electricity supplier and in 2012 it was 472,000 (ERU, 2013d). The electricity price components are illustrated in Figure 2.

5 Practices of the regulatory bodies in the Czech Republic and other states of the EU

In this chapter, we focus on methods and practices of the regulatory bodies. Firstly, we describe methods of ERU in the Czech republic. In the second part, we focus on regulators in selected states of the EU. A special attention is paid to regulation and benchmarking of DSOs. We use the benchmarking methods in our empirical part to assess the Czech DSOs in international comparison.

5.1 Methods of ERU in the Czech Republic

The process of deregulation and unbundling is widely described in the two previous chapters. The regulatory periods have covered both the electricity and gas industries. In this section, we focus on practices aiming at the electricity sector used in the third regulatory period. Special emphasis is put on regulation of DSOs.

ERU has been using the incentive regulation since its establishment in 2001. The first regulatory period ranged from 2002 to 2004 and ERU based the regulation on the revenue cap scheme. The companies were given allowed revenues for the whole period adjusted for the inflation and the X factor (basically in line with the general revenue cap formula).

The regulation was adjusted in the second regulatory period that ranged from 2005 to 2009. ERU identified deficiencies in the first period and addressed them. The period was prolonged from three to five years, more emphasis was put on investments and efficiency improvements, and particularities of transmission and distribution operators were taken into account and these were included in the regulatory formula (ERU, 2005). Before the adoption of the final regulatory framework, the incumbents had opportunity for commenting the draft.

5.1.1 Parameters of regulatory formula

The third regulatory period was created in line with the Regulatory Impact Assessment (RIA) and the consultation process started in 2008 (ERU, 2009). The Czech government decided to apply RIA to improve the transparency in the decision making process and to improve the communication. ERU called upon public, incumbents and specialists to take part in the consultation process and raise comments.

The fundamental question prior to the setting of particular parameters was to decide whether the revenue cap regulation was appropriate. ERU was choosing between the price cap and revenue cap schemes. Finally, ERU decided not to change the methodology and followed the revenue cap regulation. The decision was justified by the fact that the price cap regulation can be used only in stable environment where the parameters of the regulatory formula are unlikely to change during the regulatory period, and this condition was allegedly not fulfilled (ERU, 2009).

Under the revenue cap, the parameters of the regulatory formula are set at the beginning of the period and they are reviewed and revised every year. Using these parameters, the maximal allowed revenues are computed and they are employed to compute the price cap based on the energy consumption.

The regulatory formula is based on accounting data of the regulated companies and other factors that influence their operation. Allowed revenues are derived from costs, depreciation (plus amortisation), profit, X factor and price indices.

The costs for particular period are derived from the accounting costs from the previous period. The costs for the first year of the regulatory period (2010) were based on an average of accounting costs from 2007 and 2008, adjusted to the 2009 price level. In the following years, the costs were indexed by the escalation and the X factor. Formally,

$$CA_i = CA_{i-1}(1-X)^i \times \frac{\prod_{t=1}^{1+i-1} I_t}{100}, \tag{5.1}$$

where CA are the allowed costs; X refers to the X factor; I is a parameter for escalation factor; t is a time coefficient; and i is a subscript for a particular year. The escalation factor adjusts the parameters of the regulatory formula for inflation and changes in prices. As described in subsection 2.5, it is important to cautiously handle the inflation. The escalation factor was adjusted for the third regulatory period and it is defined as

$$I_t = 0.7 \times IPS_t + 0.3 \times (CPI_t + 0.01), \tag{5.2}$$

where IPS is a business service price index given a 70% weight and CPI is a consumer price index that is increased by 1% and given a 30% weight. Both indices are obtained from the Czech Statistical Office.

ERU sought to implement the X factor at two levels - the individual and the general X factor. The individual efficiency factor should have reflected the efficiency of particular firms and penalise the less efficient firms. There were complications with the specification and ERU finally decided to use only the general X factor. ERU (2009) noted that the X factors are usually set by benchmarking of comparable companies, but due to the fact that the data were not feasible, ERU set without further explanation the value as 9.75% for the five-year period (the costs should decrease over the period by 9.75%). The annual rates are computed as

$$X = 1 - \sqrt[5]{(1 - 0.0975)} = 0.02031, \tag{5.3}$$

and all companies are obliged to reduce their costs (increase the efficiency) annually by 2.031%.

For DSOs, depreciation is set according to the planned level of accounting depreciation. In the Czech accounting standards, there are two types of depreciation - accounting and tax. The accounting depreciation should reflect the actual depreciation of assets while the tax depreciation should be in line with the legislature. The selection of the accounting depreciation is reasonable. ERU initially chose the tax depreciation in the proposal for the fourth regulatory period for the gas industry and the choice was broadly criticised. It is likely that ERU will include the accounting depreciation in the fourth regulatory period for the electricity sector. The difference between estimated and actual values of depreciation is corrected using a correction factor. The formula for depreciation is

$$\delta = \delta_{planned} + KF_{\delta}, \tag{5.4}$$

where δ represents depreciation and KF_{δ} is a correction factor.

The parameter for profit is defined as a product of a rate of return (RR) and a value of regulated asset base (RAB). In 2011 and 2012, investment correction factor from the second regulatory period was included. The profit correction factor has been added to the formula since 2012. For the correction factor denoted KF_{Π}, the expression is

$$\Pi = RAB \times \frac{RR}{100} + KF_{\Pi}. \tag{5.5}$$

The initial value of RAB (RAB_0) is based on the residual value of assets from 2009 adjusted for initial revaluation to guarantee the companies profitability. The value is based on the booked value of the companies' assets (from audited financial statements).

The initial values were increased by the difference of completed investments (CI) and depreciation (δ). The depreciation is multiplied by a revaluation coefficient (k_i) computed as the planned RAB in year $t-1$ (RAB_{t-1}) divided by the planned residual asset value in year $t-1$ (RAV_{t-1}).

The setting of RAB is based on planned values and therefore it has to be adjusted using correction factor (KF_{RAB}) for real (audited) values. The correction is computed as a difference between the completed investments (capitalised expenditures) and the real value of depreciation. The depreciation is adjusted for a planned revaluation coefficient ($k_i^{planned}$) for corresponding year, and completed investments are adjusted for a planned value of depreciation multiplied by a revaluation coefficient. Formally,

$$RAB_i = RAB_0 + \sum_{t=1+l}^{l+1} \Delta RAB_t + \sum_{t=l+3}^{l+i} KF_{RABt}, \tag{5.6}$$

$$\Delta RAB_t = CI_t^{planned} - (\delta_t^{planned} \times k_t^{planned}), \tag{5.7}$$

$$k_t^{planned} = \frac{RAB_{t-1}}{RAV_{t-1}}. \tag{5.8}$$

ERU adopted WACC (Weighted average cost of capital) methodology of setting the rate of return for the third regulatory period. The methodology was changed due to the financial crisis for ERU to be able to better react to changes to individual parameters. The new methodology is related only to a debt premium. The debt to equity and beta parameters are not adjusted and are determined for the whole period. The year $i-1$ is taken as a base for WACC. In case the calculated value deviates by more than +/- 0.2 percentage points, the calculated value is applied.

The costs of debt are set as a sum of risk-free rate and debt premium (formula 5.12). Because the Czech DSOs are not listed on the stock exchange, ERU derived the debt premium from current interest rates (for details refer to ERU, 2009).

There was a similar task for ERU in the determination of a beta parameter for the investment risk in the segment, because the companies are not listed. ERU based the parameter on two factors: (1) computation based on data from the stock markets and (2) computation based on regulatory practice. For stock markets, 2008 data from Reuters were obtained, specifically the 20-month beta coefficients and companies' gearing of the regulated European energy companies. These were complemented by data of the European regulators and their comparison. The coefficient β_{UL} was finally set as 0.35% for the electricity distribution companies. Expression for the levered beta is depicted in formula (5.13).

$$WACC_{NBT} = \frac{WACC_{NAT}}{1-T}, \tag{5.9}$$

$$WACC_{NBT} = (r_e \times \frac{E}{E+D}) + [r_d \times (1-T) \times \frac{D}{E+D}], \tag{5.10}$$

$$r_e = r_f + \beta_L \times ERP, \tag{5.11}$$

$$r_d = r_f + D_p, \tag{5.12}$$

$$\beta_L = \beta_{UL} \times [1 + (1-T) \times \frac{D}{E}], \tag{5.13}$$

where $WACC_{NBT}$ is a nominal WACC before taxation; $WACC_{NAT}$ is a nominal WACC after taxation; T is an effective tax rate; D is debt; E is equity; r_e represents cost of equity; r_d represents cost of debt; r_f is a risk-free rate; ERP is an equity risk premium; β_L is a levered beta; β_{UL} is an unlevered beta; and D_P is a debt premium. For more details, refer to ERU (2009).

5.1.2 Quality parameters

Quality of the distribution services is measured using standard indicators. These are SAIDI (System Average Interruption Duration Index) and SAIFI (System Average Interruption Frequency Index). SAIDI expresses the average interruption duration for each customer served per calendar year. SAIFI represents average number of outages per customer per year. For particular DSOs, the parameters are set individually for the whole grid of each operator. The companies are not penalised or rewarded in case of +/- 5% fluctuations around the target. In case of deterioration above the threshold, ERU can penalise the companies up to 3% of the profit for the respective year. Adversely, more than 15% improvement can lead to a maximum bonus amounting to 3% of the profit.

5.1.3 Regulatory formula in the third regulatory period

In the previous section, we described the parts of the regulatory formula. The quality parameters are not included due to their characteristics. Merging the particular expressions, we arrive at the regulatory formula. It basically specifies the equation that revenues equal costs + depreciation + profit. The expression for allowed revenues of the revenue cap regulation (AR) of the third regulatory period is as follows

$$AR = CA_{i-1}(1-X)^i \times \frac{\prod_{t=1}^{1+i-1} I_t}{100} + \delta_{planned} + KF_\delta + RAB \times \frac{RR}{100} + KF_\Pi. \tag{5.14}$$

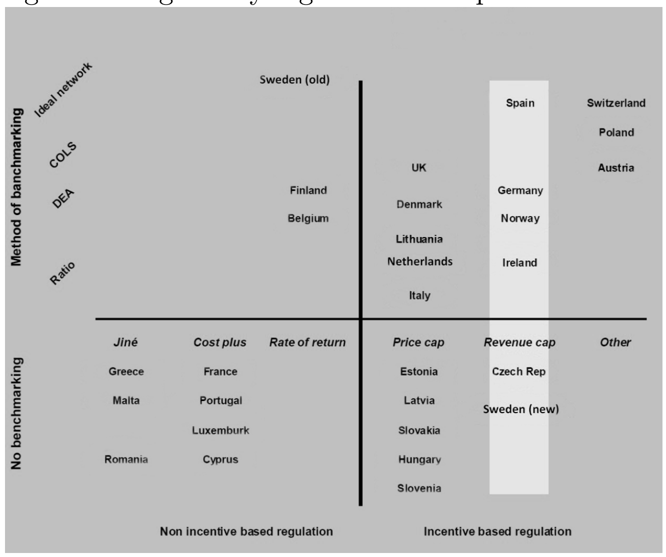
We see a problematic part of the formula in the setting of the efficiency factor. ERU admitted problems with setting of the X factor. Initially, ERU sought to introduce the individual and the general X factor, but there was allegedly shortage of information to define the individual factor and only the general X factor was applied (ERU, 2009).

Due to a small number of regional DSOs and a slow expansion of competitors in the Czech Republic, the application of the benchmarking methods using national data is constrained and almost impossible. We believe that the application of the benchmarking methods in an international comparison would enable to compare DSOs and enable to introduce the individual efficiency factors. The yardstick methods are commonly used by national regulators. Their practices are described in the following section.

ERU (2013b) considered a change to the revenue cap regulation and introduced the price cap regulation in the proposal for the fourth regulatory period of the gas industry. The proposal for the following regulatory period for the electricity has not been published in time of writing of the thesis, but it is probable that ERU considers the change also for the electricity sector. In case of the stabilisation of parameters of the regulatory formula, the price cap regulation would stabilise the prices on the market. Both methods share principal assumptions and as a result are to a large extent interchangeable. The regulatory practice confirms this (see Figure 4). If the parameters of both methods are set properly, the outcomes should be similar. The introduction of the price cap regulation would bring greater stabilisation of prices, but on the other demands stability of the parameters of the regulatory formula throughout the whole period.

We are convinced that the choice between the revenue and price cap regulation is not crucial. More important is a definition of the parameters of the regulatory formula. The inclusion of the individual X factors in the fourth regulatory period should be reconsidered to incentivise particular firms according to their true performance. We further believe that investments in smart grids should be privileged and fostered in the following regulatory period. The smart grids can increase reliability and stability of the network. They would also facilitate a better inclusion of RES that underwent significant development in the past years.

