

Louvain School of Management

How does the cost efficiency of electricity distribution system operators in Belgium, the Netherlands, Portugal, Ireland and the United Kingdom compare over the period 2021-2025, and to what extent are differences in cost efficiency associated with differences in regulatory frameworks and energy-transition indicators?

Author(s): PETEN Séverine
Supervisor(s): AGRELL per Joakim
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Abstract

This thesis compares the cost efficiency of 22 electricity distribution system operators (DSOs) in Belgium, the Netherlands, Portugal, Ireland, and the United Kingdom over the 2021–2025 period, and examines the extent to which differences in efficiency and two energy transition indicators—the smart meter penetration rate and decentralised generation capacity per connection point—are linked to differences in regulatory design.

Cost efficiency is calculated using an input-oriented DEA model, with capital expenditures (CAPEX) and operating expenditures (OPEX) as inputs, and the number of connection points, network length, and energy supplied as outputs. To ensure the most realistic comparison possible, the data are harmonised. The resulting scores are subjected to various analysis: an outlier detection process to identify distribution system operators exerting excessive influence on the efficiency frontier, as well as the calculation of the Malmquist index, which distinguishes changes in efficiency from technological developments. The DEA test is followed by an econometric analysis testing the relationship between efficiency, transition indicators, and the intervention power index (IP). This second step is performed using a Tobit regression.

It follows that the stringency of a regulatory model is not, on its own, a determinant of cost-efficiency and performance in terms of the energy transition. Other factors, notably national policy, must be taken into account. The relationship between cost-efficiency and the energy transition factor is negative. This is explained by the large investments made by DSOs to accommodate distributed generation.

Keywords: Distribution System Operators; Cost Efficiency; Data Envelopment Analysis; Regulatory Intervention Power; Energy Transition

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Declaration on the Use of Artificial Intelligence

During the preparation of this master's thesis, the author used several artificial intelligence tools to support specific tasks throughout the research and writing process.

The following tools were used for the following purposes:

1. **DeepL Translator** was used to translate text between French and English.
2. **DeepL Write** was used to improve the wording, grammar and style of sentences written by the author.
3. **Claude** was used to reformulate sections of text for improved clarity and academic style, while preserving the underlying ideas and arguments developed by the author.
4. **Claude** and **ChatGPT** were used to assist with the writing and debugging of R code used for the empirical analysis.
5. **ChatGPT** was also used to assist with L^AT_EX formatting, including the preparation of tables, equations, references and bibliography formatting.

All scientific reasoning, literature review, research design, empirical analysis, interpretation of the results and conclusions are the author's own work. After using these tools, all generated content was carefully reviewed, verified, edited and, where necessary, corrected by the author, who assumes full responsibility for the final content of this thesis.

By signing this declaration, I affirm that this master's thesis reflects my original work, supported by the responsible and transparent use of artificial intelligence tools.

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List of frequent abbreviations

TSO = Transmission system operator

DSO = Distribution System Operator

DEA = Data Envelopment Analysis

SFA = Stochastic Frontier Analysis

DMU = Decision Making Unit

TOTEX = Total Expenditure

CAPEX = Capital Expenditure

OPEX = Operational Expenditure

RAB = Regulated Asset Base

WACC = Weighted Average Cost of Capital

RPI-X = Retail Price Index minus X

RIIO : Revenue = Incentives + Innovation + Outputs

TIM = Totex Incentive Mechanism

ODI = Output Delivery Incentive

IQM = Information Quality Matrix

PR = Price Review

AIF = Agile Investment Framework

DNO = Distribution Network Operator

RRP = Regulatory Reporting Pack

SMETS2 = Smart Metering Equipment Technical Specifications 2

RSRI = Regulamento de Serviços de Redes Inteligentes

VRS = Variable Returns to Scale

CRS = Constant Returns to Scale

NDRS = Non-Decreasing Returns to Scale

MPI = Malmquist Productivity Index

List of abbreviations

CREG = Commission for Electricity and Gas Regulation (federal, Belgium)
VREG = Vlaamse Regulator voor Elektriciteit en Gas (Flanders)
VNR = Vlaamse Nutsregulator (Flanders)
CWaPE = Commission wallonne pour l'Energie (Wallonia)
BRUGEL = Brussels regulator for energy markets (Bruxelles Gaz Électricité)
Ofgem = Office of Gas and Electricity Markets (United Kingdom)
ACM = Autoriteit Consument & Markt (Netherlands)
CRU = Commission for Regulation of Utilities (Ireland)
ERSE = Entidade Reguladora dos Serviços Energéticos (Portugal)
CEER = Council of European Energy Regulators
ACER = EU Agency for the Cooperation of Energy Regulators
AIEG = Association Intercommunale d'Électricité et de Gaz de Gembloux
AIESH = Association Intercommunale d'Électricité du Sud du Hainaut
ORES = Opérateur des Réseaux Gaz & Électricité
RESA = Réseau d'Énergie de Seraing et Environs
UKPN = UK Power Networks
NGED = National Grid Electricity Distribution
NPg = Northern Powergrid
ENWL = Electricity North West Limited
SPEN = SP Energy Networks
SSEN = Scottish and Southern Electricity Networks
ESB Networks = Electricity Supply Board Networks
EDA = Empresa de Eletricidade dos Açores
EEM = Empresa de Eletricidade da Madeira

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Chapter 1

Introduction

1.1 Motivation

The energy sector is at the heart of the European energy transition. Distribution networks play a key role with the introduction of solar panels, electric cars, batteries and heat pumps. It is the distribution network that must manage these new flows.

Managing these flows comes at a very high cost: The European Commission (2023) estimates that € 584 billion of investment in the electricity grid will be needed by 2030. Added to this is the fact that 40 per cent of grid is over 40 years old. In this context, energy transition is not just about generation but also distribution.

DSOs are monopolies under the control of a regulator. The regulator's aim is to protect consumers by keeping prices low whilst ensuring the DSO has sufficient funds for investment. These two objectives often conflict. Investments to prepare the grid for the transition drive up costs in the short term, just at a time when the regulator is pushing to reduce costs. The way in which each regulator manages this dilemma therefore likely influences the performance of DSOs.

There are no common European rules governing distribution. Each regulator, which has national remit, regulates in its own way. Some countries offer operators a high degree of security, whilst others prioritise efficiency. These differences in regulatory models make it possible to carry out comparative studies. However, there is no common benchmark for measuring and comparing the efficiency of DSOs across countries.

This thesis will address this gap by analysing a sample of 22 DSOs in Belgium, the Netherlands, Portugal, Ireland and the United Kingdom over the period from 2021 to 2025.

1.2 The study

The divergence in regulatory approaches raises a research question:

How does the cost efficiency of electricity distribution system operators in Belgium, the Netherlands, Portugal, Ireland and the United Kingdom compare over the period 2021–2025, and to what extent are differences in cost efficiency associated with differences in regulatory frameworks and energy-transition indicators?

Five countries are observed over a five-year period. Two transition indicators are defined. The first is the smart meter rollout and the second, the installed decentralised capacity.

The analysis is structured around four sub-questions:

1. *How does the cost efficiency of Belgian, Dutch, Irish, Portuguese and British DSOs compare over the period 2021–2025?*
2. *To what extent is the regulatory intervention power associated with differences in DSO cost efficiency and energy-transition indicators?*
3. *Are more cost-efficient DSOs also those that perform better in the energy transition, as measured by smart meter deployment and decentralised generation capacity?*
4. *Does the fragmentation of electricity regulation across the three Belgian regions lead to differences in cost efficiency and energy-transition performance?*

1.3 Outline

Chapter 2 focuses on the literature review, covering energy supply, the theoretical foundations of regulation, the challenges of the energy transition, regulatory models, and a comparative analysis of Belgium, the Netherlands, Ireland, Portugal and the United Kingdom. Chapter 3 describes the dataset, the DSO perimeter, the harmonisation of the data (currency conversion, purchasing power parity adjustment, Malmquist index), and their description. Chapter 4 presents the empirical model : the DEA, the Malmquist decomposition, the Intervention Power index, the second stage analysis. Chapter 5 reports the numerical results including efficiency, descriptive comparisons, sensitivity analysis and limitations of the analysis. The thesis concludes with a synthesis of the main findings and implications for future research.

Chapter 2

Literature review

This chapter begins with an introduction to the energy supply chain to help the reader understand how energy is generated, transmitted and distributed. It then provides an overview of the regulatory framework governing distribution system operators in the context of the energy transition. Subsequently, the main regulatory models are explained and discussed, followed by a comparative analysis of the five countries studied.

2.1 Energy Supply Chain

Electricity networks are traditionally organised vertically, following this sequence: generation, transmission and distribution, followed by consumption (Figure 2.1). The amount of electricity generated must equal the amount consumed plus any losses. This constraint makes the management of electricity networks complex. (Bouri, 2021)

Figure 2.1 illustrates the process from energy generation to distribution:

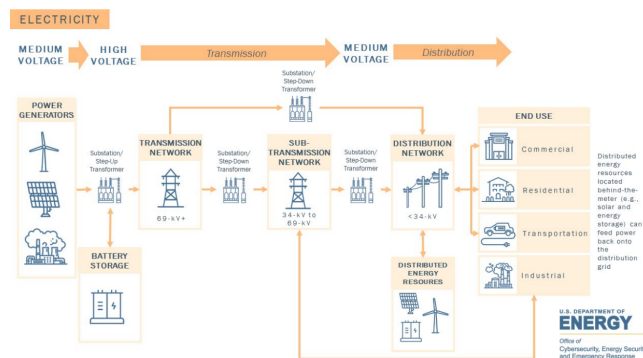


Figure 2.1: Energy Supply Chain (US Department of Energy)

- generation: all components of the generation units (alternators, motors, turbines, etc.). The following equation must be maintained at all times: $\text{generation} = \text{consumption} + \text{losses}$
- head-raising structures: all components capable of converting energy through a change in elevation
- transmission and distribution: all components involved in the transmission of energy

2.1.1 Production

Electricity is generated from a wide range of sources. On the one hand, there are so-called ‘dispatchable’ sources, such as gas- or coal-fired power stations and nuclear power. On the other hand, there are intermittent sources such as wind, solar and hydroelectric power.¹ A source is considered intermittent when its output depends on the following factors: the weather, the time of day and the seasons. The nature of intermittent sources is the technical reason why the energy transition complicates grid management. Indeed, it is more difficult to predict and balance output.

2.1.2 Transmission

Once electricity has been generated at a power station, it must be transported over long distances to the areas where it is consumed. Transmission system operators (TSOs) carry electricity over long distances at extra-high voltage (400 kV and 220 kV) to minimise losses. This is followed by an intermediate level (70–150 kV) which acts as a link between the transmission network and the distribution network. It also enables very large industrial plants to be supplied directly.

2.1.3 Distribution

Distribution System Operators (DSOs) take over from the transmission network. The voltage is stepped down via transformer stations (substations) to between 230 and 400 volts. Historically, electricity flowed directly in one direction only, from power stations to meters. With the advent of renewable energy technologies (solar panels, batteries, wind turbines), electricity can now flow in both directions. A person who both consumes and generates electricity is known as a prosumer.

¹Intermittent renewable resources are sources that are not continuously available: their output fluctuates with environmental conditions and must therefore be accounted for in the operational scheduling of distribution systems. See ScienceDirect Topics, “Intermittent renewable energy resource”, <https://www.sciencedirect.com/topics/engineering/intermittent-renewable-energy-resource> (accessed 7 August 2026).

2.2 Theoretical foundations of network regulations

2.2.1 Why regulate?

To understand why we regulate the electricity network, it is important to understand the economic nature. Electricity networks are typical examples of natural monopolies. A natural monopoly exists when an industry's cost function is subadditive: it is cheaper for a single firm to produce the entire output than for several firms to share production (Baumol, 1977; Sharkey, 1982).

Electricity networks satisfy this condition because of their fixed costs, the economies of scale and their massive investments in infrastructure (power lines, substations, meters, transformers). These costs are irrecoverable once engaged and are independent of the number of customers served. Joskow (2008) highlights the challenge facing the regulator, which is to replicate the beneficial effects of competition in a structurally monopolistic sector. Without regulators, the network operator has market power that allows it to set prices above costs and under-invest in quality, all to the detriment of the consumer.

Network regulation therefore serves two complementary purposes. First, it protects consumers from high prices and ensures a minimum standard of service. Secondly, regulation guarantees the financial viability of network operators, who face significant infrastructure investment costs. Regulation can be analysed as an agency problem in which the regulator defines a revenue function dependent on the available information, whilst leaving a certain margin of discretion to operators. Regulation is made complex by an information asymmetry between the regulator and the network operators. Because the operator alone has direct knowledge of its own cost structure and the effort required to control it, a principal-agent problem arises.

Throughout this thesis, national regulatory authorities (NRAs) are understood to approve the revenue or tariff proposals submitted by network operators, rather than to set final consumer tariffs directly; the operator remains responsible for translating an approved revenue allowance into an actual tariff structure.

2.2.2 Principal-agent problem

In the context of electricity network regulation, the principal-agent problem arises because the regulator delegates network management to the operator, while the two parties do not have access to the same information. The operator has a near-perfect knowledge of its own costs and inefficiencies, whereas the regulator can only observe reported figures and performances. (Laffont and Tirole, 1993). This asymmetry highlights two problems: adverse selection and moral hazard. The first, adverse selection, means that, before signing the regulatory contract, the operator may

present itself as less efficient than it actually is in order to secure less ambitious targets and thus higher tariffs. The second, moral hazard occurs after the contract is signed: the operator may relax its efforts to improve efficiency, as the regulator cannot directly observe the level of effort being made. (Laffont and Tirole, 1993)

As Joskow (2008) points out, the regulator’s main challenge is precisely to maximise the efficiency of network operators without access to all the necessary information. This challenge has driven the development of increasingly sophisticated regulatory models over time, from the cost-plus schemes described to the incentive and output frameworks discussed in Section 2.4.

2.3 Energy Transition and regulation

As mentioned earlier, electricity grids have long operated according to a simple, one-way model. Power stations generated electricity, which was then transmitted via high-voltage transmission grids and finally distributed to end consumers. The consumer play a passive role, meaning they simply consume the electricity supplied. The energy transition is having a significant impact on electricity grids. With the integration of intermittent renewable energies such as wind and solar power, and new loads, grids must be reinvented to become bidirectional.

These new decentralised and intermittent energy sources are disrupting the system. Generation is fed directly into the distribution network at the consumer level, and the balance between supply and demand is more complex to manage. New electrical loads such as electric cars, heat pumps, domestic batteries and data centres should not be overlooked. These are new forms of consumption to which the energy supply must adapt, as they create unusual local peaks in demand. This is why electricity flows are becoming bidirectional and the consumer is becoming a prosumer, as they both consume and produce energy (Bolton and Poulter, 2025).

To address these challenges, network operators are investing in tools that increase network flexibility. The roll-out of smart meters is one such tool. Smart meters enable real-time consumption measurement, which facilitates active demand management and improves incident detection. (European Commission, 2019). Other tools include the development of smart grids, infrastructure automation and the digitalisation of networks. In the context of the energy transition, the European Union has set a target of achieving climate neutrality by 2050 and reducing net greenhouse gas emissions by at least 55 per cent by 2030 (European Commission, 2019; European Union, 2021).

2.3.1 Fit and Forget

Bolton and Poulter (2025) demonstrate that the traditional ‘Fit and Forget’ strategy is becoming economically and technically unsustainable in this new context. This strategy involved designing the grid to cope with the maximum foreseeable load, and then not worrying about it until the next upgrade. It assumed predictable, stable and unidirectional flows. With thousands of decentralised and intermittent generation sources connected to the local grid, this approach creates two major problems. On the one hand, under this logic, cables and transformers would need to be upgraded to handle bidirectional flows. This would entail significant costs, which would impact consumers’ bills. On the other hand, operational flexibility must be introduced, involving the use of software tools, smart meters and dynamic pricing mechanisms. These would enable real-time flow management, the reduction of peaks and the optimisation of existing cables. This approach replaces capital expenditure (CAPEX) with operational expenditure (OPEX). It is more agile, less costly in the long term and better suited to the uncertainty of the energy transition (Bolton and Poulter, 2025).

2.3.2 DSOs

In this new decarbonised, decentralised and digitalised system, the role of DSOs is taking on a new dimension. According to Agrell and Teusch (2015), distribution already accounts for a significant proportion of the total cost of the electricity system, and this proportion is set to grow in the context of the energy transition. DSOs must respond more quickly to real-time changes in electricity flows, which are influenced by weather conditions and consumption patterns. To achieve a balance between supply and demand, prevent grid congestion and minimise costs, flexibility in management is essential. Smart meters make it possible to obtain large volumes of real-time consumption data. This data must be used effectively to optimise grid management. Effective grid management also depends on coordination between DSOs and TSOs. Better coordination would enable congestion issues to be addressed more effectively (European Commission, JRC, 2022).

2.3.3 Major challenges facing networks during the transition

The first challenge concerns the ageing infrastructure of the networks. According to the European Commission’s EU Action plan for Grids (2023), nearly 40% of distribution networks are more than forty years old. The European Commission estimates that around €584 billion of investment in electricity grids is needed over the decade to 2030, of which roughly €375–425 billion for distribution alone (European Commission, 2023). However, current investment falls far short of what is needed.

The second challenge concerns the variability and flexibility of the networks. The modern network must manage production flows in all directions, with thousands of small-scale distributed energy resources. These resources include photovoltaics, electric cars and domestic batteries. This bidirectional nature poses problems of network congestion (ERSE, 2023).

The third challenge is systemic because it involves the consumer. Flexibility requires dynamic pricing and smart meters. Smart meters are a key tool in the energy transition. They enable real-time consumption monitoring, faster detection of faults, measurement of electricity fed into the grid via solar panels, and the implementation of dynamic pricing (Vitiello et al., 2022). The roll-out of smart meters varies across European countries. Bolton and Poulter emphasise that the success of the transition depends on the regulator’s ability to transform these ‘engineering’ monopolies into agile digital service companies. (European Commission, DG Energy, 2019).

