Changing times: Incentive regulation, corporate reorganisations, and productivity in Great Britain's gas networks

Authors:
Victor Ajayi[x]
University of Cambridge
Michael G. Pollitt[x]
University of Cambridge

Date:
July 2022

The Productivity Institute
Working Paper No. 023

[x] Energy Policy Research Group, Judge Business School

Key words
Total factor productivity, incentive regulation, corporate reorganisations, gas networks, data envelopment analysis

JEL codes
D24, H23, L43, L94

Authors' contacts
va301@cam.ac.uk

Acknowledgements
The authors wish to thank the Office of Gas and Electricity Markets (Ofgem) for their initial encouragement to work on the productivity issue. This paper arises from the work of Ajayi et al. (2018). We particular wish to thank Mark Hogan at Ofgem for his help with data collection. All errors are our own. We acknowledge the financial support of The Productivity Institute, funded by the UK Economic and Social Research Council (grant number ES/V002740/1).

Suggested citation

V. Ajayi, M.G. Pollitt (2022) *Changing times: Incentive regulation, corporate reorganisations, and productivity in Great Britain's gas networks*. Working Paper No. 023, The Productivity Institute.

The Productivity Institute is an organisation that works across academia, business and policy to better understand, measure and enable productivity across the UK. It is funded by the Economic and Social Research Council (grant number ES/V002740/1).

More information can be found on The Productivity Institute's website. Contact us at theproductivityinstitute@manchester.ac.uk

Publisher

The Productivity Institute, headquartered at Alliance Manchester Business School, The University of Manchester, Booth Street West, Manchester, M15 6PB.

Abstract

The gas industry in Great Britain has witnessed periodic regulatory reviews and large corporate changes over the last few decades. We undertake two separate analyses for the total factor productivity (TFP) of the gas networks using a non-parametric data envelopment analysis (DEA) approach to assess how these changes are impacting on productivity growth. First, we set out different models for the TFP analysis, each for gas transmission and distribution network, to examine how changes in incentive mechanism have influenced the measured TFP using quality of service and environmental targets.

Quality standards from regulators warrant some adjustment to explore industry productivity growth. Second, we construct a combined single series for distribution and transmission using financial data to uncover how corporate reorganisations have impacted measured productivity to get a new perspective in the years before and after restructuring, when the industry went from being a single integrated transmission and distribution network to the disintegrated networks of today. We find a negative TFP growth of -1.6% p.a. for gas transmission over the sample period (2006/07-2018/19). Although, this is reversed to a positive growth once quality is included.

For gas distribution, we actually find productivity regress at -6.2% p.a. over the sample period (2006/07-2018/19), with the negative TFP trend observed across all the models, despite the inclusion of quality variables. However, we find a slightly higher TFP growth of 1% using corporate accounts over the 25 years from 1995/1996-2020/2021. The period before restructuring has a more positive productivity compared to the post-restructuring era with negative productivity growth.

1. Introduction

Over the past three decades, a number of organisational changes have occurred in the gas industry in Great Britain (GB) in line with the Government's privatization programme to foster competition in the industry, as well as other corporate decisions of gas companies. Historically, British Gas (BG) was responsible for all aspects of natural gas supply, including exploration and production, transmission, distribution, and customer sales and service following its privatisation in 1986 as a vertically integrated monopoly (Price & Weyman-Jones,1996; Price, 1997). Due to the absence of competitive pressures, regulation was perceived as an effective way of improving the efficiency of the natural monopoly segments of the industry, and BG was subjected to RPI-X price control by the regulator. In this way, the BG would reveal the efficient level of costs through exceeding a target that is regularly reset to return those realized gains to the customers.

Thereafter, BG was restructured to produce five new business units in 1994, with Transco assuming corporate responsibility for the transportation and storage of gas. A subsequent demerger in 1997 within British Gas produced two listed firms; Centrica plc and BG plc, which took ownership of Transco. Transco's distribution segment included twelve Local Distribution Zones[1] which were reshaped into eight regional gas distribution networks (GDNs) in April 2002 (Ofgem, 2009). The merger between Transco and National Grid Group created National Grid Transco Plc in October 2002. National Grid Transco later sold off four gas distribution networks to independent private buyers in June 2005 and continued to retain control over the other four gas distribution businesses. The four distribution networks retained by National Grid were acquired by Cadent in October 2016 (NG, 2005). Currently, there are eight gas distribution networks which maintain and operate the local gas networks that carried gas from the National Transmission System (NTS) to different homes and businesses all over the GB. National Grid Gas remains both the System Operator (SO) and Transmission Owner (TO) for the gas NTS.