Figure 4: Regulatory regimes in European countries



Source: ERU (2009, p. 12); Schweinsberg et al. (2011, p. 2); edited by author

5.2 Practices of regulatory bodies in selected EU states

In this section, we focus on the regulatory frameworks of utility regulators in the European Union. We focus in detail on the electricity regulators and their use of the benchmarking methods for the regulation of DSOs. For the comparison, we selected neighbouring countries of the Czech Republic and complemented them with Finland and Great Britain. We chose Great Britain and Finland, because the benchmarking methods are traditionally embedded in their regulatory schemes for the regulation of DSOs.

Based on Directive 96/92/EC, the EU members are obliged to set up independent national regulatory authorities for the electricity sector. The regulators are cooperating on the EU level and can benefit from mutual collaboration. In 2000, the Council of Energy Regulators (CEER) was established to enhance the cooperation. Based on Regulation No 713/2009 of European Commission, the Agency for Cooperation of Energy Regulators (ACER) was established to complement and coordinate the activity of the EU regulators. These organisations were also established to amplify the development of electricity grid and transmission system.

The general regulatory regimes are outlined in Figure 4 (it also includes the non-EU member states - Norway and Switzerland). We focus on some of them in detail in following parts. A setting of regulatory practices is left in the EU to the member states, but it should be in line with the EU legislative corpus. The unbundling process and the related legislature are described in Chapter 3.

Benchmarking usually consists of two steps, first to determine productivity improvement and then individual efficiency catch-up (Schweinsberg et al., 2011). The productivity improvement leads to a shift of the efficient frontier that is determined by efficient firms. The individual efficiency is computed by the benchmarking techniques and the firms are, based on position of the companies with respect to the frontier, assigned the efficiency scores. The benchmarking methods are developed in industries with high number of incumbents, because bigger datasets enable their use on national level. In the Czech Republic, Slovakia and Poland, the yardstick methods are not explicitly used, which can be attributable to the shortage of data. We did not identify any information indicating that regulators in these countries are using international benchmarking for the setting of the X factors.

5.2.1 Austria

The energy regulator in Austria is Energy-Control (E-Control) established in 2000. The Austrian market was liberalised in 2001 (Frontier Economics, 2012). The regulatory regime has changed over years. Between 2001 and 2005, it was based on the cost plus regulation. In 2006, the regulation of DSOs switched to a long-term incentive regulation. The regulatory periods are set to four years. The first regulatory period lasted 2006-2009, second one 2010-2013 and the third one started in 2014. The authors differ in designation of the regulatory method. Authors from WIK-Consult title the regime as a hybrid price cap (Schweinsberg et al., 2011), Frontier Economics (2012) as a revenue cap and ERU (2009) as other. We do not consider the notation important, the system is a combination of the incentive-based regulation and the benchmarking methods, and E-Control does not stress particular methodology either.

Out of 128 electricity DSOs, there are 11 serving more than 100,000 customers on the Austrian market (CEER, 2013).

E-Control applies the benchmarking methods to set the individual efficiency targets. E-Control prefers past actual data (ideally data from year t-2) to forecast or planned data obtained from companies. There are three methods used by E-Control - two DEAs and MOLS. The methods are based on cross-sectional data of around 20 DSOs (Schweinsberg et al., 2011). An input variable is TOTEX (CAPEX, OPEX and investment factor). Output variables are based on a two step reference model. In the first step, the relevant variables are set based on the engineering model. In the second step, they are tested for significance. The output variables comprise voltage lines, service area, line density, peak load density and number of transformers.

The efficiency scores are computed as a weighted sum of particular methods (60% for two DEAs and 40% for MOLS). The shift of the efficient frontier is based on international comparison. The inefficient firms shall catch-up to the frontier within eight years, however, perfect reaching of the frontier is not demanded (Frontier Economics, 2012).

5.2.2 Finland

The national regulatory office in Finland is Energiamarkkinavirasto (EMV; in English Energy Market Authority) established in 1995. The market was fully liberalised in 1997 (Schweinsberg et al., 2011). The third regulatory package was, however, not fully transposed into the national legislation - rebranding and compliance requirements were not fully implemented (CEER, 2013). The first regulatory period was in years 2005-2007, the second regulatory period was prolonged to four years and was in years 2008-2011, and the current third regulatory period is again set to four years and started in 2012.

There are 96 DSOs operating on the market, 19 out of them serve more than 100,000 customers (CEER, 2013). The Finnish market is characterised by a large number of competitors and high switching rates. Both factors foster competitiveness of the market. There is a high number of competitors relatively to the size of the market, therefore significant amount of operators lease the network capacities. The regulator treats DSOs owning the electricity network equally to DSOs that lease it to secure a high level of quality of distribution. Wholesale market is interconnected with Sweden, Norway and Denmark (Schweinsberg et al., 2011).

The Finnish regulator is one of the pioneers in the practical use of the benchmarking methods. DEA was implemented in the first regulatory period in 2005 and SFA in the second regulatory period in 2008 (Kuosmanen et al., 2013). In 2012, EMV adopted new scheme and replaced the DEA and SFA methods. The new method is called StoNED (Stochastic Semi-Nonparametric Envelopment of Data). The method combines both DEA and SFA, and utilise advantages of both methods. It employs the DEA frontier and combines it with the SFA processing of inefficiency and noise (for more details, see Kuosmanen et al., 2013). As a dependent variable, observed TOTEX (comprises CAPEX, TOTEX and interruption costs) is used. Outputs are weighted amount of energy distributed, number of customers and length of network. The additional variable, share of underground cables, is included to control for heterogeneity of the firms and from definition it can be treated neither as output nor as input.

In the setting of efficiency factors, both enterprise-specific and general efficiency growth potentials are taken into account. The firms' specific targets in current regulatory period are based on 2005-2010 data and set using the StoNED method. The general efficiency target is 2.06% per year (EMV, 2011). The high-voltage DSOs face only general efficiency targets.

The Finnish model is very complex and benefits from comparatively large dataset, stability of the market and experience with the benchmarking methods.

5.2.3 Germany

The national regulatory authority in Germany is Bundesnetzagentur (in English Federal Network Agency). The regulation of energy sectors (gas and electricity) was assigned to the Bundesnetzagentur in 2004 and since then it has been in charge of energy regulation. It had focused only on regulation of telecommunications and postal services before. The market was fully liberalised in 2001 (Frontier Economics, 2012). The regulation was based on the cost plus scheme between 2001 and 2008. Since 2009, the regulatory system has been based on the incentive regulation in form of the revenue cap. The length of regulatory period is set to five years.

There were 888 electricity DSOs operating on the market in 2013 while 76 of them served more than 100,000 customers distributing around 70% of overall quantity of distributed electricity (Bundesnetzagentur and Bundeskartellamt, 2014). The number of DSOs has been stable since 2006. The price of electricity in Germany is among the highest in the EU due to the high values of contributions for renewable energy sources. Unbundling requirements for DSOs serving more than 100,000 customers are given by the EU legislation. Smaller DSOs (serving less than 30,000) may in Germany opt for a simplified procedure that requires them to disclose less information.

There are three categories of costs that are regulated (Schweinsberg et al., 2011). The first category comprises costs that are regarded as exogenous for the company and these are updated every year and are not subject to benchmarking. The remaining two categories are taken as endogenous (can be altered by the management and are linked to the business of particular DSOs). Forecasting is not used and the cost data are based on past data using t-3 figures adjusted by expansion factor (Frontier Economics, 2012).

Bundesnetzagentur applies DEA (with non-decreasing returns to scale) and SFA for benchmarking. As an input variable, adjusted TOTEX is used. The outputs are: number of connection points, service area, peak load and network length (Frontier Economics, 2012). The high number of regulated DSOs allows the regulator to use various subsets of the outputs. The regulator runs two DEAs and two SFAs while taking into account the maximum efficiency score computed for each company; furthermore, there is a lower limit of 0.6. If the efficiency score of the company is below the threshold, the company is treated as having efficiency score equal to 0.6.

5.2.4 Great Britain

The national regulatory body in Great Britain is Office of Gas and Electricity Markets (Ofgem). Great Britain was a pioneer in the use of the incentive regulation for the network industries in the EU. The regulatory system has been in operation since privatisation in 1990 (Frontier Economics, 2012). The length of the regulatory period is set to five years. The regulatory regime is based on the price cap regulation, but there is a significant transformation of the system scheduled for the following regulatory period (beginning in 2015).

There are 14 licensed DSOs and six independent network operators in Great Britain (Ofgem, 2013). The independent network operators run smaller networks that are included in the grids of DSOs and operate specific infrastructure. British DSOs are controlled by six different groups. They are obliged by their license to meet certain requirements for the network operations. These are set maximum interruption rates, investments levels, obligations to provide information to Ofgem, etc.

The new regime starting in April 2015 is called RIIO (Revenue equals Incentives plus Innovation plus Outputs). RIIO is not designed to alter the current regulation, but it should be built on its success. It is designed to put more emphasis on innovations and investments. There are three general concerns - sustainability, efficiency and evaluation of past regulation, and complexity (Frontier Economics, 2012). RIIO is still based on the price cap regulation, but it is targeted more on outputs divided into primary outputs and secondary deliverables. The primary outputs are based on quality of supply. DSOs will be required to submit business plans for the future and Ofgem will scrutinise these plans and assess the adequacy of revenues. The base revenues will be, contrary to the current schemes in Austria and Germany, based on business plans submitted by the incumbents. These will be in the next step compared to the past performance and TOTEX benchmarking. Ofgem has been using methods based on the ordinary least squares regressions and these are planned to be applied also in RIIO (Frontier Economics, 2012).

Ofgem gains from long-term experience and stability of the market; therefore, there is a larger scope for more complex methods because of the stability of the parameters and institutional setting. The financial variables are further complemented by quality parameters (customer satisfaction, reliability, sustainability, etc.).

5.2.5 Poland

The regulator in Poland is Urzad Regulacji Energetyki (URE; in English Energy Regulatory Office) founded in 1997. The energy market in Poland is fully opened, but could not have been considered unbundled in 2012, because the third regulatory package was no implemented (URE, 2013); moreover, URE still applied consumer price regulation in 2012. The length of regulatory period is four years and the current fourth regulatory period lasts in years 2012-2015.

There are five DSOs responsible for certain distribution areas with more than 100,000 customers. The number shrunk due to the mergers. There were seven operators in 2010. Additionally, there are 177 entities active in electricity distribution while 148 are appointed DSOs by URE (URE, 2013).

The regulation is based on the cap regulation with cost plus and rate of return mechanisms (EY, 2013). The regulator applied the DEA and COLS methods in 2008 (Haney and Pollitt, 2009), but it did not disclose more detailed information about the regulatory practice and methodology. The efficiency scores of the individual operators are confidential and not public.

5.2.6 Slovakia

The regulatory authority in Slovakia is Úrad pre reguláciu sieťových odvetví (URSO; in English Office for Regulation of Network Industries) founded in 2001. The market was fully liberalised in 2007 (URSO, 2013b). The length of the regulatory period is five years and the current one lasts from 2012 to 2016. The period was prolonged to enforce the stability and reliability of the market. The previous regulatory periods were set to three years. The regulation has been based on the price cap regulation since 2009. The price cap regulation was introduced in 2009 and replaced the revenue cap method.

The structure of the distribution market is similar to the Czech Republic. There are three regional DSOs in Slovakia and these have more than 100,000 customers. There are also 159 licensed small DSOs with less than 100,000 customers (URSO, 2013a). These are operators of local distribution networks operating on the premises of manufacturing and non-manufacturing companies.

URSO mentioned a use of international benchmarking for the gas market for setting of the prices for gas storage, but the Slovak national regulatory body does not explicitly use benchmarking methods in the electricity sector. The parameters of the price cap scheme were determined for the base year of the regulatory period (2012) and they have been optimised each year using correction factors. There are positive results attributed to the price cap scheme and URSO (2011a) also emphasises positive effect on the stability of prices.

6 Empirical part

The electricity distribution sector in the Czech Republic is dominated by three regional DSOs. Their natural monopolistic structure creates a need for regulation. ERU is applying incentive based revenue cap regulation, which is designed to motivate the incumbents to improve efficiency of their operation. The problem is that the firms are treated equally, regardless of the structure of the network that they control. The regulator employs only the general X factors that implicitly assume the firms to be similar. The equal treatment of DSOs is, however, very simplistic and if there are differences in the cost efficiency among the operators, the less efficient operators are not incentivised to converge to the more cost efficient operators.