The final challenge identified is the lack of coordination between DSOs and TSOs. Indeed, as mentioned above, the growing penetration of renewable energy sources into the grid is leading to congestion issues. Effective coordination between DSOs and TSOs is crucial to managing this problem and ensuring a reliable and flexible grid.

Tariff Structures

According to Agrell and Teusch (2015), the current tariff structure is becoming unsuitable in the context of the energy transition. Demand is falling due to improved network efficiency and the increased self-generation of electricity. Tariffs were calculated based on uniform consumption. When consumers use less electricity or generate their own, distribution system operators’ revenue falls while their costs remain unchanged. This creates a structural financial imbalance. For this reason, regulation must evolve dynamically rather than being based solely on static efficiency targets. It should reward not only the minimisation of short-term costs, but also innovation, system resilience, the ability to integrate renewables, and grid flexibility.

2.4 Regulation models

Various regulatory models have been developed over the years in different countries. These include cost-based regulation, incentive-based regulation and performance-oriented hybrid regulatory models (Mulder, 2023). An explanatory comparison of these different regulatory approaches is provided in the sections below. This explanatory section will help to better understand the various regulatory approaches applied in different countries. The choice of regulatory approaches in the countries studied was based on the definitions of parameters and differences in regulation.

Five recurring mechanisms structure the country cases that follow. Cost-plus regulation reimburses an operator's actual costs plus a return on capital, offering investment security at the expense of cost-efficiency incentives (Section 2.4.1). RPI-X regulation instead caps allowed revenue growth at inflation minus an efficiency factor, creating a stronger incentive to cut costs but with limited scope for innovation. RIIO builds on this logic by explicitly rewarding outputs and innovation alongside cost performance (Section 2.4.3). Yardstick competition benchmarks each operator's allowed revenue against the sector average rather than its own costs, substituting for market competition in a natural-monopoly setting (Sections 2.4.2, 2.4.4). Finally, TOTEX treatment refers to whether capital and operating expenditure are remunerated symmetrically or asymmetrically through the regulated asset base.

Regulation in the five countries is examined across five dimensions: the treatment of the permitted return on capital, the ex-ante or ex-post treatment of operating costs, the authority responsible for approving investment, the remuneration mechanism for capital expenditure, and the length of the regulatory period.

2.4.1 The cost plus regulation

Cost-based regulation is based on reimbursing the company for its costs, plus a rate of return on capital (Agrell & Teusch, 2015). This form of regulation provides the operator with a financial guarantee, encouraging investment in infrastructure. As Agrell and Bogetoft (2017) demonstrate, reimbursement at time t can be observed:

$$R_k(t) = \text{OpEx}_k(t) + \text{Dep}_k(t) + (r + \delta) C_k(t) \quad (2.1)$$

$\text{OpEx}_k(t)$: operating expenses of DSO k at year t

$\text{Dep}_k(t)$: depreciation of fixed assets of DSO k at year t

r : rate of return on investment

δ : margin factor

$C_k(t)$: total capital invested (regulated asset base, RAB) at year t

k : DSO considered

This model offers the operator a degree of financial security, as all costs are covered, which encourages investment in infrastructure without the fear of not recouping the investment.

However, this approach has a limitation, namely the lack of incentives for efficiency.

The Averch–Johnson phenomenon explains this limitation. This phenomenon demonstrates that when the permitted rate of return exceeds the real cost of capital, the regulated firm has an incentive to over-invest in capital in order to maximise its profit. This leads to inefficient resource allocation and conflicts with modern regulatory objectives (Averch and Johnson, 1962). Furthermore, verifying information requires a considerable amount of resources (Agrell & Bogetoft, 2017).

2.4.2 Regulation in Belgium

Belgium’s energy responsibilities are divided between the federal government and the three Belgian regions. On the one hand, transmission is overseen by CREG, established in 1999. It approves the transmission tariffs and the underlying methodology proposed by the TSO (Elia and Fluxys). On the other hand, the distribution network has been regionalised since 2014 (Belgian Senate, 2013) across the three respective regions, with tariff-approval and revenue-setting powers transferred to the three regional regulators. They approve the tariff methodologies and the allowed revenues proposed by the DSOs: BRUGEL for the Brussels-Capital Region, the CWaPE for Wallonia, and the VNR for Flanders. Coordination between these various regulators is carried out via FORBEG (the Belgian Forum of Electricity and Gas Regulators). The three regional regulators manage the regulation of DSOs in different ways.

VNR

Firstly, the Vlaamse Nutsregulator (VNR), formerly VREG, which previously followed the cost-plus model, has opted for revenue regulation since 2015 (VNR, 2024).

This framework is characterized by two main features: the first focuses on ex ante the determination of the authorized revenues based on the estimated efficient revenue required to cover DSO activities, thereby providing investment certainty while maintaining incentives for cost efficiency (CEER, 2025). The second feature concerns the treatment of operating costs where a distinction is made between exogenous costs, which are outside the control of the DSO, and endogenous costs, which are controllable and therefore subject to efficiency incentives.

To determine the authorised revenue, the total revenue of a DSO is set by estimating the linear trend of the historical costs of all DSOs. Each DSO is then allocated a share of this trend value, proportional to its share of the total historical costs of the sector. This benchmarking refers to the Yardstick competition. It aimed to encourage network operators to optimise their expenditure

by comparing it to the average trend of the sector (Shleifer, 1985). Within Belgium, the VNR implements the regulatory framework with the most incentives. (Europe Economics, 2024)

CWaPE

The second regional regulator is CWaPE, which oversees five DSOs: ORES, RESA, AIEG, AIESH and REW. ORES dominates the regional market due to its significant share of distribution activity. REW has been excluded from the thesis’s panel due to the small number of its connection points.

Like the VNR, CWaPE applies an incentive-based revenue regulation framework. This framework is based on authorised revenue, but with a specific approach to efficiency benchmarking. However, the incentive intensity is lower than that of the VNR: operating costs are set in advance, but unlike the VNR’s pure trend-based approach, investments are approved by the regulator and enter the regulated asset base. Authorised revenue varies from year to year depending on cost trends. The revenue cap ensures that DSOs have sufficient revenue to fulfil their duties while incentivising them to be more efficient and maintain service quality (CWaPE, 2023). Like the VNR, the allowed WACC sits above the sample median, while the regulatory period runs for five years.

Unlike other Belgian regulators, for the 2025–2029 tariff methodology, CWaPE aims to propose a method for measuring the individual efficiency of DSOs, replacing the common efficiency factor used in the previous methodology. This shift towards individualised efficiency measurement mirrors the benchmarking techniques, including Data Envelopment Analysis, that regulators increasingly rely on to assess operator-specific performance, rather than applying a uniform, sector-wide factor. This methodology makes it possible to compare Walloon DSO operators with their European counterparts and set comparable efficiency targets.

BRUGEL

Comparing to the other Belgian energy regulators, BRUGEL oversees only one distribution system operator, namely Sibelga. As there is no comparable operator within the Brussels-Capital Region, benchmarking mechanisms such as Yardstick Competition cannot be directly implemented. Consequently, BRUGEL relies on a regulatory framework specifically designed for a single regulated operator. For the 2025–2029 regulatory period, the regulator adopted a TOTEX-based revenue cap model that integrates both operating and capital expenditures within a unified incentive framework. The model combines controllable and non-controllable costs, regulatory balances, remuneration of invested capital, and performance-based quality incentives (BRUGEL, 2023a; 2023b).

The authorised revenue can be represented in a simplified form as follows:

$$AR_t = CG_t + CNG_t + (WACC_t \times RAB_t) + RB_t + Q_t \quad (2.2)$$

where:

AR_t : authorised revenue in year t

CG_t : controllable costs

CNG_t : non-controllable costs

$WACC_t$: weighted average cost of capital

RAB_t : regulatory asset base

RB_t : regulatory balances

Q_t : quality-related adjustment factor

Under this framework, investments are incorporated into the Regulatory Asset Base and remunerated through the weighted average cost of capital. In addition, part of Sibelga's revenue is linked to the quality of service delivered, creating financial incentives to maintain network performance and reliability. The regulatory period spans five years, providing both regulatory stability and visibility for long-term investment decisions.

Although BRUGEL formally classifies its methodology as an incentive-based TOTEX regulation, the remuneration of capital through the RAB remains a central component of the model. Compared with the regulatory frameworks implemented by the CWaPE and the VNR, the Brussels system maintains a stronger link between invested capital and allowed revenues. For this reason, it can be viewed as the Belgian regulatory framework that is conceptually closest to the traditional cost-of-service approach discussed in Section 2.4.1. From the perspective of the Averch–Johnson hypothesis (Averch & Johnson, 1962), such a structure may create stronger incentives to favour capital-intensive investments, as increases in the regulated asset base directly contribute to the operator's remunerated revenue.

2.4.3 Regulation in UK

Unlike in Belgium, the regulation of gas and electricity networks is carried out by a single body, namely Ofgem. Ofgem operates under the authority of GEMA (Gas and Electricity Markets Authority). According to the report Regulatory Frameworks for European Energy Networks 2024,

one of Ofgem’s primary functions is to protect the interests of current and future consumers by ensuring security of supply and the sustainability of the system (CEER, 2025).

To provide some historical context, the gas and electricity networks were privatised in 1986 and 1989 respectively. The initial regulatory framework was RPI-X, under which the regulator limits the rise in average network costs to a rate below that of inflation, minus an efficiency factor. This encourages the company to minimise its expenditure with the aim of maximising profit. This will enable the setting of allocations for the next retail price, with the result that consumers will benefit from a reduction in the resulting costs.

This form of regulation has revealed major structural limitations when faced with the challenges of the 21st century. The first of these is a lack of dynamism, with an excessive focus on reducing immediate costs, which has stifled technological innovation in the long term (Bouckaert, 2015). The RPI-X was uninnovative and incapable of incorporating environmental objectives aimed at supporting decarbonisation targets (Ofgem, 2010).

A shift towards the current regulatory framework, the RIIO, was therefore observed in 2010.

Regulatory model

$$RIIO : Revenue = Incentives + Innovation + Outputs. \quad (2.3)$$

According to Ofgem, the primary aim of this regulation is to replicate the incentives of a competitive market within a monopolistic sector.

The regulator sets a maximum permitted revenue for network operators. This revenue then depends on performance metrics such as costs, service quality and innovation, as determined by the regulator. If an improvement is seen in these performance metrics, the companies earn more. By setting a revenue cap, the financing of companies’ investments is guaranteed.

The maximum permitted revenue is defined through the building blocks approach (Ofgem, 2022):

$$R_t = OPEX_t + DEP_t + (r \cdot RAV_t) \quad (2.4)$$

where:

$OPEX_t$: operating costs

DEP_t : depreciation of assets

RAV_t : value of regulated assets

r : cost of authorised capital

TOTEX plays a central role in this model:

$$TOTEX = CAPEX + OPEX \quad (2.5)$$

Thanks to TOTEX, the regulator no longer makes a strict distinction between capital expenditure and operating expenditure. By treating capital and operating expenditure symmetrically, the regulator eliminates the bias whereby companies over-invest in capital to maximise their regulated rate of return (the Averch–Johnson effect). Under the Totex Incentive Mechanism (TIM), any over- or under-spend relative to the allowed TOTEX is shared between the operator and consumers via a sharing coefficient s :

$$\text{Profit}_{\text{firm}} = s \cdot (\text{TOTEX}_{\text{allowed}} - \text{TOTEX}_{\text{actual}}) \quad (2.6)$$

Revenue is further adjusted by Output Delivery Incentives (ODIs), which reward or penalise companies based on their performance in areas such as reliability, safety, environmental impact, customer satisfaction and, crucially for the energy transition, the development of Distribution System Operator capabilities (Ofgem, 2022). To address the information asymmetry concerning the cost forecasts underlying R_t , Ofgem employs the Information Quality Matrix (IQM). DSOs with effective methodologies receive higher remuneration than those with overestimated forecasts. Investments are therefore approved in advance rather than retrospectively.

In practice, this combination of output-based incentives and TOTEX symmetry has been shown to lead to significantly higher investment rates than those observed under rate-of-return regimes. This is demonstrated by a comparative analysis of European energy utilities (Cambini & Rondi, 2010).

2.4.4 Regulation in the Netherlands

Electricity distribution in the Netherlands is organised on a regional basis, with six distribution system operators in total. The three largest are Liander, Enexis and Stedin, which together account for around 98 per cent of the network's connection points (ACM, 2021-2025). The ACM (Authority for Consumers and Markets) is responsible for regulating these DSOs (ACM, 2021a).

Regulatory model

Since 2000, the ACM has applied a price cap system with competitive benchmarking, also known as yardstick competition (ACM, 2021). This system is based on an ex-ante price cap with an exogenous coefficient for the efficient cost level, ensuring that all costs are covered by tariffs during the regulatory period.

The annual authorised revenue is calculated as follows:

$$TI_t = \left(\frac{1 + cpi - x + q}{100} \right) \times TI_{t-1} \quad (2.7)$$

Where the key components are:

TI_t : total income for year t

TI_{t-1} : total income for year $t - 1$

cpi : consumer price index as determined by Statistics Netherlands

x : x-factor (price differential)

q : quality component

This formula translates Yardstick's logic. The X factor is not negotiated with each individual DSO, but is derived from the sector's average efficiency performance (Newbery, 1999). CAPEX and OPEX are kept separate rather than being treated under a full TOTEX approach, and the regulatory period runs over five years.

2.4.5 Regulation in Ireland

Unlike in Belgium and the Netherlands, Ireland has only one DSO: ESB Networks. The CRU (Commission for the Regulation of Utilities) regulates this DSO and the TSO (EirGrid). The CRU approves the authorised revenues for the TSO and the DSO for a five-year period known as the Price Review (PR). The current cycle is PR6, which covers the period from 2026 to 2030. (CRU, 2025b)

Regulatory model

Ireland uses an individualised allowed-costs approach with the classic building-block formula:

$$RA_t = OPEX_t + DEP_t + (RAB_t \times WACC) \pm AIF_t \pm INC_t \quad (2.8)$$

where

$OPEX_t$: Authorised operating budget for year t

DEP_t : statutory amortisation of the RAB

$RAB_t \times WACC$: Return on invested capital

AIF_t : Net adjustment of uncertainty mechanisms

INC_t : Net adjustment to performance-related incentives

The first three terms are commonly found in regulatory models. AIF_t reflects the net effect of the agile investment framework, which incorporates the distribution uncertainty mechanism and the bidirectional capital/operating expenditure flexibility mechanism. INC_t shows the net financial effect of the CRU's performance incentive framework. This framework enables ESB Networks to be rewarded for its compliance with agreed performance indicators.

A notable feature of the Irish regulatory model is its failure to adopt a TOTEX approach. Indeed, the CRU has retained separate approaches to OPEX and CAPEX (Frontier Economics, n.d.). This is because data is more difficult to manage under a purely TOTEX approach.

Alongside adopting a CAPEX/OPEX approach, the CRU has proposed an agile flexibility mechanism that enables greater manoeuvrability by allowing the bidirectional reallocation of allowances between CAPEX and OPEX. This means that ESB Networks can reallocate funds initially

earmarked for capital investments to operational solutions during the tariff period. The Agile Investment Framework includes a distribution uncertainty mechanism. This mechanism releases additional revenue, subject to justification, in response to identified network needs. The CRU reviews the DSO's business plan forecasts for efficiency *ex ante* rather than reimbursing costs *ex post*, and the Price Review cycle runs over five years.

This combination of *ex-ante* cost review and individualised revenue setting is a design choice that, according to the empirical literature on incentive versus rate-of-return regulation, is associated with comparatively higher investment rates. This is consistent with the sustained capital expenditure growth observed in Table 3.3 (Cambini & Rondi, 2010).

2.4.6 Regulation in Portugal

In Portugal, distribution is divided by voltage. E-REDES holds the sole concession for medium- and high-voltage connections nationwide, covering approximately 97% of the total (ERSE, 2026b). The Azores and Madeira each have their own operators: EDA and EEM. Only these three distribution system operators are included in the panel; the nine others are excluded for the same reason as the Belgian operator REW (Section 3.2.1). ERSE applies a hybrid framework to the three included operators, combining a rate-of-return foundation with strong incentive mechanisms (ERSE, 2023a).

Regulatory model

The rate-of-return element remunerates the regulated asset base at the weighted average cost of capital ($RAB \times WACC$). On its own, this resembles cost-plus regulation and provides investment security. However, ERSE adds three incentive mechanisms on top of this. Firstly, an efficiency (X) factor is applied annually to OPEX and CAPEX, similar to RPI-X. This creates pressure to reduce controllable costs. Secondly, partial TOTEX treatment for low-voltage distribution offsets the CAPEX bias of a pure rate-of-return model (the Averch–Johnson effect). Thirdly, the Regulamento de Serviços de Redes Inteligentes (RSRI) quality-of-service and smart-grid incentive rewards DSOs that deliver smart-grid services.

Factor x An efficiency factor is applied each year to the DSO's OPEX and CAPEX in accordance with the RPI-X approach. This factor incentivises achieving higher levels of cost efficiency.

The TOTEX approach The second incentive factor is adopting a more TOTEX-based approach, which does not formally distinguish between operating expenditure (OPEX) and capital expenditure (CAPEX). This helps to mitigate the Averch–Johnson effect (Averch & Johnson, 1962),

which has already been introduced.

Ex-post adjustment of the rate of return During the regulatory period, an incentive rate of 100 per cent applies to the differences between forecast and actual costs. This means that all gains and losses are incorporated into the consolidated RAB at the end of the year. Thanks to this adjustment, efficiency gains are shared with consumers. Conversely, if the actual rate of return is lower than the forecast figure, the operator is protected. (ERSE, 2023a) This combination illustrates the different layers of the Portuguese regulatory framework. Portugal has a mechanism that encourages efficiency in certain areas, but which reverts to a cost-plus model in one specific area.