In principle, the price-cap regulations through the use of an RPI-X form could provide a strong incentive toward increased productivity for transmission and distribution networks but might in practice create an unequal treatment of operating expenditure (opex) and capital expenditure (capex), and may be biased in favour of operating opex as opposed to capex due to the much

[1] These twelve Local Distribution Zones were created from several individually-owned gas companies under the 1948 Gas Act.

more direct effect of opex on profits. Also, the price-cap incentive could encourage input choice distortion whereby capital investment is postponed until towards the end of the price control period to extract more gain accruing from cash flow.

Concerns have been raised that potential price reductions in the gas utilities might be at the expense of service quality which they provide to customers. To mitigate against the likelihood that GDNs take advantage of these incentives to maximise their profit by compromising on service quality, the regulator has set out a range of outputs and standards of performance that should be delivered. While there are several dimensions of service quality changes in gas industry, the regulator, Office of Gas and Electricity Markets (Ofgem) has consistently set service standards that GDNs are required to deliver service improvements in the industry. In particularly, the regulator has mandated GDNs to report on complaints handling, number and duration of non-contractual interruptions, customer satisfaction surveys, accuracy of pipeline records, environmental performance (Ofgem, 2008; 2011). These performance targets are often linked with specific incentives, with penalties awarded where actual performance falls short of targets and rewards when targets are exceeded. GB incentive regulation has over the years undergone periodic review[2] to resets the targets to facilitate improved quality service, and to ensure a regulatory regime that is responsive to customer needs, industry changes and wider society benefit, and has culminated in the move from RPI-X to the current RIIO[3] regime.

Against this backdrop, the ensuing changes could have serious implications for the measured productivity of the gas network industry. Hence, this necessitates the evaluation of productivity in the industry to pin down the likely effects of the industry reorganisation on productivity, as well as to examine whether the exacting quality of service standards are impacting of the industry productivity growth. More importantly, incentive regulation usually involves benchmarking analysis to enhance the quality of information available to regulators at price control reviews (Burns et al., 2006; Haney and Pollitt, 2009). Productivity analysis is helpful for forecasting in each price control review period (Lowry and Getachew, 2009; Cunningham et al., 2020).

[2] See Table A1 in the Appendix I for the incentive mechanisms of each price control review period implemented after structuring for both gas transmission and distribution networks. For instance, the current price control period lays out six categories of output: safety; reliability, environmental, social, connections, customer services, and associated incentives, together with cost and revenue allowances to encourage to cost efficiency.

[3] RIIO is short for Revenue = Incentives + Innovation + Outputs.

Regulation should aim to encourage productivity growth that would translate to lower prices and improvement in social welfare (Granderson and Linvill, 1996).

This paper provides a comprehensive productivity analysis by undertaking two separate analyses: one using disaggregated datasets for individual regulated transmission and distribution entities provided by Ofgem; and the other using aggregated corporate financial accounting data for the whole gas network industry to provide insights on service quality and corporate reorganisations respectively. As far as we know, this is the first academic study to reconcile the timing of such changes and their implicit effects on productivity in the gas industry.

This study employs a non-parametric input-oriented DEA approach to analyse the productivity performance of the GB gas transmission and distribution. Our preference for the DEA method stems from the fact that an input-oriented DEA specification is considered as appropriate for energy network utilities, as demand for energy services is a derived demand which is out of the control of utilities and must be met (Jamasb and Pollitt 2003). DEA captures only the underlying data and does not adjust for random measurement errors and avoids misspecification error regarding the production technology as no functional form is required. Thus, DEA is relevant in this case where the regulator faces substantial uncertainty about the technology (Agrell and Bogetoft, 2018). The inclusion of exogenous variables such as quality variables in a DEA model provides some useful insights on how productivity changes between firms and across time periods with changes in quality indicators. Hence, we present different models in our analysis for both transmission and distribution network following the GB regulator's own use of inputs and outputs with corrected ordinary least-squares (COLS) technique, while incorporating quality measures where applicable. The productivity growth results from the Ofgem's regulatory data are compared with those obtained using corporate accounting data.