Introduction of the individual efficiency factors is problematic due to only three firms dominating the market. The comprehensive analysis of the incumbents conducted to reveal their true cost efficiency is beyond the capabilities of the regulator and given the size of the companies even impossible to complete. ERU sought to introduce the individual efficiency factors, but abandoned the idea because of the shortage of data (ERU, 2009). The companies can be compared with their competitors or, as we showed in section 2.5, with comparable companies; however, as Pollitt (2005) notes, in reality it is difficult to find strictly comparable firms. Another option is to model an efficient frontier of the comparable firms that serves as a yardstick (Kuosmanen et al., 2013). Given the Czech market structure, the option might be benchmarking of gas and electricity DSOs together; however, there are significant differences between the sectors (storage, impact of the crisis, network specifics, etc.) and these may prove to be very difficult to control for. We believe that the suitable option, how to compute the efficiency of the incumbents, is to conduct a benchmarking analysis using an international dataset.

Our thesis is based on articles published in the Energy Policy journal. We draw inspiration from works of Michael Pollitt and his colleagues. International benchmarking study was conducted by Jamasb and Pollitt (2003) who benchmarked 63 regional electricity distribution and transmission companies using the DEA, SFA and COLS methods. The authors stressed the potential of international benchmarking for regulators, but they also mentioned the obstacles. We see the problematic part in inclusion of both DSOs and TSOs in the analysis because their operation is different. Haney and Pollitt (2009) conducted a survey of 40 energy regulators and found out that benchmarking techniques are widely used for the regulation of gas and electricity utilities. They further sought the determinants of best practice regulation on the same sample of countries (Haney and Pollitt, 2011). The authors examined the benchmarking practice of TSOs; they mentioned that the benchmarking methods and frontier analyses substitute the complicated engineering models of regulated methods and they also stressed that TSOs are more difficult to benchmark as they are more idiosyncratic and need to be benchmarked internationally (Haney and Pollitt, 2013, p. 277). This also confirms our assumption that DSOs and TSOs should be benchmarked separately. Kuosmanen et al. (2013) focused on the best practice benchmarking of DSOs. They compared the DEA, SFA and StoNED (for more details, refer to subsection 5.2.2 or Kuosmanen et al., 2013) methods. The StoNED methods are employed by Finnish regulator and combine advantages of DEA and SFA, however, they demand bigger datasets. Both Michael Pollitt and Timo Kuosmanen worked for national regulatory offices in England and Finland respectively, and they influenced the development of benchmarking for regulation in both countries.

As was mentioned above, a similar benchmarking study in the Czech Republic was not conducted yet. As far as we know, similar analysis was not conducted for other European countries that we examine either (namely Slovakia, Poland and Serbia). We follow papers that examined benchmarking methods in particular states. Farsi et al. (2005 and 2006) examined the panel of 59 Swiss distribution utilities using SFA estimated by generalised least squares, maximum likelihood and random effects models. Their analysis was facilitated by large dataset (around 380 observations) that significantly exceeds other studies. Agrell and Bogetoft (2011) supervised the final report on the use of benchmarking methods for the regulation of DSOs prepared for the Belgian regulator. They examined both gas and electricity DSOs and recommended DEA for the regulation. The general recommended variables were TOTEX (as input), and number of connections, lines length and transformers (as outputs).

The benchmarking studies are not only used in theoretical literature, but are widely used in the regulatory practice. According to Bogetoft and Otto (2011), there were nine European regulators that used benchmarking for the regulation of electricity DSOs. According to Schweinsberg et al. (2011), regulators in 12 out of 27 EU members used methods of cost benchmarking in energy regulation. The methods of regulators in the selected EU states are described in subsection 5.2.

Our study complements the already conducted studies and brings analysis of states that were outside of the field of interest of the researchers. We are, unfortunately, not allowed to disclose the computed efficiency scores for foreign operators due to the contractual obligations; however, the international dataset brings the efficiency comparison among the companies and allows us to determine the efficiency scores for the Czech DSOs.

In the following sections, the yardstick methods used to measure the performance of DSOs and collected data are described. We adopt the DEA and SFA methods for benchmarking while taking into account the scope of the data available. The methods widely applied to the regulation of electricity markets are described and compared in the second chapter without formalisation. The thorough formalisation of all methods and yardstick techniques (TFP, DEA, COLS, MOLS and SFA) would significantly exceed the recommended scope of the thesis. This chapter encompasses description of the DEA and SFA methods and of the dataset. The purpose of the following sections is to outline the methodology and the data used for a computation of the efficiency scores of DSOs.

6.1 Methodology

DSOs are traditionally subject to specific regulation. The regulators have been changing the rate of return schemes to incentive regulation since 1990s. The incentive regulation is usually complemented by the yardstick methods to better fit the regulated decision making units (hereafter DMUs) and to mitigate the information asymmetry. The terms DMU and firm are taken as interchangeable even though the term firm may not be inappropriate for example in the case of benchmarking the public service companies, but in context of our study they are both relevant.

The most widely used techniques are the DEA methods combined with the stochastic frontier methods or the methods based on the OLS regressions. In our study, the DEA models are preferred because of the limited scope of data. Both the constant and the variable return to scale DEA models are applied. In the literature, the DEA models are often complemented by a second stage OLS regression of efficiency parameters to control for other environmental characteristics that are typical of DSOs in the electricity sector. We checked the CRS DEA results and regressed the coefficients on population density and the estimates confirmed the results of VRS DEA. Due to the size of the dataset, we decided to apply both the CRS and the VRS DEA specifications without second stage. The DEA models are supplemented with SFA, but we are aware of the limitations stemming from the size of the dataset.

6.1.1 Data envelopment analysis

DEA is a non-parametric method that uses piecewise linear programming to calculate efficient surface (or frontier) over the data (Coelli et al., 2005). The efficient DMUs lying on the frontier envelop the less efficient firms. The efficiency of particular DMUs (firms) is calculated relative to the frontier on a $\langle 0, 1\rangle$ scale. The efficient DMU is scored one and the number indicates a point on the frontier.

The DEA models can be both input and output oriented. The input-orientated DEA calculates how much the input quantities can be reduced without changing the output values. The output-orientated DEA programmes how much the outputs can be expanded keeping the input quantities unchanged. The input-orientated DEA is generally appropriate for benchmarking of DSOs (e.g. Frontier Economics, 2012; Jamasb and Pollitt, 2003); moreover, the demand for distribution services is a derived demand, the incumbents cannot influence it and it has to be met because of the regulation (Jamasb and Pollitt, 2003). The models can be specified for the constant or the variable returns to scale (CRS, VRS respectively).

Firstly, we define the CRS input-oriented model. We follow notation established by Coelli et al. (2005). Assume the dataset of N firms containing data on K inputs and M outputs. The inputs and the outputs are represented by column vectors x_i and y_i respectively. The input matrix X ($K \times N$) and the output matrix Y ($M \times N$) represent the data for all firms.

For each firm, we would like to obtain efficiency score, which is the maximum ratio of weighted outputs to weighted inputs for each DMU, such as $u'y_i/v'x_i$ where u is a vector of output weights ($M \times 1$) and v is a vector of input weights ($K \times 1$). The efficiency score in a multiple input and output scenario is obtained by solving the linear programming problem

$$\begin{aligned} &\max_{u,v} \left(\frac{u'y_i}{v'x_i}\right) \\ &\text{s.t. } \frac{u'y_j}{v'x_j} \leq 1, \quad j = 1, \dots, N \\ &u, v \geq 0. \end{aligned} \tag{6.1}$$

The linear programming is solved for each DMU while the efficiency score must be less than or equal to one. The problem of the above mentioned programming problem is that it has an infinite number of solutions (Coelli et al., 2005). If $(\tilde{u}, \tilde{v})$ are the solutions, then for $a \,\epsilon\, \mathbb{R}$, $(a\tilde{u}, a\tilde{v})$ are solutions as well; therefore, it is necessary to modify the model and impose a constraint of weighted inputs to equal one. Formally,

$$\max_{u,v} \left(\frac{u'y_i}{v'x_i}\right) \tag{6.2}$$
$$\text{s.t. } v'x_i = 1,$$
$$\frac{u'y_j}{v'x_j} \leq 1, \quad j = 1, \ldots, N$$
$$u, v \geq 0.$$

Coelli et al. (2005) suggest equivalent form of the (6.2) linear programming problem, which is also more convenient for our analysis. Using duality, it can be rewritten as a linear programming problem

$$\min_{\theta,\lambda} \theta \tag{6.3}$$
$$\text{s.t. } -y_i + Y\lambda \geq 1$$
$$\theta x_i - X\lambda \geq 0$$
$$\lambda \geq 0,$$

where θ is a scalar (equal to the efficient score) and λ represents a $N \times 1$ vector of constants. The problem (6.3) satisfies the assumption of the efficiency score to be between zero and one while DMU with $\theta = 1$ is technically efficient. To obtain the efficient score for each DMU, the linear programming problem must be solved N times. In the model (6.3), the i-th DMU is compared to a linear combination of other firms in the sample. It is obvious from the second condition that the output vector x_i is minimised while still remaining in the feasible set of inputs that is bounded by the piece-wise linear isoquant determined by the firms included in the sample. The input vector x_i is radially contracted on the isoquant (frontier) to the point $(X\lambda,\ Y\lambda)$. This point is a linear combination of the observed data points and given the constraints in the model (6.3), it is inside the feasible set.

The radial contraction of the input vector is invariant in units so the efficiency score is not influenced by a change of measurement units. Since we assume only one cost input variable in our model, it is possible to identify output slacks. These exist only for inefficient firms and represent only the leftover portion of inefficiencies after the radial contraction and the slacks are necessary to move to firm to the efficient frontier (Ozcan, 2008).

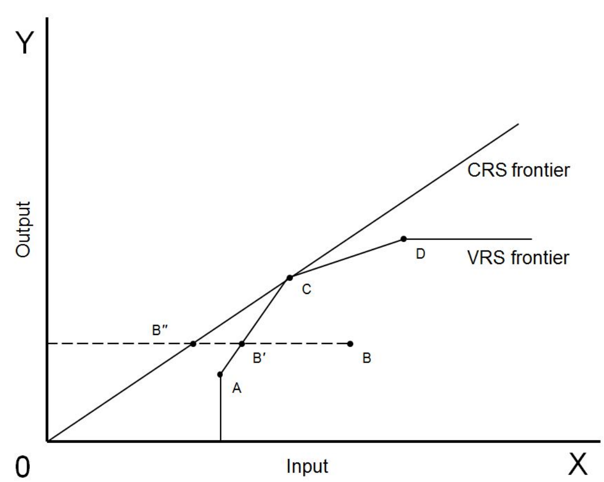
The problem of CRS DEA is that it implicitly assumes that the firms are operating at the optimal scale. This assumption is violated in case of imperfect competition, regulations and other factors that restrict the firms to operate at the optimal scale (Coelli et al., 2005). To get VRS DEA, the model (6.3) is modified by adding a convexity constraint $\sum \lambda = 1$. If the CRS specification is applied to DMUs that are not operating at the efficient scale, the technical efficiency is influenced by scale efficiencies. VRS DEA calculates technical efficiency less the scale efficiencies and the firms are compared against other DMUs with similar size. The VRS DEA model is defined as

$$
\begin{aligned}
&\min_{\theta,\lambda} \theta \\
&\text{s.t.} \; -y_i + Y\lambda \geq 1 \\
&\qquad \theta x_i - X\lambda \geq 0 \\
&\qquad N1'\lambda = 1 \\
&\qquad \lambda \geq 0,
\end{aligned}
\tag{6.4}
$$

where the $N1$ is a $N \times 1$ vector of ones.

To find out the nature of the returns to scale, Coelli et al. (2005) recommend non-increasing returns to scale specification (NIRS) where the restriction $N1'\lambda = 1$ from (6.4) is replaced by restriction $N1'\lambda \leq 1$. If the efficiency scores from VRS and NIRS differ, the increasing returns to scale exist for the particular firm. The NIRS restriction ensures that the firm is benchmarked against firms of similar size and not substantially larger.

Figure 5: DEA frontiers



Source: Author's layout

The differences between CRS and VRS DEA are depicted in Figure 5. We illustrate input-oriented model with one input (X) and one output (Y). In case of CRS, there is only one efficient DMU (marked as point C). Allowing for variable returns to scale, there are two more efficient firms (labelled A, D). The point B refers to the inefficient firm while the technical inefficiency is a distance BB'' and BB' for CRS and VRS respectively. The distance $B''B'$ is due to the scale inefficiency. Using VRS DEA, the overall effect can be decomposed into technical efficiency and scale efficiency.

Important advantage of DEA is that it does not suffer from problems with multicollinearity, because it is based on linear programming (Andor and Hesse, 2011; Went, 2007). Jensen (2005) showed that multicollinearity has a little impact even on the results of SFA.

There are several rules of setting the minimal amount of DMUs for DEA to have a good discriminatory power. The general rule of thumb is that the minimum number of DMUs should be at least twice the sum of inputs and outputs. Some authors recommend more prudent approaches - twice the multiple of inputs and outputs, three times the number of inputs and outputs and so forth (for more details, refer to Sarkis, 2007; or Cullinane and Wang, 2006).