Quality of Service and Smart Grids The latest incentive mechanism introduced by the ERSE is a non-financial incentive converted into tariff adjustments linked to quality of service. This mechanism, known as the Regulamento de Serviços de Redes Inteligentes, provides a specific financial incentive to DSOs offering smart grid services. (ERSE, 2023b)

2.5 Comparative analysis

The various regulatory models share the common objective of protecting consumers whilst maintaining the financial viability of operators. However, they differ significantly in terms of incentive structure, benchmarking methodology and their approach to balancing investment security and efficiency incentives.

2.5.1 Investment security

One of the main trade-offs in the regulation of distribution system operators concerns investment security. According to the cost-plus model, the costs of infrastructure investment are fully reimbursed to DSOs, creating less incentive to reduce them and thereby decreasing productive efficiency. At the same time, investment security is relatively high under that model (Enedis, 2024). Therefore, it can be concluded that investment security and productive efficiency are negatively correlated.

The five countries investigated in this thesis have all adopted different approaches to address this trade-off. The Netherlands appears to be the most exposed to DSO inefficiency risks. Its approach is based on yardstick competition, whereby revenues are set in relation to industry averages rather than the specific DSO's costs. Therefore, to achieve investment security, firms in the Netherlands should operate with little deviation from the industry's average costs.

Table 2.1: Comparison of the main characteristics of the regulatory frameworks

Criterion	Belgium	United Kingdom (Ofgem)	Netherlands (ACM)	Ireland (CRU)	Portugal (ERSE)
Incentives	Heterogeneous: high (Flanders) to low (Brussels)	High (RIIO/TIM)	High (Yardstick)	Moderate (single DSO, plan review)	Moderate (X-factor on RAB)
Investment	High (RAB-based in Wallonia and Brussels)	Conditional on performance	Exposed (sector-average)	High (ex-ante allocation + AIF)	Moderate–high (RAB $\times$ WACC)
Benchmark	Intra-regional comparison only	TOTEX + IQM	Yardstick (sector average)	None (forecast review)	Individual efficiency target + X
TOTEX	Mixed (BRUGEL TOTEX cap; others RAB)	Full TOTEX (TIM)	Cost-based cap (not full TOTEX)	Separate CAPEX/OPEX + flexibility	Partial TOTEX (LV)
Transition	Weak, capital-oriented (Flanders ahead)	Strong (DSO incentives, ODIs, digitalisation)	Congestion-management services	Climate Action Plan (PR5/PR6)	RSRI smart grids + renewables

Note: Source: regulatory reports and CEER *Report on Regulatory Frameworks for European Energy Networks*. The qualitative assessment of *incentive power* corresponds to the Intervention Power (*IP*) index introduced in Chapter 4.

In contrast, Ireland has adopted the opposite approach to the efficiency-investment spectrum. Its national regulator has introduced ex-ante revenue allocation, coupled with the Agile Investment Framework, which allows both cost minimisation and investment security objectives to be addressed. Indeed, Ireland’s capitalisation mechanism enables firms to meet their financing needs without overestimating investment costs, posing less risk of inefficiency, particularly for ESB Networks (CRU, 2025a).

Meanwhile, Portugal has adopted a middle-ground approach. Since 2016, ERSE has adopted the WACC approach, which seeks to fairly compensate DSOs for their expenses while encouraging the industry’s productive efficiency. In other words, under the WACC regime, investment costs are recovered based on costs plus the permitted return. This secures the investment base while minimising inefficiency risks (S&P Global Ratings, 2021). The United Kingdom has adopted a similar approach to regulating its DSOs. According to the RIIO model, firms can recover their investment costs in the form of authorised revenues. However, reimbursement is conditional upon the DSOs achieving specific targets and key performance indicators, which serves as a strong efficiency driver. By introducing profit-linked elements into the regulation, the UK authorities have secured the DSOs’ investment base while addressing firms’ concerns about their future revenues, which appears crucial for securing sufficient investment in the industry.

2.5.2 Efficiency and incentive mechanisms

The strength of the incentives to be efficient varies from one regulatory framework to another. The United Kingdom and the Netherlands, for example, have strong incentives in place. In the Netherlands, authorised revenues are determined through benchmarking. Each distribution system operator is compared against the sector-wide average cost per unit of production rather than its own costs. In the United Kingdom, DSOs share any expenditure variance relative to the authorised TOTEX budget under a TOTEX incentive mechanism. Additionally, the Information Quality Incentive rewards network operators that submit realistic and efficient cost forecasts (Ofgem, 2022).

Belgium adopts a more heterogeneous approach due to its regional regulatory structure. Although benchmarking incentives exist, the three regional regulators apply different methodologies and levels of incentive intensity. Flanders uses Yardstick competition, providing the strongest efficiency incentives. Wallonia uses a more moderate benchmarking framework, while Brussels uses a TOTEX-based revenue cap combined with quality incentives. The absence of a common benchmarking methodology across the three regions limits the overall strength and consistency of efficiency incentives.

Portugal also combines several incentive mechanisms. In addition to applying an X-factor to operating and capital expenditure, ERSE incorporates a partial TOTEX approach for low-voltage networks and rewards improvements in service quality and smart grid service deployment (ERSE, 2023).

Ireland applies a comparatively less incentive-based framework, reflecting the presence of a single DSO. As benchmarking between operators is not possible, the CRU relies on detailed assessments of ESB Networks' business plan, complementing this approach with an explicit performance-based incentive.

2.5.3 An approach to the energy transition

Integrating renewable energy has become one of the main challenges for European distribution networks. Although these sources accounted for 47.5% (Eurostat, 2025a) of gross electricity consumption in the European Union in 2024, the pace of deployment and associated regulatory responses differ considerably between countries.

Among the countries considered, Portugal recorded the highest share of renewable electricity, with renewables accounting for 65.8% of gross electricity consumption in 2024 (Eurostat, 2025). The Portuguese regulatory framework supports this transition by giving renewable generation priority grid access and by offering DSOs incentives through the RSRI scheme for providing smart-

grid services (ERSE, 2023).

The Netherlands also achieved a high share of renewable electricity, primarily driven by wind and solar generation (CBS, 2025). However, the rapid deployment of decentralised renewable generation has resulted in severe network congestion, as grid reinforcement has not kept pace with new renewable connections. In response, the ACM has introduced congestion-management mechanisms to make more efficient use of existing network capacity (ACM, 2024).

Similarly, Ireland relies heavily on wind power and has set ambitious decarbonisation targets within its PR5 and PR6 regulatory frameworks, aiming for 80% renewable electricity by 2030. Nevertheless, increasing network constraints have highlighted the need for additional investment in grid reinforcement and flexibility (CRU, 2025a; SEAI, 2025).

In the United Kingdom, RIIO-ED2 explicitly incorporates Net Zero objectives into network regulation. Compared with RIIO-ED1, allowances for load-related expenditure increased by 39% to accommodate the expected growth in electric vehicles, heat pumps, and distributed energy resources (Ofgem, 2022).

Belgium presents a more mixed picture. Although renewable electricity accounted for around 30% of electricity generation in 2024 (Elia, 2025), its share of gross final energy consumption remains among the lowest in the European Union (Eurostat, 2025).

The deployment of smart meters also varies considerably between countries. The Netherlands, Ireland and Portugal have achieved high penetration rates, reaching approximately 90%, 84% and almost universal deployment, respectively (ACER, 2026). The United Kingdom has also made significant progress through the SMETS2 programme and RIIO incentives, while Belgium has advanced more slowly. However, Flanders has achieved a higher penetration rate than the other Belgian regions due to specific regional legislation.

The figures reported in this section refer to end-of-period penetration rates as published by national sources. The panel used in Chapter 5 instead reports period averages over 2021–2025, which are mechanically lower for countries whose rollout accelerated late in the period — notably the United Kingdom.

2.6 Summary and research gap

A comparison of the different regulatory frameworks highlights several key findings. First, under cost-plus regulation, incentives for cost efficiency are weaker and the regulatory framework tends to favour capital-intensive investments over operational flexibility (Averch & Johnson, 1962; Agrell & Teusch, 2015). Second, although incentive-based regulation cannot be shown to directly accelerate

the energy transition, it appears more effective at promoting cost efficiency, as illustrated by the regulatory approaches adopted in the Netherlands and the United Kingdom. In Belgium, regulatory fragmentation limits inter-regional benchmarking and weakens competitive pressure between DSOs. Portugal and Ireland follow an intermediate approach, combining revenue-cap regulation with specific mechanisms designed to secure long-term network investment.

The closest study to this thesis is that of van Montfoort, Dijkstra and Mulder (2024), who analyse the impact of the energy transition on distribution network costs in the Netherlands and question whether yardstick competition remains appropriate when DSOs face increasingly heterogeneous investment needs. Their analysis, however, is limited to a single country operating under one regulatory framework.

More broadly, the literature provides only limited evidence on how DSO cost efficiency compares across countries operating under different regulatory regimes. Existing studies generally focus on a single national regulatory framework, making it difficult to assess whether differences in efficiency are associated with regulatory design or with country-specific characteristics. At the same time, the relationship between cost efficiency and energy-transition indicators remains largely unexplored.

This reflects a broader institutional limitation. Unlike electricity generation or transmission, there is currently no harmonised European benchmark for comparing the cost efficiency of distribution system operators in different countries. Distribution network regulation remains a national competence, and a regional one in Belgium, meaning that each regulator applies its own objectives. Consequently, cross-country efficiency comparisons remain rare and inherently challenging.

This thesis addresses this issue by comparing 22 distribution system operators operating under seven different regulatory frameworks in five European countries between 2021 and 2025. Combining DEA efficiency analysis with energy-transition indicators and a stylised Intervention Power index, it examines whether differences in regulatory design are descriptively associated with differences in cost efficiency and transition performance. Rather than proposing a harmonised benchmark, the thesis illustrates the value and limitations of cross-country benchmarking under heterogeneous regulatory frameworks.

Chapter 3

Data

3.1 Data gathering

The analysis focuses on a panel of 22 electricity distribution system operators observed between 2021 and 2025. This yields 110 observations, but only seven regulatory clusters. Within this panel, five countries are represented, each with a certain number of DSOs: six in Belgium, six in the United Kingdom, six in the Netherlands, three in Portugal and one in Ireland. There is an asymmetry which can be explained by differences in organisational structures across the various countries; for example, a fully unbundled, multi-operator system in Belgium or a single operator in Ireland. This is why this database has been constructed to allow for consistent cross-country comparisons of DSO efficiency. This supports descriptive comparison rather than robust causal inference.

Each observation is associated with three types of information:

- Two cost inputs: CAPEX, OPEX
- Three outputs: connection points, network length and energy delivery
- Two energy transition indicators: penetration of smart meter and installed decentralised generation capacity.

All financial variables are collected in nominal national currency terms at the source and subsequently converted and normalised as described in Section 3.4.

3.2 DSO perimeter

A precise definition of the DSO perimeter is essential for the comparability of the DEA results. This section specifies which legal entities are included for each country.

3.2.1 Belgium

Belgium includes six DSO entities analysed individually: Fluvius (Flanders), Ores, RESA, AIEG, AIESH (Wallonia), and Sibelga (Brussels). REW is excluded from the panel: with fewer than 30,000 connection points it falls below the reporting threshold. Fluvius represents the post-2019 legal merger. ORES is the dominant Walloon operator accounting for approximately 70% of regional connections.

Data sources: annual reports and regulatory filings with VNR, CWaPE, and BRUGEL

3.2.2 United Kingdom

The six electricity DNOs licensed by Ofgem under RIIO-ED2 are included. These are the operating companies : National Grid Electricity Distribution, UK Power Networks, Northern Powergrid, Electricity North West, Scottish and Southern Electricity Networks, and Scottish Power Energy Networks, each split into licensed areas.

Data are sourced from the Ofgem regulatory reporting packs (RRP).

3.2.3 Netherlands

The six regional DSOs regulated by the ACM are included: Liander, Enexis Netbeheer, Stedin, Coteq Netbeheer, Rendo Netwerken and Westland Infra.

Data are collected from publications by each DSO, as well as from the ACM. Some data were collected through exchanges with the DSOs.

3.2.4 Portugal

Although Portugal has 12 electricity DSOs, only three are retained in the database because the benchmarking methodology excludes DSOs with fewer than 30,000 connection points. E-REDES covers the vast majority of connection points.

The data are sourced from ERSE's regulatory reports and the operators' annual reports.

3.2.5 Ireland

There is only one DSO in Ireland: ESB Networks. As there is only one DMU per year, it is not possible to carry out a within-country efficiency analysis.

Data are sourced from CRU Price Review determinations (PR5 covering 2021–2025 and the early years of PR6) and ESB Networks regulatory accounts.

Country	DSOs included	Regulator	first Data source	Secondary source
Belgium	Fluvius, ORES, RESA, AIEG, AIESH, Sibelga	VNR/CWaPE/BRUGEL	Regulatory filings, annual reports	all year publicly available
United Kingdom	UKPN, NGED, NPg, ENWL, SPEN, SSEN	Ofgem	Ofgem RIIO-ED2 determinations	all year publicly available
Netherlands	Liander, Enexis, Stedin, Coteq, Rendo, Westland	ACM	Monitoring reports, DSO annual accounts	Some data are collected through corresponding with operators
Portugal	E-REDES, EDA, EEM	ERSE	ERSE regulatory decision , DSO annual reports	all year publicly available
Ireland	ESB Networks	CRU	ESB Network annual report, CRU Price Review determinations (PR5/ PR6)	all year publicly available

Note: Where a figure could not be sourced from a public regulatory filing or annual report, it was obtained through direct correspondence with the operator; such cases are flagged in this table and, where they affect a specific data point, in the corresponding cell of the relevant results table.

Table 3.1: DSO perimeter, regulatory assignment and data sources.

3.3 Variable construction

3.3.1 Capex and Opex

The values for both inputs were collected directly from each DSO’s annual reports for every year. CAPEX covers investments in network infrastructure, such as lines, cables, transformers and metering equipment. OPEX, on the other hand, focuses on the recurring costs of operating and maintaining the network, including labour costs for maintenance and general administration.

3.3.2 Outputs: connection points, network length and energy delivered

These data points are collected for each DSO and each year. They are obtained from the regulatory sources listed in Table 3.1, supplemented by annual reports, technical annexes, National Grid statistics, and, occasionally, direct contact with the DSO.

3.3.3 Energy Transition indicators

For the second stage of this analysis, two indicators are selected. The smart meter penetration rate defines the proportion of consumers equipped with a smart meter. This indicator depends largely on public policies and legal requirements (In Belgium, deployment depends on decisions made by each region). Second, the installed decentralised generation capacity represents the cumulative power (kVA) of distributed energy resources connected to the DSO network. This depends on external factors such as national support mechanisms for renewable energy and geographic conditions. These two variables should therefore be considered as measures of the progress of the energy transition and not as direct impacts.

These two indicators do not take into account certain aspects of the energy transition, such as grid flexibility, energy storage, and grid capacity.

3.4 Data harmonisation and quality

Combining five national datasets originally built for five different regulatory purposes requires several adjustments before the panel can be treated as a single comparable dataset.

3.4.1 Currency and price levels.

UK figures, reported in GBP, are converted to EUR using ECB annual average exchange rates for the corresponding year (Section 4.2.2). All CAPEX and OPEX series are then adjusted for purchasing power parity using Eurostat's `prc_ppp_ind` index, with Belgium in 2021 fixed as the reference country-year (normalisation factor 1.000). This two-step adjustment is necessary because a raw EUR comparison would conflate genuine cost differences with differences in the general price level between, for instance, Irish and Portuguese construction and labour markets; it does not, however, correct for differences in construction-specific price inflation, a limitation discussed in Chapter 5.

However, there remains a limitation on comparability that cannot be overcome by using PPP. OPEX and CAPEX are determined by comparable agreements and national regulations. For

example, in Belgium, OPEX far exceeds CAPEX, whereas in Ireland and UK, OPEX is equivalent to half of CAPEX. This is one of the reasons why national regulators use TOTEX as a benchmark.

Three versions of the cost data are used and are kept distinct throughout: (i) *raw* nominal values in national currency, as reported (Tables 3.2–3.4); (ii) *PPP-adjusted* values, used for the cross-sectional DEA, which correct spatial price-level differences but not temporal inflation; and (iii) *inflation-deflated* values, used for the Malmquist index, which remove year-on-year price growth. Each table states explicitly which version it reports.

3.5 Descriptive Statistics

Table 3.2: Descriptive statistics of the DEA input and output variables

Variable	Unit	Min	Median	Mean	Max	SD
TOTEX	millions	10.6	572.5	886.9	5,554.0	1,130.0
OPEX	millions	5.3	236.0	459.9	4,144.0	750.6
CAPEX	millions	4.1	281.5	427.0	1,920.0	468.2
Connection points	000s	25.8	2,403.6	2,488.6	8,535.5	2,519.2
Energy delivered	GWh	114	23,000	22,466	78,200	22,350
Network length	km	917	58,284	78,488	237,752	77,366

Note: $N = 110$ (22 DSOs $\times$ 5 years, 2021–2025). Monetary variables are raw reported values in millions of national currency, prior to currency conversion and PPP adjustment: GBP for the United Kingdom, EUR for the other four countries. The pooled statistics reported here therefore mix two currencies and are indicative only; the harmonised series used in the DEA are described in Section 3.4.1. TOTEX is the sum of OPEX and CAPEX by construction.

