Productivity growth in electricity and gas networks since 1990[1]

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Executive Summary

Ofgem approached the Energy Policy Research Group (EPRG) to provide an analysis of productivity growth in electricity and gas networks in the years since privatisation. This analysis is timely because it comes at the start of the next round of energy network price control reviews (RIIO-2).

Now is a good time to review the productivity performance of Ofgem's four regulated sectors (electricity distribution, gas distribution, electricity transmission and gas transmission). We should, in principle, have up to 31 years of data from gas privatisation (in 1986) and 27 years of data from electricity privatisation (in 1990-91).

What did we expect to find at the outset? The high-level background to productivity growth in the energy network sectors is slow overall TFP growth in the UK (at less than 1% p.a.). There is emerging evidence of a productivity puzzle, with slowing productivity growth and low unemployment.

We set out to undertake three types of productivity analysis: growth accounting analysis (GAA) of Office for National Statistics (ONS) data on the electricity and gas sectors in comparison to other countries and other sectors; Malmquist data envelopment analysis (DEA) of company data for electricity and gas distribution; and DEA analysis of whole sector for electricity and gas transmission.

Our literature review of productivity analysis of electricity and gas networks shows that the empirical literature on productivity growth in energy network industries is mostly concentrated on distribution networks. The literature, in general, shows significant increases in productivity growth and quality of service following privatisation and the introduction of incentive regulation, but usually only for a short run of years after the policy change.

For our growth accounting analysis (GAA) we undertake two separate analyses: an international comparison and a UK specific analysis.

For the international GAA make use of the EU KLEMS database for the period 1995-2015. This allows comparison of combined electricity, gas and water sectors. Our analysis compares TFP growth in four countries: Germany, Netherlands, UK and the USA. The average value added TFP growth in the UK has been around -2.3% p.a. and slower than the other countries we look at.

The UK specific GAA looks at the electricity sector as a whole (including generation, networks and retail). We find positive average value added TFP growth before the crisis (2.2% p.a., 2000-2006) and a negative one after it (-6.2% p.a., 2009-2015). Productivity growth has been slower in electricity than in water.

Next, we turn to our DEA results from each of the four sectors. In each case we have a base model consisting of a number of physical outputs (including energy delivered) and two inputs (operating expenditure (opex) and capital expenditure (capex)). We report a number of other models (often estimated over shorter periods due to lack of data) which include measures of quality as additional inputs or outputs.

Electricity Distribution: We find that electricity distribution sector shows TFP grows by 34% over the whole period (1990/91-2016/17) using a base model which does not include any quality variables. Adding quality variables in general improves measured productivity growth.

Gas Distribution: We find that gas distribution has TFP growth of 13.5% over the period 2008/09-2016/17 for the base model. Adding quality variables does not improve measured productivity growth.

Electricity Transmission: We find that electricity transmission shows a large decline in productivity for the period 2000/01-2016/17 of -30% for the base model. Adding quality variables substantially improves performance over this period.

Gas Transmission: We find a significant improvement in productivity for the period 2007/2008-2016/2017 with an increase of 72% for the base model. This is driven by lower capex figures over time. Adding a quality variable improves productivity still further.

What have we learned about productivity in electricity and gas networks from our analysis?

A major learning has been just how slow the measured TFP productivity growth for energy networks has been over the entire period (in general), but this is still better than the UK economy as a whole.

A suspected reason for low measured productivity is that energy networks have needed to invest heavily to respond to government objectives for the addition of renewables and the promotion of energy efficiency without seeing increased measured outputs.

The addition of quality variables generally helps improve measured productivity, suggesting that the emphasis we have seen in improving quality in the move from RPI-X to RIIO is justified.

The data was surprisingly difficult to collect given the emphasis that GB energy regulatory agencies (Offer, Ofgas and Ofgem) have had on using data within price controls to undertake benchmarking. The gas data was particularly poor.

A key learning was the surprisingly poor quality and consistency of the ONS data over time. We suggest that Ofgem work with the ONS to improve these important national statistics via collecting them from energy companies as part of their licence conditions.

We suggest that a possible extension of this study is to include a valuation of quality improvements in terms of willingness to pay and incorporating these into a productivity analysis.

As we look forward to the productivity impact of RIIO-2, we suggest that attention is paid by Ofgem to improving measures of customer satisfaction, measures of stakeholder engagement and the facilitation of the meeting of environmental targets (such as the addition of distributed generation to electricity distribution networks) and the valuation of the inputs and outputs of network innovation projects.

1. Introduction

Ofgem approached the Energy Policy Research Group (EPRG) to provide analysis of productivity growth in electricity and gas networks in the years since 1990. We have been asked to do this in the light of the upcoming price control reviews. From 2021, a new price control will be required for electricity transmission, gas transmission and gas distribution as their current price control periods (RIIO ET1, RIIO GT1 and RIIO GD1) run from 2013-2021, meaning that initial work for the price control will begin in earnest in 2019. Electricity distribution will have a new price control starting in 2023, as the current control (RIIO ED1) runs from 2015-2023. This next set of price controls will follow the experience of the first set of RIIO price controls set under the Revenue = Incentives + Innovation + Outputs (RIIO), which replaced RPI-X in 2010.

Now is a good time to review the productivity performance of Ofgem's four regulated sectors (electricity distribution, gas distribution, electricity transmission and gas transmission). We should, in principle, have up to 31 years of data from gas privatisation (in 1986) and 27 years of data from electricity privatisation (in 1990-91).[2] The aim of this study is to provide useful findings before the start of the next RIIO price control review process, some of which might prompt further independent analysis of the past performance of regulated companies overseen by Ofgem and its two predecessor regulators (Offer – the Office of Electricity Regulation which lasted from 1989 to 1999; and Ofgas – the Office of Gas Regulation which lasted from 1986 to 1999).

Two key issues within any price control review process relate to the productivity performance of firms in a monopoly regulated sector are: how much scope for catch up productivity remains and what is the trend frontier productivity growth? The first of these relates to the relative efficiency of the different firms to each other (both inside and outside Great Britain (GB)) and the second relates to the technical change which might be going on at the most efficient firms (certainly in GB) but also further afield. Both of these questions relate to measuring the overall productivity performance of electricity and gas transmission and distribution utilities in GB.

[2] See Pollitt (1999) for a review of privatisation in the UK, including the gas and electricity sectors.

This study focusses on cost efficiency and its associated productivity growth rather than the prices paid by customers.

In discussion with Ofgem, we scoped out an ambitious plan for the potential work that might be done – in our available timeframe - to measure productivity in the four energy network sectors since 1990 (the date of electricity privatisation). We proposed three types of exercises to be performed over the four energy network sectors, using data over the period 1990/91 to 2016/17. These have developed into the three sets of analyses that we report in this paper. First, **analysis of total factor productivity (TFP) using the EU KLEMS database (which covers the aggregate of electricity, gas and water) and standard industrial classification (SIC) data on electricity and gas from the Office of National Statistics (ONS).** This would allow comparison with the whole of UK industry, other network sectors in the UK and international comparison. Second, **aggregate industry TFP analysis using Ofgem data.** This would create an aggregate firm for the whole of each of the four sectors by summing up all of the firm level data for the network companies regulated by Ofgem, namely the 14 electricity distribution network operators (DNOs), the 8 gas distribution network operators (GDNOs), the 3 onshore electricity transmission companies (NGET, SPET, SHETL) and the single GB wide gas transmission entity (NGG). Third, **efficiency and productivity analysis of firm level data (using Malmquist DEA described below) for both electricity and gas distribution.** Here we would exploit the ability to use firm level data to decompose efficiency and technical change to give a richer picture of productivity growth for sectors where there were some good existing studies from both Great Britain and comparably regulated countries.

Ofgem kindly agreed to help us to collect all of the data that they had for the second and third types of studies above. Data appendices will be available for all of the Ofgem provided data that we have used, in order to facilitate other work on efficiency and productivity based on Ofgem's available data.

Our analysis, as we explain below, is based on the concept of **total factor productivity (TFP).** TFP relates to the capacity to transform resources (inputs: x) into products (outputs: y). TFP (also known as multifactor productivity) is represented by the ratio of output(s) to input(s). TFP change relates to the way productivity varies from one year to the next. TFP can make use of multiple outputs and inputs for its estimation, thus allowing the inclusion of additional variables of interest, such as measures of quality in order to assess how productivity more broadly defined might be changing. TFP can be estimated in several ways (as we discuss below), however we have chosen to make use of non-parametric approaches which do not account for statistical noise, in order to let the underlying data speak clearly through our results.

For the first type of study we looked at ONS data back to 1990. We considered data from Section D within the SIC which includes Electricity, Gas, Steam and Air Conditioning Supply (SIC: 35.1 through to 35.3). This data offers a decomposition into electricity generation, transmission and distribution (SIC: 35.1) and further decompositions into, for example, electricity generation (SIC: 35.11) etc. We examined comparable data for water (SIC: 36), sewerage (SIC: 37), because this sector is also similar to the electricity and gas transmission and distribution network industry. Our rationale being that if we could get usable data on other UK sectors this would provide easy points of comparison for the electricity and gas sectors productivity exercise. We began by thinking that ONS data might provide a point of international comparison with the US, Australia, Canada, New Zealand, Norway and the Netherlands. We considered these countries as potential comparators, given the supposed ease of getting their data and comparability of the incentive regulation regimes in Australia, New Zealand, Norway and the Netherlands.[3] However, in doing the TFP analysis using the EU KLEMS database, our final list comprises USA, Germany and Netherlands, due to the fact that some countries on our initial list are not part of the EU KLEMS latest database.

For the second and third types of studies we requested a large amount of data from Ofgem, both outputs, inputs and quality variables. Not all of this information turned out to be available from Ofgem (which we discuss subsequently) and we did not end up using some of the data that was available[4].

For electricity distribution we requested the following outputs: energy distributed (MWh), number of customers, network length (Km), quantity of distributed generation (DG) connected (MWs) and energy injected by distributed generation (MWh); the following inputs: capital expenditure (Capex), operating expenditure (Opex), revenues, number of employees; and the

[3] See for example Jamasb and Pollitt (2001), Haney and Pollitt (2009) and Brophy Haney and Pollitt (2013) who survey the use of efficiency measurement within incentive regulation in different countries.

[4] The main data used for the TFP analysis associated with each sector (and their respective models) are shown in Tables 4, 17, 26 and 35.

following quality variables: customer minutes lost (CML), customer interruptions (CI), energy losses (MWh), customer satisfaction and the average age of assets (e.g. value/depreciation).

For gas distribution we requested the following outputs: gas volume delivered (cubic metres), number of customers, network length (Km); and the following inputs: capex; opex; revenues and number of employees; and the following quality variables: customer minutes lost (CML), customer interruptions (CI), customer satisfaction, gas escapes (number) and the average age of assets (e.g. value/depreciation).

For electricity transmission we requested: the following outputs: energy transmitted (MWh), peak demand on the system (MW) and network length (Km); and the following inputs: capex, opex, revenues, number of employees; and the following quality variables: transmission system availability (percentage of time), energy not supplied (GWh), losses (percentage of energy) and average age of assets (e.g. value/depreciation).

For gas transmission we requested: the following outputs: gas volume transmitted (cubic metres), compressor capacity (in physical units), network length (Km); and the following inputs: capex, opex, revenues and number of employees; and the following quality variables: gas losses (GWh), energy used in gas transmission system (GWh) and the average age of assets (e.g. value/depreciation).

In addition, we also requested a time line of major events e.g. gas separation of distribution, major mergers and demergers; and data on non-major regulated utilities such as offshore transmission operators (OFTOs) and independent electricity distribution network operators (IDNOs).

What did we expect to find at the outset? The high-level background to productivity growth in the energy network sectors is slow overall TFP growth in the UK. The average growth of UK TFP 1990-2016 is reported to be just 0.62% p.a.[5] ONS analysis of multi-factor productivity growth (Solow growth decomposition which we use below) also shows slow productivity

[5] https://fred.stlouisfed.org/series/TFPGUKA

growth of around 0.34% p.a. from 1998 to 2014 for the market sector[6]. Indeed the existence of a productivity puzzle for UK aggregate productivity growth is well known, whereby the economy continues to grow slowly with low unemployment (see Coyle, 2015, and Haskel and Westlake, 2018). The productivity puzzle is partly explained by the poor quality of the data on which it is calculated and partly remains a mystery.

The report is organized as follows. We begin with an introduction to the issue of productivity measurement which outlines the different measures of TFP we will use. We then include a literature review on productivity growth in electricity and gas networks. We proceed to a discussion of the available data from ONS and the international database we have used (EU KLEMS). We then report our results from the high-level type 1 analysis of ONS and EU KLEMS data. We then present our detailed results using Ofgem data. This covers the detailed DEA results on electricity distribution (ED) and gas distribution (GD) (focussing on type 3 analysis) and high level results for electricity transmission (ET) and gas transmission (GT) (using type 2 analysis). In each of the four cases, we discuss the available data, outputs, inputs and quality variables, before proceeding to a presentation of our results. We then offer some concluding remarks.

2. Measuring Productivity Growth

Productivity growth is mainly defined as the changes in output volume over input volume, however the word productivity is often used interchangeably with technical/technological change, technical/technological progress and other terms (Mahadevan, 2003). The measurement of productivity growth is commonly required for setting prices under incentive regulation (See and Coelli, 2014; Ofgem, 2012). Productivity growth can be partially estimated from a single input and a single output (i.e. labour productivity) or it can be total factor productivity, TFP (also known as multi-factor productivity) where a set of outputs and inputs is required instead. TFP combines all the inputs and outputs in a single ratio.

[6]Excludes the non-market sector. The list of industries included in this estimation can be found at: https://www.ons.gov.uk/economy/economicoutputandproductivity/productivitymeasures/articles/multifactorproductivityestimates/experimentalestimatesto2014

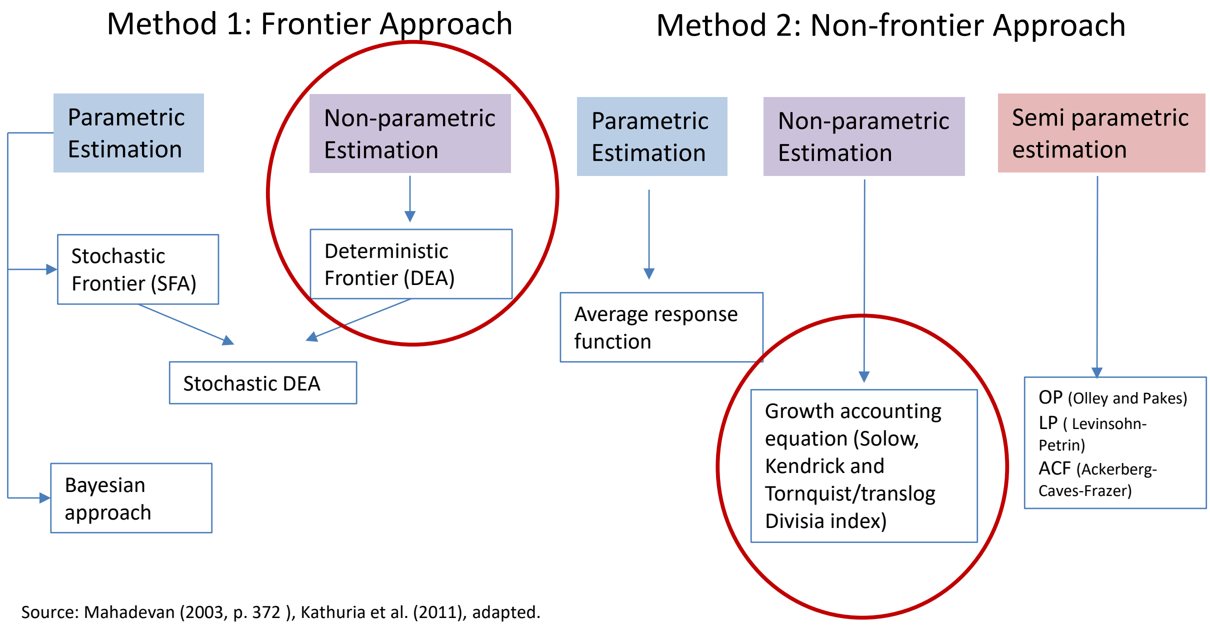
There are two different ways to measure TFP, the frontier and the non-frontier approaches. Under the non-frontier one it is assumed that firms are technically efficient while in the frontier one, the role of technical efficiency in overall firm performance is identified (Mahadevan, 2003). By comparison with the frontier methods, the non-frontier ones do not allow the decomposition of TFP growth into components such as scale efficiency change, technical efficiency change, pure efficiency change (Coelli et al., 2003, p. 23). A second classification is also observed in both cases, namely the parametric and the non-parametric. Additionally one can have a semi-parametric approach in the non-parametric case. The parametric one is solved using an econometric model that can or cannot capture the effect of statistical noise. The non-parametric one can be solved using a linear programming method or via the growth accounting method which relates to the well-known indexes such as Törnqvist. Parametric methods allow statistical testing while the non-parametric ones do not. The semi-parametric method involves three different estimation algorithms. For further details about the discussion of each of these algorithms, see Van Beveren (2009).

Within the frontier method we can distinguish two main categories: stochastic frontier analysis (SFA) and the data envelopment analysis (DEA). SFA relates to the "average" or "central tendency" behaviour of the firms, while DEA relates to the best performance and the deviation of all performances from the frontier line (Cooper et al., 2007, p. 4). In addition, SFA attempts to account for noise, in contrast with DEA. However, DEA does not impose assumptions about the functional form. The well-known Malmquist TFP indices can be estimated using DEA (based on distance functions) or SFA. Fig. 1 depicts and provides additional details of the different methods for estimating TFP growth.

In terms of the inputs and outputs involved in the estimation of TFP growth, capital is the most challenging input to measure (Parker and Martin, 1995; See and Coelli, 2014) while labour is more straightforward. According to Mahadevan (2003), due to the lack of capital services, the easiest way to approximate capital input is by assuming that capital flows are proportional to capital stock after depreciation. For instance in our TFP analysis using the growth accounting approach, capital input (from EU KLEMS data base, period 1995-2015[7]) is represented by capital services which are based on geometric depreciation rates by asset and industry in line with previous versions of EU KLEMS data base (Jäger, 2017).

[7] Available at http://www.euklems.net/

Fig. 1: TFP Growth Estimation Methods



Source: Mahadevan (2003, p. 372), Kathuria et al. (2011), adapted.

On the other hand, in Malmquist TFP analysis, capital is usually represented by capital expenditure. This has the advantage of being a measure of the actual capital cost rather than an imputed flow of capital input whose value depends on a measure of the capital stock and assumptions about asset lives and depreciation rates.

The empirical TFP analysis discussed in this report is based on two methods: (1) the growth accounting method for evaluating the productivity change at industry level using mainly data from KLEMS and the ONS[8] and (2) DEA Malmquist index for evaluating productivity change in the electricity and gas sectors (distribution and transmission) using utility-level data provided by Ofgem. The following two sections explain both methodologies.

2.1 Growth Accounting Approach (GAA) method

Growth Accounting measures the growth of outputs (i.e. GDP, value added - VA) that are explained by the growth of different inputs (such as labour, capital and intermediate inputs) and by an unaccounted or unexplained growth (knows as residual)[9] which represents the productivity growth. Theories about growth accounting methods and applications have evolved over time with some key influential studies from Abramovitz (1956), Solow (1957), Kendrick (1961), Jorgenson and Griliches (1967) and Jorgenson et al. (1987).

[8] The methodology used in this analysis, the Growth Aggregating Account approach, is based on Törnqvist index.
[9] This is also referred as a measure of ignorance", Abramovitz (1956).