6.1.2 Stochastic frontier analysis

In the previous section, we considered the non-parametric DEA to obtain the efficiency measures. In this section, parametric estimation using SFA is considered. The development of the SFA models is soundly described in the literature (e.g. Coelli et al., 2005; Greene, 2007). The main advantage of SFA compared to DEA is that it allows for statistical and functional form testing and separates noise and inefficiency. SFA requires specification of production (or cost) function requiring assumptions about production technologies of DMUs.

As well as the ordinary least squares methods, SFA requires specification of the production function and shares many properties with regression techniques, but it uses more sophisticated estimation of the production frontier. Similarly to DEA, we consider costs as dependent variable in the model. Treatment of outputs and inputs is therefore analogous.

DEA attributes the difference between the particular DMU and the efficient firm to inefficiency. The estimation of deterministic production frontier could be conducted by methods based on OLS, but any deviation from deterministic efficient frontier is again assigned to inefficiency. The deviations might not be; however, under control of the management and could be caused for example by measurement error or other source of statistical noise (Coelli et al., 2005). The stochastic frontier production function model was developed to overcome these problems.

There are several different expressions of the technology of the industry. Cobb-Douglas and translog specifications are most frequently used in the empirical applications. The Cobb-Douglas form is more restrictive in assumptions, but usually preferred over the translog specification for benchmarking of DSOs with smaller samples. SFA is estimated using maximum likelihood estimation techniques.

We start with a model for cross-sectional data and follow notational system from Coelli et al. (2005). The stochastic production function model was simultaneously proposed by Aigner et al. (1977) and Meeusen and van Den Broeck (1977) in the following form

$$\ln q_i = x_i'\beta + v_i - u_i, \tag{6.5}$$

where q_i is a dependent variable of i-th firm (input in case of cost frontier); x_i is a $K\times 1$ vector of logarithms of explanatory variables (outputs in case of cost frontier); β is a vector of unknown parameters; v_i is a symmetric random error accounting for statistical noise; and u_i is a non-negative random variable associated with inefficiency. The statistical noise is caused by measurement error, omission of relevant variables or it can arise from approximation of errors related to the functional form of the production (or cost) function. The model is bounded from above by a stochastic variable $\exp(x_i'\beta + v_i)$ that gives the model its name.

Let us further assume a production function. The SFA frontier can be illustrated graphically. Taking the Cobb-Douglas stochastic frontier (6.5) of the production function with single dependent (output) and single explanatory (input) variable, we have

$$\ln q_i = \beta_0 + \beta_1 \ln x_i + v_i - u_i. \tag{6.6}$$

If we rearrange the equation (6.6), we get

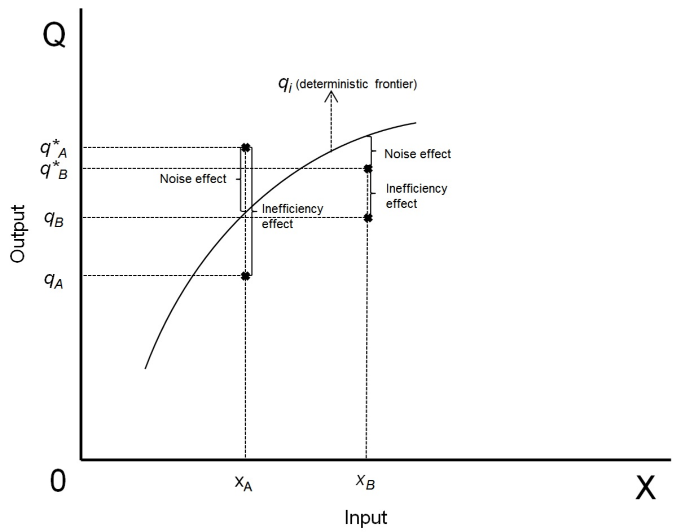
$$q_i = \exp(\beta_0 + \beta_1 \ln x_i) \times \exp(v_i) \times \exp(-u_i), \tag{6.7}$$

where $\exp(\beta_0 + \beta_1 \ln x_i)$ is deterministic component; $\exp(v_i)$ represents noise; and $\exp(-u_i)$ is an inefficiency term. Assume the deterministic frontier to reflect the decreasing returns to scale. Further assume two firms, firm A and firm B. Firm A produces output q_A using input x_A, firm B uses x_B to produce q_B. If both firms are effective, i.e. there are no inefficiency effects ($u_A = 0 \wedge u_B = 0$), the production functions are

$$q_A^* \equiv \exp(\beta_0 + \beta_1 \ln x_A + v_A) \wedge q_B^* \equiv \exp(\beta_0 + \beta_1 \ln x_B + v_B). \tag{6.8}$$

Further assume the noise effect for firm A to be positive ($v_A > 0$) and for firm B to be negative ($v_B < 0$), and the deterministic frontier $q_i = \exp(\beta_0 + \beta_1 \ln x_i)$. The stochastic production frontier is depicted in Figure 6.

Figure 6: Stochastic production frontier



Source: Coelli et al. (2005); author's layout

The position of the firm with respect to the deterministic frontier depends on the magnitudes of noise and inefficiency effects.

Most of the frontier analyses are aimed at prediction of inefficiencies. The technical efficiency is defined as ratio of observed output to the SFA output

$$TE_i = \frac{q_i}{\exp(x_i'\beta)} = \exp(-u_i). \tag{6.9}$$

The value of technical efficiency is between zero and one and it represents the ratio of the company's output to the output that could be produced by a fully efficient firm using the same vector of inputs. A drawback of SFA is that even if there are no statistical errors, some inefficiency may be wrongly regarded as noise (Jamasb and Pollitt, 2003).

The estimation of the SFA parameters is more complicated due to two random terms included on the right hand side of the equation (6.5); therefore, some assumptions concerning these terms should be made. Assume v_i are random variables that are assumed to be independently and identically distributed (i.i.d), $v_i \sim \mathrm{N}(0, \sigma_v^2)$ and independent of u_i; u_i are non-negative random variables assumed to be i.i.d, $u_i \sim |\mathrm{N}(0, \sigma_u^2)|$ (Coelli, 1996b). Aigner et al. (1977) obtained maximum likelihood estimators under these assumptions and parameterised the log-likelihood function for half-normal model. Assume $\sigma^2 = \sigma_v^2 + \sigma_u^2$ and $\lambda^2 = \frac{\sigma_u^2}{\sigma_v^2}$ for $\sigma_v^2 \geq 0$. There are no inefficiency effects if $\lambda^2 = 0$ and the deviations from frontier are due to the statistical noise. For details of this parameterisation, refer to Coelli et al. (2005).

The u_i is homoscedastic with a constant mean and uncorrelated; the v_i is homoscedastic, with a zero mean and uncorrelated (similar properties to the noise of the classical linear regression model). The OLS model cannot be used for estimation, because the intercept is biased downwards. Coelli et al. (2005) suggest the use of a maximum likelihood method for better asymptotic properties in comparison with adjusted OLS models (e.g. COLS, MOLS).

The general model (6.5) from Aigner et al. (1977) can be extended to panel data. The model is expressed as (Battese and Coelli, 1992)

$$\ln q_{i,t} = x'_{i,t}\beta + v_{i,t} - u_{i,t}, \tag{6.10}$$

where time factor t is added. Statistical noise is assumed to be i.i.d, $v_i \sim \mathrm{N}(0, \sigma_v^2)$ and independent of the inefficiency term. The inefficiency term may vary over time

$$u_{i,t} = u_i \exp[-\eta(t - T)], \tag{6.11}$$

where u_i are random non-negative variables assumed to be i.i.d. as truncations at zero of $\mathrm{N}(\mu, \sigma_u^2)$ distribution; η parameter to be estimated; and the panel dataset does not have to be balanced.

Using parameterisation of Battese and Corra (1977), we introduce $\gamma := \sigma_u^2/(\sigma_v^2 + \sigma_u^2)$ that represents the share of technical efficiency in the error term. If $\gamma = 0$, all deviations from the frontier are attributed to statistical noise; on the other hand if $\gamma = 1$, all deviations are caused by inefficiency. For more details, refer to Battese and Corra (1977), Battese and Coelli (1992), Coelli (1996a), Coelli (1996b) and Coelli et al. (2005).

Since a cost function is considered in our study (as dependent variable we take total expenditures), the equation (6.10) is adjusted (Coelli, 1996b)

$$\ln q_{i,t} = x'_{i,t}\beta + v_{i,t} + u_{i,t}, \tag{6.12}$$

keeping all other factors the same. In case the cost function in equation (6.12) is considered, the $u_{i,t}$ term defines the cost inefficiency of the firm, i.e. the distance of the firm from the cost frontier. Some authors recommend translog form of the cost function specification (e.g. Coelli et al., 2005; Agrell and Bogetoft, 2011). We considered the option, but due to the limited dataset and loss of degrees of freedom, we applied the log-linear functional form. In case of larger dataset, we would test both options and compare the results.

6.2 Data description

Our benchmarking study is based on data of electricity DSOs. We focus on the unbundled regional DSOs with more than 100,000 customers. The inclusion of smaller DSOs would increase the size of the dataset, but the differences would have significant impact on the computed efficiency scores. We complemented the Czech DSOs with companies from other European countries.

The collection of data was complicated due to their confidentiality. There were problems with provision of both financial (cost) and technical data. We contacted national regulatory authorities and communicated with the Agency for Cooperation of Energy Regulators and the Council of European Energy Regulators, but we were only referred to annual reports and to particular firms. Due to the confidentiality, we could not have been allegedly provided with the data; therefore, we contacted particular companies directly. The financial statements are publicly accessible in the Czech Republic, but it is very uncommon abroad. Sometimes consolidated data for particular energy groups are available, but they do not include detailed data. During the data collection, we had to sign several contracts and declarations on oath and had to pledge to anonymise the data. Thus we cannot mention companies' names and we can only state descriptive statistics over the dataset.

We obtained data of 15 DSOs from the Czech Republic, Slovakia, Poland, Hungary and Serbia. The data are from financial statements, annual reports, reports to the regulatory authorities, websites and mostly supplemented by data provided directly by the companies. All companies are unbundled and operating on the regional basis. We sought data from the Austrian DSOs and contacted all 11 DSOs distributing energy to more than 100,000 customers, but none of them provided us demanded data.

The only data we were able to obtain directly without help were the data of Czech DSOs. There are three regional DSOs in the Czech Republic, but we can use only two of them for our study, because the company E.On Distribuce, a.s. did not provide us with financial data that would be usable for our analysis. The published financial statements are consolidated for distribution of both gas and electricity and it was no possible to obtain the separated cost data; therefore, only ČEZ Distribuce, a.s. and PREdistribuce, a.s. are included. We obtained the data from annual reports, distribution quality reports and websites. The data and documents are available online at websites of the companies.

Selection of inputs and outputs is based on theoretical literature (e.g. Jamasb and Pollitt, 2003; Haney and Pollitt, 2009; Kuosmanen et al., 2013; Shuttleworth, 2005) and practical application (e.g. EY, 2013; Frontier Economics, 2010; Frontier Economics, 2012; Schweinsberg et al., 2011).

The data are analysed using two methods, therefore, they are adjusted for each of them accordingly. For DEA, cross-sectional data for 2012 are used. We sought most up to date data and endeavoured to obtain complete dataset of 2012. For some firms, were able to obtain data from 2010 to 2012; and they are used as panel for SFA. The balanced panel is not necessary for SFA and we utilise this characteristic.

The inputs (costs) are represented in monetary values. They are adjusted for inflation using annual growth rate and denominated in euro with 2012 as a base year. The exchange rates were used as at the end of individual years, because the costs were taken mostly from financial statements that consider exchange rate at the year end.

The summary statistics over the data are depicted in Table 1. The data are rounded to comply with the requirements of DSOs and to guarantee anonymisation. To anonymise the data, values for minimum, maximum and median are rounded to the nearest ten. Most of the minimum values have to be anonymised with designation "N/A", because the minimum values would be attributable to a specific company. We are aware of the low information value, but we are limited by the signed contracts and declarations on oath.

The efficiency scores are estimated using software developed by Timothy Coelli. For DEA, version 2.1 of software DEAP (Coelli, 1996a) and for SFA, version 4.1 of software Frontier (Coelli, 1996b) are used.