Table 3.3: Descriptive statistics for OPEX and CAPEX by country and year

Country	Year	N	OPEX (millions)			CAPEX (millions)		
			Mean	Median	SD	Mean	Median	SD
Belgium	2021	6	622.8	133.4	1,220.4	252.0	85.0	444.8
	2022	6	651.5	142.2	1,279.7	263.0	95.6	463.7
	2023	6	673.4	141.6	1,332.5	271.4	96.5	483.7
	2024	6	695.0	150.8	1,372.9	273.5	102.8	465.3
	2025	6	812.9	155.0	1,638.4	316.0	106.5	544.1
United Kingdom	2021	6	270.0	255.0	114.2	469.8	418.5	213.9
	2022	6	284.0	267.5	120.9	493.7	443.5	224.5
	2023	6	292.3	274.5	121.7	513.0	464.5	230.4
	2024	6	317.0	293.0	138.1	557.0	503.0	250.0
	2025	6	335.3	311.5	145.4	591.3	532.5	265.2
Netherlands	2021	6	439.7	300.2	482.9	437.2	349.8	477.3
	2022	6	480.4	312.0	531.8	477.0	362.7	533.2
	2023	6	556.2	352.5	622.0	533.5	423.8	581.9
	2024	6	648.8	434.9	732.3	720.2	559.1	790.4
	2025	6	582.7	464.5	606.6	881.1	709.2	959.8
Ireland	2021	1	305.0	305.0	–	328.0	328.0	–
	2022	1	438.0	438.0	–	391.0	391.0	–
	2023	1	389.0	389.0	–	477.0	477.0	–
	2024	1	466.0	466.0	–	683.0	683.0	–
	2025	1	525.0	525.0	–	760.0	760.0	–
Portugal	2021	3	152.3	52.4	184.3	111.0	26.8	150.7
	2022	3	158.7	55.8	190.1	121.3	29.1	165.2
	2023	3	165.3	59.2	196.4	133.7	31.3	183.0
	2024	3	173.3	62.1	206.0	148.0	34.7	202.7
	2025	3	183.0	65.5	217.5	162.7	38.1	222.9

Note: Raw reported values in millions of national currency (GBP for the United Kingdom, EUR otherwise), prior to currency conversion and PPP adjustment. UK operators report on an April–March financial year; each observation is assigned to the calendar year in which the financial year begins. N = number of DSOs; SD not reported for Ireland ($N = 1$). Own calculations from the combined panel.

Estimated value (2025): As the ESB Networks Distribution Annual Performance Report 2025 was not publicly available at the time of this research, the 2025 CAPEX and OPEX values were estimated. The estimates are based on the observed 2023–2024 trend and on ESB’s announced increase in regulated network investment under the transition to the PR6 regulatory period. A more moderate growth rate than that observed between 2023 and 2024 was assumed, resulting in an estimated CAPEX of EUR 760 million and an estimated OPEX of EUR 525 million. These values are used solely to preserve the balanced panel and should therefore be interpreted as approximations rather than observed data.

Table 3.4: Descriptive statistics for the three outputs by country and year

Country	Year	N	Conn. points (000s)		Network length (km)		Energy (GWH)	
			Mean	Median	Mean	Median	Mean	Median
Belgium	2021	6	1,031.2	590.8	34,681	10,448	7,954	3,794
	2022	6	1,073.3	595.1	35,386	10,500	8,366	3,560
	2023	6	1,051.4	600.6	35,799	10,490	8,113	3,432
	2024	6	1,057.5	604.9	36,267	10,613	8,166	3,580
	2025	6	1,081.8	611.1	36,086	10,653	8,116	3,433
United Kingdom	2021	6	5,019.3	3,977.1	135,311	121,913	47,127	37,000
	2022	6	5,031.6	4,008.7	133,911	116,864	47,150	36,000
	2023	6	5,077.4	4,033.5	134,902	117,460	45,876	35,250
	2024	6	5,116.4	4,059.7	135,735	118,072	44,894	34,650
	2025	6	5,161.2	4,101.1	137,250	123,922	44,200	34,250
Netherlands	2021	6	1,434.6	1,221.2	44,553	30,233	13,773	11,052
	2022	6	1,455.2	1,232.9	45,388	30,586	13,048	10,975
	2023	6	1,477.6	1,244.9	45,777	30,940	16,176	12,806
	2024	6	1,483.0	1,256.6	46,312	31,054	17,448	13,060
	2025	6	1,496.6	1,267.3	46,841	31,384	17,840	13,106
Ireland	2021	1	2,384.1	2,384.1	178,600	178,600	29,400	29,400
	2022	1	2,422.3	2,422.3	182,450	182,450	28,540	28,540
	2023	1	2,454.4	2,454.4	181,000	181,000	29,480	29,480
	2024	1	2,491.1	2,491.1	185,850	185,850	30,750	30,750
	2025	1	2,533.4	2,533.4	188,000	188,000	28,905	28,905
Portugal	2021	3	2,174.2	138.2	79,409	4,225	16,301	765
	2022	3	2,192.8	143.1	80,110	4,150	15,263	850
	2023	3	2,210.4	138.9	81,013	4,210	15,450	880
	2024	3	2,230.2	140.1	81,539	4,270	15,667	910
	2025	3	2,250.2	141.5	82,111	4,320	15,557	940

Note: Connection points in thousands; network length in km (total circuit length, underground and overhead combined); energy delivered in GWH. N = number of DSOs. Median reported alongside the mean; SD omitted for readability. Own calculations from the combined panel.

Chapter 4

Model

4.1 Overview

Chapter 3 has defined the panel, the inputs and outputs and the regulatory variables. This chapter presents the methods applied to them: the DEA estimator, the returns-to-scale and outlier choices, the Malmquist decomposition, the Intervention Power index and the second-stage regressions.

The aim of this chapter is to present the empirical model used to compare the cost efficiency of DSOs across Belgium, the Netherlands, Portugal, Ireland and the United Kingdom over the period 2021–2025. All computations are performed in R, using the Benchmarking package (Bogetoft and Otto ,2011). The analysis follows the research question : *How does cost efficiency for DSOs in Belgium, the Netherlands, Portugal, Ireland, and the United Kingdom compare over 2021–2025, and how do these patterns relate descriptively to differences in regulatory frameworks and selected energy-transition indicators?* ; a multi-step descriptive approach is adopted.

In the first stage, Data Envelopment Analysis (DEA) is used to estimate the cost efficiency of each DSO relative to an observed best-practice frontier. The DEA method is a non-parametric linear programming technique that creates the frontier based on observed input-output combinations, without imposing a specific functional form on the production technology (Charnes et al., 1978). It is particularly well-suited to distribution system operators (DSOs) for three reasons. Firstly, it handles multiple outputs simultaneously, reflecting the multidimensional nature of distribution network services. Secondly, as it is non-parametric, the production structure is defined by the data itself, with no assumption of linearity or a specific functional form. Thirdly, it yields relative performance scores that can be compared directly across units within the same frontier.

Before the main DEA estimation, outlier detection is applied to identify and review units that may distort the frontier, following the dual screening method of Agrell and Niknazar (2014).

In addition, productivity dynamics over time are analysed through the Malmquist Productivity Index (MPI), allowing changes in productivity to be decomposed into efficiency change and technological change.

A conventional parametric benchmark would estimate the average (log-linear) cost relationship

$$\ln(\text{TOTEX}_{j,c,t}) = \beta_0 + \beta_1 \ln(\text{CP}_{j,c,t}) + \beta_2 \ln(\text{NetworkLength}_{j,c,t}) + \beta_3 \ln(\text{EnergyDelivered}_{j,c,t}) + \varepsilon_{j,c,t}, \quad (4.1)$$

which fits the conditional mean of costs and would then be shifted down to a best-practice frontier.

By contrast, DEA estimates this frontier directly as the lower envelope of the observed input-output combinations. The input-oriented efficiency score measures the extent to which a DSO's inputs exceed the minimum cost required to produce its output. Efficiency is therefore assessed relative to a frontier defined by the three cost drivers presented in Section 4.2.3.

In the second stage, an analysis is conducted using Tobit regression.

4.2 DEA

4.2.1 Indices

$$\begin{aligned} t \in \mathcal{T} & : \text{years } \{2021, 2022, 2023, 2024, 2025\} \\ c \in \mathcal{C} & : \text{countries } \{\text{Belgium, Ireland, Portugal, Netherlands, UK}\} \\ j \in \mathcal{J}_c & : \text{set of DSO groups in country } c \end{aligned}$$

Each Decision Making Unit (DMU) corresponds to a DSO group j in country c observed in year t :

$$\mathcal{K} = \{(c, t, j) \mid c \in \mathcal{C}, t \in \mathcal{T}, j \in \mathcal{J}_c\}$$

The panel comprises $|\mathcal{K}| = 110$ DMUs (22 DSO groups $\times$ 5 years).

4.2.2 Input

Two inputs are used: normalised capital expenditure and normalised operational expenditure, rather than a single TOTEX aggregate, on which most regulators rely. The reason for this distinction between the inputs is specific to the research question. The OPEX/CAPEX ratio differs significantly due to a regulatory artefact. Breaking down TOTEX into CAPEX and OPEX also makes it possible to identify whether a DSO is wasting a specific input.

$$x_{1,k} = \text{CAPEX}_{j,c,t}^{\text{norm}} \geq 0, \quad x_{2,k} = \text{OPEX}_{j,c,t}^{\text{norm}} \geq 0 \quad (4.2)$$

Input specification: each normalised input is obtained by applying the same two sequential adjustments:

1. Currency conversion (UK only):

$$\text{CAPEX}_{j,\text{UK},t}^{\text{EUR}} = \text{CAPEX}_{j,\text{UK},t}^{\text{GBP}} \times e_t^{\text{GBP/EUR}} \quad (4.3)$$

$$\text{OPEX}_{j,\text{UK},t}^{\text{EUR}} = \text{OPEX}_{j,\text{UK},t}^{\text{GBP}} \times e_t^{\text{GBP/EUR}} \quad (4.4)$$

where $e_t^{\text{GBP/EUR}}$ is the ECB annual average exchange rate ($e_{2021} = 1.1628$, $e_{2022} = 1.1732$, $e_{2023} = 1.1501$, $e_{2024} = 1.1749$, $e_{2025} = 1.1676$)

2. Purchasing power parity (PPP) adjustment:

$$x_{1,k} = \text{CAPEX}_{j,c,t}^{\text{norm}} = \text{CAPEX}_{j,c,t}^{\text{EUR}} \times \frac{\text{PPP}_{c_0,t_0}}{\text{PPP}_{c,t}} \geq 0 \quad (4.5)$$

$$x_{2,k} = \text{OPEX}_{j,c,t}^{\text{norm}} = \text{OPEX}_{j,c,t}^{\text{EUR}} \times \frac{\text{PPP}_{c_0,t_0}}{\text{PPP}_{c,t}} \geq 0 \quad (4.6)$$

where $c_0 = \text{Belgium}$, $t_0 = 2021$ is the reference (normalisation factor for (BE, 2021) = 1.000).
PPP indices are sourced from Eurostat table `prc_ppp_ind` (GDP expenditure B1GQ, base EU27 = 100).

4.2.3 Outputs

Three outputs are selected:

$$y_{1,k} = \text{ConnectionPoints}_{j,c,t} \geq 0 \quad (\text{number of connected customers}) \quad (4.7)$$

$$y_{2,k} = \text{NetworkLength}_{j,c,t} \geq 0 \quad (\text{km of distribution network}) \quad (4.8)$$

$$y_{3,k} = \text{Energy Delivered}_{j,c,t} \geq 0 \quad (\text{Energy delivered in GWH}) \quad (4.9)$$

These three outputs were chosen because they are among the most commonly measured by regulatory systems and represent three core dimensions of DSO activity: connection points reflect the scale of customer service obligations, network length measures both the geographical extent and the complexity of the distribution system, and energy delivered captures the usable energy

that reaches the consumer at the point of use (Jamash & Pollitt, 2007).

4.2.4 Decision Variables

- $\theta_{k_0} \in (0, 1]$: radial contraction factor applied to the inputs of the evaluated DMU. The efficiency score is θ_{k_0} itself; the associated inefficiency, $1 - \theta_{k_0}$, is the maximum proportional reduction in CAPEX and OPEX achievable while maintaining current outputs.
- $\lambda = (\lambda_k)_{k \in K_t}$: non-negative weights defining the convex combination of reference DMUs that constructs the efficient benchmark for k_0 .

4.2.5 Methodology

For each evaluated DMU $k_0 = (j_0, c_0, t_0)$, the input-oriented DEA programme is defined as follows:

$$\min_{\theta_{k_0}, \lambda} \theta_{k_0} \quad (4.10)$$

Subject to:

$$\sum_{k \in K_t} \lambda_k \cdot x_{1,k} \leq \theta_{k_0} \cdot x_{1,k_0} \quad (\text{input constraint - CAPEX}) \quad (4.11)$$

$$\sum_{k \in K_t} \lambda_k \cdot x_{2,k} \leq \theta_{k_0} \cdot x_{2,k_0} \quad (\text{input constraint - OPEX}) \quad (4.12)$$

$$\sum_{k \in K_t} \lambda_k \cdot y_{1,k} \geq y_{1,k_0} \quad (\text{output constraint - connection points}) \quad (4.13)$$

$$\sum_{k \in K_t} \lambda_k \cdot y_{2,k} \geq y_{2,k_0} \quad (\text{output constraint - network length}) \quad (4.14)$$

$$\sum_{k \in K_t} \lambda_k \cdot y_{3,k} \geq y_{3,k_0} \quad (\text{output constraint - energy delivered}) \quad (4.15)$$

$$\sum_{k \in K_t} \lambda_k = 1 \quad (\text{VRS convexity constraint}) \quad (4.16)$$

$$\lambda_k \geq 0 \quad \forall k \in K_t \quad (\text{non-negativity}) \quad (4.17)$$

where $K_t = \{k \in \mathcal{K} \mid t_k = t\}$ is the set of all DMUs observed in year t . The efficiency frontier is constructed separately for each year, using only the DMUs observed in that year.

4.2.6 DEA Efficiency Score

The optimal solution $\theta_{k_0}^*$ constitutes the DEA efficiency score:

$$E_{j,c,t}^{\text{DEA}} = \theta_{k_0}^* \in (0, 1] \quad (4.18)$$

- $E_{j,c,t}^{\text{DEA}} = 1$: the DSO lies on the efficiency frontier.
- $E_{j,c,t}^{\text{DEA}} < 1$: the DSO could achieve an equiproportional reduction of CAPEX and OPEX by a factor of $(1 - \theta_{k_0}^*) \times 100\%$ whilst maintaining the same level of outputs.

4.2.7 The return to scale assumption

- **Constant Returns to Scale (CRS)**: No constraint on $\sum_k \lambda_k$. Assumes that a proportional scaling of all inputs and outputs is always feasible and that scale is not a source of efficiency difference. A small DSO is compared to a proportionally scaled version of a large DSO.
- **Variable Returns to Scale (VRS)**: Imposes $\sum_k \lambda_k = 1$, restricting the reference set to convex combinations of units with comparable scale. Allows for both increasing and decreasing returns to scale (Banker et al., 1984).
- **Non-Decreasing Returns to Scale (NDRS)**: Imposes $\sum_k \lambda_k \geq 1$. Assumes that scaling up is always feasible but not scaling down, i.e. that no decreasing returns to scale exist: economies of scale, once present, are never exhausted.

The VRS is used in this model. This choice is based on the heterogeneity of the sample size. It includes small DSOs such as AIESH and AIEG, with tens of thousands of connection points, as well as large DSOs such as Fluvius and UKPN. This choice makes it possible to better isolate the technical efficiency of DSOs independently of their size. Another argument in favour of the VRS is that the model makes an international comparison here, with network structures varying from one country to another. Furthermore, the VRS is based on a less restrictive assumption than the CRS. This reduces the risk of wrongly attributing inefficiency to operators whose performance is influenced by their size. This choice is also consistent with the literature on benchmarking distribution system operators, which frequently uses this approach to account for economies of scale (Jamassb & Pollitt, 2007; Bogetoft & Otto, 2011).

4.3 Outlier Detection

Before estimating the main DEA model, outliers are identified using the dual screening method of Agrell and Niknazar (2014). This procedure combines a structural test with an influence test. The structural test measures how far the unit could expand its inputs and still remain on the frontier. A threshold of $SE_k > 2.0$ flags the unit as a candidate outlier.

The influence test, by contrast, rests on the leverage a unit exerts on the scores of the others. Cook’s distance D_k measures how much DMU k shifts the efficiency scores of all remaining units, and thereby identifies peer outliers: units that are not extreme in their own score but distort the evaluation of others through their position in the reference set. The conventional cut-off $D_k > 4/(n - 2)$ is not informative in a panel of this size — with 22 units per annual frontier it stands at 0.20, a level no observation approaches. A relative criterion is therefore applied instead, flagging units that fall in the upper decile of the leverage distribution of their own year.

Units flagged are then examined against their raw data. Data errors are excluded based on certainty; units with actual but extreme values due to structural features are retained but noted. For the sensitivity analysis, results are reported as both with and without identified outliers.

4.4 Malmquist Productivity Index

Thanks to the Malmquist index, it is possible to compare each DSO with itself from one year to the next. This dynamic index complements the static data envelopment analysis model, which compares each DSO to its peers in the same year. The Malmquist index comprises two components (see Figure 4.1): efficiency change (EC) and technological change (TC). EC shows whether a DSO is making progress towards or moving away from the frontier in a given year. This index indicates whether a DSO’s location on the frontier improves or deteriorates over different years ($EC > 1$: the DSO closes the gap to best practice; $EC < 1$: the DSO falls further behind it). When $TC < 1$, best-practice operators require more inputs for a given output than before and the frontier shifts inwards; when $TC > 1$, it shifts outwards. A fall in M can therefore originate either in the operator’s own performance (EC) or in a shift of the benchmark against which it is measured (TC).

The Malmquist index is defined as the product of TC and EC: $M = EC \times TC$. The index is computed using deflated inputs (constant 2021 prices, HICP). This differs from the PPP adjustment made elsewhere in the analysis, where PPP adjusts for spatial price differences between countries at a given point in time.