The methodology we have used for estimating the TFP growth figures is based on Jorgenson et al. (1987), in line with the one used by EU KLEMS[10] project (Timmer et al., 2007). The production function for industry *i* can be written as follows:

$$Y_{i=} fi\ (Ki, Li, Mi, T) \qquad Eq. 1$$

Where Y is output, K is capital services, L is labour services, M is intermediate inputs (purchases from other industries), T accounts for technology indexed by time. Based on the assumption of constant return to scale and competitive markets[11], the growth of industry level can be expressed as[12]:

$$\Delta lnY_t = \tilde{v}^X \Delta lnX + \tilde{v}^K \Delta lnK + \tilde{v}^L \Delta lnL + \Delta lnA \qquad Eq.\ 2$$

Where $\Delta X = x_t - x_{t-1}$, ṽ represents two period average of the share of the input related to the nominal value of output given by Eq. 3, and *A* the TFP:

$$v^X = \frac{P^x X}{P^y Y}; \quad v^L = \frac{P^L L}{P^y Y}; \quad v^K = \frac{P^K K}{P^y Y} \qquad Eq.\ 3$$

In addition, the assumption of constant return to scale means that $v^X + v^L + v^K = 1$ which allows the estimation of TFP growth (ΔlnA) based on the share of the observed inputs.

The component ΔlnY_t from Equation 2, refers to the change of output growth, however a more restricted measure, such as the value added (VA) can be estimated using the same equation. In this case, only capital inputs and labour inputs are taken into account[13]. Based on Equation 1, value added can be represented as follows:

$$VA_{i=} f^i\ (K_i, L_i, T) \qquad Eq.\ 4$$

Then in agreement with Equation 2, Equation 4 can be denoted as follows:

$$\Delta lnVA_t = \bar{e}^K \Delta lnK + \bar{e}^L \Delta lnL + \Delta lnA \qquad Eq.5$$

Where $\bar{e}^L = \frac{P^L L}{P^{va} VA}$, $\bar{e}^K = \frac{P^K K}{P^{va} VA}$ *Eq. 6*

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[10] EU KLEMS stands EU level analysis for capital (K), labour (L), energy (E), materials (M) and service (S) and is an initiative founded by the European Commission. The last database series is for the period 1995-2016 covering EU countries and selected non-EU countries (USA). See: www.euklems.net/.

[11] This means that the value of output is equal to the values of all inputs then $P^Y Y = P^K K + P^L L$, where P^Y, P^K, P^L denote the prices of output, capital and labour.

[12] The decomposition made in Equation 2 is the basis of growth accounting results in the EU KLEMS database.

[13] This is explained by the fact that $Gross\ Ouput\ (GO) = Value\ Added\ (VA) + Intermediate\ Inputs\ (II)$. Then the component that reflects the share of intermediate inputs in Equation 2 is not included.

Applying the constant return to scale which means that $\bar{e}^K + \bar{e}^L = 1$, Equation 5 can be written as:

$$\Delta lnVA_t = \bar{e}^K \Delta lnK + (1 - \bar{e}^K)\Delta lnL + \Delta lnA \qquad Eq.7$$

The TFP growth estimations and discussion in this study are based on value added instead of gross output which means that intermediate inputs have been excluded from the TFP analysis[14]. Results from the two methods are different[15], and those results from value added TFP growth are usually higher than those from gross output based TFP growth (van der Wiel (1999), Oulton (2000)). Both methods have pros and cons and the selection of one of another method may depend on the purpose of the productivity measure (OECD, 2001). From the regulatory point of view, there is no preferred method. The GB energy regulator does not favour one or another but proposes a combination of both in the (1) estimation of labour productivity (VA) at constant capital; and (2) labour and intermediate inputs productivity (GO) at constant capital for the estimation of ongoing efficiency for the RIIO-T1/GD1 price control, Ofgem (2012).

2.2 DEA Malmquist TFP

About DEA

Data Envelopment Analysis (DEA) is one of the methods commonly used for estimating the Malmquist Index Total Factor Productivity (TFP) change. The construction of a frontier using linear programming (DEA basis), was initially proposed by Farrell (1957). The performance of a decision making unit (DMU) (e.g. a business unit, firm, industry, country) is estimated based on the distance to the frontier technology, which is constructed from the available data. The closer to the frontier, the higher technical efficiency[16]. Charnes, Cooper and Rhodes (1978) were the first to identify the method with the name we currently know as DEA. They proposed a constant return to scale (CRS) model using an input oriented approach, explained later in this section. A large number of studies have extended and added more sophistication to the DEA

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[14] One of the main reasons is due to the lack of information of GO variables from the latest EU KLEMS data base.

[15] According to Cobbold (2003, p.23): *"The gross output method is intended to measure disembodied technological change whereas the value-added based measure reflects an industry's capacity to translate technical change into income and into a contribution"*.

[16] The performance of each DMU (which can be expressed by the ratio of all outputs over all inputs and their specific weights, u and v respectively) needs to be estimated. For instance, if there are N inputs, M outputs, and I firms (DMUs), each DMU can be represented by the column vector xi and yi where X represents the N*1 input matrix and Y the M*1 output matrix. Based on the duality of linear programming, this can be solved as follows: $min_{\theta,\lambda,}\theta,\ st{:}-y_i + Y\lambda \geq 0,\ \theta x_i - X\lambda \geq 0, \lambda \geq 0$; where θ is a scalar that represents the efficiency score of the i-th firm and satisfies Θ≤1; and λ is a I*1 vector of constants (see Coelli et al., 2005, pp. 162-163 for further details).

method after that. Banker et al. (1984) propose a variable return scale (VRS) model for DEA[17]. The selection of one or another model (CRS or VRS) depends on different factors. For instance, CRS is appropriate if the firms operate at an optimal scale, however factors such as imperfect competition, regulation, others, may not make this possible (Coelli et al., 2005, p. 172). VRS deals with this issue by separating the scale effect which means that an inefficient firm is benchmarked with firms that have a similar size. CRS and VRS models can also be estimated using two different approaches: input or output oriented. In the input oriented model inputs are reducing while keeping the same amount of outputs, in the output oriented model outputs increase while keeping the same amount of inputs[18]. In this study we use the VRS input oriented model, for further details about this selection see Section 5.5.

Malmquist TFP index

The Malmquist productivity index was introduced by Caves et al. (1982). The index is estimated using distance function technology. Distance functions, introduced by Shephard (1953), allow the treatment of multiple inputs and multiple outputs combined in a production function. One of the main advantages of distance functions is that they do not require price data or other behavioural assumptions related to cost minimisation and allocative inefficiency[19] (Kumbhakar et al. 2015, p. 27) but only information about inputs and output quantities.

The index is built by measuring the radial distance of the observed inputs and outputs in two different periods (t and s for instance[20]) relative to a reference technology. Different indices can be computed depending on the distance technology selected (input or output oriented). Following Caves et al. (1982), the index can be expressed as the geometric average of two indices associated to the period s (Mi^s) and period t (Mi^t) technologies, see *Eq. 8*.

$$Mi(y^t, x^t, y^s, x^s) = [Mi^s(y^t, x^t, y^s, x^s) * Mi^t(y^t, x^t, y^s, x^s)]^{1/2} \qquad Eq.\ 8$$

Eq. 8 represents the Malmquist productivity index under the input-oriented method (i). The estimation of the index (Mi) requires the computation of four different distance functions, See *Eq. 9*.

[17] This is possible by adding an additional constraint to the original CRS proposal (I1'λ=1, where I1 represents an I*1 vector of ones), explained in the previous footnote. Under VRS technical efficiency scores are equal or higher than those estimated using a CRS.

[18] There is an alternative type of direction, known as the Additive Model (See Cooper et al., 2007, p. 94), which is a combination of both the input oriented and output oriented models.

[19] In this case the production technology is characterised not only by input and output quantities but also by input prices.

[20] Different nomenclatures are used for defining the periods: *(s, t), (t, t+1), (0,1).*

$$Mi(y^t, x^t, y^s, x^s) = \left[\frac{Di^s(y^t, x^t)}{Di^s(y^s, x^s)} * \frac{Di^t(y^t, x^t)}{Di^t(y^s, x^s)}\right]^{1/2} \qquad \textit{Eq. 9}$$

Following Färe et al. (1992, p.90), the Malmquist productivity index from *Eq. 9* can be represented by the following equation:

$$Mi(y^t, x^t, y^s, x^s) = \frac{Di^t(y^t, x^t)}{Di^s(y^s, x^s)}\left[\frac{Di^s(y^t, x^t)}{Di^t(y^t, x^t)} * \frac{Di^s(y^s, x^s)}{Di^t(y^s, x^s)}\right]^{1/2} \qquad \textit{Eq. 10}$$

The first component of *Eq.10* measures efficiency change (EC) while the second one technical change (TC) based on the input oriented method. From this we note that $TFP\ growth = EC * TC$. EC captures the change in relative efficiency between period s and t, also known as the catching up term. TC captures the shift in technology between the two periods. The index varies from 0 to infinity between period s and t. A positive growth happens for values greater than 1. The components of the Malmquist productivity index can be estimated using DEA[21].

An enhanced decomposition proposed by Färe et al. (1994) suggests that EC can be represented by two components, pure efficiency change (PEC) and scale efficiency change (SEC)[22]. The VRS distance function is introduced under this approach. Then *Eq. 10* for and input-oriented would be as follows:

$$Mi(y^t, x^t, y^s, x^s) = \frac{Div^t(y^t, x^t)}{Div^s(y^s, x^s)}\left[\frac{SE^t(y^t, x^t)}{SE^s(y^s, x^s)}\right]\left[\frac{Dic^s(y^t, x^t)}{Dic^t(y^t, x^t)} * \frac{Dic^s(y^s, x^s)}{Dic^t(y^s, x^s)}\right]^{1/2} \qquad \textit{Eq.11}$$

With *v*: VRS, *c*: CRS.

The first component of Equation 11 represents PEC, the second SEC and the last remains the same than Equation 10. Then $TFPgrowth = PEC * SEC * TC$. PEC is calculated under VRS. TC is calculated under CRS. SEC represents a residual scale component that represents changes in the deviation between CRS and VRS technologies, see Färe et al. (1994, pp. 74-75).

One of the main observations made about the decomposition proposed by Färe et al. (1994) was the assumption of using CRS and VRS within the same decomposition of the Malmquist index creating issues of internal consistency (Ray and Desli, 1997). These authors propose a different decomposition where only the PEC component remains the same. In their proposal,

[21] The first component can be estimated via DEA, based on the methodology explained in footnote 1. For the second one, which involves cross-time efficiency (period s and t), a modification of the methodology is required as follows: $min_{\theta,\lambda,}\theta,\ st: -y_i(t) + Y(s)\lambda \geq 0,\ \theta x_i(t) - X(s)\lambda \geq 0, \lambda \geq 0$; (Giannakis et. 2005, p. 2262).

[22] SEC captures the contribution of scale economies to productivity growth.

TC is computed using the geometric mean of the ratios of VRS distance functions while in Färe et al. (1994) this refers to the ratios of CRS distance functions. In the estimation of SEC, the geometric mean of scale efficiencies was used (instead of the simple ratio of the two bundles) but with both referring to VRS technologies as the benchmark, see Ray and Desli (1997, p. 1036).

Other decompositions of the TFP change are also observed in the literature, such as the one proposed by Balk et al. (2001) who suggest an additional component defining TFP change as the product of technical change (TC), efficiency change (EC), scale efficiency change (SEC) and output/input mix effect (O/IME)[23]. Others such as Orea (2002), propose an enhanced approach by evaluating the contribution of scale economies to productivity change without the prior calculation of scale efficiency measures. According to See and Coelli (2014), even though there are alternative Malmquist TFP decomposition methods (for non-parametric or parametric) there is not yet a wide acceptance of a particular approach. This study evaluates the Malmquist TFP based on the decomposition made by Färe et al. (1994)[24].

The inclusion of quality attributes on TFP Analysis

The quality variables in our analysis are represented by such variables as the number of customer minutes lost, the number of interruptions and energy losses for electricity distribution, customer minutes lost and number of interruptions for gas distribution, energy not supplied and system non-availability for electricity transmission and gas shrinkage[25] for gas transmission. Some studies have referred to them as non-desirable outputs. Other studies also note that while ordinary inputs (e.g. opex, capex) can be radially reduced while keeping a given level of outputs (e.g. total energy delivered), quality attributes cannot necessarily vary at the discretion of management. Banker and Morey (1986) introduce a methodology for measuring efficiency using DEA taking into account the inclusion of exogenously fixed inputs or outputs. In their proposal, a separation of the non-ordinary variables is made in the set of constraints, where only the ordinary input ones are subject to optimisation. In this study, quality variables are seen as a quality attribute of the firm's output in which a reduction (if negative quality) or

[23] This new term captures the impact of changes of the output/input mix on productivity growth.

[24] The software used for doing the Malmquist TFP analysis in this study (DEAP Version 2.1) uses this approach. It is available at https://economics.uq.edu.au/cepa/software

[25] Which includes losses and energy used in gas transmission, see https://www.nationalgridgas.com/about-us/system-operator-incentives/nts-shrinkage

increase (if positive quality) is both possible and desirable (Giannakis et al., 2005). In line with Yaisawarng and Klein (1994), we include such non-desirable outputs as ordinary inputs.

The incorporation of quality attribute variables in the estimation of the Malmquist productivity index was introduced by Färe et al. (1995). The authors demonstrate that the quality attribute of the Malmquist productivity index can be expressed as an independent component assuming that the distance functions are multiplicatively separable in attributes and inputs/outputs. The authors define the quality change index as follows:

$$Q(y^t, x^t, a^t, y^s, x^s, a^s) = \left[\frac{Di^s(y^s, x^s, a^t)}{Di^s(y^s, x^s, a^s)} * \frac{Di^t(y^t, x^t, a^t)}{Di^t(y^t, x^t, a^s)}\right]^{1/2} \qquad \textit{Eq. 12}$$

In Equation 12, the term "a" refers to attributes which are treated along with "y" as outputs. In our analysis, the quality attributes are, for example, represented by customer minutes lost and number of interruptions. The idea is to reduce the level of undesirable output attributes (quality) while maintaining a specific level of discretionary outputs.

Then in line with Equation 9, the Malmquist productivity index including the attributes can be defined as follows:

$$Mi(y^t, x^t, a^t, y^s, x^s, a^s) = \left[\frac{Di^s(y^t, x^t, a^t)}{Di^s(y^s, x^s, a^s)} * \frac{Di^t(y^t, x^t, a^t)}{Di^t(y^s, x^s, a^s)}\right]^{1/2} \qquad \textit{Eq. 13}$$

Assuming that the distance function are multiplicatively separable in quality attributes and inputs/ outputs[26], the Malmquist productivity index can be written as:

$$Mi(y^t, x^t, a^t, y^s, x^s, a^s) = Q'(y^t, x^t, a^t, y^s, x^s, a^s) * Mi(y^t, x^t, a^t, y^s, x^s, a^s) \qquad \textit{Eq. 14}$$

Where $Q' = \left[\frac{A^s(a^t)\, A^t(a^t)}{A^s(a^s)\, A^t(a^s)}\right]^{1/2}$ *Eq. 15*

Finally, in agreement with Equation 11, Equation 14 can be represented as follows:

$$Mi(y^t, x^t, a^t, y^s, x^s, a^s) = Q' * PEC * SEC * TC \qquad \textit{Eq. 16}$$

We do not actually make use of this further decomposition in our analysis, but note in here for completeness.

[26] This means that $Di^s(y^s, x^s, a^t) = A^s(a^t) Di'^s(y^s, x^s)$, see Färe (1995, p. 139). This approach is used for each of the components of Q' described in Equation 16.

3. Literature Review on Productivity Analysis of Energy Networks

3.1 Electricity distribution network

There are a relatively large number of studies on productivity growth in electricity distribution utilities. A strand of literature that examines the impact of service quality into the electricity distribution productivity rate includes Giannakis et al. (2005), which incorporates quality of service into a DEA model using number of interruptions and customer minutes lost. Giannakis et al. (2005) compute the productivity change indices for 4-year intervals for a panel of 14 electricity distribution utilities in the UK from 1991/92 and 1998/99. The results from the Malmquist indices show that the sector achieved average overall productivity gains of between 12% and 38% for the above 4-year periods between 1991/92 and 1998/99, corresponding to annual TFP growth rates of between 1.5% and 4.75% over the whole sample period. The productivity gains were attributed to reduced efficiency gap among the firms, frontier shift, and improved quality of service.

Productivity growth in the electricity distribution industry has been analysed in the context of regulated rate setting. In an international comparison, Hattori et al (2005) compare the relative performance of electricity distribution systems in 12 UK regional electricity companies (RECs) and 9 electric utilities in Japan between 1985 and 1998 using both stochastic frontier and DEA approach. They find a productivity improvement in the UK sector of 1% p.a. under a price-cap regulation versus 0.3% p.a. in Japan which was using rate of return regulation.

Country-specific studies of the impact of regulatory policies on productivity, for instance on Norway, include Edvardsen et al., (2006), Miguéis et al., (2012), and Senyonga and Bergland, (2018). The impact of incentive regulation on Norwegian electricity distribution productivity growth has been mixed. Controlling for customer density and load factor, Edvardsen et al (2006) find that average annual productivity growth rate for the Norwegian electricity distribution companies are 1.1% and 2.1% for the two models estimated from 1996 to 2003. Senyonga and Bergland (2018) found a significant productivity growth improvement with the average annual total factor productivity rate of 1.54% for 121 Norwegian utilities from 2004 to 2012. They conclude that the industry experienced significant improvements in productivity growth under yardstick competition (2007–2012) when compared to RPI-X incentive regulation (2004–2006). By contrast, Miguéis et al. (2012) find no evidence of a substantial productivity change over time as TFP grows at 0.3% p.a. for a sample of 127 Norwegian distribution companies from 2004 to 2007 under RPI-X incentive regulation using forest, snow and coast as environmental variables. Another recent study on Canada is Dimitropoulos and Yatchew (2017) which found a negative productivity growth rate of -1% p.a. for 73 Ontario electricity distribution companies for the period 2002 to 2012 in a price-cap framework.

Other studies have analysed the impact of privatisation on the electricity distribution productivity rate and found positive impacts of privatisation on TFP using DEA. For example Pérez-Reyes and Tovar (2009) examine the trends of productivity of 14 Peruvian distribution electricity distribution companies from 1996 to 2006. The study reveals a positive impact of privatisation on productivity with the average annual TFP growth rate of 4.3%. Çelen (2013) analyse the productivity change of 21 Turkish electricity distribution companies during the period of 2002–2009 using DEA. The author incorporates customer density, customer structure[27], loss and theft ratio as environmental variables and finds a TFP growth rate of 3.3% p.a. over the sample period.

Studies on Brazil include Ramos-Real et al. (2009) which uses a DEA approach in a study of the Brazilian electricity utilities and distributors during the period 1998 to 2005 while controlling for service area[28]. Assessing the impact of privatisation, the study finds the TFP index witnessed a yearly positive growth rate of 1.3% p.a. over the whole period under analysis for all firms. Meanwhile, Tovar and De Almeida (2011) test the null hypothesis that firm size affects the performance of the electricity distribution industry by calculating productivity development in the Brazilian electricity distribution firms from 1998 to 2005. The results indicate the TFP exhibited a positive annual growth of only 0.9% during the period. They conclude that firm size contributes positively to the change in TFP.

3.2 Electricity transmission network

There is a dearth of empirical studies that analyse firms' performance in the electricity transmission sector. Llorca et al. (2016) carry out an empirical analysis of US electricity transmission companies for the period 2001–2009 using alternative stochastic frontier models

[27] Defined as the proportion of residential sales to total sales.

[28] Service area refers to the geographic area where the licenced distribution electricity firms operate.

that identify the determinants of firms' inefficiency. The results suggest that unit costs fall at a rate of 2.5% p.a. over the whole sample period.

3.3 Gas distribution network

A few studies examine the impact of privatisation and incentive regulation on gas distribution networks. Price and Weyman-Jones (1996) find the UK gas industry productivity growth was 23% across the period 1977/78 to 1990/91, averaging 1.64% p.a. They conclude that bulk of productivity gain was recorded after privatisation and the introduction of incentive regulation in 1986. Having undergone privatisation in 1992, Rossi (2001) finds a positive average annual productivity growth of 2.8% p.a. using SFA for 8 Argentinian gas distribution firms in the post privatisation period, 1994–1997. Similarly, Casarin (2014) investigates productivity patterns in price cap regulated utilities around price reviews for Argentinian gas distribution companies using an econometric variable cost function sample from 1993 to 2001. The study reports the negative impact of the two regulatory cycles with an average annual TFP of -0.189 % p.a. for a time trend model and a marked decline in TFP of -0.833 % p.a. in an index model. However, Gugler and Liebensteiner (2016) investigated the TFP growth of all 20 regulated Austrian gas distribution companies over the period 2002–2013, covering the times before and after the introduction of incentive regulation in 2008. They found an average annual TFP growth rate of 1.83% for the companies, with a marked decrease in the TFP growth rate in the period after privatisation. They conclude that technological opportunities were higher in the early years of the sample (before incentive regulation was implemented) than in later years, and the Austrian regulatory authority managed to fully pass through potential cost savings to consumers in the year 2008 (and subsequent years), when incentive regulation was initiated in Austria’s gas distribution sector.