Table 1: Summary statistics over dataset

Variable	Minimum	Maximum	Median	Mean
TOTEX ('000 000 EUR)	N/A	10	0	0.532
Distributed energy in TWh	N/A	50	10	12.280
Number of customers ('000 000)	N/A	10	0	1.552
Service area ('000 sq. km)	N/A	80	20	26.048
Grid length ('000 km)	10	220	30	67.298
HV lines ('000 km)	10	150	20	42.668
MV lines ('000 km)	N/A	70	10	22.030
LV lines ('000 km)	N/A	10	0	2.609
Underground cables ('000 km)	N/A	70	10	20.085
Overhead lines ('000 km)	N/A	160	30	47.212
Number of transformers	N/A	60	10	20.527
SAIFI	40	1 800	350	503.328
SAIDI	N/A	20	0	5.661

Source: Data collected by author

6.2.1 Input variables

DEA can be used for estimation of multiple inputs and outputs while SFA requires a specification of the cost function (or production function) with a single dependent variable. The single input model utilises comparability of the results of both methods.

We use input variable (dependent variable in case of SFA) in monetary terms in form of total expenditures (TOTEX). We obtained capital expenditures, however, the investments in distribution networks are cyclical and given the scope of the analysis (panel data for SFA), the use of CAPEX would require long panel data or adjustments. Therefore, we prefer to benchmark total costs.

The costs are converted from national currencies to euro. Jamasb and Pollitt (2003) converted their costs using purchasing power parities to equalise the price differences among countries. We decided to transform the data using only the exchange rates, because the capital expenditures comprise mostly of materials not traded in national currencies (except for dollar and euro) and the direct labour costs form a minor share of TOTEX of the utilities. We do not consider the transformation using the purchasing power parity to be convenient. In other studies, we did not observe similar adjustments.

In some of the models, the total costs are weighted by distributed energy and represent costs of unit of distributed energy.

6.2.2 Output variables

Our models are based on output (dependent) variables that we obtained. The selection is based on the literature and the practice of regulators. We consider these variables as major cost drivers. Except for the quality parameters (SAIFI and SAIDI), the parameters are assumed to be non-discretionary or to a limited extent manageable by the incumbents. The output variables are

- distributed energy in MWh,
- number of clients (grid connection points),
- service area (sq. km),
- grid length (area),
- low voltage lines (km);
- medium voltage lines (km);
- high voltage lines (km);
- length of underground cables (km);
- length of overhead lines (km),
- number of transformers,
- quality parameters - SAIDI, SAIFI.

These are the general variables used for estimation. The specifications of models based on these data are described in the following section.

6.3 Estimated models

6.3.1 Estimated DEA models

The input (dependent) variable of all models is represented by total expenditures. The explanatory (output) variables differ. For DEA, we use four output variables for the analyses and consider methods with both CRS and VRS. We use a mean normalisation of the data to correct for imbalances in data magnitudes. The normalisation is recommended by Sarkis (2007) to address possible scaling effects of the software. DEAP did not indicate any problems, but we decided to normalise the data for the sake of accuracy. The normalisation is defined

$$\bar{A}_i = \frac{\sum_{n=1}^{N} A_{ni}}{N}, \tag{6.13}$$

where $\bar{A}_i$ is the mean for i-th output or input; N is the number of DMUs; and A_{ni} is the value of particular input (output) of n-th DMU.

The outputs for the first DEA model (**DEA1**) are:

- (1) area (sq. km),
- (2) grid length (km) weighted by distributed energy (MWh),
- (3) transformers (count) weighted by distributed energy (MWh),
- and (4) inverse value of interruption duration (min) per MWh.

The interruption duration is computed from the SAIDI coefficient, which is multiplied by number of customers and weighted by distributed energy. The value is inverted, because the lower the interruption duration is, the more costly the grid maintenance is assumed to be. The weighting of parameters is used to address multicollinearity of the output variables (the correlation coefficients among the output variables are depicted in the Appendix in Tables 7, 8 and 9). As mentioned above, multicollinearity is not a problem for DEA, but high correlations among variables may decrease the descriptive power. The weighting is also preferred in the practical usage of DEA (e.g. benchmarking of DSOs in Norway, refer to Frontier Economics, 2012).

For the second DEA model (**DEA2**), the outputs are

- (1) area of the distribution network (sq. km)
- (2) grid length (km) weighted by distributed energy (MWh)
- (3) transformers (count) weighted by distributed energy (MWh),
- and (4) share of underground cables (%).

The interruption duration parameter is replaced by percentage share of underground network that is generally considered to be more costly to maintain and thus we decided to include it.

6.3.2 Estimated stochastic frontier models

In regulatory practice, the parameters used for SFA are similar to DEA and both methods are compared. We estimate three models. Two of them are using similar variables as our DEA model.

We use unbalanced panel specification of the SFA cost model in a log-linear model specification. This specification employs a Cobb-Douglas cost functional form and it is linear in logs of the variables. The log-linear model specification for **SFA1** is

$$\begin{aligned} \ln TOTEX_{i,t} = \beta_0 + \beta_1 \ln AREA_{i,t} + \beta_2 NETW_{i,t} \\ + \beta_3 TRAN_{i,t} + \beta_4 INTE_{i,t} + u_{i,t} + v_{i,t}, \end{aligned} \tag{6.14}$$

where the dependent variable $TOTEX$ represents total expenditures expressed in euro weighted by distributed energy; explanatory variables ($AREA$, $NETW$, $TRAN$ and $INTE$) are similar to outputs in DEA1; u is an inefficiency term; v is a noise term; βs are unknown parameters to be estimated; $i \epsilon \{1, .., 15\}$ is the coefficient for particular company; and $t \epsilon \{1, 2, 3\}$ is a time parameter for the years 2010-2012. The variable for interruptions is not inverted, because inversion is not necessary in the case of SFA. The variables are not weighted by MWh as in the case of DEA, because the values must be greater than one due to the logarithmic form. For SFA, the data were scaled by 10 TWh instead of GWh of delivered energy.

The **SFA2** is specified similarly, only the variable for interruption duration is replaced by the share of cable lines ($CABL$).

The third SFA model, **SFA3**, we defined as unweighted. We are aware of the high correlation coefficient between distributed energy and number of transformers (0.87); however, Jensen (2005) showed that multicollinearity has little impact on the results of SFA and therefore we decided to include the unscaled model as well. The selection of explanatory variables was based, similarly to the previous models, on regulatory practice. The model is defined

$$\ln TOTEX^u_{i,t} = \beta_0 + \beta_1 \ln DIST + \beta_2 CABL + \beta_3 TRAN^u_{i,t} + u_{i,t} + v_{i,t}, \tag{6.15}$$

where the dependent variable $TOTEX^u$ represents unscaled total costs; explanatory variables are $DIST$ (represents distributed energy), $CABL$ (previously defined cables' share), and $TRAN^u$ (unscaled number of transformers) other variables keeping similar to two previous models.

An important advantage of SFA is the possibility of statistical testing. The significance of estimated parameters (βs) can be tested comparing the computed t-statistics with critical values from ordinary statistical tables. In addition to testing of the parameters of the cost function, the existence of inefficiency effects can be tested. SFA requires an a priori assumption about the distribution of inefficiency term. There are two options, either to conduct a simple z-test or a likelihood-ratio test (LR test). Coelli et al. (2005) suggest using one sided LR test, because the z-test has a poor performance for small samples. The Frontier programme automatically gives values of the one-sided likelihood ratio test. The null hypothesis is the inexistence of inefficiency effects, i.e. $H_0 : \lambda = 0$ for the half-normal model and $H_0 : \mu = \sigma_u^2 = 0$ for the truncated-normal model. The statistic value of the LR test of the half-normal model is to be compared with $\chi^2_{1-2\alpha}(x)$ distribution where α is a level of statistical significance and x refers to a number of restrictions. The critical value for the truncated-normal model can be obtained from Table 1 in Kodde and Palm (1986).

The appropriateness of the truncated-normal model over the half-normal model can be also tested using values computed by Frontier. The LR test statistic is

$$\lambda = -2\left[\ln L(H_0) - \ln L(H_1)\right], \tag{6.16}$$

where $\ln L(H_0)$ and $\ln L(H_1)$ are statistics for log-likelihood values reported for half-normal and truncated-normal distributions. The null is $H_0 : \mu = 0$ against the alternative $H_1 : \mu \neq 0$. The value of the test statistic (6.16) is to be compared with $\chi^2_{1-\alpha}(x)$ where α is a level of statistical significance and x refers to a number of iterations of the half-normal model.

7 Results

This chapter presents the results of the models described in the previous chapter. In the first section, the results of the DEA models are discussed. Subsequently, the results of the SFA models are presented and the assumptions of the SFA models are tested. In third section, the summary statistics of efficiency scores are presented. The chapter is concluded with evaluation of the models and policy implications.

7.1 DEA models

As described in the previous chapter, there are two specifications of the DEA models to be tested. We apply input-based VRS specification of the models while DEAP presents also efficiency scores for the CRS specification. The DEAP in addition computes values for NIRS DEA to compute the nature of the returns to scale. The technical efficiency scores are depicted in Table 2, which contains values of both DEA models and encompasses the efficiency scores for the CRS and VRS specifications, scale effects, and nature of the returns to scale (abbreviation irs is for increasing returns to scale, drs for decreasing returns to scale and dash for constant return to scale).

Given the CRS specification, we assume that the firms are operating on the same scale. Since the dataset is comprised of companies of diverse size and from different countries, we consider the VRS specification to be more appropriate. If we use the CRS model, the technical efficiency scores might be confounded by scale efficiencies. The scale efficiency is defined by computing both CRS and VRS models, and then decomposing the efficiency scores obtained by CRS DEA to scale and pure technical inefficiency. If the efficiency scores obtained from the CRS and VRS models differ, then it indicates the existence of scale inefficiency. The technical efficiency score of the CRS specification is equal to multiple of the VRS efficiency score and the scale efficiency score.

In case of the CRS DEA models, there are three and two firms lying on the frontier. The lowest efficiency score is equal to 0.201 and 0.239 respectively. The values indicate significant differences among the firms. For the VRS DEA models, the number of firms on the frontier increases in both cases to five and the mean efficiency increases in both cases. Most of the firms exhibit non-constant returns to scale, but there are still significant differences among the benchmarked firms. The problem of VRS specification is that the validity depends on the size of the sample and VRS DEA tends to overstate the efficiency scores (Jamasb and Pollitt, 2003). The various categories of the firms should be sufficiently

Table 2: Summary of DEA efficiency scores

	DEA1				DEA2			
Firm	CRS	VRS	Scale	RtS	CRS	VRS	Scale	RtS
1	0.356	0.429	0.831	irs	0.422	0.446	0.947	irs
2	1.000	1.000	1.000	-	0.642	1.000	0.642	drs
3	0.241	0.319	0.757	irs	0.241	0.319	0.757	irs
4	0.378	0.413	0.915	irs	0.239	0.362	0.658	irs
5	0.281	0.454	0.619	irs	0.299	0.454	0.658	irs
6	0.747	0.906	0.825	irs	0.834	0.926	0.900	irs
7	1.000	1.000	1.000	-	1.000	1.000	1.000	-
8	1.000	1.000	1.000	-	1.000	1.000	1.000	-
9	0.721	1.000	0.721	drs	0.800	1.000	0.800	drs
10	0.207	0.430	0.483	irs	0.264	0.430	0.615	irs
11	0.386	1.000	0.386	drs	0.386	1.000	0.386	drs
12	0.300	0.366	0.820	irs	0.300	0.366	0.820	irs
13	0.201	0.415	0.484	irs	0.293	0.440	0.666	irs
14	0.315	0.386	0.815	irs	0.315	0.386	0.815	irs
15	0.622	0.910	0.684	irs	0.828	0.953	0.869	irs
mean	0.517	0.669	0.756	-	0.524	0.672	0.769	-

Source: Author's calculations

represented in the sample that is, however, limited in our case due to the small sample of firms.

Both of the DEA models give similar results. The validity may be increased by the larger dataset, because different categories of the firms would be better represented and thus the validity of VRS DEA would increase, but the data gathering is very complicated as was described in the previous sections.

7.2 SFA models

The SFA models are computed using the programme Frontier. All the SFA models are defined in the Cobb-Douglas log-linear specification and modelled as cost functions. The dataset in unbalanced for 15 firms with 28 observations. Both truncated-normal and half normal distributions of the inefficiency term are considered and tested. Summary statistics are reported in Table 3 for the half-normal and Table 4 for the truncated-normal models. The values of estimated coefficients are reported in columns while in parentheses the t-statistics are depicted. The level of significance of the estimates is represented by stars in parentheses. For LR test, the number of restrictions is depicted in parentheses. The nature of the variables is described in detail in the previous chapter.

Table 3: Summary of SFA parameters with half-normal distribution of inefficiency term

	SFA1 (H-N)	SFA2 (H-N)	SFA3 (H-N)
Variable	Coefficients (t-statistics)		
Intercept	7.956 (3.544***)	10.954 (12.499***)	-0.555 (-0.308)
AREA	-0.076 (0.972)	-0.109 (1.862*)	-
NETW	-0.224 (-0.763)	-0.468 (-1.916*)	-
TRAN	0.130 (0.509)	0.059 (0.279)	-
INTE	-0.194 (-0.929)	-	-
CABL	-	-0.715 (-6.188***)	-0.378 (-3.478***)
DIST	-	-	1.132 (5.262***)
TRAN^{U}	-	-	-0.386 (-2.222**)
σ^2	0.334 (1.710*)	0.116 (1.937*)	0.159 (2.206**)
γ	0.948 (18.368***)	0.852 (7.445***)	0.907 (15.533***)
Statistics	Values		
Log-likelihood	-0.824	5.869	5.427
LR one-sided test	7.222 (1 res.)	5.880 (1 res.)	11.971 (1 res.)