4.4.1 Decomposition

The MPI for DMU k between periods t and $t + 1$ is defined as (Färe et al., 1994):

$$M_k^{t,t+1} = EC_k^{t,t+1} \times TC_k^{t,t+1} \quad (4.19)$$

where:

$$EC_k^{t,t+1} = \frac{E_k^{\text{DEA}, t+1}}{E_k^{\text{DEA}, t}} \quad (4.20)$$

$$TC_k^{t,t+1} = \left[\frac{D^t(x^{t+1}, y^{t+1})}{D^{t+1}(x^{t+1}, y^{t+1})} \times \frac{D^t(x^t, y^t)}{D^{t+1}(x^t, y^t)} \right]^{1/2} \quad (4.21)$$

and $D^s(x, y)$ denotes the efficiency score of a DMU with inputs x and outputs y evaluated relative to the period- s frontier.

4.4.2 Interpretation

Component	Value	Meaning
$EC > 1$	Efficiency improvement	DMU moved closer to the frontier
$EC < 1$	Efficiency deterioration	DMU fell further from the frontier
$TC > 1$	Technological progress	The frontier shifted outward
$TC < 1$	Technological regress	The frontier shifted inward
$M > 1$	Productivity improvement	Overall input-output productivity increased
$M < 1$	Productivity deterioration	Overall input-output productivity declined

Table 4.1: Interpretation of Malmquist index components.

The MPI is computed for each DSO and each annual transition, then aggregated to the country level using connection-point weights:

$$M_c^{t,t+1} = \sum_{j \in J_c} w_{j,c,t} \cdot M_k^{t,t+1} \quad EC_c^{t,t+1} = \sum_{j \in J_c} w_{j,c,t} \cdot EC_k^{t,t+1} \quad TC_c^{t,t+1} = \sum_{j \in J_c} w_{j,c,t} \cdot TC_k^{t,t+1} \quad (4.22)$$

where $w_{j,c,t}$ is DSO j 's share of country c 's total connection points in year t , so that larger operators contribute proportionally more to the country-level index

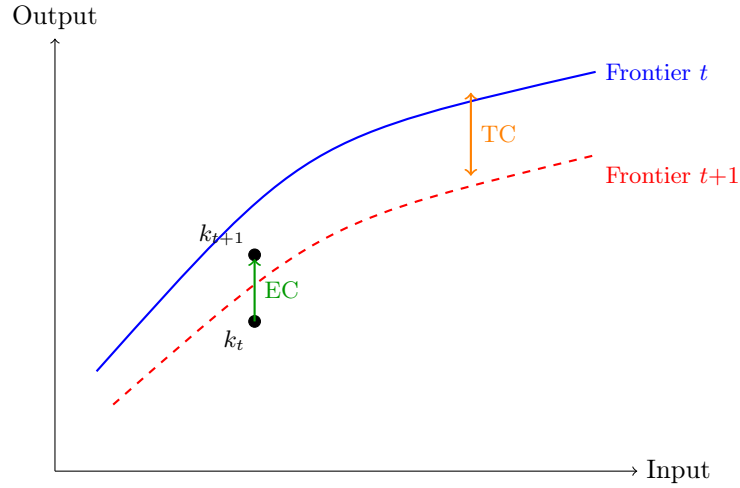


Figure 4.1: Malmquist decomposition

Note: EC (efficiency change) measures the movement of a DSO toward its own-year frontier; TC (technological change) measures the shift of the frontier between periods. Here $TC < 1$: the frontier shifts inward.

4.5 Intervention Power Index (IP)

The Intervention Power Index is a stylised index that incorporates the design elements of regulatory models. Each of the five dimensions is scored 0 or 1, so that $IP_j \in \{0, \dots, 5\}$. Its purpose is to classify frameworks from high-power incentives (low IP) to cost-plus (high IP).

“Incentive power” refers to the extent to which incentives affect operator efficiency. “Intervention power” indicates the degree of regulatory intervention. For Belgium, a connection-point-weighted country average IP_c is used (see Equation 4.30). The five dimensions selected are as follows:

Table 4.2: Intervention Power Index — Dimension Definitions			
Dimension	Description	Score = 0 (Incentive)	Score = 1 (Cost-plus)
D1: WACC level	Generosity of the allowed weighted average cost of capital, determining DSO returns on regulated assets	Allowed WACC at or below the sample median: DSO must be efficient for adequate returns	Allowed WACC above the sample median: returns are secured even if the DSO operates inefficiently
D2: OPEX control	Assess whether the regulator is controlling operational costs	DSOs are autonomous and manage their operating expenses freely within the ex-ante cap on revenue	The regulator verifies the operating expenses and reimburses them ex post
D3: Investment control	Who decides which investments proceed, and when regulatory approval is granted	DSO selects and justifies its investments ex ante, within a fixed envelope	Regulator approves investments ex post, so the DSO carries no risk on its investment choices
D4: Investment revenue	How capital expenditure is translated into allowed revenue, once undertaken	Symmetric treatment of CAPEX and OPEX (TOTEX), so capitalising confers no financial advantage	CAPEX added to the RAB or compensated through an adjustment factor, creating a bias towards capital solutions
D5: Regulatory horizon	Length of the regulatory period	Long period (≥ 5 years): provides regulatory stability, enables long-term DSO planning	Short period (< 5 years): frequent revisions enable ongoing regulatory intervention and adjustment

Notes: (1) A median-based threshold is used rather than an absolute cut-off because WACC levels are not directly comparable across regulatory contexts; a relative threshold is more defensible in a sample of this size. (2) The threshold is binary because partial or discretionary OPEX control practices are not systematically disclosed across the seven frameworks and cannot be scored reliably on a finer scale. (3) The distinction is based on the timing of regulatory approval, since this is the criterion that determines whether the DSO or the regulator bears the risk on investment choices. (4) A binary distinction is used because the qualitative difference between symmetric TOTEX treatment and RAB-based capital remuneration is a discrete regulatory design choice, not a matter of degree; this asymmetry is what creates the Averch–Johnson incentive to over-capitalise. (5) A threshold of five years is used because shorter regulatory cycles multiply the number of review and intervention points, independently of the cycle’s substantive content.

scoring formula

$$IP_j = D1_{WACC} + D2_{OPEXcontrol} + D3_{Investment.control} + D4_{Investment.revenue} + D5_{Horizon} \quad (4.23)$$

A higher IP indicates stronger regulatory intervention and therefore weaker efficiency incentives. Throughout this thesis, incentive power refers to the strength of the efficiency incentives faced by the operator, in the sense of Laffont and Tirole (1993), while intervention power refers to the degree of regulatory intervention. The two run in opposite directions: a high-powered incentive scheme corresponds to a low IP score.

- $IP = 0-1$: strong incentive regulation
- $IP = 2-3$: hybrid or intermediate regulation
- $IP = 4-5$: strong cost-plus regulation

IP sensitivity

To verify the robustness of the IP index, one sensitivity test is conducted. The first is the “leave-one-dimension-out” test, which recalculates the IP score after removing each of the five dimensions in turn.

Table 4.3: Sensitivity of the Intervention Power index to dimension choice

Framework	IP	D1	D2	D3	D4	D5	Stable
ACM / Ofgem	0	0	0	0	0	0	V
VNR	2	1	2	2	2	1	V
CRU	2	1	2	2	1	2	V
CWaPE	3	2	3	2	2	3	V
ERSE	3	2	2	3	3	2	V
BRUGEL	4	3	3	3	3	4	V

Note: Each Dk column reports the IP index after excluding dimension k. The ordering of the frameworks is preserved up to ties in every specification; the only reversal concerns VNR and CRU when D4 is excluded, and it does not affect the extremes of the ranking.

Table 4.4: Intervention Power (IP) Index by Regulatory Framework

Country	Regulator	D1	D2	D3	D4	D5	IP
		WACC	OPEX	Inv. Control	Inv. Revenue	Horizon	Total
Netherlands	ACM	0	0	0	0	0	0
UK	Ofgem	0	0	0	0	0	0
Belgium	VNR	1	0	0	0	1	2
Ireland	CRU	1	0	0	1	0	2
Belgium	CWaPE	1	0	1	1	0	3
Portugal	ERSE	1	1	0	0	1	3
Belgium	BRUGEL	1	1	1	1	0	4

Sources: ACM Methodebesluit 2017–2021 and 2022–2026; Ofgem RIIO-ED1 and RIIO-ED2 Final Determinations; VNR tariff methodology 2021–2024; CWaPE méthodologie tarifaire 2019–2023 (extended to 2024); BRUGEL méthodologie tarifaire 2020–2024; CRU PR5 Determination; ERSE Regulamento Tarifário.

With an IP score of 0, the Dutch framework is one of the most incentive-based in the sample, alongside that of the United Kingdom. Authorised revenue is sector-specific (Yardstick), with no ex-post reimbursement for cost overruns.

The United Kingdom also has a score of 0 due to the TOTEX mechanism for sharing variances, the uncertainty mechanism and ODIs, similar to the Netherlands.

In Belgium, the three regulators are distinguished from one another. The VNR has a score of 2 because authorised revenue is set against a sector-wide trend of historical costs ex ante, with no ex-post reimbursement. This makes it the most incentive-based of the three Belgian frameworks. The score is raised by two dimensions: the allowed WACC is above the sample median and the regulatory period runs over four years rather than five.

The CWaPE’s IP score is 3 due to ex ante operational costs that are not reimbursed if exceeded. Investments are approved by the regulator and form part of the regulated asset base, which is adjusted annually; the permitted weighted average cost of capital is also above the sample median.

Finally, BRUGEL has a score of 4. As the regulator of a single operator, it applies ex-post verification of operating costs and adds approved investments to the RAB, with an annual rebalancing of regulatory accounts as its only incentive mechanism; only the five-year horizon scores 0.

Ireland’s score is 2: the revenue cap, the efficiency targets and the five-year price review limit intervention on both operating costs and the regulatory horizon. The score is nevertheless above the Dutch and British benchmark on two dimensions: the allowed return is above the sample median, and the CRU has explicitly declined to adopt a TOTEX approach, retaining a separate treatment of CAPEX remunerated through RAB x WACC.

Portugal’s score is 3. The X factor is applied to OPEX and CAPEX, and the low-voltage distribution receives a partial TOTEX treatment and RSRI quality incentives, which together keep investment discipline high. The allowed return is above the sample median, operating costs

are subject to an ex-post adjustment that consolidates the full variance between forecast and actual costs into the RAB at the end of the year — providing cost recovery in substance — and the regulatory period runs over four years.

4.6 Second stage estimation: Tobit and OLS

4.6.1 Aggregate Efficiency Index $E_{c,t}$

To compare efficiency between countries and over time, a connection-point-weighted aggregate index is defined for country c and year t :

$$E_{c,t} = \sum_{j \in J_c} w_{j,c,t} \cdot E_{j,c,t}^{\text{DEA}} \quad (4.24)$$

where weights are proportional to connection points:

$$w_{j,c,t} = \frac{\text{ConnectionPoints}_{j,c,t}}{\sum_{j' \in J_c} \text{ConnectionPoints}_{j',c,t}} \quad (4.25)$$

The aggregate index $E_{c,t}$ is retained as a descriptive summary of national cost performance since consumers' distribution costs are dominated by the largest operators. However, it is not used as the dependent variable in the second stage. Due to connection-point weighting, the index reflects a single operator in more concentrated countries. In Portugal, for example, E-REDES holds approximately 97% of connection points, and the weighted index of 0.972 contrasts with an unweighted DSO-level mean of 0.549. Hypothesis testing is therefore conducted at the DSO level, where the full variation of the panel is preserved.

4.6.2 Regulation and the Energy Transition

In this section, the analysis will focus on the influence of the type of regulation on the energy transition. The analysis will help answer the following question: Do regulatory incentive frameworks (low IP) promote the roll-out of smart meters and improve efficiency?

First model

This section investigates whether DSOs with a more stringent regulatory framework, i.e. a high IP_j , exhibit reduced efficiency, taking energy transition variables into account.

$$\text{Inefficiency}_{j,c,t} = 1 - E_{j,c,t}^{\text{DEA}} \quad (4.26)$$

Table 4.5: Variables used in the second-stage descriptive analysis

Variable	Level	Domain	Description	Source
IP_j	DSO/reg.	$\{0, \dots, 5\}$	Regulatory intervention-power score	This thesis (Tab. 4.4)
$\overline{IP}_c$	Country-yr	$[0, 5]$	Conn.-point-weighted country avg. of IP_j	This thesis (Eq. 4.30/ 4.24)
$SmartMeter_{j,c,t}$	DSO-yr	$[0, 1]$	Share of customers w/ smart meter	ACER, DSO reports
$DecentralCap_{j,c,t}$	DSO-yr	≥ 0 (kVA)	Installed decentralised gen. capacity	DSO reports, regulators
$Inefficiency_{j,c,t}$	DSO-yr	$[0, 1]$	$1 - E_{j,c,t}^{DEA}$, dep. var. Model A	Step 1 (calculated)
$SmartMeter_{c,t}$	Country-yr	—	Aggregated dep. vars., Model B	Eq. 4.31
$DecentralCap_{c,t}$				

The inefficiency value is calculated because a significant proportion of DSOs are located on the efficiency frontier, resulting in a DEA score of 1. This suggests that the level of inefficiency is zero, representing the lower bound imposed by the DEA methodology. In a simple regression model, this value of zero represents a censoring effect.

In this context, a standard ordinary least squares (OLS) regression is inappropriate, as it assumes a continuous, uncensored dependent variable. The Tobit model is therefore selected. This model relies on the existence of a latent inefficiency variable that can take negative values, but only positive values are observed, with negative values being censored at zero. This model also yields consistent estimates given this type of dependent variable distribution.

Furthermore, a Tobit specification has been chosen over a bootstrap regression, . According to Simar and Wilson’s algorithm (2007), the 110 DEA scores are not independent of one another as they are all calculated relative to the same estimated frontier. The observations are not independent for two reasons: all scores depend on the same estimated frontier (Simar and Wilson), and the intervention power index (IP) does not vary within a regulatory group (wild cluster bootstrap). Simar and Wilson only address the former issue, meaning that each resample would still contain the same seven regulatory rules. Furthermore, Simar and Wilson recommend a truncated regression, whereby observations at the boundaries are removed. However, 35 of the 110 DSOs have a score of 1, so removing them would result in a third of the panel being lost. The Tobit model retains the entire panel. Finally, with seven regulatory frameworks, the second stage of the analysis does not demonstrate a causal effect of regulation on efficiency. Nevertheless, it should be stated clearly that this leaves the Simar–Wilson concern uncorrected. The reported p-values are conservative with respect to clustering and uncorrected with respect to dependence between DEA scores. They should therefore be interpreted as an upper bound on the level of confidence supported by the data.

The second stage of the model is conducted at the DSO level over a five-year period. All variables vary over time, except for the intervention power index. To account for this hierarchical data structure, standard errors are clustered at the regulator level rather than the DSO level. However, the sample comprises only seven regulatory groups, which can lead to an underestimation of standard errors when using standard robust estimators alone. To address this, the results were also estimated using a wild cluster bootstrap procedure in line with the recommendations of Cameron, Gelbach and Miller (2008). The results obtained using both methods are presented in Chapter 5.

$$Inefficiency_{j,c,t}^* = \beta_0 + \beta_1 \cdot SmartMeter_{j,c,t} + \beta_2 \cdot DecentralCap_{j,c,t} + \beta_3 \cdot IP_j + \epsilon_{j,c,t} \quad (4.27)$$

$$Inefficiency_{j,c,t} = \max(0, Inefficiency_{j,c,t}^*) \quad (4.28)$$

where $\epsilon_{j,c,t} \sim \mathcal{N}(0, \sigma^2)$. The maximum likelihood estimator distinguishes between censored and uncensored observations:

$$L(\beta, \sigma) = \prod_{j: y_j=0} \Phi\left(\frac{-x'_j \beta}{\sigma}\right) \times \prod_{j: y_j>0} \frac{1}{\sigma} \phi\left(\frac{y_j - x'_j \beta}{\sigma}\right) \quad (4.29)$$

where $\Phi(\cdot)$ and $\phi(\cdot)$ are, respectively, the cumulative distribution function and the probability density function of the standard normal distribution.

Under H1, a higher IP_j (weaker incentive intensity) is expected to be associated with higher inefficiency, i.e. $\beta_3 > 0$.

Second model : Intervention power and transition indicators

This analysis examines whether a model similar to the cost-plus model is associated with limited adoption of transition technologies. Stronger regulation is expected to be associated with a lower uptake of transition technology, i.e. $\gamma_1 < 0$ and $\delta_1 < 0$. This statement holds under H2.

$$IP_c = \sum_{j \in J_c} w_{j,c,t} IP_j, \quad SmartMeter_{c,t} = \sum_{j \in J_c} w_{j,c,t} SmartMeter_{j,c,t}, \quad DecentralCap_{c,t} = \sum_{j \in J_c} w_{j,c,t} DecentralCap_{j,c,t} \quad (4.30)$$

The regressions are estimated at the DSO level, with the intra-Belgian variation across the three regional frameworks contributing to identification. The country-year counterpart, calculated using the IP_c weighted by the connection points in equation 4.30, reported in Section 5.2.2.

Two descriptive OLS regressions are then estimated:

$$\text{SmartMeter}_{j,c,t} = \gamma_0 + \gamma_1 IP_j + u_{j,c,t} \quad (4.31)$$

$$\frac{\text{DecentralCap}_{j,c,t}}{CP_{j,c,t}} = \delta_0 + \delta_1 IP_j + v_{j,c,t} \quad (4.32)$$

No new controls are introduced. With only seven regulatory clusters and a constant regressor in each, adding a covariate would use up the mathematical model's remaining degrees of freedom. Decentralised capacity is normalised by the number of connection points, ensuring that the size of the operator does not influence the specification.