3.4 Gas transmission network

The latest study on the US gas transmission pipelines by Jamasb et at. (2008) assesses the impact of various regulatory changes on productivity of the US gas industry under rate of return regulation. The authors employ DEA Malmquist to compute the TFP growth of US 39 interstate companies from 1996 to 2004. The study shows that regulatory change in the US is accompanied by ‘‘cost productivity’’ and ‘‘revenue productivity’’ improvements. The average yearly TFP growth rates for total expenditure models lie between 2.9% and 5.9% whilst the respective TFP growth rates ranges for the revenue models are 4.5–6.9%. They authors argued that, unlike cost, revenue is more likely to be driven by the particular tariff regime and/or market power, inter alia.

3.5 Other UK network industries

3.5.1 Water and sewage network

There are empirical studies that explore the impact of privatisation on the productivity growth rate in other network industries (which might be broadly comparable to energy networks). Using a panel of 10 water and sewerage industry in England and Wales, Saal and Parker (2001) find an average annual TFP growth rate of 1.8% over a period 1985–1999 and Saal et al. (2007) report a slightly lower TFP growth rate of 1.68% between 1985–2000. Both studies find that productivity growth was not significantly different after privatisation and that productivity growth rates were lower in the 1995–2000 period than they had been before privatisation while a mixed finding was reported on whether the incentive regulation contributed to the growth of TFP. Maziotis et al. (2015) show that the average quality-adjusted TFP improved by 51.7% and average quality-unadjusted TFP improved by only 22.9%, averaging annual TFP growth of 2.87% and 1.27% respectively for 10 English and Welsh water and sewerage companies (WaSCs) using index numbers over the period 1991 to 2008. The quality-adjusted measures of output for water and sewerage services are the product of water output and a drinking water quality index, and sewerage output and a sewage treatment quality index, respectively. Molinos-Senante, et al., (2014) argue that productivity growth declined from the beginning of the 2005 price control period for the English and Welsh water companies. They indicate that productivity growth declined across all the years evaluated for 22 English and Welsh WaSCs and water-only companies (WoCs) from 2001 to 2008.

3.5.2 Rail network

Surprisingly, a sparse body of literature (Cowie, 2002 and Smith, 2006) provides empirical evidence on productivity performance of the privatised British passenger railway. Cowie, (2002) explores the average annual growth in TFP for the privatised UK rail network between financial years 1995/96 and 1998/99 using the Törnqvist index and finds that total productivity rose on average by 4.6% p.a. over the post-privatisation period. Smith (2006) assesses post-Hatfield cost and TFP levels against the historical precedents set by British Rail and the early experience of the newly privatised industry and shows faster TFP growth after privatisation.

The TFP gains achieved over the period up to the Hatfield accident (1999/00) were however more than wiped out by post-Hatfield falls; leaving TFP in 2001/02 just below 1963 levels.

Summary

The literature review shows that the empirical literature on productivity growth in energy network industries is mostly concentrated on distribution networks. One important insight from the past studies is that total factor productivity growth for the network industries is examined vis-à-vis different testable hypotheses such as the impact of quality of service, changes in regulation, the effect of privatisation and firm size. Most of the past studies on productivity of energy network industries conducted have tested one or a combination of hypotheses. For instance, studies on the UK test hypotheses about quality of service, privatisation and the nature of regulation; studies on Norway, Canada, Japan and the United States mainly examine the incentive regulation hypothesis, namely that there is a positive impact from introducing incentive regulation on productivity. The studies on emerging economies such as Brazil emphasize privatisation and firm size hypotheses (whether larger firms are more efficient / have faster productivity growth) while studies on Peru and Turkey test primarily an impact of privatisation on network industries' productivity.

In terms of methodology, Data Envelopment Analysis (DEA) has typically been the most applied technique, followed by Stochastic Frontier Analysis (SFA). The overview of the literature indicates, in most cases, overwhelming evidence of positive but low TFP growth, of the order of 1% p.a. Interestingly, the studies show some short periods of significantly more rapid growth following privatisation, the introduction of incentive regulation or rapid demand growth. However, this is not sustained over long periods, indeed most studies are for short runs of years. There is no evidence that recent growth (since 2005) is likely to be higher than the longer run trend.

There are obvious differences among the authors in the choice of variables used in the studies of the electricity network. However, there seems to be more consensus in terms of variable choices for other networks industries (perhaps due to the lower numbers of studies). For electricity distribution the most frequently used output variables are units of energy delivered and the number of customers, while the most widely used input variables are number of employees, network length, total expenditure and operating expenditure in the electricity distribution network. Customer density, load factors, number of interruptions, customer time lost and service areas have been the common environmental variables.

Table 1: Summary of the literature for network industries (electricity and gas)

[a] DEA: data envelopment analysis, SFA: stochastic frontier analysis
[b]O:Output(s), I:Input(s), EX: environmental variables, C: cost, IP: input price

Authors	**Method(s)[a]**	**Data**	**Variables used[b]**	**Main findings**
		Electricity	**Distribution Network**	
Giannakis et al. (2005)	DEA	14 UK companies electricity distribution, 1991/92 and 1998/99	O: Energy sales (kWh), number of consumers, distribution network length (km) I: Operational costs, total operational costs (includes capital costs) EX: number of interruptions (NINT) and customer time lost due to interruptions (TINT)	The average productivity gains of between 12% and 38% for 4-year intervals between 1991/2 and 1998/99, corresponding to annual TFP growth rates of between 1.5% and 4.75% over the whole sample period Quality of service contributes substantially to TFP gains
Hattori et al. (2005)	SFA and DEA	21 utilities (12 UK RECs and 9 Japanese electric utilities), 1985-1998.	O: Number of customers, electricity delivered I: Total expenditure, operating expenditure EX: Customer density, load factor	The average annual productivity improvement in the UK sector is 1% while the corresponding estimate for the Japanese sector is 0.3%. Increased productivity in the UK is attributed to price-cap regulation as positively
Edvardsen et al. (2006)	DEA Malmquist cost productivity index	Norwegian electricity distributors from 1996 to 2003	O: Number of customers, total energy delivered, Low voltage transmission grid, high voltage transmission grid, expected costs of energy not supplied I: Capital, loss, goods and services, labour, materials, actual costs of energy not supplied C: Total costs IP: interest and depreciation capital rates	The average productivity rate for the panel model and the sample average unit (SAU) are was 1.1% and 2.1% p.a. respectively. Change in regulatory regimes affects productivity growth

Miguéis et al. (2012)	DEA	127 Norwegian distribution companies from 2004 to 2007	O: Energy delivered, customers, Cottage customers I: High voltage lines, Network stations, Interface, EX: Forest, snow, coast	The TFP grew at 0.3% p.a. over the sample periods RPI-X incentive regulation has not contributed significantly to productivity growth.
Senyonga and Bergland (2018)	SFA Malmquist	121 Norwegian utilities over for a period of 9-years 2004–2012	O: Number of customers, energy delivered, voltage line and area served. I: Capital, OPEX EX: Underground cable, Customers growth and distance to road.	The average annual productivity growth rate of 1.54% p.a. Significant improvements in productivity growth under yardstick competition (2007–2012) when compared to RPI-X incentive regulation (2004–2006)
Ramos-Real et al. (2009)	DEA Malmquist	18 Brazilian electricity distribution firms from 1998-2005	O: Number of customers, electricity delivered I: Length of electricity grids, number of employee, losses EX: Service areas	TFP index records a yearly positive growth rate of 1.3% in the whole period under analysis for all firms Privatisation does not seem to have led the firms to be significantly impact of the Brazilian productivity.
Tovar and De Almeida (2011)	SFA	17 Brazilian firms from 1998 to 2005	O: Number of customers, total sales I: Network length, number of employee, losses.	The TFP exhibited a positive annual growth of only 0.9% during the 1998–2005 period. Firm size contributes positively to the change in TFP.
Pérez-Reyes and Tovar (2009)	DEA Malmquist	14 distribution Peruvian companies, for the period 1996–2006.	O: Number of customers, annual sales I: Network length, number of employee, the numbers of MV to LV conversion substations losses	The annual average of the total factor productivity is 4.3%, Significant relationship between the restructuring of distribution sector through the privatisation and the enhancement of productivity.
Çelen (2013)	DEA	21 Turkish electricity distribution companies, 2002–2009.	O: Electricity delivered, Number of customer I: Length of distribution line, number of employee, Transformer capacity, Outage hours per customer, Loss&theft ratio,	The TFP increase by 3.3% p.a. over the period of 2002–2009. Privatisation contributes significantly to positively to productivity gain.

			EX: Customer density, Customer structure, Loss&theft ratio, dummies for restructuring and ownership	
Dimitropoulos and Yatchew, (2017)	Törnqvist Index, SFA cost function	73 Ontario distributors for the period 2002 to 2012.	O: Number of customers served, energy delivered, and system capacity C: Total cost IP: Capital price, Labour Price EX: regional dummies, Wind speed, Precipitation, Capex/Opex ratio, growth in demand	The productivity growth estimates are approximately -1% p.a. Price-cap regulation framework does not significantly impact productivity growth
		Electricity	**Transmission Network**	
Llorca et al; (2016)	SFA	59 US electricity transmission companies for the period 2001–2009.	O: Peak Load, energy delivered, Network length and total Capacity of Substations C: Total cost IP: Capital price, OM&A input price EX: Distribution line length, service territory area, undergrounding.	The TFP grew at 2.5% p.a. over the sample periods.
		Gas	**Distribution Network**	
Price and Weyman-Jones (1996)	Malmquist mathematical programming models	UK natural gas industry in 12 regions, 1977/78 to 1990/91.	O: domestic (i.e. residential) gas sales (therms), industrial gas sales (therms), commercial gas sales (therms), number of customers served, gas using appliances sold I: numbers of employees, length of the gas mains transmission and distribution system	The overall productivity growth in the UK gas sector was 23% for the whole period, averaging 1.64% p.a.

Rossi (2001)	SFA	8 Argentinian gas distribution companies from 1994–1997.	O: number of customers I: kilometres of pipes, number of employees, labour input EX: concession area, market structure, maximum demand	The average productivity growth was 2.8% p.a., which can be decomposed into technical change of 2.4% and technical efficiency of 0.4%.
Casarin (2014)	Econometric variable cost function	8 Argentinian gas distribution companies from 1993 to 2001.	O: Delivery volume, number of customers I: capital, labour, and intermediate inputs C: variable costs (sum of operation and maintenance expenses) IP: labour price, price of capital and price of intermediate inputs EX: Load, residential to total gas deliveries, customers per km of pipe, area served, customer density.	The average annual TFP as measured with the time trend model was -0.189 % p.a. year, whereas the index model suggests a marked decline in TFP of - 0.833 % p.a.
Gugler and Liebensteiner (2016)	Econometric cost function	20 Austrian gas distribution companies for a period of 2002– 2013	O: Network length, metering points of households and small businesses, and Installed capacity of industry and large businesses I: Total expenditures	The average annual TFP growth rate was 1.83% in the Austrian gas distribution sector in the period 2002–2013.
		Gas	**Transmission Network**	
Jamasb et al (2008)	DEA Malmquist	US 39 interstate transmission companies, 1996–2004.	O: Total delivery volume, length of pipe and total horsepower rating I: Total cost or revenue	TFP growth rates ranges for the Totex models are between 2.9% and 5.9%. TFP growth rates ranges for the Revenue models are 4.5–6.9%.

4. TFP Using Growth Accounting Approach

The first part of the TFP analysis made in this section makes use of the EU KLEMS database for the period 1995-2015[29] which is in 2010 prices. One of the advantages of using EU KLEMS is its consistency in the estimation of variables across different countries. Our analysis compares TFP growth in four countries: Germany, Netherlands, UK and the USA (Norway and Australia, which might be considered to have comparable regulatory regimes to the UK are not in the database). The EU KLEMS database covers electricity, gas and water supply data, bundled all together. The data is categorised under the code D-E. The TFP analysis has been made using the Value Added approach. The second part of the analysis in this section evaluates the TFP growth from three different sectors electricity (production[30], distribution, and transmission), gas and water sectors based on the databases available from the Office for National Statistics (ONS)[31] for the period 1995-2016. There are two datasets associated with this analysis, one from 1995-2007 and the other from 2008-2016. In analysing TFP using ONS data, we found some difficulties due to the lack of key data for specific years. Some approximations were made using interpolation methods especially for the electricity and gas industries. Both TFP analysis are based on the GAA method.

4.1 TFP Growth based on EU KLEMS database

Results from the TFP analysis of the EU KLEMS data show that for the period of study value added TFP growth for the aggregated sectors has been negative for the UK and USA, while Germany is has the highest annual average value added TFP growth, see Fig. 2. In the case of the UK a negative value added TFP growth is observed before the 2008 crisis, starting in 2005. It is after 2010 that the aggregated industries show some improvement. The average value added TFP growth in the UK has been around -2.3% with an average of -3.4% after the 2008 crisis. The Netherlands was doing relatively well until 2006. An important downward trend is observed in the TFP growth with a peak of -5.2% in 2012. The Netherlands has achieved an average value added TFP growth of 0.16% for the period 2001-2015. This is in line with the fact that the Netherlands was among the countries less affected by the 2008 crisis (Masselink and van den Noord, 2009). The 2008 crisis had a positive impact on energy productivity due

[29] The periods differ across the countries due to the lack of data for the initial years. This is the case of Netherlands where the first estimation of value added TFP growth was made for 2000 instead.

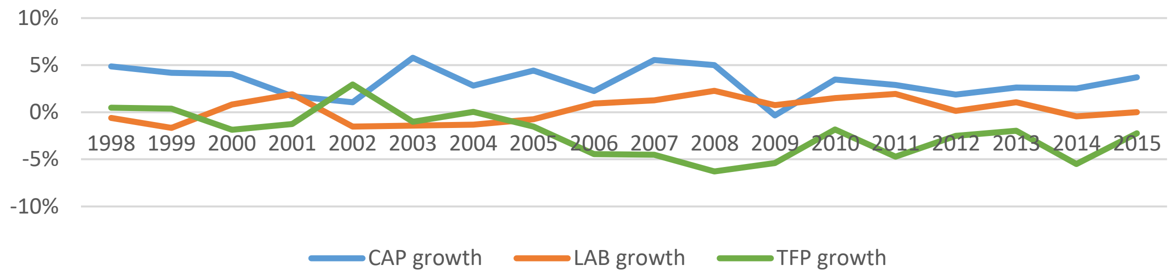
[30] The ONS data base refers to production instead of generation but both have the same meaning.

[31] The database refers to the Annual Business Survey (ABS) covering only the UK-Non-Financial Business Economy.

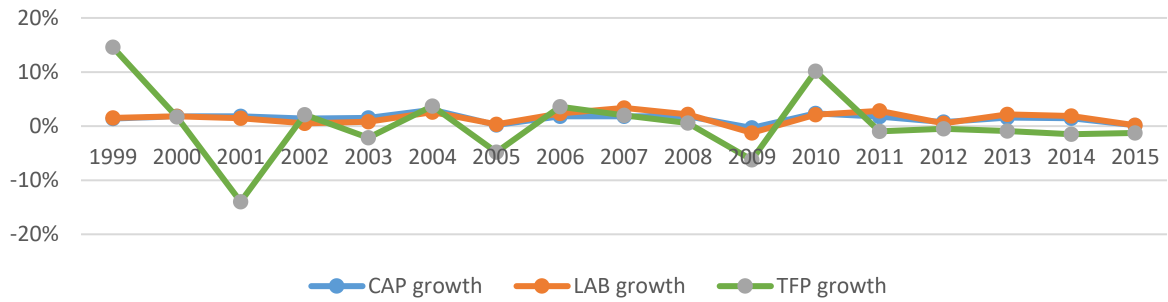
to a significant reduction in energy use when compared with the fall of value added (Colijn and van Ark, 2014).

Fig. 2: TFP Growth (annual percentage change)

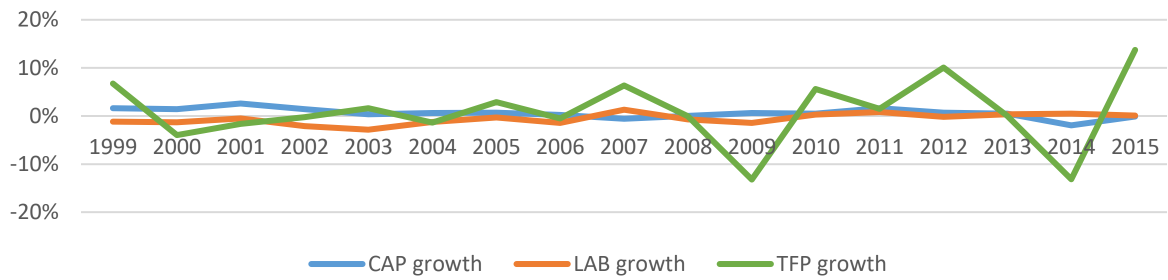
(a) UK (period 1998-2015)



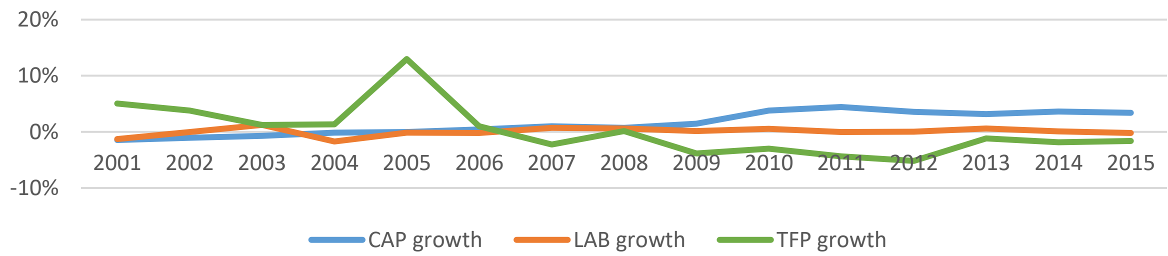
(b) USA (1999-2015)



(c) Germany (period 1998-2015)



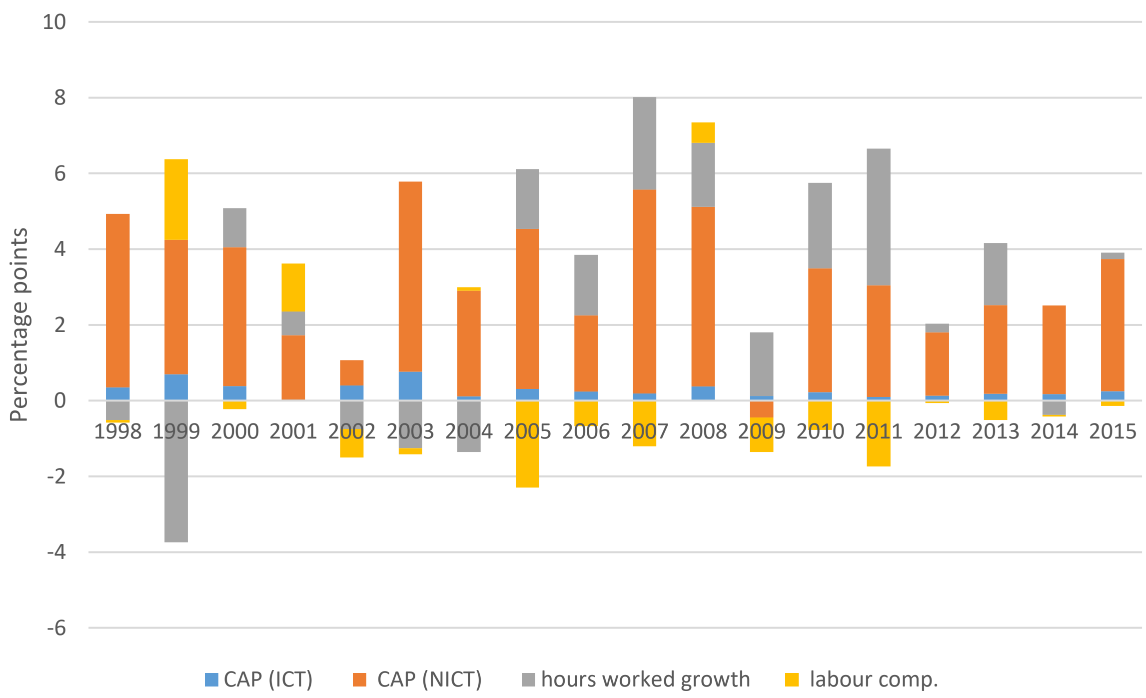
(d) Netherlands (period 2001-2015)



In the case of the USA, the aggregated sectors have been noticeably affected by the 2001 crisis with a peak annual value of -15%. Finally, in Germany the aggregated sectors have been affected in two specific periods, 2009 and 2014 with an average value added TFP growth of -13%. Despite these setbacks, Germany is the country with the highest TFP growth over the period of study, amounting to 0.84% p.a.