Statistical significance: * refers to 10%, ** refers to 5%, and *** refers to 1% significance.

Source: Author's calculations

The SFA1 specification shows poor statistical results. None of the variables is significant at the 10% level. The value of γ indicates that 95% of the variation in error term is attributable to technical efficiency and only 5% to statistical noise. In the SFA2 model, two coefficients are weakly significant at the 10% level of significance, one is significant at the 1% level and remaining coefficient at variable $TRAN$ is not statistically significant at the 10% level. The second model exhibits lowest variance and only 15% of the variation in error term is attributable to noise. In the third model, all coefficients are significant at least at the 5% level. The model has lower variance than model SFA1 and around 9% of the error term is attributable to statistical noise. To test the existence of inefficiency effects with $H_0 : \lambda = 0$, the values of LR test are compared with $\chi^2_{0.9}(1) = 2.706$. Since the values reported for the models exceed the critical value, we can reject the null hypothesis of no inefficiency effects at the 5% level of significance.

The specification of the truncated-normal distribution of the inefficiency term brings similar results. The SFA1 specification shows poor statistical results. None of the variables is significant at the 10% level. The value of γ indicates that 86% of the variation in error term is attributable to technical efficiency. The SFA1 model has the lowest variance. The SFA2 model brings slightly better results, one coefficient is weakly significant at the 10% level of significance, one is significant at the 5% level, one at the 1% level and the remaining coefficient at variable $TRAN$ is not statistically significant at the 10% level. Only 6% of the variation in error term is attributable to noise at the SFA2. In the third model, all

Table 4: Summary of SFA parameters with truncated-normal distribution of inefficiency term

	SFA1 (T-N)	SFA2 (T-N)	SFA3 (T-N)
Variable	Estimated parameters (t-statistics)		
Intercept	7.313 (4.216***)	11.200 (12.719***)	-0.519 (-0.330)
AREA	-0.091 (-1.156)	-0.107 (-1.903*)	-
NETW	-0.093 (-0.348)	-0.516 (2.111**)	-
TRAN	0.772 (0.282)	0.079 (0.376)	-
INTE	-0.147 (-0.959)	-	-
CABL	-	-0.742 (-6.531***)	1.150 (6.092***)
DIST	-	-	-0.384 (-3.845***)
$\mathrm{TRAN}^{\mathrm{U}}$	-	-	-0.414 (-2.688**)
σ^2	0.117 (1.945*)	0.317 (0.247)	0.503 (0.726)
γ	0.862 (7949***)	0.944 (4.224***)	0.970 (2.050**)
μ	0.629 (2.460**)	-1.035 (-0.159)	-1.397 (0.544)
Statistics	Values		
Log-likelihood	0.630	5.955	5.559
LR one-sided test	10.123 (2 res.)	6.050 (2 res.)	12.235 (2 res.)

Statistical significance: * refers to 10%, ** refers to 5%, and *** refers to 1% significance.

Source: Author's calculations

coefficients are significant at least at the 5% level. The model has highest variance and only 3% of the variation in error term is attributable to statistical noise.

The negative signs of estimates and the high coefficients at intercepts may seem to be difficult to interpret. Initially, we were surprised with the signs, but the results are in line with previous research (e.g. Jamasb and Pollitt, 2003). The negative signs can be interpreted by scale effects and increasing returns to scale. The high values of γ indicates that most of the error term is attributable to inefficiency. The low values would indicate wrong specification of the model and on the contrary very high values approaching 100% would need to be cautiously treated, because the absence of noise is not likely to occur especially in the cross-country comparison.

The existence of inefficiency effects is tested in different way compared to the half-normal model. The null hypothesis is inexistence of inefficiency effects in the model specification, i.e. $H_0 \; : \; \mu = \sigma_u^2 = 0$ (Coelli et al., 2005). The values of LR test are compared with critical values obtained from Table 1 in Kodde and Palm (1986). Taking the 5% level of significance, the critical value is equal to 5.138. The reported values exceed the critical value thus we can reject the null at the 5% level of significance.

In the last step, we test the appropriateness of using the truncated-normal over the half-normal distribution of the inefficiency term. The test statistic is defined in expression

(6.16). The null hypothesis is that the half-normal model is adequate, $H_0 : \mu = 0$, against alternative $H_1 : \mu \neq 0$. The computed statistics of the test give

- $\lambda_{SFA1} = -2[7.222 - 10.123] = 5.802$,
- $\lambda_{SFA2} = -2[5.880 - 6.050] = 0.34$,
- $\lambda_{SFA23} = -2[11.971 - 12.235] = 0.528$,

and the critical value at the 5% level of significance is $\chi^2_{0.95}(1) = 3.841$; therefore, we have to reject the null in case of first model and we cannot reject the null for SFA2 and SFA3 at the 5% level of significance.

Due to the statistically insignificant parameters, we do not include the model SFA1 in our comparison. None of the parameters was significant that indicates inappropriate specification. The results from remaining models are better and thus are included in our analysis. The models SFA2 and SFA3 are included in their half-normal specification, as we have rejected the adequacy of truncated-normal distribution of inefficiency term at the 5% level of significance. The values are depicted in Table 5.

Table 5: Summary of SFA cost efficiency estimates

	SFA2 (H-N)	SFA3 (H-N)
Firms	Efficiency estimates	Efficiency estimates
1	0.476	0.400
2	0.596	0.583
3	0.752	0.586
4	0.724	0.800
5	0.731	0.800
6	0.916	0.863
7	0.907	0.881
8	0.922	0.889
9	0.747	0.642
10	0.835	0.716
11	0.846	0.816
12	0.843	0.786
13	0.749	0.728
14	0.879	0.900
15	0.899	0.946
mean	0.764	0.720

Source: Author's calculations

7.3 Summary of results

In this section, results from preferred models are described and summarised. The results are depicted in Table 6. We include the CRS and VRS efficiency scores obtained by both of the DEA models and efficiency scores of the SFA2 and SFA3 models. The SFA models are specified with the half-normal distribution of inefficiency term.

The results significantly differ across the firms. As we can see, the mean efficiency is in an interval from 52% (CRS DEA1) to 76% (SFA2). The diversity in out results is not exceptional in comparison with other studies and practice. For example, the efficiency scores computed by the German regulator experienced similar variation. It ranged between 45% and 77% with lower values for DEA and higher for SFA (Frontier Economics, 2012). The variation of results is caused by differences in the nature of the methods.

In the regulatory benchmarking practice, the results from different methods are considered. Usually, the results are weighted and final efficiency scores are based on scaling. The weighted sum of efficiency scores helps to deal with particularities of different models. In the current 2014-2018 regulatory period in Austria, the results from two DEAs and MOLS are scaled and used.

The Austrian energy regulatory office employs CRS DEA. The CRS specification is chosen under the assumption that possible scale inefficiencies would be solved by mergers or joint ventures within the market (Frontier Economics, 2012). The German regulator applies CRS DEA and SFA and takes into the account results from both methods; however, the benchmarking in Austria and Germany is based on the data of national DSOs, and since our study is based on international dataset, we believe that the VRS specification is also valid. Having considered the practice of regulators, we include both specifications in our final comparison.

The correlations of efficiency scores obtained by all methods are depicted in the Appendix in Table 10; other descriptive statistics are in Table 11 of the Appendix. The correlation scores among the DEA and SFA models reflect limited consistence of the rankings with the change of method used for the benchmarking. The high correlations within the DEA and SFA models indicate high consistency of model specifications.

As the data of the Czech companies in the sample are publicly accessible, we can reveal results for Czech DSOs included in the dataset. The company 1 is ČEZ Distribuce, a.s. and company 2 PREdistribuce, a.s. We are not allowed to disclose the names of other companies due to the contractual obligations. The efficiency scores of ČEZ Distribuce,

Table 6: Summary of computed efficiency scores

	CRS DEA1	VRS DEA1	CRS DEA2	VRS DEA2	SFA2 (H-N)	SFA3 (H-N)
Firms			Efficiency scores			
1	0.356	0.429	0.422	0.446	0.476	0.400
2	1.000	1.000	0.642	1.000	0.596	0.583
3	0.241	0.319	0.241	0.319	0.752	0.586
4	0.378	0.413	0.239	0.362	0.724	0.800
5	0.281	0.454	0.299	0.454	0.731	0.800
6	0.747	0.906	0.834	0.926	0.916	0.863
7	1.000	1.000	1.000	1.000	0.907	0.881
8	1.000	1.000	1.000	1.000	0.922	0.889
9	0.721	1.000	0.800	1.000	0.747	0.642
10	0.207	0.430	0.264	0.430	0.835	0.716
11	0.386	1.000	0.386	1.000	0.846	0.816
12	0.300	0.366	0.300	0.366	0.843	0.786
13	0.201	0.415	0.293	0.440	0.749	0.728
14	0.315	0.386	0.315	0.386	0.879	0.900
15	0.622	0.910	0.828	0.953	0.899	0.946
mean	0.517	0.669	0.524	0.672	0.764	0.720

Source: Author's calculations

a.s. are among the lowest in the sample. The efficiency scores for PREdistribuce, a.s. are better than for ČEZ Distribuce, a.s., and in a half of the results the company is lying on the frontier. The better results might lead us to assign them to different structure of the service area of both operators; however, DSOs similar to both ČEZ Distribuce, a.s. and PREdistribuce, a.s. are included in the sample. The efficiency scores of city operators are on average similar to efficiency scores of DSOs operating larger regions with lower population densities; therefore, the better performance of PREdistribuce, a.s. cannot be simply attributable to the smaller area the company is distributing the electrical energy on.

The SFA models indicate that the Czech DSOs are operating inefficiently, or more precisely below an average efficiency. There might be other important factors that were omitted from our study, but the selection of variables is based both on practical literature and regulatory practices for DSOs. We did not include more variables to avoid an overspecification of our models. Although the variation in our results might seem very high, it is in line with previous research (e.g. Jamasb and Pollitt, 2003; EY, 2013).

7.4 Policy implications

The energy sector in the Czech Republic can be considered as infant. There are ongoing discussions about the setting of the regulatory parameters. The obstacles were shown during the discussion process preceding the fourth regulatory period of the regulation of the gas sector in the Czech Republic. There were problems with definitions of amortisation and depreciation, investments, etc. There could be problems inherited from the past that may be beyond control of the managements. The current regulatory setting does not generate sufficient incentives for development. In the current regulatory formula, the quality and development parameters are not sufficiently emphasised. Additional parameters promoting development of the grid should be encompassed in the regulation and also considered in the setting of benchmarking methods. DSOs ought to be more incentivised to invest in new technologies. The development of smart grids, smart metering and more effective methods of management of renewable energy sources in the Czech Republic should be more accented in the future.

We are convinced that the use of an international comparison would enable thorough comparison and introduction of individual efficiency factors. Having taken into account constraints stemming from the structure of the market, we believe that the performance of incumbents should be assessed by international benchmarking when the monopolistic domestic market structure with only three companies operating the market restricts representativeness of the majority of methods. Our model specification is very narrow with only a handful of parameters, but this specification is in accordance with both the theory and the foreign regulatory practice. Benchmarking is used for an evaluation of the relative performance in comparison with peers and we consider it as an auxiliary tool for regulation. We are aware of possible shortcomings of the methods that are also endorsed by the use of international dataset.

Setting the efficient companies lying on the frontier (DEA), or the most efficient companies (in case of SFA), as a yardstick would be too restrictive. We would propose to set the objective efficiency value as a mean (or median) efficiency score. Similar methodology is applied by the Norwegian regulator (Frontier Economics, 2012). The companies operating above the mean (or median respectively) are considered as effective and allocated only the general X factor. The companies operating below would be incentivised by the individual X factors to improve the efficiency of their performance. Another method could set the floor similarly to the way that the German regulator does. If the company is below some artificial value (in Germany 0.6), it would be treated as having this minimum value.

We realise that international benchmarking is problematic. Similarly, the size of our dataset confines the representativeness of our results. The use of benchmarking would be the tool which suitability was proven in the regulatory practice if the Czech regulator seeks to set the individual X factors in the future; moreover, the Czech regulator is able to acquire the data of the EU regulated companies and conduct a comprehensive analysis with a larger dataset. We were informed by the representatives of ERU that the data are exchanged by the EU regulators within the Agency for Cooperation of Energy Regulators on a regular basis.