4.7 Hypotheses

H₁. *DSOs operating under regulatory frameworks with weaker efficiency incentives (higher IP_j) exhibit lower DEA cost-efficiency scores over the period 2021–2025.*

In the Laffont and Tirole (1993) framework, the power of an incentive mechanism corresponds to the share of cost savings retained by the operator. Under high-powered incentive mechanisms (low IP_j), operators capture the residual benefit of cost reductions, giving them a strong incentive to minimise costs. Conversely, in systems with high IP_j , the incentive to reduce costs is weakened due to ex-post reimbursement and capital remuneration based on the value of regulated assets.

H_{2a}. *DSOs operating under regulatory frameworks with stronger efficiency incentives (lower IP_j) exhibit higher smart meter penetration.*

H_{2b}. *DSOs operating under regulatory frameworks with stronger efficiency incentives (lower IP_j) exhibit higher decentralised generation capacity per connection point.*

Stronger incentives should coincide with higher smart meter penetration rates and greater decentralised capacity per connection point. This is because incentive frameworks reward digital investments and transition-related flexibility more heavily, in addition to static cost minimisation (Bolton & Poulter, 2025; Jenkins & Pérez-Arriaga, 2017).

H₃. *Higher DEA cost-efficiency is positively associated with smart meter penetration and decentralised generation capacity per connection point.*

There is a positive relationship between efficiency and energy transition indicators if the DSOs most advanced in the transition are the most cost-efficient. Conversely, if transition investments

increase short-term costs, this relationship could be negative. Empirical analysis will determine which of these two hypotheses is most consistent with the data.

H₄. *Within Belgium, regional differences in regulatory intervention power are associated with differences in DSO cost efficiency and energy-transition performance, measured by smart meter penetration and decentralised generation capacity.*

Although the three Belgian regions share the same macroeconomic environment, technologies, and general energy policy, they are governed by authorities with differing intervention powers. This setup provides a suitable framework for examining whether differences in regulatory design are associated with disparities in economic efficiency and energy-transition performance. The findings should be interpreted with caution, given the limited number of regulators and operators. H4 is tested in two parts: H4a examines smart meter penetration, and H4b examines cost efficiency. Decentralised capacity is reported descriptively, as the three-regulator panel does not support a separate test.

Chapter 5

Empirical analysis and results

This chapter is divided into two parts. First, efficiency is calculated using the DEA model developed in Chapter 4 over the period 2021–2025 and the results are explained. Second, these efficiency scores are used in the two-stage model to determine whether a certain type of regulation is associated with the energy transition and with cost-efficiency. The objective is to assess whether regulatory intensity relates to the transition. The results are then interpreted, and the chapter closes with the limitations of the analysis.

Table 5.1: DSO-level descriptive statistics by country

Country	DSOs	IP	Efficiency	Min	Max	SmartMeter	DecentralCP
UK	6.000	0.000	0.955	0.837	1.000	0.555	1.905
Ireland	1.000	2.000	0.945	0.892	1.000	0.581	2.661
Belgium	6.000	3.000	0.629	0.222	1.000	0.169	1.348
Portugal	3.000	3.000	0.549	0.272	1.000	0.425	0.567
Netherlands	6.000	0.000	0.456	0.203	1.000	0.900	3.133

Note: Descriptive statistics are reported at the DSO level over the period 2021–2025 ($N = 110$ DSO-year observations). *IP* denotes the Intervention Power index of the regulatory framework.

Efficiency corresponds to the DEA VRS efficiency score.

SmartMeter is the smart meter penetration rate, and

DecentralCP represents installed decentralised generation capacity (kVA) per connection point.

The Belgian IP reported here is the unweighted mean across the six Belgian DSOs. The connection-point-weighted index IP_c defined in Equation 4.30 is used only in the country-year specification reported in Section 5.2.2, where it yields a lower value for Belgium because Fluvius ($IP = 2$) dominates the weighting.

This table presents descriptive statistics for the five-year period. The United Kingdom has the highest average efficiency, followed by Ireland. Belgium, Portugal, and the Netherlands have significantly lower scores.

Figure 5.1 shows the efficiency score of each country. A marked heterogeneity is observable across the sample. The UK and Ireland are concentrated near the frontier, while Belgium, the Netherlands and Portugal display a wider distribution covering almost the entire range (0.20–1.00). This heterogeneity is not the same everywhere. Belgium, the Netherlands and Portugal cover

almost the whole scale, which suggests that the DSO itself matters more than the country. The UK and Ireland are grouped near the frontier, so their dispersion says little.

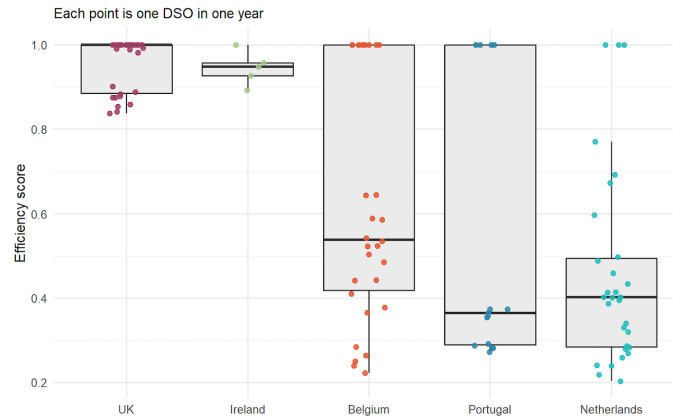


Figure 5.1: Cost efficiency by country (DSO level)

Note: The figure displays the distribution of DEA cost-efficiency scores (VRS) for each country over the period 2021–2025. Each point corresponds to one DSO-year observation. The boxplots show the median, interquartile range and dispersion of efficiency scores within each country.

These results do not support the hypothesis that regulatory intensity is related to efficiency. The clearest evidence is the contrast between the Netherlands and the United Kingdom: both operate under frameworks scored $IP = 0$, the most incentive-oriented in the sample, yet their mean efficiency differs by half a point (0.456 against 0.955). Belgium and Portugal point in the same direction from the opposite end of the scale: they share an identical average IP of 3.0 and nonetheless record mean scores of 0.629 and 0.549 respectively. Within a given level of regulatory intervention, the dispersion of efficiency is thus of the same order as the dispersion observed across levels. Regulatory intensity alone therefore does not explain cost performance.

5.1 Results of the DEA

Table 5.2: DEA efficiency scores by country (VRS, DSO level)

Country	DSOs	Obs	Mean	Median	Min	Max	SD	OnFrontier	PctFrontier
UK	6	30.000	0.955	1.000	0.837	1.000	0.063	16.000	53.333
Ireland	1	5.000	0.945	0.947	0.892	1.000	0.040	1.000	20.000
Belgium	6	30.000	0.629	0.539	0.222	1.000	0.289	10.000	33.333
Portugal	3	15.000	0.549	0.364	0.272	1.000	0.332	5.000	33.333
Netherlands	6	30.000	0.456	0.401	0.203	1.000	0.232	3.000	10.000

The DEA scores are presented in Table 5.2. The average score for the entire sample is 0.674. This indicates that, on average, a reduction in inputs is possible while maintaining the same level of output. Several observations regarding the different countries are evident. British operators are

characterised by high operational performance, given that more than half of their observations lie on the DEA frontier. Ireland, represented by a single operator, shows a high efficiency score. As for Belgium, regulatory fragmentation affects the results, a point discussed later in this section. The dominant position of E-REDES in Portugal shapes the frontier. Dutch network operators perform relatively less efficiently.

Table 5.3: Aggregate efficiency with and without frontier-defining operators

Country	Full frontier	Outliers excluded	Change
Belgium	0.377	0.952	0.575
Portugal	0.972	0.640	-0.332
Netherlands	0.307	0.524	0.217
UK	0.966	0.988	0.022

Note: Ireland is omitted because it comprises a single DSO; the frontier cannot be re-estimated by excluding its own frontier-defining operator.

Outlier detection

As noted above, the DEA frontier is defined by the most efficient operators. The dual screening procedure of Section 4.3 flags six operators. Super-efficiency removes the "overly efficient" operator from the panel to assess the others. Three stand out over the whole period, UKPN, NGED and E-REDES, for which no convex combination of the remaining 21 units can replicate their output level; their super-efficiency is therefore infinite (Table A.4). Portugal shows the largest downward revision ($0.972 \rightarrow 0.640$), confirming its dependence on E-REDES; For Belgium, the Netherlands and the United Kingdom the change is mechanical: the aggregate index is dominated by Fluvius, Liander and the large English DNOs respectively. Their scores rise because UKPN, NGED and E-REDES have been withdrawn from the reference set. Following the review rule of Section 4.3, none of these six reflects a data error; all are retained but documented, and the sensitivity analysis (Table 5.3, Table A.5) reports results with the frontier re-estimated without them.

Return to scale and scale efficiency

Table 5.4 reports mean efficiency under the three returns-to-scale assumptions together with scale efficiency, defined as $SE_{j,c,t} = E_{j,c,t}^{CRS} / E_{j,c,t}^{VRS}$

The comparison between CRS, VRS and NDRS shows that CRS scores are consistently lower than VRS scores, particularly for Belgium and the Netherlands. This indicates a scale penalty, meaning that operators lose efficiency because of their size rather than management.

In Belgium, this gap focuses on small operators (AIESH, AIEG). They both lie on the VRS frontier in every year but under the CRS, their scores fall sharply. The NDRS and VRS specifications produce near-identical results: the two scores differ for only 4 of the 110 observations,

all located in the decreasing-returns region (three UK operators and one Belgian). The choice between the two therefore has no material influence on the panel.

Table 5.4: Returns to scale by country: specification comparison and classification

Country	E VRS	E CRS	E NDRS	Scale eff	IRS	CRS	DRS
UK	0.9547	0.9519	0.9546	0.9970	13.0000	14.0000	3.0000
Ireland	0.9445	0.9434	0.9445	0.9988	4.0000	1.0000	0.0000
Belgium	0.6291	0.4794	0.6290	0.8403	29.0000	0.0000	1.0000
Portugal	0.5491	0.5105	0.5491	0.8799	10.0000	5.0000	0.0000
Netherlands	0.4564	0.3651	0.4564	0.8182	29.0000	1.0000	0.0000

Malmquist

Table 5.5: Malmquist decomposition by country, 2021–2025 (geometric means, HICP deflator)

Country	EC	TC	M
Belgium	1.0383	0.9157	0.9508
United Kingdom	1.0026	0.9443	0.9467
Portugal	1.0001	0.9326	0.9327
Netherlands	0.9843	0.9376	0.9228
Ireland	0.9714	0.9184	0.8922

Note: Geometric means, ordered by decreasing productivity change. Distance functions estimated under CRS following Färe et al. (1994). The Malmquist index is computed on inflation-deflated inputs (HICP, base 2021), whereas the PPP adjustment used elsewhere corrects spatial price differences only; $TC < 1$ therefore reflects an inward shift of the cost frontier rather than nominal price growth. Components satisfy $M = EC \times TC$ up to rounding; the identity is verified operator by operator.

Caveat: The Irish decomposition covers the 2024–2025 transition using estimated rather than observed CAPEX and OPEX values. Since the estimate assumes continued growth in regulated investment under PR6, it mechanically contributes to the inward shift of the frontier recorded for Ireland, which posts the lowest productivity index in the sample. The Irish figure should therefore be read as indicative. The qualitative finding of the decomposition – that $TC < 1$ in all five countries and that the productivity decline originates in frontier movement rather than in efficiency change – does not depend on it, since it holds for the four countries observed throughout.

Measured productivity (M) is below 1 in all five countries (see Table 5.5). The decomposition reveals that this decline was caused by the technological-change component ($TC < 1$), rather than by a change in the efficiency. The operators did not contract their distance to the frontier; rather, the frontier itself shifted inwards between the years. This result can be interpreted in two ways. The first is that an inward shift of the cost frontier is consistent with the general increase in investment intensities discussed in Chapter 3. This would increase the cost per unit for all operators and shift the frontier upwards.

The second interpretation is that a uniform $TC < 1$ across all five countries is exactly what would be expected if inputs were measured in current rather than constant prices. The Malmquist index is however computed on HICP-deflated inputs (base 2021), so general price growth is already removed. The inward shift is therefore not an artefact of nominal price growth in general. It may nonetheless reflect network-specific input-price inflation that the HICP does not capture. The two

readings are not mutually exclusive, and separating them would require a network-specific cost deflator, which is not available on a harmonised basis for the five countries.

5.2 Two stage : testing the hypothesis

5.2.1 H1: Intervention power and efficiency

This hypothesis posits that a higher IP score corresponds to lower efficiency. Efficiency is converted into inefficiency and regressed on the two transition indicators and the IP index using the Tobit specification of Section 4.6. Table 5.6 reports the estimation, with standard errors clustered at the regulator level. The Tobit coefficient on IP is positive (0.1436), which is the direction predicted by H1: a more interventionist framework is associated with higher inefficiency. What matters here, however, is how fragile that result becomes once inference is made more conservative. Under naive standard errors the coefficient is highly significant ($p = 0.0002$); once errors are clustered at the regulator level it survives only at the 10% level ($p = 0.091$); and under the wild cluster bootstrap it can no longer be distinguished from zero ($p = 0.617$; Table 5.7). This loss of precision is expected: IP barely varies within a regulator, and with only seven regulatory clusters the naive standard errors overstate precision. The relationship is not even monotonic: DSOs with $IP = 3$ are on average more efficient than those with $IP = 2$ (Table A.13). H1 is therefore not robustly supported. The estimated sign is consistent with H1, but valid inference cannot separate the effect from zero, and other factors clearly dominate.

Table 5.6: Model A — Tobit regression explaining inefficiency (DSO level)

Variable	Estimate	Std. error	z	p
Intercept	−0.4065	0.3930	−1.035	0.301
Smart meter penetration	0.0988	0.4427	0.223	0.823
Decentralised capacity (kVA/conn. pt)	0.2088	0.0977	2.137	0.033
Intervention power index	0.1436	0.0850	1.689	0.091
$\log(\sigma)$	−0.9929	0.1071	−9.273	< 0.001

Note: $N = 110$ (35 left-censored at zero, 75 uncensored). Standard errors clustered at the regulator level (7 clusters). The three p -values reported for H1 correspond to three inference procedures applied to the same Tobit coefficient. The naive p -value (Table 5.7) comes from the unclustered model; this table reports the regulator-clustered version ($p = 0.091$); the wild cluster bootstrap p -value (Cameron, Gelbach & Miller, 2008) is used as the reference for the final conclusion. Because the panel contains only seven regulatory clusters, the naive p -value overstates statistical precision and is reported for transparency only.

5.2.2 H2a: Intervention power and smart meter penetration

Smart meter penetration is regressed on IP over the 110 DSO-year observations. The slope is negative (0.157) and significant under the wild cluster bootstrap ($p = 0.047$), with an R^2 of 0.495.

A more interventionist framework is therefore associated, on average, with a lower penetration of smart meters. The sign is the one predicted by H2a.

This result should be read with caution. The $IP = 0$ category pools two countries with very different rollout histories: the Netherlands averages 0.900 over the period, the United Kingdom 0.555. That is a 35-point gap within a single IP value. The same holds at $IP = 3$, where Portuguese observations range from roughly 7% to 80%. Much of the variation reflects when each national programme began rather than the regulatory framework itself. H2a therefore holds descriptively rather than predictively.

The same regression at country-year level, using the weighted index IP_c , gives a smaller slope that is not significant. This is an effect of the aggregation, not a contradiction. Belgium's three regional scores are averaged into a single country value, and that regional variation is precisely what identifies the DSO-level coefficient.

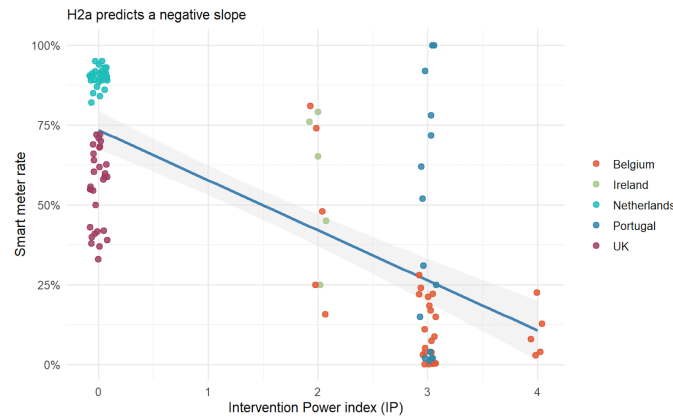


Figure 5.2: Smart meter penetration and regulatory intervention power

Note: Each point represents one DSO-year observation (2021–2025). The horizontal axis reports the Intervention Power (IP) index of the regulatory framework, while the vertical axis shows the smart meter penetration rate. Colours distinguish the five countries included in the sample.

There are several observations to be made regarding this figure. The first is the negative slope. Next, at $IP=0$, the Netherlands is close to 90% and UK is around 55%, which represents a 35-point gap. Belgium's score is more logical, as the IP varies between operators.

5.2.3 H2b: Intervention power and decentralised capacity

Decentralised capacity per connection point is regressed on IP over the same 110 observations. The slope is negative (0.480): DSOs under stronger regulatory intervention have less decentralised capacity per connection point. The sign matches H2b. The coefficient is not significant once clustering is taken into account (bootstrap $p = 0.125$), so H2b is not confirmed. As with smart

meters, the pattern is confounded by country-level factors and cannot be attributed to regulatory design.

5.2.4 H3: Cost efficiency and transition performance

The hypothesis here focuses not on IP scores but on DSO efficiency and its impact on the transition.