The other thing that we observe is that capital rather than labour is the one that has driven the trend of value added growth across the four countries. The contribution of capital in this growth is especially important in the UK and less relevant (in comparison with labour) in Germany. A closer look at the breakdown of the contribution of labour (represented by hours worked and labour composition) towards value added TFP growth shows that the contribution of labour is driven by the hours worked in the European countries and by labour composition in the USA. On the other hand, non-ICT capital services are the ones that drive the value added TFP growth in the four countries. Fig. 3 shows the breakdown contribution of capital and labour to value added growth in the UK.

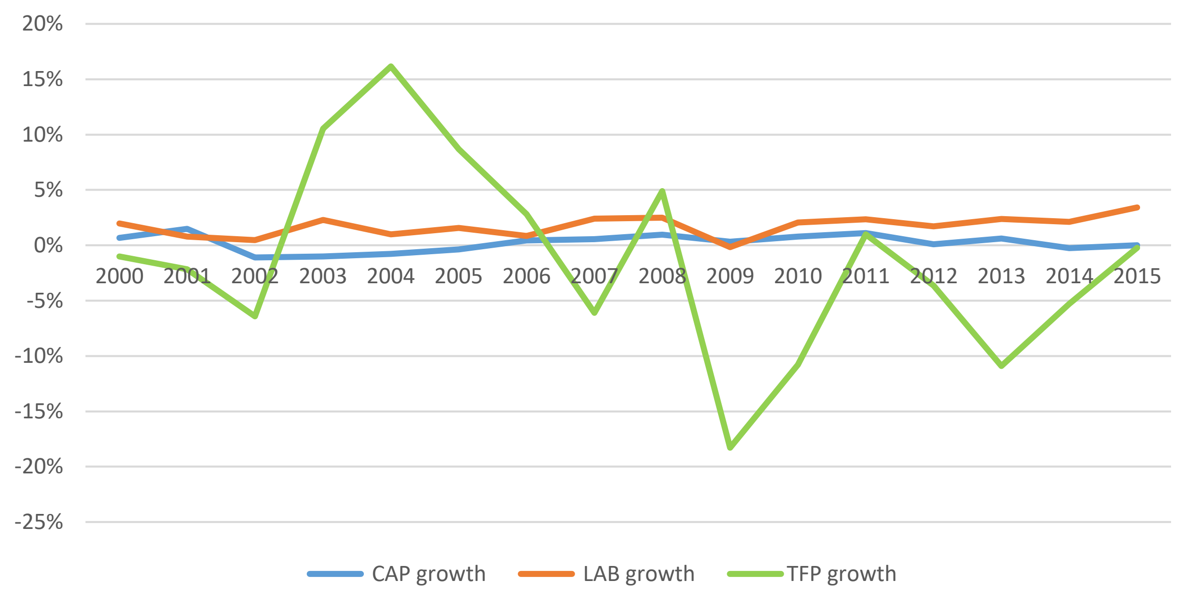
Fig. 3: Compensation of capital and labour (breakdown) in value added TFP growth - UK



4.2 TFP Growth based on ONS data

An exercise similar to the one with the EU KLEMS data was performed using the ONS data for the period 1995-2015[32]. Data was obtained from two different accounts for the period 2008-2016 (Account D: electricity/gas, Account E: water) and period 1995-2007 (Account E: electricity/gas/water). The labour and capital variables are represented by labour compensation and total net capital expenditure[33] respectively. Data about deflators was obtained from EU KLEMS data base (for valued added and labour and capital indexes, 2010 base). We used these because they represented aggregate deflators that covered the three sectors we wanted to evaluate separately in this analysis. The value added TFP growth was estimated for each market: electricity (which involves production, distribution and transmission), gas (manufacturing, distribution) and water (excluding sewerage services). Due to the lack of data, especially in terms of value added and total net capital expenditures some interpolations were made. Fig. 4 shows the results of the TFP analysis for the electricity as a whole.

Fig. 4: Value added TFP growth in the electricity market[34]



We can observe two peaks value here, the first one in 2004 and the second one after the 2008 crisis. These results are – partly - in line with our later Malmquist DEA TFP growth analysis

[32] Based on the results from the Annual Business Survey.

[33] The selection of this variable is in line with the capital input variable used (represented by capital expenditures) in the TFP at utility level, Section 4.

[34] The capital deflator we have used (from EU KLEMS) is available only from 2000 onwards until 2015. This explains the exclusion of the final year (2016) of the ONS database.

for electricity distribution and electricity transmission, with a positive productivity figure and a negative one in 2003/04 and 2008/09 respectively. For further discussion see Sections 5 and 7. We also note a positive average value added TFP growth before the crisis (2.2% p.a., 2000-2006) and a negative one after it (-6.2% p.a., 2009-2015). The other thing that contrasts these results with the previous ones is that the value added TFP growth is driven by the contribution of labour rather than capital (on average for the whole period). Among the reasons that may explain this difference is the use of total capital expenses instead of capital services (as reported by EU KLEMS and used in the previous analysis) and the fact that this analysis is focused only on electricity while the previous one covers electricity, gas, water. TFP growth results from the gas sector do not show a proper trend of growth and have very high peaks (positive and negative) during the period of analysis. Again, this may be driven by the type of variable selected including the deflators and also by the lack of key data in this sector. Information in the water sector is the most comprehensive of the ONS data we look at, especially for the period 2007-2015. However, a very high increase in some specific figures (from one year to other) attracted our attention, and had an impact on our results. This is the case of value added and cost variables in the water sector for the years 2006 and 2007 (i.e. an increase of around 90% was observed in the value added account). A similar case was observed for the gas sector for the year 2016 where the value of total net capital expenditure, most oddly, increased by 500% in one year. Results from the TFP analysis in the water sector are shown in Table 2. Again, there are some difficult to explain peaks and troughs, which would seem to suggest data quality issues.

About the use of deflators

There are different kinds of deflators than can be used for the TFP analysis. There are general deflators such as the Retail Price Index (RPI) (i.e. the one used by Ofgem) and others more specific to the type of variable (e.g. for capital and for labour) and others that are sector specific (e.g. for energy, transport or construction). In this section, we have used the deflators from EU KLEMS database (for capital, labour and value added). However, it is important to note that the selection of one or another should be evaluated very carefully, especially if the results of the TFP analysis are expected to be used for regulatory purposes (i.e. price control). For instance, by using RPI instead of the – more slowly increasing - capital deflator, capex figures deflate quicker. If a capital deflator is used instead this will inflate the real capital input, reducing productivity growth. Table 3 compares the different deflators from the EU KLEMS database (UK – electricity/gas/water sectors) and from the ONS (UK whole economy).

Table 2: Value added TFP growth in the water sector

Year	CAP growth	LAB growth	TFP growth
1998	-0.5%	4.2%	4.7%
1999	-1.4%	3.8%	-5.4%
2000	0.7%	3.6%	-9.8%
2001	1.5%	1.4%	12.6%
2002	-1.0%	0.9%	-13.7%
2003	-1.0%	5.8%	-7.5%
2004	-0.8%	2.9%	5.6%
2005	-0.4%	4.1%	19.3%
2006	0.4%	2.1%	-9.7%
2007	0.5%	5.4%	55.7%
2008	1.0%	4.9%	0.7%
2009	0.4%	-0.3%	-27.0%
2010	0.7%	2.7%	10.1%
2011	0.8%	2.4%	2.9%
2012	0.1%	1.6%	-7.9%
2013	0.5%	2.0%	-3.0%
2014	-0.2%	1.8%	-3.6%
2015	0.0%	2.5%	-4.1%
average	0.07%	2.88%	1.11%

Table 3: A Comparison of Deflators (2010 base year)

	EU KLEMS (UK , period 1995-2015) - electricity/gas/water supply			UK (whole economy)		
	Value added	Capital	Labour	Gross fixed capital formation deflator	Gross value added implied deflator	RPI
1995	80.0		104.2	76.1	74.1	66.7
1996	81.4		97.9	80.0	77.3	68.3
1997	82.4	49.8	96.3	79.6	77.6	70.4
1998	79.9	53.4	94.4	79.4	78.1	72.9
1999	78.3	56.8	89.6	80.2	78.2	74.0
2000	75.9	60.3	91.9	82.2	79.9	76.2
2001	74.6	61.9	97.4	84.4	80.9	77.5
2002	78.7	62.8	93.1	85.9	83.0	78.8
2003	82.2	68.5	89.1	87.0	85.1	81.1
2004	80.2	71.6	85.9	88.5	87.2	83.5
2005	81.9	76.9	84.3	90.1	89.4	85.9
2006	94.3	79.8	86.3	93.6	92.2	88.6
2007	98.7	87.3	89.2	95.8	94.5	92.4
2008	94.5	95.0	94.4	99.3	97.4	96.1
2009	121.1	94.5	96.3	100.8	99.7	95.6
2010	100.0	100.0	100.0	100.0	100.0	100.0
2011	99.0	105.4	104.5	101.5	101.2	105.2
2012	118.7	108.8	104.9	104.0	103.2	108.5
2013	125.2	113.6	107.8	105.9	105.6	111.9
2014	132.5	118.4	106.6	107.4	106.9	114.5
2015	129.9	125.8	106.7	108.6	107.2	115.6

Source: EU KLEMS - UK (period 1995-2015), ONS.

5. Analysis of Electricity Distribution Efficiency

5.1 Data and model specifications

Selecting the input–output variables is an important step in DEA. To model the technology of electricity distribution, we have to specify the relevant measures of inputs, outputs, and other quality factors. The basic design features of electricity distribution systems and the technologies used in them are similar the world over, but comparative productivity analysis studies have adopted different input and output variables. Thus, there is no firm consensus on which variables best describe the operation of distribution utilities. Table 1, above, which provided a summary of the literature, outlined the most widely used variables in productivity studies of electricity distribution utilities. In our case, the choice of variables is based on the availability of data (following our original information request discussed at the beginning of the report), and on our previous discussion of the current literature and on Ofgem's own use of outputs with COLS (see Jamasb and Pollitt, 2007). We have data for the 14 distribution network operators from Ofgem for the 1990/91–2016/17 period. Data are used in quantities where available, expenditures are measured in million pounds 2012/13 prices[35]. Table A1 from the Appendix summarizes the inputs, outputs, and quality attributes used in the models where quality attributes are treated as inputs as discussed below. We discuss the choice of inputs, outputs and quality factors used in the study in the next subsections. The following table summarises the five models that are discussed in this section. Further details of the models are provided in Section 5.5.

Table 4: Models for Electricity Distribution

Model	Non-quality variables						Quality variables				Periods
	opex	capex	Cust	END	NL	PD	CML	CI	Loss	CS	
Model 1	I	I	O	O	O						1990/91-2016/17
Model 2	I	I	O	O	O		I	I			1990/91-2016/17
Model 3	I	I	O	O	O		I	I	I		1990/91-2004/05, 2015/16-2016/17
Model 4	I	I	O	O	O	O	I	I			2010/11-2016/17
Model 5	I	I	O	O	O	O	I	I		O	2012/13-2016/17

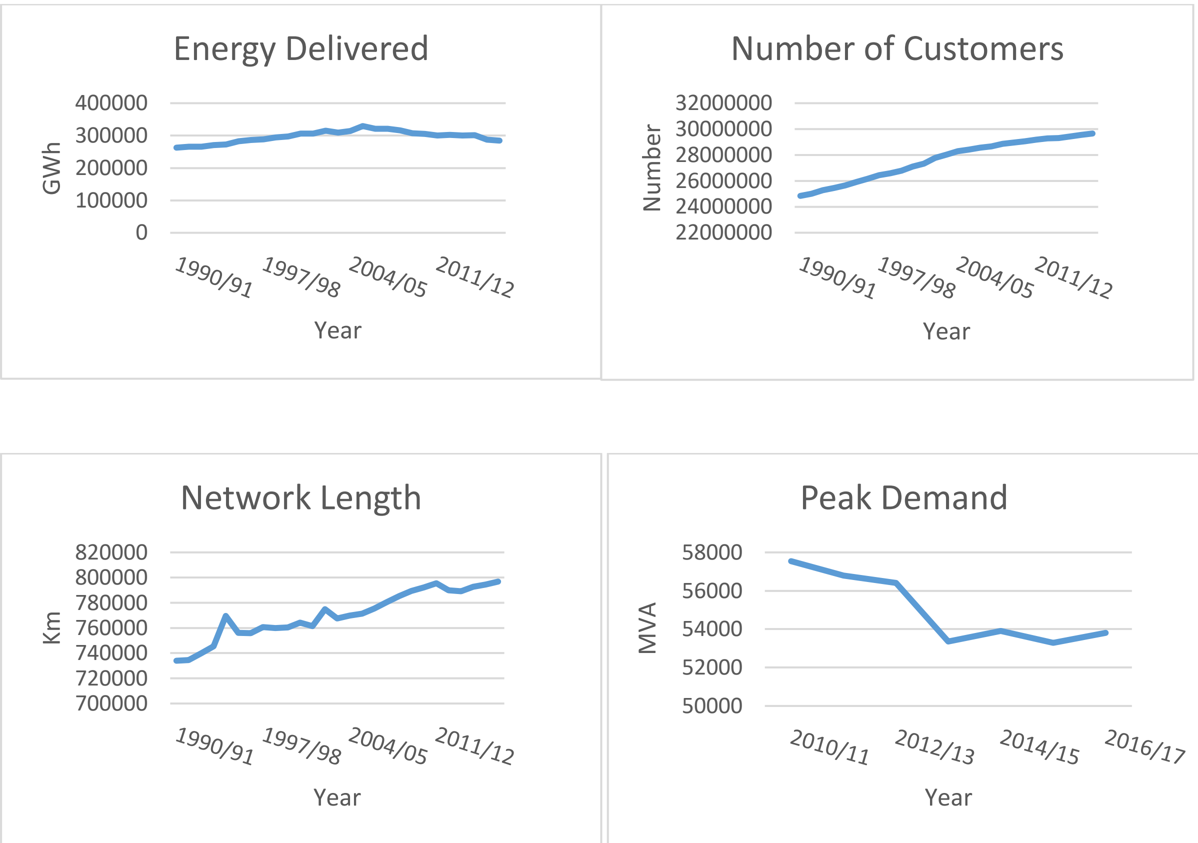
I: input, O: output, Cust: # of customers, END: energy delivered, NL: network length, PD: peak demand, CML: customer minutes lost, CI: # interruptions, Loss: energy losses, CS: customer satistaction

[35] Adjusted expenditure data (for electricity and gas) was provided by Ofgem in 2013/12 prices. Ofgem used the retail price index (RPI) for deflating these figures.

5.2 Outputs

It is quite difficult to define the output of electricity distribution services and to find the relevant measures. A review of productivity studies of electricity distribution utilities shows that the most widely used output variables are units of energy delivered and the number of customers as the cost of distribution services varies according to both. Since the product of a distribution utility is a set of specific quantities of electricity distributed to particular geographic locations, network length captures the extent of that geographical area. Following Giannakis et al (2005), we use units of energy delivered, number of customers and network length as it usually specified by Ofgem. We also consider peak demand as part of output in the alternative models estimated in the report. Although, it has been argued that peak demand can be priced separately, nevertheless, we included it in the alternative models as it is one variable which drives the size and cost of the network. The units of energy delivered is measured in GWh and network length measured in Km. Fig. 5 shows the annual evolution of the output variables; energy delivered, number of customers, network length and peak demand.

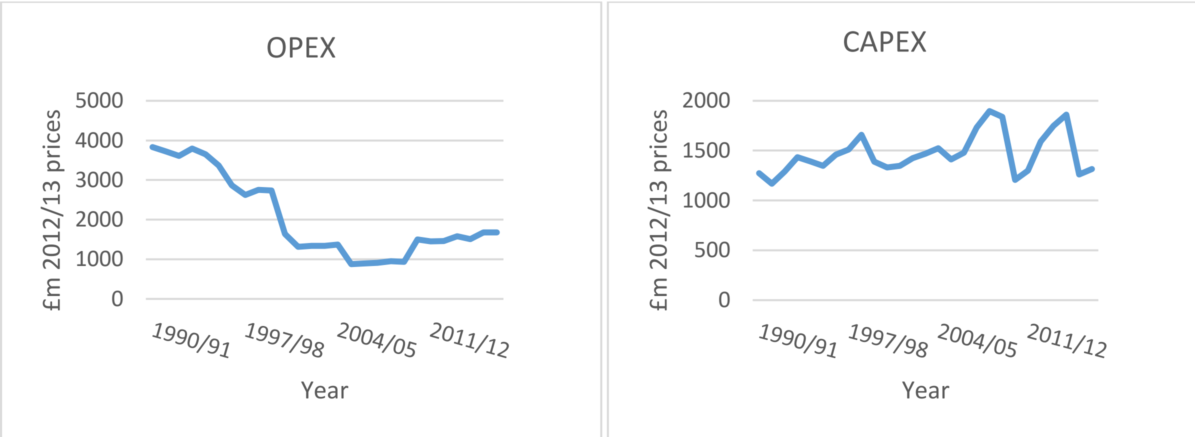
Fig. 5: Annual evolution of outputs for the electricity distribution sector



5.3 Inputs

Operating and total (operating + capital) costs are the most commonly used inputs in productivity analysis of the distribution network utilities. Although, others have instead used physical measures of the main inputs, we rely on monetary values of inputs to evaluate the performance of regulated firms using either operating expenditure (OPEX) and capital expenditure (CAPEX). We have treated them as separate inputs having deflated all the input data annually by RPI. Fig. 6 shows the annual evolution of the input variables.

Fig. 6: Annual evolution of inputs for the electricity distribution sector



5.4 Other Variables

We have just discussed the inputs and outputs in the estimated models, but there are other variables which can be influenced by operating and capital expenditures of electricity distribution. Our models include quality variables, which are variables that consumers value in addition to conventional outputs. Due to the paucity of data, we focus primarily on two important quality variables; customer minutes lost (CML) and customer interruptions (CI) which measure the quality attribute of output; a reduction in which is regarded as desirable. Other quality variables incorporated in our analysis include energy losses (Loss) and customer satisfaction (CS). Energy losses affect power supply because more losses mean that generators would need to increase the amount of energy that goes through the network to compensate for losses. Energy loss is measured in GWh. In order to include customer minutes lost, customer interruptions and customer satisfaction in a DEA model, we multiply the values by the number of customers, to make the variables scalable. We treat the CML, CI and Loss quality variables as inputs meaning that ceteris paribus, a reduction in their values is an increase in productivity. The CS quality variable is treated as an output because ceteris paribus an increase in its value is an increase in productivity.

5.5 Model specifications

We use a set of progressively more comprehensive set of DEA models. We specify five different types of DEA models, which employ different combinations of the variables introduced above. The objective is to assess policy issues related to the DNOs' productivity from the perspective of output variables as well as explanatory factors. Given that the quantities of physical outputs delivered by distribution utilities are, due to the derived nature of electricity demand, beyond the control of the management of network companies, we use input-oriented DEA models[36] to calculate the DNOs' relative efficiency in terms of the extent by which they can reduce their inputs while maintaining a given level of output. This is because the main goal of these companies should be to minimize inputs without changing outputs, which are set exogenously.