The company ČEZ Distribuce, a.s. showed efficiency below an average in all models we conducted and the results indicate inefficient operation. The company's score was only in one case above the median value. The company PREdistribuce, a.s. obtained better scores and in the three DEA models it was a frontier firm, but in both SFA models it obtained efficiency scores below the mean and median. The Czech DSOs scored worse than comparable firms from abroad, which indicate potential for improvement. There are only three companies dominating the Czech market, and the regulator can hardly dispose of complete information about the firms. There is a risk of regulatory capture. We mentioned all the regulatory constraints defined by Laffont and Tirole (1996), and the political risk may also be an issue. The regulator is established as independent, but two out of three incumbents are still controlled by the state. The inefficient operation is indicated in the international comparison by fees for distribution included in the price of electricity. The Slovak regulator conducted an analysis of fees for electricity distribution in the selected EU countries (URSO, 2011b). The examined countries were Slovakia, the Czech Republic, Poland, Hungary, Germany and Austria. The fee was in the Czech Republic on average (the average fee for all voltage lines) higher than in Slovakia, Poland and Hungary and comparable with Austria. In Germany, the average fee was highest due to the by far largest fee imposed on the households to bear significant amount of cost that skewed the average value.

In the third regulatory period, ERU was not able to set the individual X factors for regulatory formula based on the revenue cap incentive scheme. We are convinced that the international benchmarking is a tool that would enable the establishment of the individual X factors. The introduction of the individual X factors without the international comparison would demand thorough analysis of the incumbents and would be complicated due to the above mentioned constraints the regulator has to always face. We showed in our analysis that the efficiency between the Czech DSOs differ markedly and that their operation is less efficient in comparison to foreign firms. The inclusion of only one general efficiency factor in the regulatory formula is therefore not sufficient to improve their operation. We are aware of the fact that a more comprehensive dataset is necessary for the precise setting of the individual X factors and we are also aware of problems stemming from the limited size of the dataset we used. The larger dataset would increase the descriptive power of our results, however, the minimum criteria for DEA were fulfilled. Similarly, the more comprehensive dataset would improve the results of SFA. We recommend ERU to conduct a similar benchmarking analysis with a larger dataset. The results should be used for the adjustment of the general X factor and primarily to introduce the individual X factors that ERU was not able to incorporate in the regulatory formula of the current third regulatory period.

8 Conclusion

In our thesis, we focused on the regulation of the electricity sector in the Czech Republic with main emphasis put on the implementation of benchmarking methods for the distribution system operators.

The Czech electricity market was liberalised in the last two decades, and the unbundling was completed in 2006. Yet there are still sectors within the market that are monopolised and therefore create demand for regulation. The distribution and transmission services are traditionally regulated. The objective of ERU in the regulation of DSOs is to set prices that are affordable for customers and guarantee the incumbents reasonable profits while providing services at a certain level of quality. These seemingly contradictory concerns are further complemented by incentives for the incumbents to invest in new technologies and to increase efficiency of their operation. Through incentive regulation, national regulatory authorities mitigate the information asymmetry and motivate the firms to improve their operation. The regulatory schemes are defined for longer periods to create a transparent and stable environment within the market.

The incentive schemes require a precise specification of parameters. Even though the incentive schemes may improve the performance of regulated firms, an incorrect setting may lead to inefficient operation and welfare losses. The essential step for establishment of the incentive regulation is the assessment of the performance of the firms to be regulated. Many authors and consulting firms have studied the regulatory methods for the distribution networks (e.g. Joskow, 2013; Haney and Pollitt, 2011; or Schweinsberg et al., 2011; EY, 2013; Frontier Economics, 2012). They showed that the setting of parameters is crucial and that the regulatory practices differ across the states. The Czech regulator does not apply benchmarking methods to the regulation based on an argument that there are only three regional distribution companies controlling the market; and thus there is not enough data available for robust analysis, based on national data, to be conducted (ERU, 2009). There is only the general X factor (efficiency factor) similar for all incumbents that determines the prescribed level of efficiency gains, which should be attained.

In our thesis, we analysed the regulatory formula of the current third regulatory period. We came to the conclusion that investments in smart grids should be emphasised in the forthcoming regulatory period to increase the stability of the grid.

In the empirical part of our thesis, we decided to utilise the benchmarking studies focusing on electricity distribution companies and examine the applicability of the benchmarking methods to DSOs in the Czech Republic. We sought the data of foreign companies to complement the dataset. The natural monopolistic market structure that DSOs are inclined toward, facilitates the application of international benchmarking as the companies are usually controlling certain regions. Due to the liberalisation that was institutionalised at the EU level, the companies also share similar structure, because they have to be unbundled from other activities.

The main research goal was to evaluate the use of benchmarking methods for the regulation of DSOs. The benchmarking of the incumbents would facilitate the introduction of the individual X factors corresponding to efficiency of particular incumbents. A similar analysis has not been conducted yet, as far as we know.

We collected a dataset comprising of 15 unbundled companies from the Czech Republic, Slovakia, Poland, Hungary and Serbia. The data gathering was complicated due to confidentiality. We are not allowed to disclose the data and the names of the foreign companies, however, it does not affect representativeness of our thesis as we sought to find the efficiency scores for the Czech DSOs. The dataset comprises companies that are similar to the Czech DSOs in terms of areas and population served. The data of the Czech companies are public and therefore we can present our results. We were only able to use the data for ČEZ Distribuce, a.s. and PREdistribuce, a.s. The financial statements for E.On Distribuce, a.s. are consolidated for distribution of electricity and gas and the company refused to provide us with unconsolidated cost data.

For the empirical analysis, we applied both non-parametric and parametric efficiency measurement methods. The data envelopment analysis was applied to cross-sectional data of the firms for 2012 in constant and variable returns to scale specifications. The stochastic frontier analyses were based on the unbalanced panel for 2010-2012 years. The data were adjusted for inflation using annual growth rate and denominated in euro with 2012 as a base year. The total expenditures were taken as input (dependent variable) and the outputs (dependent variables) were based on grid parameters and outputs. The selection of parameters was based on the theory and the practical experience of regulators applying benchmarking of DSOs. The weighting of outputs was applied to address a high correlation among the output variables.

The results of our analysis showed significant differences among efficiency scores of both Czech companies. The efficiency scores of ČEZ Distribuce, a.s. were below mean efficiency in all six models conducted while only in one case the efficiency score was above median. The company PREdistribuce, a.s. obtained higher scores. In three cases out of four DEA models, it was a frontier firm; however, in the SFA models the efficiency was below the mean and median. Our models confirmed varied efficiency of Czech DSOs that should be addressed in the coming fourth regulatory period. We believe that individual efficiency factors should be implemented to control for these differences.

Benchmarking serves as a suitable tool for the assessment of the cost efficiency of the Czech operators in the international comparison. The results showed that the Czech DSOs are in the international comparison among the less efficient companies. This fact is in line with a study of the Slovak regulatory office, which compared fees for the distribution included in the electricity price for final customers. URSO (2011b) showed that the fee was in the Czech republic on average higher than in Hungary, Slovakia and Poland and comparable with Austria.

We are aware of the limitations stemming from the size of the dataset. A larger dataset would improve the robustness of the frontier methods. As the regulator can acquire more data within the Agency for Cooperation of Energy Regulators, we recommend the Czech regulator, based on our analysis, to include the benchmarking methods in the setting of parameters for the forthcoming fourth regulatory period. Our results indicated that the efficiency scores differ for the Czech DSOs and their efficiency is worse in comparison with their foreign peers. Benchmarking would enable setting of individual X factors and modifications of the general X factor to better correspond to the current market situation. We showed that the shortage of national data, which restrained the adoption of benchmarking, could be overcome by the use of international firms.

Bibliography

Per Agrell and Peter Bogetoft. Development of benchmarking models for distribution system operators in Belgium. Technical report, SUMICSID, 2011.

Dennis Aigner, Knox Lovell, and Peter Schmidt. Formulation and estimation of stochastic frontier production function models. *Journal of Econometrics*, 6(1):21–37, 1977. ISSN 0304-4076.

Ian Alexander, Ian Bartle, Chris Bolt, Martin Cave, David Currie, Antonio Estache, Goodwin Stuart, Jose-Luis Guasch, Stephen Littlechild, Hans-Martin Niemeier, Pippo Ranci, John Smith, Jon Stern, Lourdes Trujillo, and Maria Vagliasindi. The UK Model of Utility Regulation. In Ian Bartle, editor, *A 20th Anniversary Collection to Mark the 'Littlechild Report' Retrospect and Prospect*. The University of Bath, 2003.

Mark Andor and Frederik Hesse. A Monte Carlo simulation comparing DEA, SFA and two simple approaches to combine efficiency estimates. CAWM Discussion Papers 51, Center of Applied Economic Research Munster (CAWM), University of Mï¿œnster, 2011.

Mark Armstrong and Robert H Porter, editors. *Handbook of industrial organization*, volume 3. Access Online via Elsevier, 2007. URL `http://www.sciencedirect.com/science/handbooks/1573448X/3`.

Harvey Averch and Leland Johnson. Behavior of the Firm Under Regulatory Constraint. *The American Economic Review*, 52:1052–1069, 1962.

Veronika Bachanova. Regulace a deregulace v CR v obdobi 1990-2005 (in Czech). *Research Centre for Competitiveness of Czech Economy*, 6:4–50, 2006.

George Battese and Timothy Coelli. Frontier production functions, technical efficiency and panel data: With application to paddy farmers in India. *Journal of Productivity Analysis*, 3(1-2):153–169, 1992. ISSN 0895-562X.

George Battese and Greg Corra. Estimation of a Production Frontier Model: With Application to the Pastoral Zone of Eastern Australia. *Australian Journal of Agricultural Economics*, 21(3):169–179, 1977.

William Jack Baumol and Alvin Klevorick. Input Choices and Rate-of-Return Regulation: An Overview of the Discussion. *The Bell Journal of Economics and Management Science*, 1:162–190, 1970.

Sanford Berg and Jinook Jeong. An evaluation of incentive regulation for electric utilities. *Journal of Regulatory Economics*, 3(1):45–55, 1991.

Jeffrey Bernstein and David Sappington. Setting the X Factor in Price-Cap Regulation Plans. *Journal of Regulatory Economics*, 16(1):5–26, 1999.

Peter Bogetoft and Lars Otto. *Benchmarking with DEA, SFA, and R*, volume 157. Springer, 2011.

Eberhard Bohne. Conflicts between national regulatory cultures and EU energy regulations. *Utilities Policy*, 19(4):255–269, 2011.

Ronald Braeutigam and John Panzar. Effects of the change from rate-of-return to price-cap regulation. *The American Economic Review*, 83(2):191–198, 1993.

Bundesnetzagentur and Bundeskartellamt. Monitoring Report 2013. Online, 2014. URL `http://www.bundesnetzagentur.de/SharedDocs/Downloads/EN/BNetzA/PressSection/ReportsPublications/2013/MonitoringReport2013.pdf?__blob=publicationFile&v=10`.

Carlo Cambini and Laura Rondi. Incentive regulation and investment: evidence from European energy utilities. *Journal of Regulatory Economics*, 38(1):1–26, 2010.

CEER. Status Review on the Transposition of Unbundling Requirements for DSOs and Closed Distribution System Operators. Online, 2013. URL `http://www.energy-regulators.eu/portal/page/portal/EER_HOME/EER_PUBLICATIONS/CEER_PAPERS/Cross-Sectoral/Tab/C12-UR-47-03_DSO-Unbundling_StatusReview_Public.pdf`.

CEPS. Annual Report 2003. Online, 2004. URL `http://www.ceps.cz/CZE/O-spolecnosti/Hospodarske-vysledky/Documents/Vyrocni-zpravy/CEPS_vyrocni_zprava_2003.pdf`.

CEPS. 2012 Annual Report. Online, 2013. URL `http://www.ceps.cz/ENG/O-spolecnosti/Hospodarske-vysledky/Documents/Vyrocni_zprava_AnnualReport_CEPS_a.s._2012.pdf`.

CEZ. Annual Report 2012 CEZ Group. Online, 2013. URL `http://www.cez.cz/edee/content/file/investors/2012-annual-report/VZ2012aj.pdf`.

Timothy Coelli. A Guide to DEAP, Version 2.1: A Data Envelopment Analysis (Computer Program). Technical Report 8, CEPA Working paper, 1996a.

Timothy Coelli. A guide to FRONTIER version 4.1: A computer program for stochastic frontier production and cost function estimation (Vol. 96, No. 07). Technical Report 7, CEPA Working paper, 1996b.

Timothy Coelli, Prasada Rao, Christopher O'Donnel, and George Battese. *An Introduction to Efficiency and Productivity Analysis*. Springer, 2nd edition, 2005.