The remainder of the paper is structured as follows. Section 2 presents the literature review and Section 3 presents the methodological approach. Section 4 describes the gas transmission data and results. Section 5 discusses gas distribution data and results. Section 6 presents gas corporate accounting data and results. Section 7 offers conclusions and policy implications.

2. Literature Review

Our review of the existing literature centres on both gas distribution and transmission networks. Sickles and Streitwieser (1992), Granderson (2000) and Nieswand et al., (2010) examine efficiency of the United States natural gas transmission companies. Utility efficiency studies on gas distribution include: Fabbri et al. (2000), Capece et al.(2021) and Romano et al. (2022) which examine the efficiency of natural gas distribution utilities in Italy; Farsi et al. (2007) and Alaeifara et al. (2014) which investigate the Swiss gas distribution utilities; Kim and Lee (1995) which analyse the South Korean gas distribution; Ertürk and Türüt-As¸ik (2011) which analyse the efficiency of Turkish gas distribution firms; Sadjadi et al. (2011), Amirteimoori and Kordrostam (2012) estimate the efficiency of Iranian gas distribution utilities; and Tovar et al. (2015) estimate efficiency of Brazilian gas distribution, among others. International efficiency comparison studies of gas distribution are: Carrington et al. (2002) for Australia and US gas firms; Zori´c et al. (2009) for gas distribution utilities from Slovenia, the Netherlands and the UK; and Goncharuk and Lo Storto (2017) for Italian and Ukrainian gas distribution companies. Apparently, this plethora of gas efficiency studies, especially on gas distribution utilities, have been driven by the need to produce a benchmark for use in incentive regulation. However, these studies did not go further to investigate the productivity growth, which is another important analysis in incentive regulations.

There are only few studies that have paid attention to the investigation of productivity in gas industry[4]. Studies on gas transmission network productivity are Granderson and Linvill (1996) who evaluate the productivity growth of twenty interstate natural gas pipelines companies between 1977 and 1987. Their companies experienced an average annual TFP growth rate of 6.4%. They authors argue that although regulation did have an impact on the characteristics of the production technology, the effect on the level of growth was considered to be small. Jamasb et at. (2008) assess 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 lay between 2.9% and 5.9% whilst the respective TFP growth rates range for the revenue models are 4.5–

[4] Table A2 in the Appendix I shows the summary of the literature on productivity analysis of gas networks.

6.9% p.a. They conclude that, unlike cost, revenue is more likely to be driven by the particular tariff regime and/or market power, inter alia. Kim et al. (1999) undertake a cross-country productivity analysis for 9 transmission companies and 19 integrated companies[5] across 8 countries from 1987 to 1995 using a Tornqvist productivity index. The authors find average productivity growth per year from 1% p.a to -36.9% p.a. for their transmission companies' group and from -2.3% p.a. to -31.2% p.a. for their integrated companies' group.

Past studies on gas distribution productivity include Price and Weyman-Jones (1996) who find that the GB gas industry productivity growth was 23% across the period 1977/78 to 1990/91, averaging 1.64% p.a. for 12 separate distribution regions using non-parametric DEA method. They assert 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 stochastic frontier analysis (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. using the generalized index model.

However, Gugler and Liebensteiner (2019) investigated the TFP growth of 20 regulated Austrian gas distribution companies over the period 2002–2013, covering 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. Meanwhile, Hollas et al. (2002) show that productivity performance of the U.S. gas distribution industry has not been affected by the restructuring of during 1975–1994 using DEA.

[5] Integrated companies are firms which engage in the distribution as well as transmission of natural gas.

Indeed, from the literature review above, there is a very small body of existing studies on the productivity of gas transmission and distribution networks. Whilst past studies have examined the impact of the effect of privatisation and firm size on firm performance, so far, none has attempted to incorporate service quality of incentive regulation and account for the effect of business reorganisation on productivity. In addition, the only previous academic study on the UK gas utilities is somewhat dated (Price and Weyman-Jones, 1996). To fill this gap, we carry out two separate analyses. In the first analysis, we set out different models for the TFP analysis, each for gas transmission and distribution network, beginning from the basic model to general models with the inclusion of quality variables. In the second analysis, we construct a combined single series for distribution and transmission using financial data to unveil what has been happening to distribution and transmission, particularly to get a new perspective in the years before and after the separation and disintegration of transmission and distribution. As far as we know, this is the first study that has undertaken such a comprehensive analysis on gas networks productivity over such a long period.