Model 1: Base model

Model 1 is the base model and does not account for the inclusion of quality variables. The specification resembles that of Ofgem's COLS model used in benchmarking of distribution utilities. The model considers two inputs (OPEX and CAPEX) and three outputs that correspond to the standard components of Ofgem's composite size variable (number of customers, energy delivered and network length). The model covers the entire 27-year sample period, 1990/91–2016/17.

Model 2 (Model 1-CML-CL)

Model 2 extends Ofgem's base model to incorporate important quality dimensions such as customer minutes lost and customer interruptions. The model outputs and sample period remain the same.

[36] Input-oriented models are often used in a DEA model if a decision making unit (DMU) can reduce its inputs while keeping its outputs at their current levels. Output-oriented models are used if a DMU can increase its outputs while keeping the inputs at their current levels. The choice of input- or output-oriented models depends upon the production process characterizing the firm (i.e. minimize the use of inputs to produce a given level of output or maximize the level of output given levels of the inputs). For the purpose of estimating network industries' performance, the input-oriented DEA measures are more applicable because the overall demand on the network is not primarily determined by network companies.

Model 3 (Model 1-CML-CL-Loss)

Model 3 extends Ofgem's base model but in addition to customer minutes lost and customer interruptions, we also account for energy losses in the model. Due to missing data for energy losses, the model has a shorter sample period, 1990/91-2004/05 and 2015/16-2016/17. However, outputs remain the same as model 2.

Model 4 (Model 1-Peak demand-CML-CL)

Model 4 simply extends model 2 by specifying four outputs: number of customers, energy delivered, network length and peak demand. The model has a shorter sample period due to missing data associated with peak demand. The model spans 2010/11 – 2016/17. However, the input and quality variables are the same.

Model 5 (Model1-Peak demand-CML-CL-CS)

Model 5 is similar to Model 4 by incorporating customer service into the model. It spans only 2012/13 – 2016/17.

5.6 TFP Results

The Malmquist productivity index is based on the DEA model and its decomposition is calculated for each year relative to the previous year. The results for the total factor productivity change and its components from the DEA models using (variable returns to scale) VRS technology structures are presented in line with Ofgem's distribution price control review regime. Index values higher than 1 indicate productivity improvement while values lower than 1 represent productivity regress: for instance a value of 1.02 indicates a 2% increase in productivity. Although the Malmquist indices calculated could fluctuate from one year to the next, the length of the period under study allows us to examine the productivity trend under different price control sub-periods.

First, we consider the base Model 1. Fig. 7 illustrates the evolution of total factor productivity change and its components over the period 1990/91–2016/17 without controlling for quality variables. The labels, 1995/96, 2000/01, 2005/06, 2010 /11 and 2015/16 on markers on the total factor productivity change line indicates the first years of new price control.

Fig. 7: Average Annual Total Factor Productivity Change and its Components

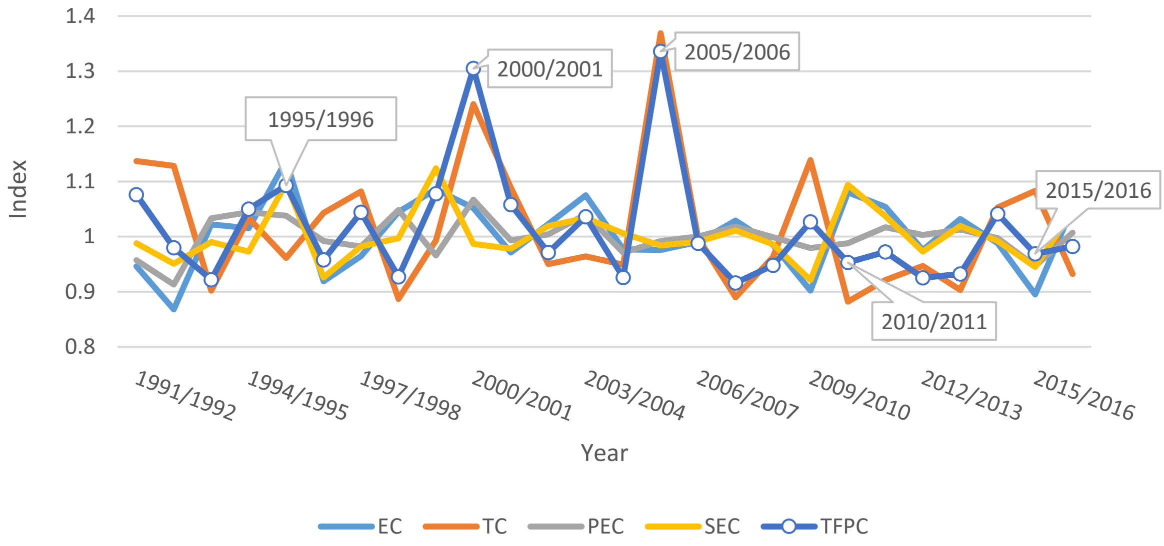


Table 5 reports the Malmquist index summary of annual geometric means when the year 1990/91 is set as the base reference point for observing the annual changes. It presents our results for the model where total productivity change index is decomposed into efficiency change (EC), technical change (TC), pure efficiency change (PEC), scale efficiency change (SEC), and total factor productivity change (TFPC). The results indicate that the sector experienced an average TFP growth rate of 1.1% p.a. over the whole sample period. Tellingly, the index decomposition shows that TFP which wanders through the sample period. Efficiency change also meanders considerably mirroring the pattern of TFP change. The indices for average productivity growth show that average technical changes account for most of the growth in productivity compared to efficiency change and its decomposition into pure efficiency change and scale efficiency change.

Table 5: Model 1 (Average Annual Total Factor Productivity Change and its Components)

Year	EC	TC	PEC	SEC	TFPC
1991/1992	0.946	1.137	0.957	0.988	1.076
1992/1993	0.868	1.128	0.913	0.951	0.980
1993/1994	1.022	0.902	1.033	0.99	0.922
1994/1995	1.015	1.034	1.044	0.973	1.050
1995/1996	1.138	0.961	1.038	1.097	1.093
1996/1997	0.919	1.043	0.992	0.926	0.958

1997/1998	0.965	1.082	0.982	0.982	1.044
1998/1999	1.045	0.887	1.048	0.997	0.927
1999/2000	1.086	0.993	0.966	1.124	1.078
2000/2001	1.052	1.24	1.067	0.987	1.305
2001/2002	0.971	1.089	0.993	0.978	1.058
2002/2003	1.023	0.95	1.004	1.019	0.971
2003/2004	1.075	0.964	1.04	1.034	1.036
2004/2005	0.977	0.949	0.971	1.006	0.926
2005/2006	0.976	1.369	0.992	0.984	1.336
2006/2007	0.99	0.998	1	0.991	0.988
2007/2008	1.029	0.89	1.018	1.011	0.916
2008/2009	0.985	0.963	0.999	0.986	0.948
2009/2010	0.902	1.139	0.979	0.921	1.027
2010/2011	1.08	0.882	0.988	1.094	0.953
2011/2012	1.054	0.921	1.017	1.037	0.972
2012/2013	0.976	0.947	1.003	0.973	0.925
2013/2014	1.032	0.903	1.013	1.019	0.932
2014/2015	0.988	1.053	0.997	0.992	1.041
2015/2016	0.895	1.083	0.947	0.945	0.969
2016/2017	1.053	0.932	1.007	1.046	0.982
Mean	**1.000**	**1.011**	**1.000**	**1.001**	**1.011**

Table 6 presents our results for the average of each price control periods as sub-periods 1990/91-1994/95, 1995/96-1999/2000, 2000/01-2004/05, 2005/06-2009/10, 2010/11-2014/15 and 2015/16-2016/17. The first, second, third, fourth and fifth sub-periods represent corresponding distribution price controls and the last sub-period corresponds to first part of the current RIIO price controls. The first distribution price control review (DPCR0)[37] was put in place by the government and executed by the Department of Energy at the time of restructuring, and permitted price increases that ranged up to 2.5 percentage points above the inflation rate (Offer, 1994)[38]. In August 1994, for the second distribution price control review (DPCR1/2) for 1995/96–1999/2000 (which was reopened in 1996), Offer introduced reductions averaging 14 per cent in final electricity prices to take effect in the first year. Distribution charges were, thereafter, required to fall by an X-factor of 2 per cent p.a. in real terms for the duration of the price control review. The third price control review (DPCR3) for 2000/01–2004/05 introduced further cuts on distribution businesses averaging 3 per cent for the next 5 years, with an initial cut in RECs' distribution revenue by about 23.4 per cent. This amounted to an overall initial

[37] See Ofgem (2009) for a good summary of the price control periods.
[38] Price controls on the RECs' supply businesses only allowed price rises limited to no more than inflation during the period 1990/1991–1994/1995.

revenue cut of £503 million at 1995 prices (Ofgem, 1999a). In April 2005, the fourth price control review (DPCR4) was introduced when prices were allowed to increase in line with inflation (i.e. X = 0). It allowed for investment of £5.7 billion over the years 2005 – 2010 to deliver improved performance and represented a significant increase in capital expenditure (Ofgem, 2004). The fifth distribution price control review (DPCR5) was introduced in April 2010 and allowed the DNOs a 20 per cent increase (or £2.3bn) on expenditure in DPCR4. This represents an 8 per cent (or £1.3bn) reduction from the forecasts in the DNOs' business plans (Ofgem, 2009). The current network price control (RIIO-ED1) runs for eight years, from 2015-2023. Slow-track DNOs will be able to spend around £17bn over the period to renew, maintain and operate their networks (Ofgem, 2014).

Table 6: Model 1 (Distribution Price Control Review period)

DPCR	EC	TC	PEC	SEC	TFPC
0	0.961	1.046	0.985	0.975	1.005
1/2	1.028	0.991	1.005	1.023	1.018
3	1.019	1.033	1.014	1.005	1.052
4	0.976	1.059	0.998	0.978	1.033
5	1.025	0.939	1.004	1.022	0.964
RIIO-ED1	0.971	1.005	0.977	0.994	0.975
Whole Period	**1.000**	**1.011**	**1.000**	**1.001**	**1.011**

Taking the geometric average over all the 14 DNOs and price control sub-periods, the results from the base model suggest that the sector achieved the highest average productivity gains of 5.2% during the third distribution price control review period, which was higher than the average annual productivity growth for the whole period. This is followed by the fourth and second distribution price control review periods with an average productivity growth rate of 3.3% and 1.8% respectively. No appreciable productivity growth was recorded in the first price control period. However, the average productivity declined by -3.6% in the fifth price control period occasioned by reduction in technical change. This result strongly suggests that the transition to the fifth price control had at least a short term detrimental impact on productivity growth. Furthermore, this transition effect did not rapidly disappear. Productivity growth was also significantly dampened in the current price control period as the negative TFP growth from the preceding period affects the efficiency change and productivity change into the RIIO-ED1 period.

Table 7: Model 2 (Average Annual Total Factor Productivity Change and its Components)

Year	EC	TC	PEC	SEC	TFPC
1991/1992	0.942	1.124	0.96	0.982	1.059
1992/1993	1.008	0.977	1.034	0.975	0.985
1993/1994	0.941	1.064	0.951	0.99	1.001
1994/1995	1.047	0.972	1.058	0.989	1.017
1995/1996	1.097	0.984	1.03	1.065	1.079
1996/1997	0.98	1.022	0.99	0.99	1.001
1997/1998	0.966	1.041	0.993	0.972	1.006
1998/1999	1.089	0.945	1.039	1.049	1.03
1999/2000	0.97	1.083	0.975	0.996	1.05
2000/2001	0.999	1.175	1	0.999	1.174
2001/2002	0.986	1.05	0.983	1.003	1.035
2002/2003	1.031	0.968	1.023	1.007	0.998
2003/2004	1.037	0.983	1.018	1.018	1.019
2004/2005	0.994	0.99	0.989	1.005	0.984
2005/2006	0.992	1.286	0.993	0.999	1.276
2006/2007	0.982	0.999	0.998	0.984	0.981
2007/2008	1	0.945	1	1.001	0.945
2008/2009	0.986	0.974	0.997	0.989	0.96
2009/2010	0.938	1.1	0.986	0.952	1.032
2010/2011	1.077	0.887	1.014	1.062	0.956
2011/2012	1.027	0.983	1.006	1.021	1.01
2012/2013	0.999	0.968	1.005	0.994	0.967
2013/2014	1.007	0.943	1.008	1	0.95
2014/2015	0.994	1.068	0.997	0.998	1.062
2015/2016	0.941	1.11	0.959	0.982	1.045
2016/2017	1.01	0.955	1.002	1.008	0.965
Mean	**1.001**	**1.020**	**1**	**1.001**	**1.020**

As mentioned earlier, in order to take into account quality of service, we incorporate customer minutes lost and customer interruptions into Model 2. Table 7 reports an increase in total factor productivity growth rate when we account for quality of service, as average TFP grows at the rate of 2.0% p.a. This result suggests the incentives for quality of service improve overall productivity performance significantly.

Comparing the models from the standpoints of price control periods, it is noteworthy to mention in Table 8 that TFP increased significantly in the first, second and current price control periods relative to Model 1. Model 2 also shows that the TFP growth in the current RIIO-ED1 period is positive as opposed to negative growth recorded in Model 1. Similar to Model 1, the fifth period experienced negative productivity growth rate of 1.2%.

Table 8: Model 2 (Distribution Price Control Review period)

DPCR	EC	TC	PEC	SEC	TFPC
0	0.983	1.032	1.000	0.984	1.015
1/2	1.019	1.014	1.005	1.014	1.033
3	1.009	1.031	1.002	1.006	1.040
4	0.979	1.054	0.995	0.985	1.032
5	1.020	0.968	1.006	1.015	0.988
RIIO-ED1	0.975	1.030	0.980	0.995	1.004
Whole Period	1.001	1.020	1.000	1.001	1.020

Although with a relative shorter sample period as result of missing data, a further adjustment for energy losses and service quality in Model 3 reveals a marked upward trajectory in the sector's productivity gains, with a TFP growth rate of 1.9% p.a. over the sample period as reported in Table 9.

Table 9: Model 3 (Average Annual Total Factor Productivity Change and its Components)

Year[39]	EC	TC	PEC	SEC	TFPC
1991/1992	0.986	1.06	0.992	0.994	1.045
1992/1993	1.002	1.006	1.003	1	1.009
1993/1994	1.003	1.013	0.996	1.007	1.016
1994/1995	1.012	1.007	1.016	0.996	1.019
1995/1996	1.013	1.025	1.005	1.008	1.038
1996/1997	0.987	1.012	0.996	0.991	0.999
1997/1998	1.011	1.012	1.004	1.007	1.024
1998/1999	1.002	1.006	1	1.002	1.009
1999/2000	1	1.025	1	1	1.025
2000/2001	0.994	1.121	1	0.994	1.114
2001/2002	0.969	1.111	0.984	0.985	1.076
2002/2003	1.03	0.991	1.011	1.019	1.021
2003/2004	1.001	1.007	1.003	0.998	1.008
2004/2005	0.987	1.022	0.988	0.999	1.008
2015/2016	1.009	1.131	1.007	1.002	1.141
2016/2017	0.997	0.974	0.997	1	0.971
Mean	**1.000***	**1.019***	**1.000***	**1.000***	**1.019***

*Mean accounts for missing years.

[39] Due to missing data from 2005/06 to 2014/15, the productivity change is between 2004/05 and 2015/16.

Meanwhile, dimensioning the TFP growth rate by price control regime, Table 10 shows that all the price control sub-periods experienced positive the productivity growth. However we need to adjust for the fact that the data for 2015/16 is measured relative to 2004/05 in calculating the averages for the whole period, and we cannot attribute particular growth to RIIO-ED1 due to missing data. Similar improvement in average TFP growth was recorded in the third distribution price control review period as under Model 1 and Model 2. Table 10 does look at the whole period correcting for the missing years.

Table 10: Model 3 (Distribution Price Control Review period)

DPCR	EC	TC	PEC	SEC	TFPC
0	1.001	1.021	1.002	0.999	1.022
1/2	1.003	1.016	1.001	1.002	1.019
3	0.996	1.049	0.997	0.999	1.045
Whole Period	**1.000**	**1.019**	**1.000**	**1.000**	**1.019**

The inclusion of peak demand as an additional output variable in Model 4 for the available sample periods leads to an overall negative average annual TFP growth rate of -0.2% over the sample periods as report in Table 11.

Table 11: Model 4 (Average Annual Total Factor Productivity Change and its Components)

Year	EC	TC	PEC	SEC	TFPC
2011/2012	1.027	0.983	1.006	1.021	1.009
2012/2013	0.999	0.965	1.005	0.994	0.964
2013/2014	1.007	0.935	1.008	1.000	0.942
2014/2015	0.995	1.067	0.997	0.998	1.062
2015/2016	0.942	1.113	0.962	0.980	1.049
2016/2017	1.009	0.956	1.005	1.005	0.965
Mean	**0.996**	**1.001**	**0.997**	**0.999**	**0.998**

The results for TFP growth rate by price control period in Table 12 shows no substantial growth in average TFP in the sector relative to Model 2. Spanning just only two sub-periods, the sector recorded an average productivity growth rate of -0.7% in the fifth distribution price control review period but the RIIO period still maintains a marginally positive TFP growth rate.

Table 12: Model 4 (Distribution Price Control Review period)

DPCR	EC	TC	PEC	SEC	TFPC
5	1.007	0.986	1.004	1.003	0.993
RIIO-ED1	0.975	1.032	0.983	0.992	1.006
Whole Period	0.996	1.001	0.997	0.999	0.998

Model 5 which is a variant of Model 4 that adds customer satisfaction. Table 13 indicates that the sector's productivity is marginally positive, over the period for which we have data, with TFP growth of 0.9% p.a. This reflects the fact that performance is marginally improved by the inclusion of improving customer satisfaction figures.

Table 13: Model 5 (Average Annual Total Factor Productivity Change and its Components)

Year	EC	TC	PEC	SEC	TFPC
2013/2014	1.004	0.952	1.002	1.002	0.956
2014/2015	0.995	1.07	0.997	0.998	1.064
2015/2016	0.941	1.116	0.962	0.978	1.051
2016/2017	1.01	0.959	1.005	1.005	0.968
Mean	**0.987**	**1.022**	**0.991**	**0.996**	**1.009**

Finally, the sector witnessed average TFP growth rate in the two sub-periods of 0.9%, for the fifth and RIIO distribution price control review periods at the current price review, see Table 14. Though we note that both of these sub-periods do not cover entire price control periods.

Table 14: Model 5 (Distribution Price Control Review period)

DPCR	EC	TC	PEC	SEC	TFPC
5	0.999	1.009	0.999	1.000	1.009
RIIO-ED1	0.975	1.035	0.983	0.991	1.009
Whole Period	**0.987**	**1.022**	**0.991**	**0.996**	**1.009**

To enhance clear comparison across models, Table 15 summarises the TFP growth rate of all the models estimated while Table 16 highlights the TFP growth rate based on distribution price control periods. Overall, Model 2 records the highest average annual total factor productivity growth among the five models estimated for the electricity distribution network, with a growth rate of 2.1% p.a. over the whole period. Interestingly, the inclusion of additional variables to the basic model appears to marginally drive up the average annual total factor productivity growth, although the additional data covers fewer sample periods. Average productivity growth rate is consistently positive and appreciably higher in the third price control period relative to others. The inclusion of additional quality and output variables results in positive TFP growth rate in the current price control regime.