The coefficient on smart meters penetration is not significant ($p = 0.29$). The coefficient on decentralised capacity per connection point, however, is negative (-0.0865) and remains significant under the wild cluster bootstrap ($p = 0.047$). The DSOs with higher decentralised capacity per customer are the ones with the lowest efficiency. The separation is clearly visible on the figure: the UK and Ireland are located around 0.85 to 1 range and there is a lower band comprising Belgium, the Netherlands and Portugal. H3 is therefore rejected. Rather than the positive association it predicted, the data support a statistically significant inverse relationship between transition intensity and cost efficiency. This is consistent with transition-related investment raising costs in the short run — a mechanism developed for the Dutch case. With regard to the energy transition indicators, the regulatory design matters but transition is also influenced by national policy, ownership, geography or investments cycles. (Table A.11)

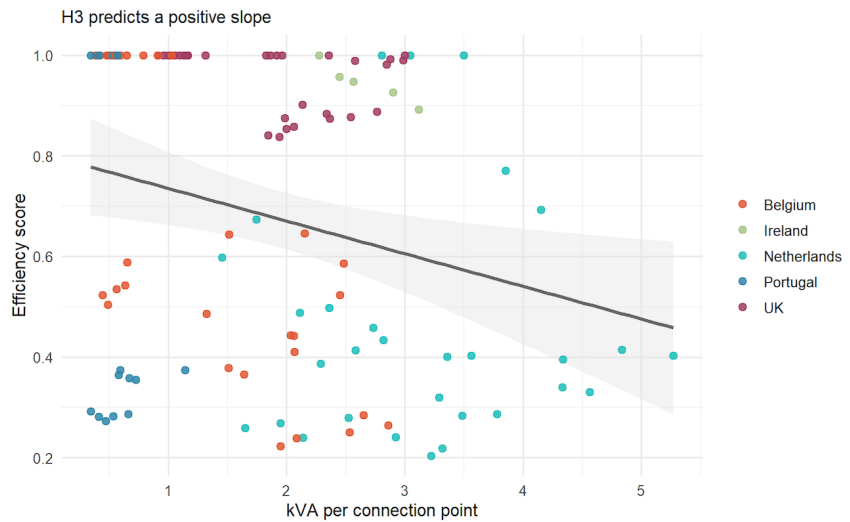


Figure 5.3: Cost efficiency and decentralised capacity per connection point

Note: Each point represents one DSO-year observation (2021–2025). The vertical axis reports the DEA cost-efficiency score (VRS), while the horizontal axis shows decentralised generation capacity per connection point. Colours distinguish the five countries included in the sample.

5.2.5 H4: Fragmentation in Belgium

Belgium provides an interesting case study due to the regional fragmentation of its regulatory frameworks, which are subject to the same national context. The regulatory frameworks are as follows: Flanders (VNR): IP = 2; Wallonia (CWaPE): IP = 3; Brussels (BRUGEL): IP = 4. The results show that Flanders, with a more incentive-based regulatory framework, has better energy transition indicators, with the highest rates of smart meters and installed decentralised capacity. The within-Belgium gradient carries the expected sign for smart meter penetration and decentralised capacity, but cannot be tested reliably: Belgium contains only three regulators.

These results should be interpreted with caution due to the limited amount of data, which does not allow statistically robust conclusions: under wild cluster bootstrap neither the smart-meter gradient (H4a, $p=0.500$) nor the efficiency gradient (H4b, $p=0.875$) is significant. Furthermore, Flanders is represented by only one DSO, which is the largest DSO in Belgium, and this affects the efficiency results. The analysis comparing the three regions is therefore more descriptive than causal. The efficiency gradient also runs in the opposite direction to H1. Within Belgium, the regions with more interventionist frameworks have the higher efficiency scores. The coefficient is not significant ($p = 0.875$), so nothing can be concluded from it. But it points the same way as Section 5.2.1, where the relationship between IP and efficiency was already found to be non-monotonic. Scale plays a role here. Flanders is represented by Fluvius alone, which sits below the frontier, while the two smallest Walloon operators reach it every year. The more robust evidence is the monotonicity of the gradient, which holds for smart meters in four of the five years and for decentralised capacity in every year (Table A.12).

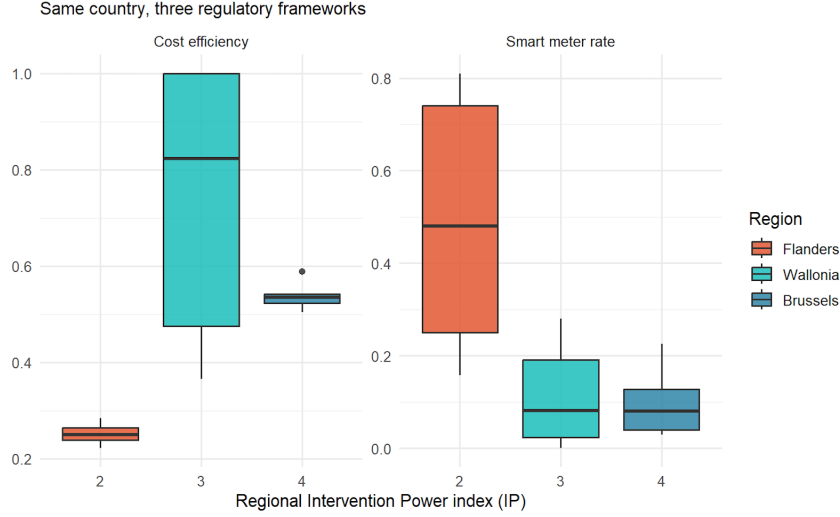


Figure 5.4: Cost efficiency and smart meter penetration across the three Belgian regional regulatory frameworks

Note: The left panel shows cost efficiency, the right panel smart meter penetration, for the Belgian DSOs over 2021-2025. Colours distinguish the three regional regulatory frameworks: VNR (Flanders), CWaPE (Wallonia) and BRUGEL (Brussels).

5.2.6 Conclusion on the hypothesis

Hypothesis	Variable	Estimate	p naive	p bootstrap	N
H1	IP	0.1436	0.0002	0.6172	110
H2a	IP	-0.1569	0.0000	0.0469	110
H2b	IP	-0.4803	0.0000	0.1250	110
H3	dec_per_cp	-0.0865	0.0078	0.0469	110
H4a	IP	-0.1935	0.0009	0.5000	30
H4b	IP	0.1433	0.1181	0.8750	30

Note: Bold values indicate results that remain statistically significant under the wild cluster bootstrap inference ($p < 0.05$), which is used as the reference inference procedure throughout this thesis. Naive p -values of 0.0000 are values below 10^{-4} .

Under naive standard errors several coefficients appear significant, but those tests treat the 110 observations as independent, which they are not: IP is essentially constant within the regulator, and the panel contains only seven regulatory groups. Once inference is based on wild cluster bootstrapping, only one of the regulatory intervention power hypotheses survives. H1 displays the theoretically expected sign but is not significantly different from zero (bootstrap $p = 0.6172$) and is non-monotonic. H2a is significant at the 5% level ($p = 0.0469$), though the effect is weak and largely driven by the contrast between the Netherlands and the more interventionist frameworks. H2b carries the expected sign but is not significant ($p = 0.1250$). Finally, H3 is rejected in favour of the opposite relationship. H4 cannot be tested reliably: with three regulators, the smallest attainable bootstrap p -value is 0.250.

Overall, it is difficult to argue that the intensity of regulatory intervention substantially affects

cost efficiency or transition indicators; in most cases, the outcomes are conditioned by policies implemented at the national level or adopted at the EU level.

5.3 Interpretation

The aim of this research was to analyse how different types of regulatory frameworks are associated with economic factors and energy transition metrics. The results show that the DSO efficiency varies across and within countries. On one hand, Belgium, Portugal and the Netherlands each display a within-country range covering almost the full scale (Table 5.2, standard deviations of 0.29, 0.33 and 0.23). On the other hand, the UK and Ireland are tightly clustered near the frontier. This suggests that the management practices of each DSO have greater influence than the national regulatory framework.

The coefficients on IP in the transition regressions carry the sign predicted by H2a and H2b : stronger incentives coinciding with higher smart-meter penetration and higher decentralised capacity. However, the associations are weak, largely driven by the Netherlands, and not significant under valid inference. H2b is not confirmed once clustering is considered. H2a, although significant, rests on a contrast that is largely between-country. This hypothesis is therefore weakly supported and should not be interpreted causally. The strength of regulatory incentives is not, on its own, a reliable predictor of transition indicators. While regulation does not appear to hinder the energy transition, the transition itself depends heavily on external factors such as national policy, shareholder investment choices and state-defined priorities.

Hypothesis 3 was also rejected, indicating that there is no positive relationship between efficiency and energy transition indicators. The results showed that this relationship is actually negative. This can be explained by transition-related investments, which increase costs and consequently reduce efficiency.

Finally, the fragmentation of the Belgian system results in distinct regulatory frameworks. This hypothesis cannot be tested reliably, as Belgium contains only three regulatory frameworks.

UK

The three largest operators lie on the efficiency frontier in every year and a fourth reaches it once. These results confirm what was observed in Chapter 2: the RIIO system incentivises efficiency. This position is measured relative to the estimated frontier and is sensitive to the outlier treatment of NGED and UKPN.

Portugal

The results show high efficiency; however, this is largely driven by E-REDES. Excluding E-REDES brings the aggregate efficiency from 0.972 to 0.640. The other two operators have efficiencies of 0.283 and 0.365.

Ireland

With a single operator, no within-country comparison is possible. ESB Networks' efficiency trajectory remains stable, ranging around 0.9.

Belgium

As a large operator, Fluvius has a significant impact on the results with its domination of the connection-point-weighted index (average 0.377 vs DSO-level mean: 0.629). Fluvius sits below the frontier and depresses the aggregate. Moreover, under VRS, convexity restricts the reference set to operators of comparable scale. AIESH and AIEG have few peers. Their super-efficiency is finite but the frontier they define locally rests on a thin reference set.

Netherlands

The Netherlands has the lowest DEA efficiency scores in the sample. This is surprising because its TOTEX level is comparable to that of Belgium. It does not necessarily mean the DSOs are managed less effectively: they had to make massive investments in 2024 and 2025 to address grid congestion, and the expansion of decentralisation required significant CAPEX while capacity could not be expanded at the same pace. This explains the lower DEA score, and also why the Netherlands combines high smart-meter and decentralised-capacity levels with low economic efficiency, exactly the inverse relationship identified in H3.

5.4 Limitations

The results presented in this chapter should be read in light of several limitations, which concern in turn the size of the sample, the estimation method, the way regulation is measured, and the coverage of the transition indicators.

The first and most important limitation concerns the sample size. The analysis is based on only 22 distribution system operators observed over a five-year period and, more constraining still for the second stage, on only seven distinct regulatory frameworks. The Intervention Power index is essentially constant within each regulator and takes only four distinct values across the panel.

Because of that, the effective number of independent observations is far smaller than the 110 DSO-year data points would suggest. This explains why naive standard errors and the wild cluster bootstrap differ so greatly. It also explains why it is difficult to distinguish the coefficients on IP from zero when making conservative inferences. Due to the small number of regulatory regimes, the model’s ability to capture the causal effect of regulation is limited. Therefore, the results should be interpreted descriptively. For example, Ireland only has one DSO, ESB Networks, so it is not possible to make a within-country comparison, and the efficiency score actually represents a cross-country comparison.

Another issue is that the five national datasets were compiled for different regulatory purposes and used different cost definitions and methods of purchasing power parity adjustments, which restricts comparability. Although exchange rate differences are equalised in PPP calculations, within-country inflation peculiar to construction or labour costs, and divergences in OPEX/CAPEX accounting practices, obscure comparisons of individual expenditure items. OPEX exceeds CAPEX in Belgium for instance whereas the reverse is true in Ireland and the United Kingdom. In addition the 2025 figures for ESB Networks were estimated from the trend and announced PR6 investment rather than being observed directly and are kept only to maintain the balanced panel.

The second limitation involves the DEA method itself, which measures efficiency in relative terms. The scores depend directly on the estimated frontier, so that a small number of operators – E-REDES, UKPN and NGED – have a disproportionate impact on the results, as the outlier and sensitivity analyses show. The returns-to-scale assumption compounds this. Under VRS, convexity restricts the reference set to operators of comparable size, so the smallest units, AIEG and AIESH, are compared with a very thin set of peers and are mechanically flattered: they reach the frontier every year, yet their scale efficiency is low. A parametric or stochastic frontier approach would not eliminate this problem but would attribute part of the residual to noise rather than to inefficiency.

The third limitation concerns the IP index. Placing the seven regulators on a single scale from 0 to 5 makes them comparable, but the simplification is substantial. Each dimension is binary, so a regulator either controls OPEX ex post or it does not, and the intermediate arrangements that regulators use in practice cannot be represented. The index also says nothing about how the incentives are calibrated, nor about how strictly the rules are applied in practice. The Netherlands and the United Kingdom both score 0, yet yardstick competition and RIIO are not equivalent regimes for an operator.

Finally, the two transition indicators cover less ground than the transition itself. Smart meter penetration and decentralised capacity per connection point were chosen because they are consistently measured across the five countries, not because they are sufficient. They say nothing about

flexibility, storage or how well a network copes with congestion, all of which were identified as the harder part of the problem in Chapter 2.

Smart meter penetration timing has to be taken into account. The panel reports averages from 2021 to 2025. Therefore, a country that started late will be penalised even if the rollout has since been rapid. The United Kingdom is a good example: its average score of 0.555 underestimates its current position. These results are best read as descriptive. Regulation, transition progress and network condition are interrelated, and it is not possible to separate them using two indicators observed over five years.

Chapter 6

Conclusion

The purpose of this thesis was to compare the economic efficiency of DSOs in Belgium, the Netherlands, Portugal, Ireland, and the United Kingdom over the period from 2021 to 2025 and to examine the extent to which the observed differences are associated with regulatory frameworks and energy transition indicators. The analysis combined a data envelopment analysis model with a Malmquist productivity decomposition and a second-stage regression relating the transition indicators to a stylised intervention power index.

The results relating to the first sub-question, cost efficiency compares across countries, demonstrate significant heterogeneity. British and Irish operators are closest to the efficiency frontier, while Belgian, Portuguese, and Dutch operators show a more scattered pattern.

The second research question, which examined intervention power, cost efficiency and energy transition factors, could not be fully answered as the evidence in favour of the main hypothesis was inconclusive. Although the coefficient in support of H1 was positive, it was not statistically different from zero. This means that it failed to provide sufficient evidence to support the hypothesis. Evidence in support of H2a was only moderate and there was no support for H2b. Overall, the results suggest that regulations with strong incentive components tend to have better energy transition indicators, albeit with a low level of certainty.

This indicates that, for the most part, the intervention power of the regulator is not a significant driver of either cost efficiency or energy transition. Smart meter penetration and decentralised capacity factors should be considered as country-specific effects with a limited impact on DSOs' performance.

The second-to-last sub-question addressed whether more cost-efficient DSOs are also transition leaders. The results do not support Hypothesis 3. DSOs with better transition indicators are not more cost-efficient. Decentralised capacity is associated with lower economic efficiency. This result

can be explained by significant investments in the integration of renewable energy, which increase costs in the short term. The case of the Netherlands illustrates this phenomenon.

Finally, with regard to the fourth sub-question, regulatory fragmentation in Belgium results in different outcomes and performance, which cannot be explained solely by fragmentation. The influence of the number of regulators is conditional in the case of heterogeneous operators in terms of size and returns. According to the results, Flanders is presented as a region that differs from the other two. Hypothesis 4 cannot be confirmed given the small number of regulators and operators analysed.

Overall, based on the results, this study suggests that regulatory frameworks influence the performance of DSOs, but they are not the primary determinants. The effect of regulation is limited compared to other factors such as public policies, investment cycles, or characteristics specific to each operator. Regulatory frameworks vary by country, which makes cross-country comparisons more complex.

These results should be interpreted with caution. Firstly, the study is based on a small sample of just 22 distribution system operators, who were observed over a relatively short period of time. This severely restricts the possible conclusions that can be drawn. Secondly, DEA scores essentially derive from the relative performance of each observed entity, and the two transition indicators capture only a limited set of activities of distribution network operators.

There are several avenues for future research. The first step would be to undertake the same analysis with a larger sample size and over a longer period. Secondly, future research could build on this thesis by applying a stochastic frontier analysis to the same dataset, using a TOTEX specification and a more refined intervention power index. This would address the methodological limitations identified in this thesis. Most importantly, however, developing harmonised regulatory data at EU level would enable truly comparable analyses of the regulatory framework and its impact on the performance of distribution system operators.

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Appendix A

Appendix

A.0.1 Analysis

Returns to scale — comparison and classification

	Country	E_VRS	E_CRS	E_NDRS	Scale_eff	IRS	CRS	DRS
1	UK	0.9547	0.9519	0.9546	0.9970	13	14	3
2	Ireland	0.9445	0.9434	0.9445	0.9988	4	1	0
3	Belgium	0.6291	0.4794	0.6290	0.8403	29	0	1
4	Portugal	0.5491	0.5105	0.5491	0.8799	10	5	0
5	Netherlands	0.4564	0.3651	0.4564	0.8182	29	1	0

Observations in the decreasing-returns region: 4 of 110.

Observations where VRS and NDRS differ: 4 of 110.