3. Methodology

3.1 Data Envelopment Analysis

DEA is one of the methods commonly used for estimating the Malmquist index TFP change. DEA uses linear programming (LP) to obtain the measures of technical efficiency (TE). The performance of a decision making unit (DMU) is estimated based on the distance to the frontier technology. The closer to the frontier, the higher technical efficiency. The closer to the frontier, the higher TE. Charnes, Cooper and Rhodes (1978) propose a constant return to scale (CRS) DEA model using an input-oriented approach. The input-orientated DEA LP is formulated in to maximise the TE score of the *i*-th firm, subject to production remaining within the feasible set of production possibilities. For instance, if there are *N* inputs, *M* outputs, and *I* firms (DMUs), each DMU can be represented by the column vector $\mathbf{x}_i$ and $\mathbf{y}_i$ where **X** represents the $N \times 1$ input matrix and **Y** the $M \times 1$ output matrix. Linear programming problem for the DEA CRS model can be solved as follows:

$$
\begin{aligned}
& min_{\theta,\lambda,}\theta, \\
& st: \ -\mathbf{y}_i + \boldsymbol{Y}\lambda \geq \mathbf{0}, \\
& \theta\mathbf{x}_i - \boldsymbol{X}\lambda \geq \mathbf{0}, \\
& \lambda \geq \mathbf{0},
\end{aligned}
\tag{1}
$$

where θ is a scalar that represents the efficiency score of the i-th firm and satisfies $\theta \leq 1$; and λ is a $I \times 1$ vector of constants[6].

However, in the event that there exist scale effects, the efficiency scores obtained from this DEA model will be affected. Many studies have extended and added more sophistication to the DEA method, for example, Banker et al. (1984) proposes a variable return scale (VRS) model for DEA[7]. 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. Thus, the solution to CRS LP can be modified to accommodate a variable return to scale VRS DEA technology by including a convexity constraint, resulting in the following LP:

$$\begin{aligned} & min_{\theta,\lambda,}\theta, \\ st:\ & -\mathbf{y}_i + \boldsymbol{Y}\lambda \geq \mathbf{0}, \\ & \theta\mathbf{x}_i - \boldsymbol{X}\lambda \geq \mathbf{0}, \\ & \boldsymbol{N}\mathbf{1}'\lambda = 1, \\ & \lambda \geq \mathbf{0}, \end{aligned} \tag{2}$$

where $\boldsymbol{N}\mathbf{1}$ is a vector of ones. Essentially, "pure" technical efficiency scores can be computed from the VRS specification, which are devoid of scale efficiency effects. In this study we use the VRS input-oriented model.

3.2 Malmquist productivity index

The Malmquist productivity index uses the Shepherd distance function technology to evaluate the TFP change of homogenous Decision Making Units (DMUs). Distance functions, introduced by Shephard (1953), allow the treatment of multiple inputs and multiple outputs combined in a production function[8]. The index measures the radial distance of the observed inputs and outputs in two different periods (t and t + 1) relative to a reference technology. Each DMU unit employs the combination of input and output (x^t, y^t) in period t, and (x^{t+1}, y^{t+1}) in period t + 1, and compared relative to all other DMUs at one point in time and the frontier for each time point envelops the observations from this period only. The Malmquist productivity index be decomposed into technical efficiency change index and technical change

[6] See Coelli et al., 2005, pp. 162-163 for further details.
[7] Under VRS technical efficiency scores are equal or higher than those estimated using a CRS.
[8] One of the main advantages of distance functions are that they do not require price data or other behavioural assumptions related to cost minimisation and allocative inefficiency (Kumbhakar et al. 2015, p. 27) but only information about inputs and output quantities.

index. Following Caves et al. (1982), the Malmquist productivity index is computed as geometric means of two indices;

$$MPI = \left[\frac{D_i^t(x^{t+1}, y^{t+1})}{D_i^t\ (x^t, y^t)} \times \frac{D_i^{t+1}(x^{t+1}, y^{t+1})}{D_i^{t+1}\ (x^t, y^t)}\right]^{\frac{1}{2}} \tag{3}$$