Table 15: Average Annual TFPC and its Components for Models 1-5

Year	TFPC-M1	TFPC-M2	TFPC-M3	TFPC-M4	TFPC-M5
1991/1992	1.076	1.059	1.045		
1992/1993	0.980	0.985	1.009		
1993/1994	0.922	1.001	1.016		
1994/1995	1.050	1.017	1.019		
1995/1996	1.093	1.079	1.038		
1996/1997	0.958	1.001	0.999		
1997/1998	1.044	1.006	1.024		
1998/1999	0.927	1.03	1.009		
1999/2000	1.078	1.05	1.025		
2000/2001	1.305	1.174	1.114		
2001/2002	1.058	1.035	1.076		
2002/2003	0.971	0.998	1.021		
2003/2004	1.036	1.019	1.008		
2004/2005	0.926	0.984	1.008		
2005/2006	1.336	1.276			
2006/2007	0.988	0.981			
2007/2008	0.916	0.945			
2008/2009	0.948	0.96			
2009/2010	1.027	1.032			
2010/2011	0.953	0.956			
2011/2012	0.972	1.01		1.009	
2012/2013	0.925	0.967		0.964	
2013/2014	0.932	0.95		0.942	0.956
2014/2015	1.041	1.062		1.062	1.064
2015/2016	0.969	1.045	1.141	1.049	1.051
2016/2017	0.982	0.965	0.971	0.965	0.968
Mean	**1.011**	**1.020**	**1.019**	**0.998**	**1.009**

*M1= Model 1, M2= Model 2, M3=Model 3, M4=Model 4, M5=Model5

Table 16: TFPC by Price Control Periods Models 1-5

DPCR	TFPC-M1	TFPC-M2	TFPC-M3	TFPC-M4	TFPC-M5
0	1.005	1.015	1.022		
1/2	1.018	1.033	1.019		
3	1.052	1.040	1.045		
4	1.033	1.032			
5	0.964	0.988		0.993	1.009
RIIO-ED1	0.975	1.004		1.006	1.009
Whole Period	**1.011**	**1.020**	**1.019****	**0.998**	**1.009**

*M1= Model 1, M2= Model 2, M3=Model 3, M4=Model 4, M5=Model 5

** This figure does cover the whole period.

In addition to the annual TFP growth values, looking at the whole period we notice that the electricity distribution sector shows a TFP growth rate of 34% (period 1990/91-2016/17) using Model 1. With the addition of quality attributes in Model 2 the comparable growth rate is around 69%. Looking at Model 3, we have a growth rate of 49% for the period 1990/91-2004/05 and a rate of only 11% for the periods that involve RIIO-ED1. A negative aggregate TFP growth rate of 1.5% is observed in Model 4 for the period 2011-2017, when controlling for peak demand. Finally, in Model 5 the aggregate growth rate is still positive but not significant.

6. Analysis of Gas Distribution Efficiency

6.1 Data and Model Specifications

In line with the previous TFP analysis, the choice of variables is based on the availability of data, the discussion of the current literature for gas distribution and on Ofgem's own use of outputs and inputs. The descriptive statistics for the gas data are given in Appendix Table A2. The data was supplied by Ofgem for the 8 gas distribution network operators in Great Britain for the period 2008/09 - 2016/17[40]. Table 17 summarises the three models proposed for the TFP analysis.

[40] The availability of data for gas distribution varies for different periods (i.e. capex/opex data is available from the period 2002/03 – 2016/17 while network length from 2008/09-2016/17 only. This explains the use of a shorter period for the TFP analysis in this case.

Table 17: Models for Gas Distribution

Model	Non-quality variables					Quality variables			Period
	opex	capex	Cust	UnitsD	NL	CML	CI	CS	
Model 1	I	I	O	O	O				2008/09-2016/17
Model 2	I	I	O	O	O	I	I		2008/09-2016/17
Model 3	I	I	O	O	O	I	I	O	2008/09-2016/17

I: input, O: output, Cust: # of customers, UnitsD: units of gas distributed, NL: network length, CML: customer minutes lost (total), CI: customer interruptions (total), CS: customer satisfaction

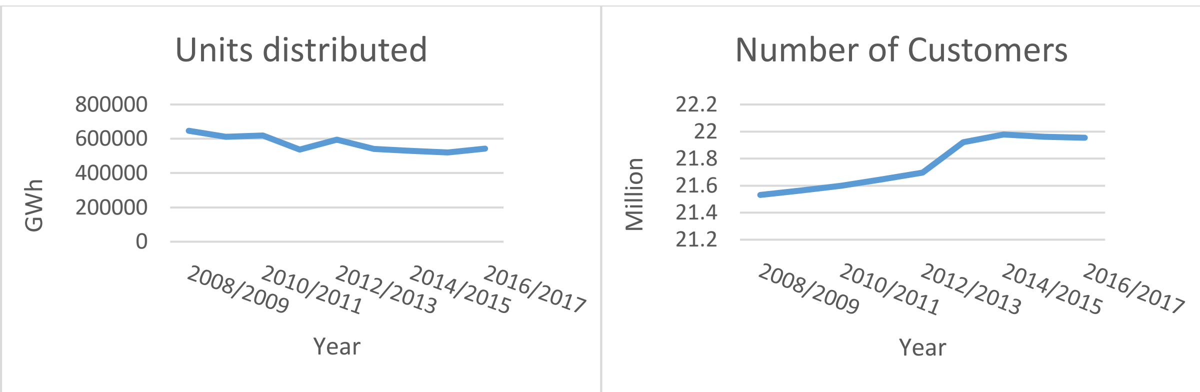
6.2 Outputs

The output variables used for the gas distribution network productivity analysis are units of gas distributed, number of customers and network length, as obtained from Ofgem. The units of gas distributed is measured in GWh and network length measured in Km. The data were supplied for the 8 gas distribution network operators in Great Britain. Fig. 8 shows the annual evolution of the output variables: energy distributed, number of customers and network length.

6.3 Inputs

Similar to electricity distribution, we use monetary values of inputs i.e. operating expenditure (OPEX) and capital expenditure (CAPEX). The variables are treated separately as inputs and are deflated annually by the retail price index (RPI). Fig. 9 shows the annual evolution of the input variables.

Fig. 8: Annual evolution of outputs for the gas distribution sector



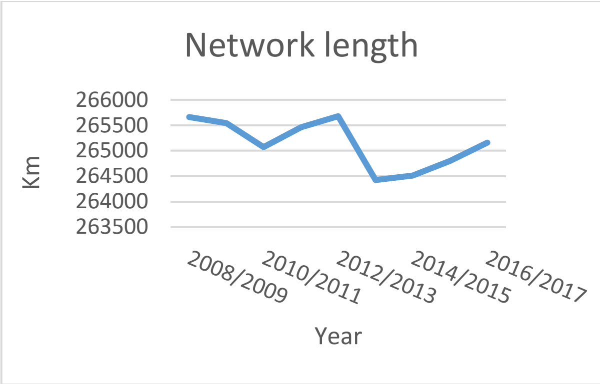
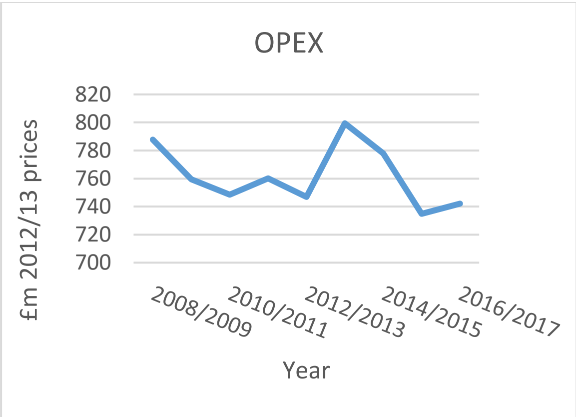
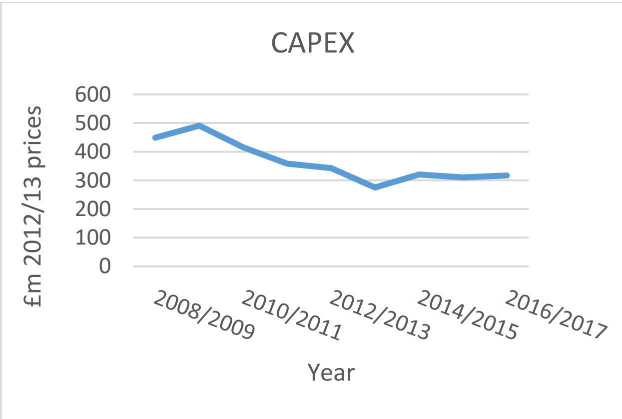


Fig. 9: Annual evolution of inputs for the gas distribution sector





6.4 Other Variables

We consider the continuity dimension of quality by applying quality of service variables such as total customer interruptions and total customer minutes lost. These are measures of security of supply and availability of supply. We also have a measure of customer satisfaction. As for electricity distribution we scale the measure of customer satisfaction in order to include it in the DEA (by multiplying customer satisfaction by number of customers)[41]. Once again lower values of customer interruptions and customer minutes lost and higher values of customer satisfaction, ceteris paribus, imply higher productivity.

[41] Customer minutes lost and number of interruptions figures for gas distribution are total values and do not need additional scaling.

6.5 TFP results

TFP growth estimates are obtained from the estimated DEA model by employing a Malmquist productivity index over the period 2008/09–2016/17 without controlling for quality variables in Model 1. The data covers two price control periods for gas distribution: GDPCR1 (2008/09-2012/13) and RIIO-GD1 (2013/14-2020/21). Model 2 extends the basic model to include customer minutes lost and customer interruptions. Model 3 is an extension of Model 2 adds a scaled measure of customer satisfaction. Fig. 10 reports the annual averages of the gas distribution network firm specific TFP estimates and their decomposition into technical change, efficiency change, pure efficiency change and a scale efficiency change. Scale efficiency change has consistently had the least impact, among the components, on productivity growth.

Fig. 10: Average Annual Total Factor Productivity Change and its Components

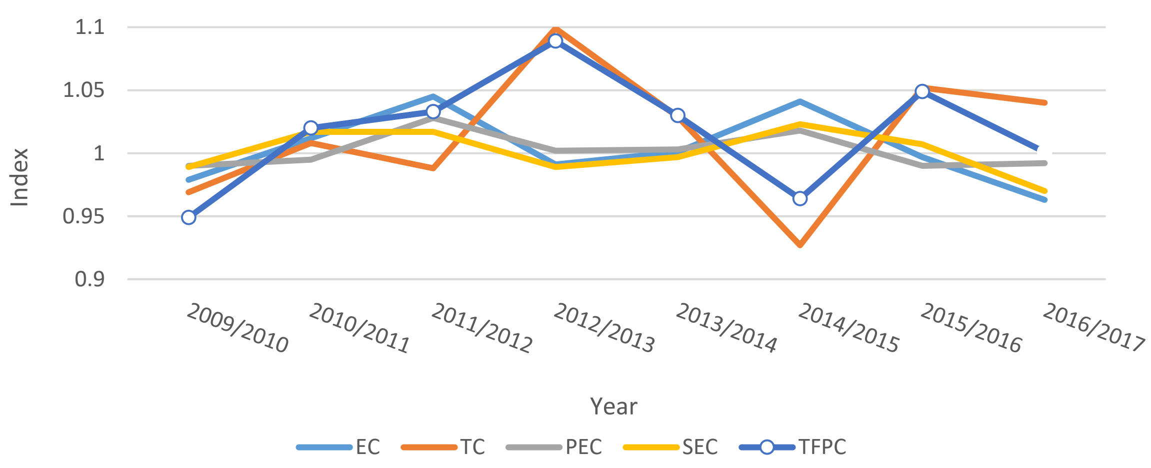


Table 18 shows an annual average of the productivity growth rate of 1.6% for the gas distribution industry over the sample period using Model 1. The index decomposition shows that TFP which has been relatively stable through the sample period, with technical change being the main driver of productivity growth.

Table 18: Model 1 (Average Annual Total Factor Productivity Change and its Components)

Year	EC	TC	SEC	PEC	TFPC
2009/2010	0.979	0.969	0.990	0.989	0.949
2010/2011	1.012	1.008	0.995	1.017	1.020
2011/2012	1.045	0.988	1.028	1.017	1.033

2012/2013	0.991	1.099	1.002	0.989	1.089
2013/2014	1.001	1.029	1.003	0.997	1.030
2014/2015	1.041	0.927	1.018	1.023	0.964
2015/2016	0.997	1.052	0.990	1.007	1.049
2016/2017	0.963	1.040	0.992	0.970	1.001
Mean	**1.003**	**1.013**	**1.002**	**1.001**	**1.016**

As shown in Table 19, there has been a slowdown in productivity from the first price control period covered by the data to the second.

Table 19: Model 1 (Distribution Price Control Review period)

GDPCR	EC	TC	PEC	SEC	TFPC
GDPCR1	1.006	1.015	1.004	1.003	1.022
RIIO-GD1	1.000	1.011	1.001	0.999	1.010
Whole Period	1.003	1.013	1.002	1.001	1.016

Controlling for quality of service in the gas distribution network, we incorporate customer minutes lost and customer interruptions into Model 1. Table 20 reports that the sector experiences productivity change with a TFP growth rate of 0.7% p.a. over the whole period. This indicates a significant decrease in total factor productivity growth rate when quality of services is accounted for relative to base model with an annual TP growth of 1.6%. The reduction in productivity change was occasioned by the cumulative effects of declining growth of technical change, scale efficiency change and efficiency change. This might be due to dispersion in the quality of services between gas distribution companies.

Table 20: Model 2 (Average Annual Total Factor Productivity Change and its Components)

Year	EC	TC	PEC	SEC	TFPC
2009/2010	0.980	0.928	1.014	0.966	0.910
2010/2011	1.059	0.937	1.016	1.042	0.992
2011/2012	1.019	1.030	0.999	1.020	1.049
2012/2013	0.981	1.083	0.986	0.995	1.063
2013/2014	0.987	1.028	1.011	0.976	1.014
2014/2015	1.034	0.939	1.003	1.030	0.971
2015/2016	0.977	1.070	0.996	0.981	1.045
2016/2017	0.980	1.040	0.983	0.997	1.019
Mean	**1.002**	**1.005**	**1.001**	**1.001**	**1.007**

Table 21 shows a significant improvement in productivity growth rate across the sub-periods. This improvement is largely attributed to technical change, especially during the current RIIO-GD1when the technical change (TC) experiences a growth rate of 1.8% p.a. which was sufficient enough to counteract the reduction in average efficiency change between the two periods.

Table 21: Model 2 (Distribution Price Control Review period)

GDPCR	EC	TC	PEC	SEC	TFPC
GDPCR1	1.009	0.992	1.004	1.005	1.002
RIIO-GD1	0.994	1.018	0.998	0.996	1.012
Whole Period	1.002	1.005	1.001	1.001	1.007

Adjusting for customer satisfaction, the model leaves productivity with an increase growth rate of 1.1% p.a. as shown in Table 22 and Table 23. The improvement in technical change in both, the past and especially the current RIIO-GD1 period made a positive contribution to TFP growth for the period 2009/10-2016/17.

Table 22: Model 3 (Average Annual Total Factor Productivity Change and its Components)

Year	EC	TC	PEC	SEC	TFPC
2009/2010	0.98	0.931	1.014	0.966	0.913
2010/2011	1.059	0.936	1.016	1.042	0.991
2011/2012	1.02	1.046	1	1.02	1.067
2012/2013	0.981	1.085	0.986	0.995	1.064
2013/2014	0.987	1.037	1.011	0.976	1.023
2014/2015	1.034	0.942	1.003	1.03	0.973
2015/2016	0.977	1.075	0.996	0.981	1.05
2016/2017	0.98	1.04	0.983	0.997	1.019
Mean	**1.002**	**1.01**	**1.001**	**1.001**	**1.011**

Table 23: Model 3 (Distribution Price Control Review period)

GDPCR	EC	TC	PEC	SEC	TFPC
GDPCR1	1.009	0.997	1.004	1.005	1.007
RIIO-GD1	0.994	1.022	0.998	0.996	1.016
Whole Period	**1.002**	**1.01**	**1.001**	**1.001**	**1.011**

For brevity, Table 24 reports the average annual TFP growth rate for the three models estimated for gas distribution companies, while Table 25 presents a snapshot of the TFP growth rate by distribution price control periods. Given the trends in technical change, efficiency change, scale change and total factor productivity change across the estimated models, the addition of quality of service has a significant negative impact of TFP growth, while the further addition of customer satisfaction causes overall productivity growth to improve.

Table 24: Average Annual TFPC and its Components for Models 1-3

Year	TFPC-M1	TFPC-M2	TFPC-M3
2009/2010	0.949	0.910	0.913
2010/2011	1.020	0.992	0.991
2011/2012	1.033	1.049	1.067
2012/2013	1.089	1.063	1.064
2013/2014	1.030	1.014	1.023
2014/2015	0.964	0.971	0.973
2015/2016	1.049	1.045	1.05
2016/2017	1.001	1.019	1.019
Mean	**1.016**	**1.007**	**1.011**

*M1= Model 1, M2= Model 2, M3=Model3

Table 25: TFPC by Price Control Periods Models 1-3

DPCR	TFPC-M1	TFPC-M2	TFPC-M3
GDPCR1	1.022	1.002	1.007
RIIO GD1	1.010	1.012	1.016
Whole Period	**1.016**	**1.007**	**1.011**

*M1= Model 1, M2= Model 2, M3=Model3

Finally, in terms of the whole period, a TFP growth rate of 13.5% is observed for the gas distribution market over the period 2008/09-2016/17 for Model 1. For Model 2 which includes two quality variables in comparison Model 1, there is positive growth of around 5.5%. Finally in Model 3, which includes one additional quality variable, customer satisfaction, we have a higher TFP growth of 9.4% over the period.

7. Analysis of Electricity Transmission Efficiency

7.1 Data and Model Specifications

The selection of the variables for our study of electricity transmission is based on the availability of data and the current literature. The summary statistics of the variables used in this section are reported in the Appendix, Table A3. The data was supplied by Ofgem for the 3 electricity transmission network companies in Great Britain (NGET, SPET and SHETL) for the period 2000/01-2016/17. This data covers the price control periods TPCR3 (2001-07, TPCR4 (2007-13)[42] and RIIO-ET1 (2013-21). Due to the small number of electricity transmission companies involved in the analysis and the fact that the companies are not comparable in size (NGET is very much bigger than both SPET and SHETL), the data was aggregated together to analyse overall industry performance (i.e. one aggregate firm evolving through time).

We specify three different types of DEA models, which employ different combinations of the variables. Model 1 is the basic model which comprises of two outputs: energy transmitted and network total length; and two inputs: opex and capex. Model 2 extends the basic model by including energy not transmitted as an additional input, thereby specifying two outputs and three inputs. In Model 3 we include one more output represented by maximum demand and one more input represented by system non-availability, with a total of three outputs and four inputs. Table 26 summarises the three models used in our TFP analysis[43].

Table 26: Models for Electricity Transmission

Model	Non-quality variables					Quality variables		Periods
	opex	capex	ET	NL	MaxD	ENS	SNA	
Model 1	I	I	O	O				2000/01-2016/17
Model 2	I	I	O	O		I		2000/01-2016/17
Model 3	I	I	O	O	O	I	I	2000/01-2016/17

I: input, O:output, ET: energy transmitted, NL: network length, MaxD: Max. demand, ENS: energy not supplied, SNA: system non-availability

7.2 Outputs

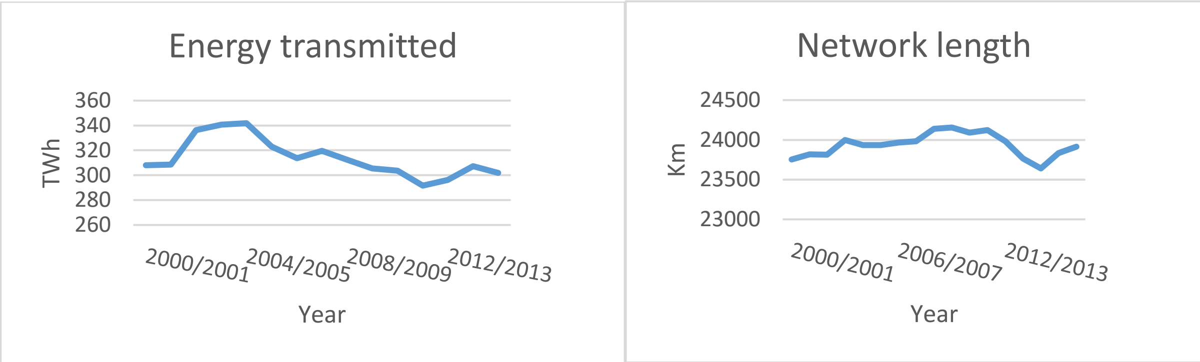
The output variables used for the electricity transmission network performance analysis are units transmitted and network total length. This parallels what we have done for electricity distribution. Energy transmitted is measured in Terawatt hours (TWh) and network length is

[42] We take the price control periods for NGET as defining our price control periods as this covers the majority of the sector.