Kevin Cullinane and Teng-Fei Wang. Chapter 23 Data Envelopment Analysis (DEA) and Improving Container Port Efficiency. *Research in Transportation Economics*, 17(1): 517–566, 2006.

EC. European Commission - Competition: Commission energy sector inquiry confirms serious competition problems. Online, 2007. URL `http://europa.eu/rapid/press-release_IP-07-26_en.htm`.

Frontier Economics. RPI-X@20: The future role of benchmarking in regulatory reviews. Online, 2010. URL `http://www.frontier-economics.com/_library/publications/Froniterreport-Benchmarkingfinalreport.pdf`.

Frontier Economics. Trends in electricity distribution network regulation in North West Europe: A report prepared for Energy Norway. Online, 2012. URL `http://www.nve.no/PageFiles/13979/DistributionnetworkregulationinNorway-final-stc.pdf?epslanguage=no`.

EMV. Regulatory methods of distribution system operators for years 2012-2015. Online, 2011. URL `http://www.energiavirasto.fi/documents/10179/0/Appendix_1-Confirmation_decision_Methods_of_determining_reasonable_return_2012-2015_DSOs_+revised-29112013.pdf/b80af5e9-1023-48ba-82d1-1fff0c359d1f`.

EY (Ernst&Young). Mapping power and utilities regulation in Europe. Online, 2013. URL `http://www.ey.com/Publication/vwLUAssets/Mapping_power_and_utilities_regulation_in_Europe/FILE/Mapping_power_and_utilities_regulation_in_Europe_DX0181.pdf`.

ERU. Report on the approach to setting the key parameters of the regulatory formula and prices for the second regulatory period in the electricity industry. Online, 2005. URL `http://eru.cz/user_data/files/matodikaregulace/elektro/aj_strateg_elektro.pdf`.

ERU. Final Report of the Energy Regulatory Office on the regulatory methodology for the third regulatory period, including the key parameters of the regulatory formula and pricing in the electricity and gas industries. Online, 2009. URL `http://www.eru.cz/documents/10540/462856/Report_III_ro_en.pdf/43917006-06ee-4e71-a48f-fe8cefc57310`.

ERU. National Report of the Energy Regulatory Office on the Electricity and Gas Industries in the Czech Republic for 2012. Online, 2013a. URL http://www.eru.cz/documents/10540/488714/NR_2012.pdf/1f82372e-bfd8-43e7-8ce7-086bebaf7481.

ERU. Navrh Energetickeho regulacniho uradu na metodiku regulace IV. regulacniho obdobi pro odvetvi plynarenstvi (in Czech). Online, 2013b. URL http://eru.cz/user_data/files/konzultace_ukonceni_obdobi/IV_RO_metodika_VKP_05-04-13.pdf.

ERU. Report on the Activities and Finances of the Energy Regulatory Office for 2012. Online, 2013c. URL http://eru.cz/user_data/files/vyrocnizpravy/anglicky/ERU2012_ENG.pdf.

ERU. Yearly Report on the Operation of the Czech Electricity Grid for 2012. Online, 2013d. URL http://www.eru.cz/documents/10540/462820/Annual_Data_Summary_of_EPS_2012.pdf/ad4faab0-4026-401f-a2b4-842b1698b0b5.

Antonio Estache, Martin Rodriguez-Pardina, Jose Rodriguez, and German Sember. An Introduction to Financial and Economic Modeling for Utility Regulators. *The World Bank: Policy Research Working Papers*, 3001:1–26, 2003.

Mehdi Farsi, Aurelio Fetz, and Massimo Filippini. Benchmarking Analysis in Electricity Distribution. *CEPE Report*, 4:1–30, 2005.

Mehdi Farsi, Massimo Filippini, and William Greene. Application of Panel Data Models in Benchmarking Analysis of the Electricity Distribution Sector. *Annals of Public and Cooperative Economics*, 77(3):271–290, 2006.

Mehdi Farsi, Aurelio Fetz, and Massimo Filippini. Benchmarking and Regulation in the Electricity Distribution Sector. *CEPE Working Paper No. 54*, 54:1–23, 2007.

William Greene. *The Econometric Approach to Efficiency Analysis*, chapter 2nd, pages 92–250. Oxford Scholarship Online, 2007.

Aoihe Brophy Haney and Michael Pollitt. Efficiency analysis of energy networks: An international survey of regulators. *Energy Policy*, 37(12):5814–5830, 2009.

Aoihe Brophy Haney and Michael Pollitt. Exploring the determinants of "best practice" benchmarking in electricity network regulation. *Energy Policy*, 39(12):7739–7746, 2011.

Aoihe Brophy Haney and Michael Pollitt. International benchmarking of electricity transmission by regulators: A contrast between theory and practice? *Energy Policy*, 62: 267–281, 2013.

Tooraj Jamasb and Michael Pollitt. International benchmarking and regulation: an application to European electricity distribution utilities. *Energy Policy*, 31(15):1609–1622, 2003.

Tooraj Jamasb, Paul Nillesen, and Michael Pollitt. Strategic behaviour under regulatory benchmarking. *Energy Economics*, 26(5):825–843, 2004.

Uwe Jensen. Misspecification Preferred: The Sensitivity of Inefficiency Rankings. *Journal of Productivity Analysis*, 23(2):223–244, 2005.

Paul Lewis Joskow. *Incentive Regulation in Theory and Practice: Electricity Distribution and Transmission Networks*, chapter 5th, pages 1–103. University of Chicago Press, 2013.

Paul Lewis Joskow and Richard Schmalensee. Incentive regulation for electric utilities. *Yale*, 4:1–49, 1986.

David Kodde and Franz Palm. Wald Criteria for Jointly Testing Equality and Inequality Restrictions. *Econometrica*, 54(5):1243–1248, 1986.

Timo Kuosmanen, Antti Saastamoinen, and Timo Sipilainen. What is the best practice for benchmark regulation of electricity distribution? Comparison of DEA, SFA and StoNED methods. *Energy Policy*, 61:740–750, 2013.

Jean-Jacques Laffont and Jean Tirole. *A Theory of Incentives in Procurement and Regulation*. The MIT Press, 1993.

Catherine Liston. Price-cap versus rate-of-return regulation. *Journal of Regulatory Economics*, 5(1):25–48, 1993.

Wim Meeusen and Julien van Den Broeck. Efficiency Estimation from Cobb-Douglas Production Functions with Composed Error. *International Economic Review*, 18(2): 435–444, 1977. ISSN 00206598.

MDCR (Ministerstvo dopravy Ceske republiky). Regions of the Czech Republic. Online, 2003. URL `http://www.mdcr.cz/mdcr/flash/rocenka_03/Yearbook/texty_uk/..$\delimiter"026E30F$html_uk$\delimiter"026E30F$uk03_95.htm`.

Thomas Nagel and Margarethe Rammerstorfer. Price-cap regulation and investment behaviour: how real options can explain underinvestment. *The Journal of Energy Markets*, 1(4):23–45, 2008.

Ofgem. 2013 Great Britain and Northern Ireland National Reports to the European Commission. Online, 2013. URL `https://www.ofgem.gov.uk/publications-and-updates/2013-national-report-european-commission`.

OTE. Annual Report 2002. Online, 2003. URL `https://www.ote-cr.cz/o-spolecnosti/soubory-vyrocni-zprava-ote/Vyrocni_zprava_2002.pdf`.

OTE. Annual Report 2012. Online, 2013. URL `https://www.ote-cr.cz/about-ote/files-annual-reports/annual-report-2012.pdf`.

Yasar Ozcan. *Health Care Benchmarking and Performance Evaluation*, chapter Performanc, pages 15–41. Springer, 2008.

David Parker. Price cap regulation, profitability and returns to investors in the UK regulated industries. *Utilities Policy*, 6(4):303–315, 1997.

Konstantin Petrov, Viren Ajodhia, Daniel Grote, and Denis Resnjanskij. Third Annual Conference on Competition and Regulation in Network Industries. In *Regulatory Incentives for Investments in Electricity Networks*, Brussels, Belgium, 2010.

Michael Pollitt. The role of efficiency estimates in regulatory price reviews: Ofgem's approach to benchmarking electricity networks. *Utilities Policy*, 13(4):279–288, 2005.

PXE. 2012: Annual Report. Online, 2013. URL `http://www.pxe.cz/Pxe_downloads/Info/ar12-en-PXE.pdf`.

Joseph Sarkis. *Modeling Data Irregularities and Structural Complexities in Data Envelopment Analysis*, chapter Preparing Your Data for DEA, pages 305–320. Springer US, 2007.

Andrea Schweinsberg, Marcus Stronzik, and Matthias Wissner. Cost Benchmarking in Energy Regulation in European Countries - Study for the Australian Energy Regulator (WIK - Consult). Online, 2011. URL `http://www.accc.gov.au/system/files/CostbenchmarkinginenergyregulationinEuropeancountries-WIK-Consult.pdf`.

Graham Shuttleworth. Benchmarking of electricity networks: Practical problems with its use for regulation. *Utilities Policy*, 13(4):310–317, 2005.

Lubos Smrcka. Photovoltaics in the Czech Republic: example of a distorted market. In *EE11 Proceedings of the 6th IASME-WSEAS international conference on Energy & environment*, pages 378–383, 2011.

Wadim Strielkowski, Stepan Krska, and Evgeny Lisin. Energy Economics and Policy of Renewable Energy Sources in the European Union. *International Journal of Energy Economics and Policy*, 3(4):333–340, 2013.

URE. National Report. The President of the Energy Regulatory Office in Poland. 2013. Online, 2013. URL http://www.ure.gov.pl/download/2/436/NationalReport2013.pdf.

URSO. Regulacna politika na nastavajuce regulacne obdobie 2012-2016 (in Slovak). Online, 2011a. URL http://www.urso.gov.sk/sites/default/files/RegulacnaPolitika_2012-2016.pdf.

URSO. Benchmarking of the fees for electricity distribution in the selected EU countries - Analyza porovnania jednoslozkovej ceny za distribuciu elektriny vo vybranych krajinak EU (V4 plus Rakusko a Nemecko) pre definovanych koncovych odberatelov elektriny (in. Online, 2011b. URL http://www.urso.gov.sk/sites/default/files/PorovnanieDistTarif_07092011.pdf.

URSO. Annual Report 2012. Online, 2013a. URL http://www.urso.gov.sk/sites/default/files/VS2012_svk.pdf.

URSO. National Report 2012 submitted as of 30 June 2013. Online, 2013b. URL http://www.urso.gov.sk/sites/default/files/NarodnaSprava2013_EN.pdf.

Peter Went. Analyzing Risks And Returns In Emerging Equity Markets. *Journal of Business & Economics Research*, 5(8):11–25, 2007.

WB (World Bank). World Bank national accounts data, and OECD National Accounts data files. Industry, value added (% of GDP) (NV.IND.TOTL.ZS). Online, 2014. URL http://data.worldbank.org/.

Appendix

Table 7: Correlation coefficients of outputs (DEA1, SFA1)

	Area	Grid length (scaled)	Transformers (scaled)	Interruptions^{-1}
Area	1			
Grid length (scaled)	0.538	1		
Transformers (scaled)	0.613	0.740	1	
Interruptions^{-1}	-0.382	-0.581	0.515	1

Source: Author's calculations

Table 8: Correlation coefficients of outputs (DEA2, SFA2)

	Area	Grid length (scaled)	Transformers (scaled)	Cables share
Area	1			
Grid length (scaled)	0.538	1		
Transformers (scaled)	0.613	0.740	1	
Cables share	-0.318	-0.688	0.513	1

Source: Author's calculations

Table 9: Correlation coefficients of outputs (SFA3)

	Distributed energy	Cables share	Transformers
Distributed energy	1		
Cables share	0.300	1	
Transformers	0.874	-0.029	1

Source: Author's calculations

Table 10: Efficiency scores correlations

	CRS DEA1	VRS DEA1	CRS DEA2	VRS DEA2	SFA2 (H-N)	SFA3 (H-N)
CRS DEA1	1.000					
VRS DEA1	0.855	1.000				
CRS DEA2	0.912	0.854	1.000			
VRS DEA2	0.846	0.998	0.861	1.000		
SFA2 (H-N)	0.195	0.294	0.369	0.297	1.000	
SFA3 (H-N)	0.202	0.277	0.322	0.275	0.890	1.000

Source: Author's calculations

Table 11: Summary statistics of efficiency scores

	CRS DEA1	VRS DEA1	CRS DEA2	VRS DEA2	SFA2 (H-N)	SFA3 (H-N)
Minimum	0.201	0.319	0.239	0.319	0.476	0.400
Maximum	1	1	1	1	0.922	0.946
Mean	0.517	0.669	0.524	0.672	0.788	0.756
Median	0.378	0.454	0.386	0.454	0.835	0.8
St. Error	0.076	0.074	0.073	0.076	0.032	0.037

Source: Author's calculations