DEA — Efficiency scores by country

	Country	DSOs	Obs	Mean	Median	Min	Max	SD	OnFrontier	PctFrontier
1	UK	6	30	0.955	1.000	0.837	1	0.0630	16	53.3
2	Ireland	1	5	0.945	0.947	0.892	1	0.0398	1	20.0
3	Belgium	6	30	0.629	0.539	0.222	1	0.2888	10	33.3
4	Portugal	3	15	0.549	0.364	0.272	1	0.3319	5	33.3
5	Netherlands	6	30	0.456	0.401	0.203	1	0.2319	3	10.0

Operators reaching the frontier at least once:

country	dso	Years_on_frontier
Belgium	AIEG	5
Belgium	AIESH	5
Portugal	E-Redes	5
UK	NGED	5
UK	NPg	5
UK	UKPN	5
Netherlands	Westland Infra	3
UK	ENWL	1
Ireland	ESB network	1

H1 — Regulation and cost efficiency (Tobit, DSO level)

Call:

```
AER::tobit(formula = inefficiency ~ smart_meter + decentral_per_cp +
  IP, left = 0, data = panel)
```

Observations:

Total	Left-censored	Uncensored	Right-censored
110	35	75	0

Coefficients:

	Estimate	Std. Error	z value	Pr(> z)
(Intercept)	-0.40653	0.15446	-2.632	0.008488 **
smart_meter	0.09884	0.17240	0.573	0.566418
decentral_per_cp	0.20881	0.04639	4.501	6.77e-06 ***
IP	0.14363	0.03868	3.714	0.000204 ***
Log(scale)	-0.99291	0.08778	-11.312	< 2e-16 ***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Scale: 0.3705

Gaussian distribution

```

Number of Newton-Raphson Iterations: 4
Log-likelihood: -59.81 on 5 Df
Wald-statistic: 26.47 on 3 Df, p-value: 7.5908e-06

--> Clustered by regulator:

z test of coefficients:

              Estimate Std. Error z value Pr(>|z|)
(Intercept)   -0.406535   0.392988 -1.0345  0.30092
smart_meter    0.098844   0.442723  0.2233  0.82333
decentral_per_cp 0.208814   0.097703  2.1372  0.03258 *
IP             0.143635   0.085029  1.6893  0.09117 .
Log(scale)    -0.992908   0.107072 -9.2733  < 2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

--> Wild cluster bootstrap on 'IP' (7 clusters, 128 exhaustive draws): p = 0.6172
      Computed on the OLS analogue of the same specification (Tobit unsupported).
      Smallest attainable p-value with 7 clusters: 0.016

```

H2a - SMART METER PENETRATION AND REGULATION (DSO level)

```

Call:
lm(formula = smart_meter ~ IP, data = panel)

Residuals:
      Min       1Q   Median       3Q      Max
-0.4036 -0.1850 -0.0381  0.1679  0.7365

Coefficients:
              Estimate Std. Error t value Pr(>|t|)
(Intercept)   0.73412     0.03030   24.23  <2e-16 ***

```

```

IP          -0.15688    0.01524  -10.30   <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.2379 on 108 degrees of freedom
Multiple R-squared:  0.4954,    Adjusted R-squared:  0.4907
F-statistic: 106 on 1 and 108 DF,  p-value: < 2.2e-16

--> Wild cluster bootstrap on 'IP' (7 clusters, 128 exhaustive draws): p = 0.0469
    Smallest attainable p-value with 7 clusters: 0.016
    The summary above treats all rows as independent; they are not.

```

H2b - DECENTRALISED CAPACITY PER CONNECTION POINT (DSO level)

```

Call:
lm(formula = decentral_per_cp ~ IP, data = panel)

Residuals:
    Min       1Q   Median       3Q      Max
-1.6615 -0.6239 -0.1834  0.6582  2.6991

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  2.57290    0.11596  22.187   < 2e-16 ***
IP          -0.48030    0.05831  -8.236 4.51e-13 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.9106 on 108 degrees of freedom
Multiple R-squared:  0.3858,    Adjusted R-squared:  0.3801
F-statistic: 67.84 on 1 and 108 DF,  p-value: 4.507e-13

--> Wild cluster bootstrap on 'IP' (7 clusters, 128 exhaustive draws): p = 0.1250

```

Smallest attainable p-value with 7 clusters: 0.016

The summary above treats all rows as independent; they are not.

H3 - EFFICIENCY AND TRANSITION INDICATORS (DSO level)

Call:

```
lm(formula = E_DEA ~ smart_meter + decentral_per_cp, data = panel)
```

Residuals:

Min	1Q	Median	3Q	Max
-0.47735	-0.26727	0.08737	0.25521	0.41669

Coefficients:

	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	0.78047	0.05838	13.369	< 2e-16 ***
smart_meter	0.11689	0.11075	1.055	0.29362
decentral_per_cp	-0.08654	0.03192	-2.711	0.00782 **

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.296 on 107 degrees of freedom

Multiple R-squared: 0.07066, Adjusted R-squared: 0.05329

F-statistic: 4.068 on 2 and 107 DF, p-value: 0.01983

--> Wild cluster bootstrap on 'decentral_per_cp' (7 clusters, 128 exhaustive draws): p = 0.0469

Smallest attainable p-value with 7 clusters: 0.016

The summary above treats all rows as independent; they are not.

H4a - SMART METER PENETRATION, BELGIUM ONLY (DSO level)

Call:

```
lm(formula = smart_meter ~ IP, data = panel_be)
```

Residuals:

Min	1Q	Median	3Q	Max
-0.20432	-0.13079	-0.00878	0.06953	0.44761

Coefficients:

	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	0.74947	0.15971	4.693	6.42e-05 ***
IP	-0.19354	0.05228	-3.702	0.000928 ***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.1653 on 28 degrees of freedom

Multiple R-squared: 0.3286, Adjusted R-squared: 0.3047

F-statistic: 13.71 on 1 and 28 DF, p-value: 0.0009282

--> Wild cluster bootstrap on 'IP' (3 clusters, 8 exhaustive draws): p = 0.5000

Smallest attainable p-value with 3 clusters: 0.250

The summary above treats all rows as independent; they are not.

NOTE: significance at 5% is unattainable with this few clusters.

H4b - COST EFFICIENCY, BELGIUM ONLY (DSO level)

Call:

```
lm(formula = E_DEA ~ IP, data = panel_be)
```

Residuals:

Min	1Q	Median	3Q	Max
-0.2684	-0.2346	-0.1637	0.3709	0.3709

Coefficients:

	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	0.19910	0.27163	0.733	0.470
IP	0.14334	0.08891	1.612	0.118

Residual standard error: 0.2812 on 28 degrees of freedom

Multiple R-squared: 0.08494, Adjusted R-squared: 0.05226

F-statistic: 2.599 on 1 and 28 DF, p-value: 0.1181

--> Wild cluster bootstrap on 'IP' (3 clusters, 8 exhaustive draws): p = 0.8750

Smallest attainable p-value with 3 clusters: 0.250

The summary above treats all rows as independent; they are not.

NOTE: significance at 5% is unattainable with this few clusters.

Table A.1: Aggregate efficiency index $E_{c,t}$ (connection-point weighted, VRS)

Country	2021	2022	2023	2024	2025	Mean
Belgium	0.335	0.373	0.391	0.401	0.382	0.377
Ireland	1.000	0.947	0.926	0.957	0.892	0.945
Netherlands	0.303	0.313	0.343	0.296	0.282	0.307
Portugal	0.972	0.972	0.972	0.972	0.973	0.972
UK	0.964	0.963	0.966	0.966	0.973	0.966

Note: Weights proportional to connection points (Equation 4.25). Own calculations.

Table A.2: Mean efficiency by returns-to-scale assumption, and scale efficiency

Country	E (VRS)	E (CRS)	E (NDRS)	Scale eff.
UK	0.955	0.952	0.955	0.997
Ireland	0.945	0.943	0.945	0.999
Belgium	0.629	0.479	0.629	0.840
Portugal	0.549	0.511	0.549	0.880
Netherlands	0.456	0.365	0.456	0.818

Note: Note: Scale efficiency is computed at the observation level as $SE_{j,c,t} = E_{j,c,t}^{CRS} / E_{j,c,t}^{VRS}$ and then averaged within each country; it is therefore the mean of the individual ratios, not the ratio of the reported country means, and the two do not coincide. Values below one indicate that part of the distance to the frontier reflects operating at a scale other than the most productive one, rather than managerial inefficiency.

Table A.3: Returns-to-scale classification (Färe , Grosskopf & Lovell test)

Country	DRS	IRS	CRS
Belgium	1	29	0
Ireland	0	4	1
Netherlands	0	29	1
Portugal	0	10	5
UK	3	13	14

Note: A unit is classified CRS when $E^{CRS} = E^{VRS}$; among the remaining units, DRS when $E^{NDRS} \neq E^{VRS}$ and IRS otherwise. Under the VRS technology ($\sum_k \lambda_k \geq 1$) retained in Section 4.2.7, scaling up is feasible but scaling down is not, so the NDRS and VRS scores coincide precisely for units operating below their most productive scale. This test documents the empirical basis for the returns-to-scale assumption retained.

Table A.4: Outlier screening: super-efficiency and leverage

Year	Country	DSO	E^{DEA}	Super-eff.	Leverage
2021	UK	UKPN	1.000	∞	0.0072
2021	UK	NGED	1.000	∞	0.0003
2021	Portugal	E-Redes	1.000	∞	0.0540
2022	UK	UKPN	1.000	∞	0.0071
2022	UK	NGED	1.000	∞	0.0018
2022	Portugal	E-Redes	1.000	∞	0.0495
2023	UK	UKPN	1.000	∞	0.0173
2023	UK	NGED	1.000	∞	0.0090
2023	Portugal	E-Redes	1.000	∞	0.0617
2024	UK	UKPN	1.000	∞	0.0249
2024	UK	NGED	1.000	∞	0.0105
2024	Portugal	E-Redes	1.000	∞	0.0825
2025	UK	UKPN	1.000	∞	0.0246
2025	UK	NGED	1.000	∞	0.0152
2025	Portugal	E-Redes	1.000	∞	0.0860
2023	Belgium	AIESH	1.000	1.559	0.0345
2024	Belgium	AIESH	1.000	1.523	0.0219
2021	Belgium	AIESH	1.000	1.498	0.0351
2021	Ireland	ESB network	1.000	1.273	0.0165
2025	Belgium	AIEG	1.000	1.265	0.0273
2022	Belgium	AIESH	1.000	1.239	0.0088

Note: An infinite super-efficiency score means that no convex combination of the remaining units can reproduce the unit's output vector under VRS, i.e. the unit defines the frontier for want of a comparator. Flagged when super-efficiency exceeds 2 or when leverage falls in the upper decile of the year, following the relative criterion set out in Section 4.3.

Table A.5: Aggregate efficiency with the frontier re-estimated excluding outliers

Country	2021	2022	2023	2024	2025
Belgium	0.952	0.950	0.948	0.960	0.949
Netherlands	0.397	0.404	0.637	0.599	0.586
Portugal	0.589	0.587	0.630	0.694	0.700
UK	0.985	0.975	1.000	0.982	1.000

Note: Units excluded: AIESH, UKPN, NGED, ESB network, E-Redes, AIEG . To be read against Table A.1.

Table A.6: Country-average Malmquist decomposition, 2021–2025

Country	EC	TC	M	$EC \times TC$
Belgium	1.038	0.916	0.951	0.951
Ireland	0.971	0.918	0.892	0.892
Netherlands	0.984	0.938	0.923	0.923
Portugal	1.000	0.933	0.933	0.933
UK	1.003	0.944	0.947	0.947

Note: Geometric means, which preserve the identity $M = EC \times TC$; the final column verifies it. Distance functions are estimated under CRS following Färe and al. (1994).

Table A.7: Malmquist decomposition by annual transition

Country	Period	EC	TC	M
Belgium	2021–2022	1.111	0.910	1.012
Belgium	2022–2023	1.051	0.912	0.958
Belgium	2023–2024	1.055	0.913	0.963
Belgium	2024–2025	0.944	0.928	0.876
Ireland	2021–2022	0.946	0.806	0.762
Ireland	2022–2023	0.978	0.961	0.940
Ireland	2023–2024	1.034	0.953	0.985
Ireland	2024–2025	0.931	0.964	0.898
Netherlands	2021–2022	1.007	0.912	0.918
Netherlands	2022–2023	1.143	0.976	1.116
Netherlands	2023–2024	0.861	0.915	0.787
Netherlands	2024–2025	0.947	0.949	0.898
Portugal	2021–2022	1.000	0.929	0.929
Portugal	2022–2023	1.000	0.924	0.924
Portugal	2023–2024	1.000	0.932	0.932
Portugal	2024–2025	1.000	0.946	0.946
UK	2021–2022	0.998	0.924	0.922
UK	2022–2023	1.004	0.986	0.990
UK	2023–2024	1.000	0.926	0.927
UK	2024–2025	1.008	0.942	0.949

Table A.8: Model A — sensitivity of the H1 inference to the level of clustering (DSO level)

Variable	Estimate	Std Error	Statistic	p value
Intercept	-0.4065	0.2682	-1.516	0.130
Smart meter	0.0988	0.3725	0.265	0.791
Decentralised cap. (kVA/conn. pt)	0.2088*	0.0888	2.353	0.019
IP index	0.1436*	0.0667	2.155	0.031
$\log(\sigma)$	-0.9929***	0.1360	-7.302	0.000

Note: $N = 110$ (35 left-censored at zero, 75 uncensored). Identical specification to Table 5.6; the two tables differ only in the level at which standard errors are clustered. Here errors are clustered at the DSO level (22 clusters), whereas Table 5.6 clusters at the regulator level (7 clusters), the level at which IP_j actually varies. The point estimates are therefore identical by construction, and only the standard errors change. Significance: *** 0.001, ** 0.01, * 0.05, . 0.10.

Table A.9: Model A with connection density as an additional control

Variable	Estimate	Std Error	Statistic	p value
Intercept	-0.6072*	0.3080	-1.971	0.049
Smart meter	0.0962	0.3421	0.281	0.778
Decentralised cap. (kVA/conn. pt)	0.2259**	0.0872	2.591	0.010
IP index	0.1372*	0.0659	2.084	0.037
Density (conn. pt/km)	0.0050	0.0034	1.490	0.136
$\log(\sigma)$	-1.0219***	0.1251	-8.167	< 0.001

Note: $N = 110$. Standard errors clustered at the DSO level, as in Table A.9. The purpose of this table is to test whether the coefficient on IP is robust to the inclusion of a control, not to establish its significance: the conservative regulator-level clustering of Table 5.6 is not reapplied here, so the reported p -values overstate precision and should not be read as evidence for H1. The point estimate on IP (0.137) is close to the 0.144 obtained without the control, which is the result of interest. Significance: *** 0.001, ** 0.01, * 0.05.

Table A.10: Model A restricted to Belgium: inefficiency and regional regulatory framework

Variable	Estimate	Std Error	Statistic	p value
Intercept	0.7258	0.7518	0.965	0.334
IP index	-0.1433	0.2394	-0.599	0.549
$\log(\sigma)$	-0.9404*	0.4070	-2.311	0.021

Note: $N = 30$ (6 Belgian DSOs $\times$ 5 years). National energy policy, EU obligations and macroeconomic conditions are held constant, so that only the regulatory framework varies (VNR 2, CWaPE 3, BRUGEL 4). This is the cleanest identification available in the design, but it rests on three regulators. The dependent variable is *inefficiency* ($1 - E_{j,c,t}^{DEA}$), consistent with Model A in Section 4.6.2, whereas H4b in Table 5.7 is reported on the *efficiency* scale. The two coefficients on *IP* are the same estimate under opposite sign conventions (-0.1433 here, $+0.1433$ in Table 5.7) and carry the same substantive reading: within Belgium, a more interventionist regional framework is associated with *higher* measured cost efficiency — the opposite of the direction predicted by H1.

Table A.11: Correlations between aggregate efficiency $E_{c,t}$ and transition indicators

indicateur	r	p
Smart meter	-0.005	0.983
Decentralise per client	-0.523	0.007
absolut decentralise	0.015	0.945

Note: $N = 25$ country-year observations. H3 predicts a positive association.

Table A.12: Monotonicity of the within-Belgium gradient, by year

Year	Smart meter	Decentral. cap.	Efficiency
2021	no	yes	no
2022	yes	yes	no
2023	yes	yes	no
2024	yes	yes	no
2025	yes	yes	no

Note: ‘yes’ indicates that the three regions rank in the inverse order of their IP scores (Flanders > Wallonia > Brussels) for that year.

Table A.13: Mean cost efficiency by value of the Intervention Power index

IP	Frameworks	Obs	Mean efficiency
0	ACM, Ofgem	60	0.706
2	VNR, CRU	10	0.598
3	CWaPE, ERSE	35	0.617
4	BRUGEL	5	0.532

Note: $N = 110$. Unweighted DSO-year means. H1 predicts efficiency to fall monotonically as IP rises. The ranking is not monotonic: frameworks scored IP = 3 record a higher mean than those scored IP = 2. IP = 0 also pools the Netherlands and the United Kingdom, whose means differ by half a point (Section 5.1).

This dissertation compares the cost efficiency of 22 electricity distribution system operators (DSOs) in Belgium, the Netherlands, Portugal, Ireland, and the United Kingdom over the 2021–2025 period, and examines the extent to which differences in efficiency and two energy transition indicators—the smart meter penetration rate and decentralised generation capacity per connection point—are linked to differences in regulatory design.

Cost efficiency is calculated using an input-oriented DEA model, with capital expenditures (CAPEX) and operating expenditures (OPEX) as inputs, and the number of connection points, network length, and energy supplied as outputs. To ensure the most realistic comparison possible, the data are harmonised. The resulting scores are subjected to various analysis: an outlier detection process to identify distribution system operators (DSOs) exerting excessive influence on the efficiency frontier, as well as the calculation of the Malmquist index, which distinguishes changes in efficiency from technological developments.

The DEA test is followed by an econometric analysis testing the relationship between efficiency, transition indicators, and the intervention power index (IP). This second step is performed using a Tobit regression.

It follows that the stringency of a regulatory model is not, on its own, a determinant of cost-effectiveness and performance in terms of the energy transition. Other factors, notably national policy, must be taken into account. The relationship between cost-effectiveness and the energy transition factor is negative. This is explained by the large investments made by DSOs to accommodate distributed generation.

Keywords : Distribution System Operators ; Cost Efficiency ; Data Envelopment Analysis ; Regulatory Intervention Power ; Energy Transition

UNIVERSITÉ CATHOLIQUE DE LOUVAIN
Louvain School of Management

Place des Doyens, 1 bte L2.01.01, 1348 Louvain-la-Neuve
Boulevard Emile Devreux 6, 6000 Charleroi, Belgique
Chaussée de Binche 151, 7000 Mons, Belgique

www.uclouvain.be/lsm