[43] Similar to gas distribution, the availability of data for this sector varies considerably. While we do have opex data for the the period 1990/91 – 2016/17, network length is only available for 2000/01-2016/17. This explains the use of a shorter period for the TFP analysis.

measured in Km. Fig. 11 shows the trends in the main output variables: energy transmitted and network length.

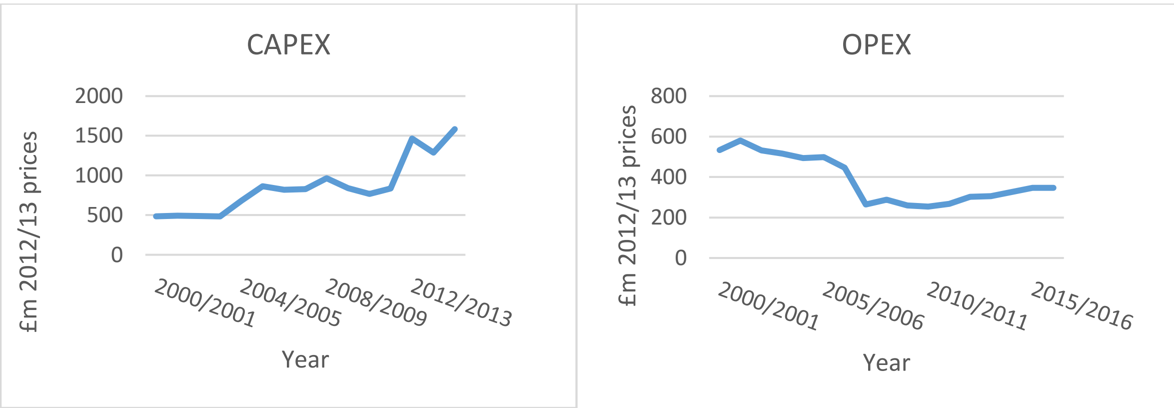
Fig. 11: Annual evolution of outputs for electricity transmission sector



7.3 Inputs

Consistent with what we have done for the other network industries, we use both operating and capital expenditure as our main inputs. The variables are normalized by Retail Price Index to 2012/13 prices. Fig. 12 shows the trends in the input variables.

Fig. 12: Annual evolution of inputs for electricity transmission sector



7.4 Other Variables

Other variables considered in the analysis of electricity transmission network performance are energy not supplied measured in MWh and transmission system non-availability (in %) multiplied by network length expressed in Km (this can be thought of as the percentage of the network not available). Both of these quality variables are treated as inputs because they have the property that reductions in these variables, ceteris paribus, improve productivity.

7.5 TFP Results

Given that the electricity transmission network is treated as single firm, the 'company' cannot be assessed against other firms. In effect, its own efficiency against itself will be 1, although the productivity against itself overtime (technical efficiency) can be computed. Therefore, we compute TFP from the estimated DEA model by employing a Malmquist productivity index over the period 2000/01–2016/17. This computation is equivalent to the geometric mean of output and input ratios. Fig. 13 shows the average annual productivity change in Model 1 without controlling for other variables.

Fig. 13: Average Annual TFPC

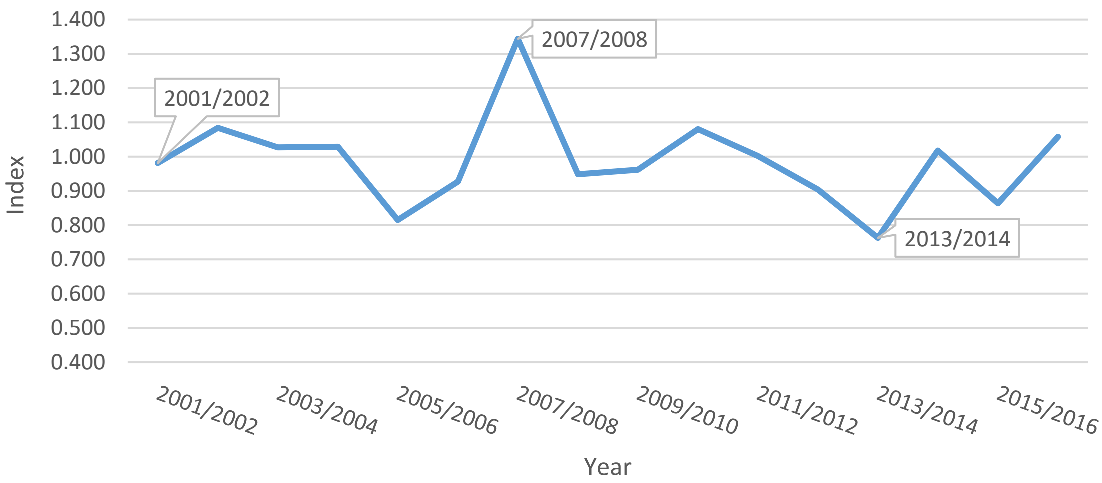


Fig. 13 shows that the productivity growth rate has the reached the highest peak between 2006/07 and 2007/08. Incidentally, this marks the boundary between the end of the third transmission price control review (TPCR3) and the beginning of the fourth price control review (TPCR4). Table 27 reports the Malmquist index summary of annual geometric means when the year 2000/2001 is set as the base reference point for observing the annual changes. Although, the estimated output reports values for the efficiency change (EC), technical change (TC), pure efficiency change (PEC), scale efficiency change (SEC), we only discuss the total factor productivity change (TFPC) as no decomposition can be observed. The results indicate that the sector experienced an average negative TFP growth rate of 2.2% p.a. over the whole sample period. We note however that we only have data since 2000/01 and not from privatisation.

Table 27: Model 1 (Average Annual Total Factor Productivity Change and its Components)

Year	EC	TC	PEC	SEC	TFPC
2001/2002	1.000	0.981	1.000	1.000	0.981
2002/2003	1.000	1.045	1.000	1.000	1.045
2003/2004	1.000	1.027	1.000	1.000	1.027
2004/2005	1.000	1.029	1.000	1.000	1.029
2005/2006	1.000	0.845	1.000	1.000	0.845
2006/2007	1.000	0.927	1.000	1.000	0.927
2007/2008	1.000	1.344	1.000	1.000	1.344
2008/2009	1.000	0.949	1.000	1.000	0.949
2009/2010	1.000	0.962	1.000	1.000	0.962
2010/2011	1.000	1.080	1.000	1.000	1.080
2011/2012	1.000	1.002	1.000	1.000	1.002
2012/2013	1.000	0.904	1.000	1.000	0.904
2013/2014	1.000	0.735	1.000	1.000	0.735
2014/2015	1.000	1.018	1.000	1.000	1.018
2015/2016	1.000	0.864	1.000	1.000	0.864
2016/2017	1.000	1.058	1.000	1.000	1.058
Mean	**1.000**	**0.978**	**1.000**	**1.000**	**0.978**

Presenting the TFP results by transmission price control reviews, Table 28 shows that the sector only experienced positive TFP growth of 3.1% in the fourth price control review period. However, negative growth in the third and the current periods strongly influences the growth of the sector resulting in the negative TFP growth for the whole period.

Table 28: Model 1 (Transmission Price Control Review period)

TPCR	EC	TC	PEC	SEC	TFPC
TPCR3	1.000	0.973	1.000	1.000	0.973
TPCR4	1.000	1.031	1.000	1.000	1.031
RIIO-ET1	1.000	0.909	1.000	1.000	0.909
Whole Period	**1.000**	**0.978**	**1.000**	**1.000**	**0.978**

The inclusion of the energy not supplied in Model 2 substantially bolstered the overall sector TFP growth, from negative productivity growth in Model to a positive TFP growth of 6.6% as shown in Table 29. This result suggests the importance of quality variables to the determination of TFP growth in the electricity transmission sector, especially over a period which has seen a very large rise in capital expenditure.

Table 29: Model 2: (Average Annual Total Factor Productivity Change and its Components)

Year	EC	TC	PEC	SEC	TFPC
2001/2002	1.000	1.361	1.000	1.000	1.361
2002/2003	1.000	1.299	1.000	1.000	1.299
2003/2004	1.000	0.573	1.000	1.000	0.573
2004/2005	1.000	1.097	1.000	1.000	1.097
2005/2006	1.000	0.763	1.000	1.000	0.763
2006/2007	1.000	1.708	1.000	1.000	1.708
2007/2008	1.000	0.723	1.000	1.000	0.723
2008/2009	1.000	1.338	1.000	1.000	1.338
2009/2010	1.000	1.029	1.000	1.000	1.029
2010/2011	1.000	0.881	1.000	1.000	0.881
2011/2012	1.000	0.855	1.000	1.000	0.855
2012/2013	1.000	1.284	1.000	1.000	1.284
2013/2014	1.000	1.273	1.000	1.000	1.273
2014/2015	1.000	0.875	1.000	1.000	0.875
2015/2016	1.000	3.853	1.000	1.000	3.853
2016/2017	1.000	0.461	1.000	1.000	0.461
Mean	**1.000**	**1.066**	**1.000**	**1.000**	**1.066**

The positive productivity growth in the third and the current transmission price control periods in Model 2 accounts for the significant positive average annual productivity growth for whole sample period.

Table 30: Model 2 (Transmission Price Control Review period)

TPCR	EC	TC	PEC	SEC	TFPC
TPCR3	1.000	1.064	1.000	1.000	1.064
TPCR4	1.000	0.994	1.000	1.000	0.994
RIIO-ET1	1.000	1.186	1.000	1.000	1.186
Whole Period	**1.000**	**1.066**	**1.000**	**1.000**	**1.066**

Model 3 accounts for maximum demand and for system non-availability, in addition to the inputs and outputs from Model 2. The overall mean remains nearly the same for the whole period in comparison with the previous model. The positive annual TFP growth is 6.5% as shown in Table 31. However, some differences are observed in specific years, such as 2002/03, 2005/06 and 2011/12.

Table 31: Model 3 (Average Annual Total Factor Productivity Change and its Components)

Year	EC	TC	PEC	SEC	TFPC
2001/2002	1.000	1.362	1.000	1.000	1.362
2002/2003	1.000	1.325	1.000	1.000	1.325
2003/2004	1.000	0.564	1.000	1.000	0.564
2004/2005	1.000	1.097	1.000	1.000	1.097
2005/2006	1.000	0.763	1.000	1.000	0.763
2006/2007	1.000	1.708	1.000	1.000	1.708
2007/2008	1.000	0.730	1.000	1.000	0.730
2008/2009	1.000	1.338	1.000	1.000	1.338
2009/2010	1.000	1.029	1.000	1.000	1.029
2010/2011	1.000	0.888	1.000	1.000	0.888
2011/2012	1.000	0.843	1.000	1.000	0.843
2012/2013	1.000	1.248	1.000	1.000	1.248
2013/2014	1.000	1.277	1.000	1.000	1.277
2014/2015	1.000	0.882	1.000	1.000	0.882
2015/2016	1.000	3.853	1.000	1.000	3.853
2016/2017	1.000	0.459	1.000	1.000	0.459
Mean	**1.000**	**1.065**	**1.000**	**1.000**	**1.065**

Looking at individual price control review periods in Table 32, we can see that the fourth control period exhibits negative annual TFP growth in contrast to the positive growth in the other two periods.

Table 32: Model 3 (Transmission Price Control Review period)

TPCR	EC	TC	PEC	SEC	TFPC
TPCR3	1.000	1.065	1.000	1.000	1.065
TPCR4	1.000	0.994	1.000	1.000	0.994
RIIO-ET1	1.000	1.181	1.000	1.000	1.181
Whole Period	**1.000**	**1.065**	**1.000**	**1.000**	**1.065**

For ease of comparability, we present the average annual TFPC for the three models specified for electricity transmission, see Table 33. As discussed earlier, while the sector experiences large productivity gains as we move from Model 1 to Model 2, there is little difference between the Model 2 and Model 3 despite controlling for transmission system non-availability.

Table 33: Average Annual TFPC and its Components for Models 1-3

Year	TFPC-M1	TFPC-M2	TFPC-M3
2001/2002	0.981	1.361	1.362
2002/2003	1.045	1.299	1.325
2003/2004	1.027	0.573	0.564
2004/2005	1.029	1.097	1.097
2005/2006	0.845	0.763	0.763
2006/2007	0.927	1.708	1.708
2007/2008	1.344	0.723	0.730
2008/2009	0.949	1.338	1.338
2009/2010	0.962	1.029	1.029
2010/2011	1.080	0.881	0.888
2011/2012	1.002	0.855	0.843
2012/2013	0.904	1.284	1.284
2013/2014	0.735	1.273	1.248
2014/2015	1.018	0.875	0.882
2015/2016	0.864	3.853	3.853
2016/2017	1.058	0.461	0.459
Mean	**0.978**	**1.066**	**1.065**

*M1= Model 1, M2= Model 2

Table 34 reports productivity change by price control period. It shows a large TFP decline for the sector in the fourth price control when comparing Model 1 with Models 2 and 3. However, this was offset by a large productivity improvement in Models 2 and 3 in the third and current periods.

Table 34: TFPC by Price Control Periods Models 1-3

TPCR	TFPC-M1	TFPC-M2	TFPC-M3
TPCR3	0.973	1.064	1.065
TPCR4	1.031	0.994	0.994
RIIO-ET1	0.909	1.186	1.181
Whole Period	**0.978**	**1.066**	**1.065**

*M1= Model 1, M2= Model 2, M3=Model3

Looking at the whole period, using Model 1 we observed a large decline in productivity for the period 2000/01-2016/17 of -30%. This is the result from Table 27. The introduction of energy non-delivered in Model 2, produces a large improvement in productivity of 176% for the whole period[44]. In Model 3 a similar TFP growth rate is observed with the introduction of two more variables, maximum demand and system unavailability.

8. Analysis of Gas Transmission Efficiency

8.1 Data and Model Specifications

We analyse the gas transmission industry as a single firm by specifying two different types of DEA models, similar to electricity transmission. In this case the industry is made up of only one gas transmission firm, National Grid Gas (NGG). Data was provided by Ofgem for the period 2006/07-2016/17. The summary statistics for the data used are reported in the Appendix, Table A4. In terms of models, Model 1 is the basic model which comprises three outputs: actual gas flow transmitted at system entry points, actual gas NTS demand and network length. Model 2 extends the basic model by including gas shrinkage as an additional input, thereby making three outputs and three inputs. Further details about the selection of outputs, inputs and quality variables are provided in the next subsections. Table 35 summarises the models.

Table 35: Models for Gas Transmission

Model	Non-quality variables					Quality variable	Periods
	opex	capex	GT	NL	GD	GS	
Model 1	I	I	O	O	O		2006/07-2016/17
Model 2	I	I	O	O	O	I	2006/07-2016/17

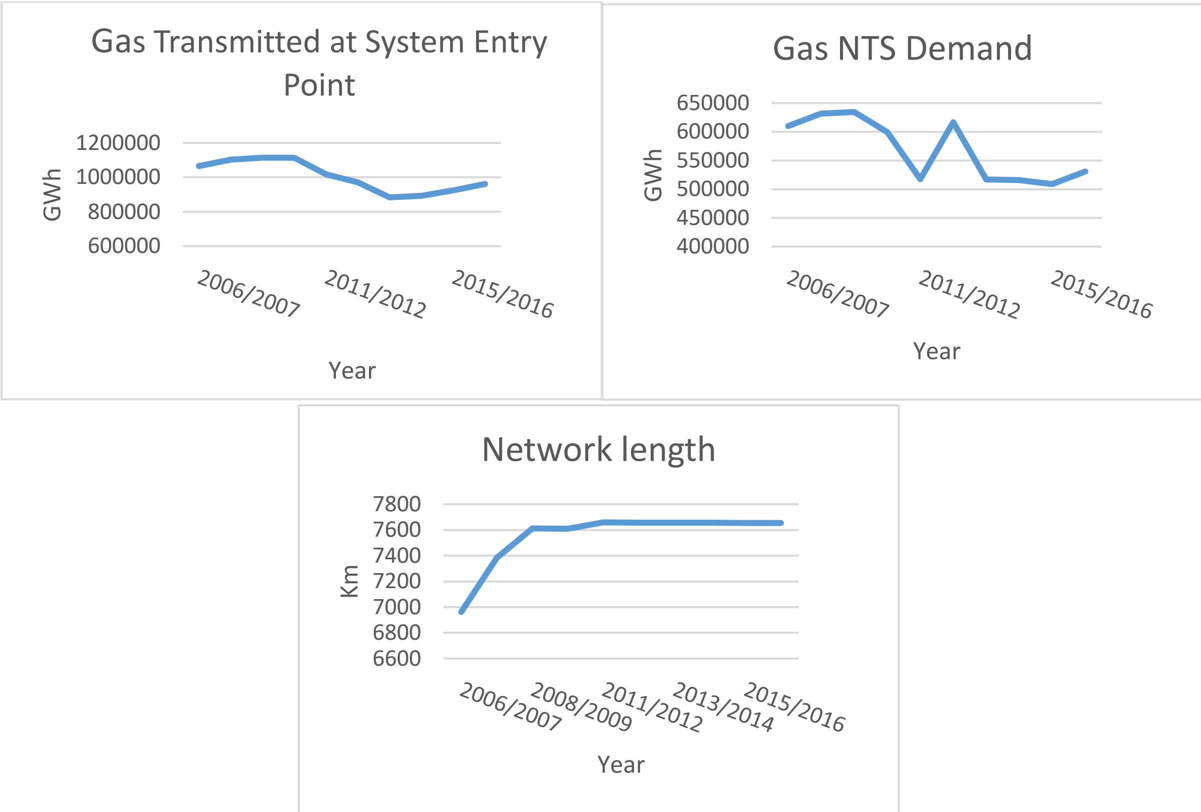
I: input, O: output, GT: gas transmitted at system entry points, NL: network length, GD: gas NTS demand, GS: gas shrinkage

8.2 Outputs

Actual gas flow transmitted at system entry points, actual gas NTS demand and network length are the outputs for the analysis of total factor productivity of the gas transmission network. Gas flow transmitted at system entry points (which includes throughput of gas to other countries, including Ireland) and gas NTS demand (which is GB demand for gas) are measured in GWh. These display a decline followed by a mild upward trend in recent years. Total network length is measured in Km. Fig. 14 shows network length has remained constant in recent years.

[44] Looking at the trend in energy not supplied, the 2015/16 figures show a very low value, 20.02 MWh in comparison with the previous year (2014/15: 374.19 MWh) and for one year later (2016/17: 105.01 MWh). This produces an annual average TFP growth rate of 385% (see Table 29) which may be influencing the TFP growth rate for the whole period.

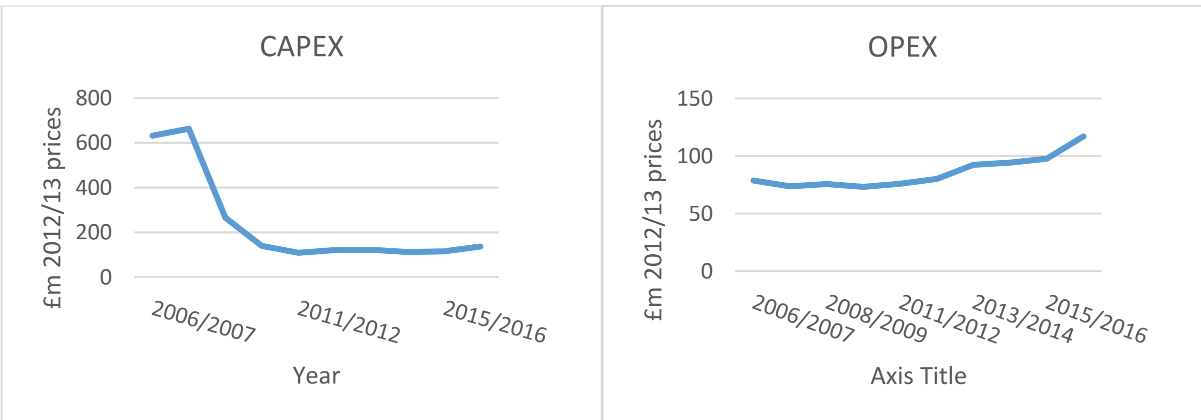
Fig. 14: Annual evolution of inputs for the gas transmission sector



8.3 Inputs

Instead of using physical measures inputs of gas transmission network such as length of pipelines, number of employees and transformer capacity, we use monetary operating expenditure (OPEX), capital expenditure (CAPEX) deflated using 2012/2013 prices as they are readily available from Ofgem. Fig. 15 reveals that there is a downward trend in CAPEX while OPEX has been on the increase over the sample period.

Fig. 15: Annual evolution of inputs for the gas transmission sector



8.4 Other Variables

The only quality variable we obtained for the gas transmission system was gas shrinkage (due to compressor fuel use, calorific value shrinkage and unaccounted for gas)[45]. The variable is measured in GWh and it is treated as an input in the DEA as less shrinkage, ceteris paribus, is associated with a higher level of productivity.

8.5 TFP Results

Similar to our approach to productivity analysis of electricity transmission network, we treat the gas transmission network as a sole decision making unit (DMU) in the DEA model and we only report the total factor productivity as a change against itself over time. The TFP from the DEA model was computed by employing a Malmquist productivity index over the period 2006/07–2016/17. The data spans two gas transmission price control periods: 2007/08-2012/13 (TPCR4); and 2013/14-2020/21 (RIIO-GT1). Due to missing data, the year 2010/11 is omitted from the analysis. Fig. 16 shows the average annual productivity change for Model 1 without controlling for quality.

Fig. 16: Average Annual TFPC

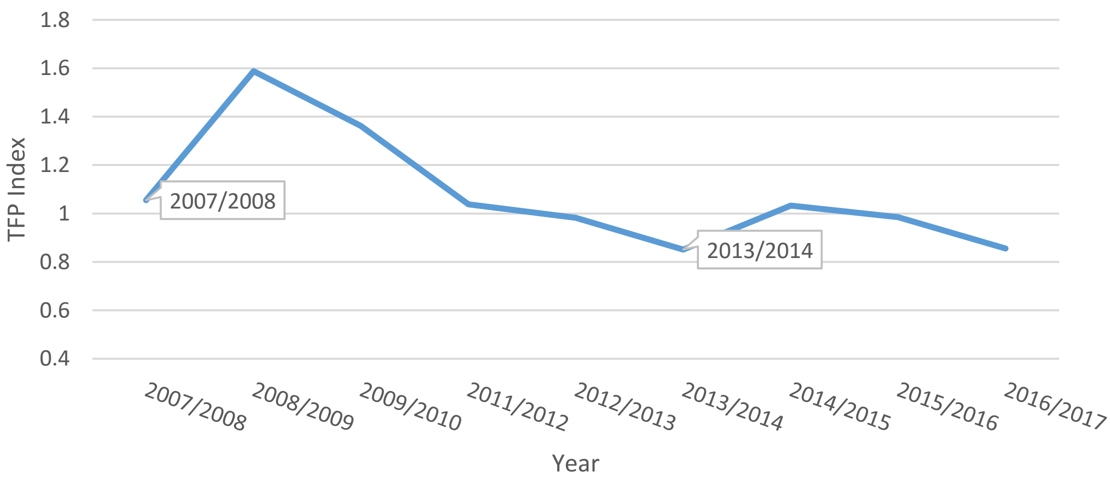


Fig. 16 shows that the productivity growth rate has been sloping downward for nearly the entire sample period. Table 36 reports the Malmquist index summary of annual geometric means when the year 2006/2007 is set as the base period for observing the annual changes. As for electricity transmission, we only discuss the total factor productivity change (TFPC), as no

[45] See https://www.nationalgridgas.com/about-us/system-operator-incentives/nts-shrinkage

decomposition can be achieved in the case where there is only one firm to analyse. The results indicate that the sector experienced an average annual TFP growth rate of 5.6% p.a. over the whole sample period.

Table 36: Model 1 (Average Annual Total Factor Productivity Change and its components)

Year	EC	TC	PEC	SEC	TFPC
2007/2008	1.000	1.055	1.000	1.000	1.055
2008/2009	1.000	1.588	1.000	1.000	1.588
2009/2010	1.000	1.362	1.000	1.000	1.362
2011/2012	1.000	1.038	1.000	1.000	1.038
2012/2013	1.000	0.982	1.000	1.000	0.982
2013/2014	1.000	0.851	1.000	1.000	0.851
2014/2015	1.000	1.033	1.000	1.000	1.033
2015/2016	1.000	0.985	1.000	1.000	0.985
2016/2017	1.000	0.855	1.000	1.000	0.855
Mean	**1.000**	**1.056**	**1.000**	**1.000**	**1.056**

Note: Mean accounts for missing year.

It is interesting to note in Table 37 that much of the growth in the sample period was recorded in the previous transmission price control review (2007-13), averaging 15.1% productivity growth. This was not offset by a productivity slowdown in the current price control period. This large overall rise in productivity is driven by a large reduction in capex.

Table 37: Model 1 (Transmission Price Control Review period)

TPCR	EC	TC	PEC	SEC	TFPC
TPCR4	1.000	1.151	1.000	1.000	1.151
RIIO-GT1	1.000	0.928	1.000	1.000	0.928
Whole Period	**1.000**	**1.056**	**1.000**	**1.000**	**1.056**

Note: Figures account for missing year.

Table 38: Model 2: (Average Annual Total Factor Productivity Change and its Components)

Year	EC	TC	PEC	SEC	TFPC
2007/2008	1.000	1.114	1.000	1.000	1.114
2008/2009	1.000	1.405	1.000	1.000	1.405
2009/2010	1.000	1.362	1.000	1.000	1.362
2011/2012	1.000	0.974	1.000	1.000	0.974

2012/2013	1.000	1.201	1.000	1.000	1.201
2013/2014	1.000	0.876	1.000	1.000	0.876
2014/2015	1.000	1.085	1.000	1.000	1.085
2015/2016	1.000	0.906	1.000	1.000	0.906
2016/2017	1.000	0.972	1.000	1.000	0.972
Mean	**1.000**	**1.076**	**1.000**	**1.000**	**1.076**

Note: Mean accounts for missing year

Controlling for gas shrinkage in Model 2 resulted in an increase in the overall sector TFP productivity growth, with an average TFP growth of 7.6% p.a. over the sample period as shown in Table 38. The large TFP growth rate of the previous transmission price control review also helped offset the impact of -4.4% productivity growth in the current period as reported in Table 39.

Table 39: Model 2 (Transmission Price Control Review period)

TPCR	EC	TC	PEC	SEC	TFPC
TPCR4	1.000	1.165	1.000	1.000	1.165
RIIO-GT1	1.000	0.956	1.000	1.000	0.956
Whole Period	**1.000**	**1.076**	**1.000**	**1.000**	**1.076**

Placing the productivity growth rates of the two estimated models side by side shows the impact of accounting for gas shrinkage as an input in Model 2. Table 40 indicates the productivity difference of 2% p.a. between the two models. Table 41 reveals the productivity dynamics between the two different price control review periods.

The overall results for gas transmission are similar to electricity transmission in the sense that the addition of quality variables seems to significantly improve measured productivity, emphasizing the importance of quality of service provision for transmission networks characterized by declining or flat energy demand.

Table 40: Average Annual TFPC and its Components for Models 1-2

Year	TFPC-M1	TFPC-M2
2007/2008	1.055	1.114
2008/2009	1.588	1.405
2009/2010	1.362	1.362
2010/2011	1.038	0.974
2012/2013	0.982	1.201
2013/2014	0.851	0.876
2014/2015	1.033	1.085

2015/2016	0.985	0.906
2016/2017	0.855	0.972
Mean	**1.056**	**1.076**

Adjusting for missing year; *M1= Model 1, M2= Model 2

Table 41: TFPC by Price Control Periods Models 1-2

TPCR	TFPC-M1	TFPC-M2
TPCR4	1.151	1.165
RIIO-GT1	0.928	0.956
Whole Period	**1.056**	**1.076**

*M1= Model 1, M2= Model 2

In terms of the whole period productivity growth, an increase of 72% is observed for Model 1. This is driven by lower capex figures over time. In Model 2, with the introduction of the quality variable (gas shrinkage), a much higher productivity rate is observed of 109%.

9. Conclusions

What have we learned about productivity in electricity and gas networks from our analysis? A major learning has been just how slow the measured TFP productivity growth has been. We find productivity growth as measured by DEA over the whole period as being in the region of 1% p.a. over the up to 26 years that we have data for (1990/91 through to 2016/17) for electricity distribution. This figure is in line with other studies that find a TFP growth rate mainly between 1 and 2% for the electricity distribution sector in the UK (Giannakis et al, 2005; Hattori et al., 2004) and with studies from other countries (Edvarsen et al., 2006; Senyonga and Berlgland, 2018; Ramos-Real et al., 2009). We find a slightly higher figure for gas distribution, but over a shorter period (2008/09-2016/17), which immediately follows a major restructuring of the sector. For electricity transmission, we actually find productivity regress for the basic model (for the period 2000/01-2016/17), though this is reversed once quality is included. Only gas transmission, which saw a large fall in investment (capex)[46], over the short period for which we have data (2006/07-2016/17) shows rapid productivity growth.

[46] Capex falls substantially from £631m in 2006/07 to £133.55m in 2016/17 (both in 2012/13 prices).

When analysing the entire periods for which we have data, electricity distribution performs better than gas distribution, with a maximum growth rate of 69% when quality variables are taken into account. On the other hand, TFP growth rate in gas distribution has a maximum value of 13.5%, which decreases up to 5.5% when quality variables (CML, CI) are introduced in the model. In terms of the transmission sector, gas transmission performs better even for the short period that was analysed (2006/07-2016/17), with a maximum rate of 109%, while electricity transmission productivity contracts by -30%. However this negative growth rate turns positive after including quality variables. To some extent the differences between the sectors can be viewed as being a function of the asset replacement cycle. Electricity transmission in particular experienced increases in capex (over the period we analyse) in line with the need to replace capital installed in the 1960s and 70s, by contrast the gas transmission network benefited from a period of low replacement capital expenditure.

Overall however, energy network sectors should be viewed as having performed better than the reported performance of the whole market economy in the UK. This performance is hardly surprising given that the productivity growth for the whole economy has also been slow and the headline figures for the price controls are to some extent consistent with this (a 30-40% maximum fall in the real price for electricity networks from 1990 to 2005[47], with rises following this).

Within the different price controls the period 2000-05 was a particularly strong growth period for electricity distribution, but growth has slowed after this. This slowing is in line with the aggregate UK productivity figures reported by the ONS which were affected by the global financial crisis[48]. The slowing of productivity growth in energy networks has come as outputs have grown slowly, especially in terms of units of energy distributed and transmitted. Both electricity and gas demand have fallen across our sectors since around 2005 and are substantially lower in 2017 than in 2005. By contrast other outputs such as network length and number of customers have, generally, grown slowly. This creates challenging conditions for productivity growth. In addition, rising small scale electricity generation increases system demands on both electricity transmission and distribution while reducing aggregate energy volumes. Indeed if energy networks are making investments and incurring operating

[47] See Ofgem (2009).

[48] https://www.ons.gov.uk/economy/economicoutputandproductivity/productivitymeasures/articles/multifactorproductivityestimates/experimentalestimatesto2014

expenditures which facilitate the wider energy transition, this may show up as them exhibiting negative productivity growth, as the benefits of this transition (e.g. clean air and meeting environmental targets) are not part of their measured outputs. Gas demand continues to fall, partly due to large increases in energy efficiency. Our ONS and EU KLEMS data analysis shows negative growth and, if anything, weaker productivity growth in energy compared with other sectors (for the ONS data of electricity vs water) and between UK energy, gas and water sectors combined and the US, Germany and the Netherlands.

The data was surprisingly difficult to collect given the emphasis Offer, Ofgas and Ofgem have had on using data within price controls to undertake benchmarking. A big issue has been missing data and the collection of data for short periods because of the presence of time-limited incentives. Three examples of this are: the fact that energy losses in electricity distribution were not collected by Ofgem from 2005/06 to 2014/15 because of a change in incentives around energy losses; that overall statistics on the output of the gas transmission sector were not available from until 2006/07 meaning that we could not calculate even an aggregate firm productivity figure for most of the post 1990 period; and for gas distribution, even though there were separate divisions for gas distribution within British Gas at privatisation and the current gas distribution companies were formed in 2004, limited data was only available from 2005-06. There was no data on gas from the pre-Ofgem period (pre-1999) at all, suggesting that any data that might have been collected by Ofgas is not easy to access. There were other examples of data that we asked for (and agreed with Ofgem that it would be reasonable to have) that was not available over the period over which it might have been expected to be available. Indeed, as we indicated above out of the quality variables that we asked for, probably less than half were available as expected.

Given the emphasis in RIIO on a wider range of outputs and incentives it would have been good to include these directly in our analysis. However, it is still early days in terms of the new measures that have been incentivized, especially on customer satisfaction and the promotion of distributed generation. Several other quality measures don't lend themselves well to analysis within a quantitative framework (e.g. gas escapes or safety measures), partly because they don't show up as continuous improvement in the same way as standard output to input ratios. Indeed, measures of underlying asset quality and risk reduction are hard to quantify and add to a model of productivity because their levels of improvement may be small or they may require highly subjective judgement as to whether they have improved. However, as an encouragement to Ofgem, our analysis shows that the addition of most of the quality measures we did have did improve measured productivity. The energy network industry has clearly been responding to incentives to improve quality: most of the available quality measures did show significant improvements over the periods for which we had data.

The sorts of measurement issues identified by Coyle (2015) could be significant. We would expect that an energy network sector faced with the need to invest heavily to respond to government objectives for the addition of renewables and the promotion of energy efficiency would face rising costs without seeing increased measured outputs. To give a couple of examples of how significant this might be, consider the following. If companies had increased their spending from zero to 2.5% of their total expenditure (totex) on such measures (it could be higher than 2.5% under RIIO) this could slow productivity growth by nearly 0.1% p.a. over the period since 1990 (or perhaps 10% of the measured productivity growth). In addition, significant parts of the industry are now in the hands of 'new economy' type companies such as stand-alone offshore transmission companies (OFTOs) and independent electricity distribution network operators (IDNOs). We did not have good enough data to include these in our analysis: if these 'new' competitively tendered entities are of above average productivity this would depress productivity growth. Similarly, Haskel and Westlake (2018) note that investment in intangible capital such as better management (to be more responsive to stakeholders as required and remunerated by RIIO) is not counted as an investment in the future, but is usually just seen as opex. If companies were again allowed to increase their totex expenditure share on better management of stakeholder relations to exploit RIIO incentives from zero to say 4% over the period the impact is again to significantly reduce the level of measured productivity growth (by more like 0.15% p.a. over 26 years).

A bigger learning was the surprisingly poor quality and consistency of the ONS data over time. Given the size of the energy industry and the importance of its productivity in determining a key set of prices within the economy it was surprising that the underlying data on the energy sector was so patchy and that more of an effort had not been made to consistently fill in the data for each year. We would suggest that Ofgem work more closely with the Office for National Statistics (ONS) to help with populating the high level ONS data and to facilitate the sort of international and cross-sectoral comparisons which we originally identified as being important for putting context around the measured performance of the firms that Ofgem is responsible for. Ofgem's licencing system for generators, transmission, distribution and retail can identify the universe of firms in each of these sectors, as exemplified by some of the analysis in Ofgem's annual State of the Energy Market Report[49]. Ofgem could make data reporting at the level of the ONS data a standard licence requirement and hence populate all of the missing data we identified in the ONS industry level data. Similar activity by the rail, water and telecoms regulators would facilitate inter regulated industry comparisons at a high level.

A possible extension of this study is to include a valuation of quality improvements in terms of willingness to pay. Here, we use a set of quality attributes measured in non-monetary units (customer minutes lost (CML), customer interruptions, customer satisfaction, energy losses). However these can each be valued and incorporated into a productivity analysis. For instance, Yu et al. (2009) in their study of the electricity distribution market, find that the social cost of outage[50] is higher than the utilities' incentives/penalty scheme. On the other hand, Jamasb et al. (2010) estimate the marginal cost of improving quality of service and find that if the incentives offered to utilities are lower than their marginal costs of improving quality, then utilities are not sufficiently strongly incentivised to reduce CML. Giving a specific value to each quality attribute (e.g. customer satisfaction) is a separate exercise and that is why we have not done it in this study.

Overall, we would want to emphasise the importance of good data for analysis of performance in sectors where large amounts of expenditure are being incurred, especially where the drivers of some of this expenditure are difficult to measure outputs, such as stakeholder engagement and environmental quality. As we look forward to RIIO-2, we would suggest that particular attention is paid by Ofgem to measures of customer satisfaction, measures of stakeholder engagement and the facilitation of the meeting of environmental targets (such as the addition of distributed generation to electricity distribution networks) and the valuation of the inputs and outputs of network innovation projects. We would also suggest that output measures relating to quality are valued in monetary terms (where possible) and incorporated systematically into the efficiency analysis done for RIIO-2. This is not a straightforward task but it is increasingly important if performance measures (and future target setting based on past performance) are to be meaningful going forward.

[49] Ofgem (2018).

[50] Computed as the product of CML and business and domestic willingness to pay.

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Appendix

Table A1: Descriptive Statistics for Electricity Distribution Network

	Variable	Unit	Mean	Std. Dev	Min	Max
Capex	Input	£m	104.91	37.71	37.47	269.09
Opex	Input	£m	146.49	90.06	18.52	432.04
Energy Distributed	Output	GWh	21201.60	7167.34	7117.00	37513.00
Number of Customers	Output	Number	1972698.00	690070.70	590000.00	3614431.00
Network Length	Output	Km	55042.29	15915.86	29432.00	97631.97
Peak Demand	Output	MVA	3929.52	1421.03	1417.00	6966.00
Customer Minutes Lost	Quality variable	Thousand	150841.90	127751.80	29030.75	2108400.00
Customer Interruptions	Quality variable	Thousand	146926.60	69307.82	40132.00	360400.00
Losses	Quality variable	GWh	1279.31	449.67	304.50	2468.00
Customer Satisfaction	Quality variable	Number	3263811	7318101	0	3.11E+07

Table A2: Descriptive Statistics for Gas Distribution Network

	Variable	Unit	Mean	Std. Dev	Min	Max
Capex	Input	£m	45.54	18.74	17.88	112.95
Opex	Input	£m	95.23	23.61	59.20	161.28
Unit Distributed	Output	GWh	71417.47	20942.47	43002.69	120219.00
Number of Customers	Output	Million	2.72	0.83	1.75	4.20
Network Length	Output	Km	33143.23	10286.14	20224.58	49365.86
Customer Minute Lost	Quality variable	Million	39.55	23.65	13.72	140.72
Customer Interruptions	Quality variable	Number	68470.96	21909.30	26695.00	127202.00
Customer Satisfaction	Quality variable	Million	22.27	7.10	13.64	36.89

Table A3: Descriptive Statistics for Electricity Transmission Network

	Variable	Unit	Mean	Std. Dev	Min	Max
Capex	Input	£m	871.69	364.77	483.78	1583.88
Opex	Input	£m	385.91	116.58	254.00	580.61
Energy Transmitted	Output	TWh	311.50	16.13	291.63	341.87
Network Length	Output	Km	23932.00	147.38	23640.45	24155.39
Energy not Supplied	Quality variable.	MWh	855.11	559.04	20.02	1938.66
System non-availability	Quality variable	%*Km	1135.22	253.11	738.30	1500.48

Table A4: Descriptive Statistics for Gas Transmission Network

	Variable	Unit	Mean	Std. Dev	Min	Max
Capex	Input	£m	241.52	218.71	108.69	662.96
Opex	Input	£m	85.83	14.24	73.16	117.07
Gas Transmitted	Output	GWh	1004549.00	90657.51	883985.50	1114250.00
Gas NTS Demand	Output	GWh	568287.70	54024.23	508959.60	634447.50
Network Length	Output	Km	7550.33	223.28	6961.93	7658.71
Gas Shrinkage	Quality variable.	Gwh	5191.97	1310.90	3523.61	7432.58