Following Fare et al., (1992), the Malmquist productivity index from Eq. 3 can be represented as follows:

$$MPI = \frac{D_i^{t+1}(x^{t+1}, y^{t+1})}{D_i^t\ (x^t, y^t)}\left[\frac{D_i^t(x^{t+1}, y^{t+1})}{D_i^{t+1}\ (x^{t+1}, y^{t+1})} \times \frac{D_i^t(x^t, y^t)}{D_i^{t+1}\ (x^t, y^t)}\right]^{\frac{1}{2}} \tag{4}$$

The first component of Eq.4 measures efficiency changes between time t and t+1, which captures the change in relative efficiency between period t and t+1, also known as the catching up term. The second component is technical change between the two periods and accounts captures the shift in technology at the input level and mix of each firm between the two periods. The index varies from 0 to infinity between period t and t+1. An improvement in productivity growth happens when the indexes values are greater than 1. Also, efficiency change can be separated into two components, pure efficiency change (PEC) and scale efficiency change (SEC)[9]. SEC captures the contribution of scale economies to productivity growth.

4. Gas Transmission Network

4.1. Transmission data

To model the DEA technology of gas transmission, we have to specify the relevant measures of inputs, outputs, and other quality factors. The selection of the variables for our study of gas transmission is based on the availability of data and the current literature. We analyse the gas transmission industry as a single firm by specifying two different types of DEA models. The industry is made up of only one gas transmission firm, National Grid Gas (NGG). NGG is both the System Operator (SO) and Transmission Owner (TO) for the gas National Transmission System (NTS). 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

[9] See Färe et al. (1994) for details about the decomposition of efficiency change into pure efficiency change and scale efficiency change.

transmission network. Gas flow transmitted at system entry points measures flows onto the high pressure NTS operated by NGG and includes throughput of gas to other countries including the island of Ireland. Actual gas flow transmitted is measured in Gigawatt hours (GWh) and gas NTS demand (which is GB demand for gas) are measured in GWh. Total network length is measured in km. Fig. 1 shows that gas transmitted and NTS have been declining over time while network length recorded a fleeting upward trend before maintaining a constant level for the most part.

We use monetary operating expenditure (Opex) and capital expenditure (Capex) as inputs because they are readily available from Ofgem as opposed to physical input measures of gas transmission network such as length of pipelines, number of employees and transformer capacity. We adjusted expenditure data using capital goods index to deflate capital expenditure and wage index to deflate operating expenditure. Data on these indices are obtained from the ONS database. These variables are modelled separately as inputs as rather than single input total expenditure. We consider shrinkage and business carbon footprint as quality variables in the analysis of gas transmission network performance. These variables are monetised and operating expenditure adjusted with the cost equivalents of the variables. Shrinkage broadly refers to gas either consumed within or lost from a transporter's system i.e. gas shrinkage due to compressor fuel use, calorific value shrinkage and unaccounted for gas[10]. The variable is measured in GWh and data was provided by Ofgem for the period 2006/07-2018/19[11] and it basically covers two price control periods TPCR4 (2007-13) and RIIO-GT1 (2013-21). We calculate the cost of shrinkage by multiplying gas transmission shrinkage in MWh by the average annual UK National Balancing Point (NPB) gas prices expressed in £/MWh[12]. Business carbon footprint obtained from Ofgem starting from 2013/2014, and its valuation covers only RIIO period. To calculate the cost of business carbon footprint, we multiply quantity of business carbon footprint expressed in tCO2e by annual social price of carbon measured in £/CO2 expressed in 2012/13 prices and obtained from by the Department of Energy and Climate Change and Department of Business, Energy & Industrial Strategy [13].

---

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

[11] Our analysis does not include year 2010/2011 as there was no available data for the year. Hence the TFP indices was adjusted to account for the missing year.

[12] We use the UK annual spot average price series (NPB Price Data) as wholesale gas price. We thank David Newbery and Kong Chyong of the EPRG for sharing the NBP price series with us.

[13] The social price of carbon is the short-term traded carbon value used by Ofgem and for other UK public policy appraisal prepared by the Department of Energy and Climate Change and Department of Business, Energy & Industrial Strategy. This measures the value of additional carbon savings not directly priced in emissions allowance prices and carbon taxes. We use the values of central scenarios as reported in the document titled

The summary statistics for the data used are reported in the Appendix I on Table A3. Fig. 2 reveals the trends of the input variables, with Capex experiencing a downward trend while Opex has been on the increase and nearly converging with shrinkage -and emission- adjusted opex at the later years of the sample periods.

Fig. 1: Annual evolution of outputs for gas transmission sector

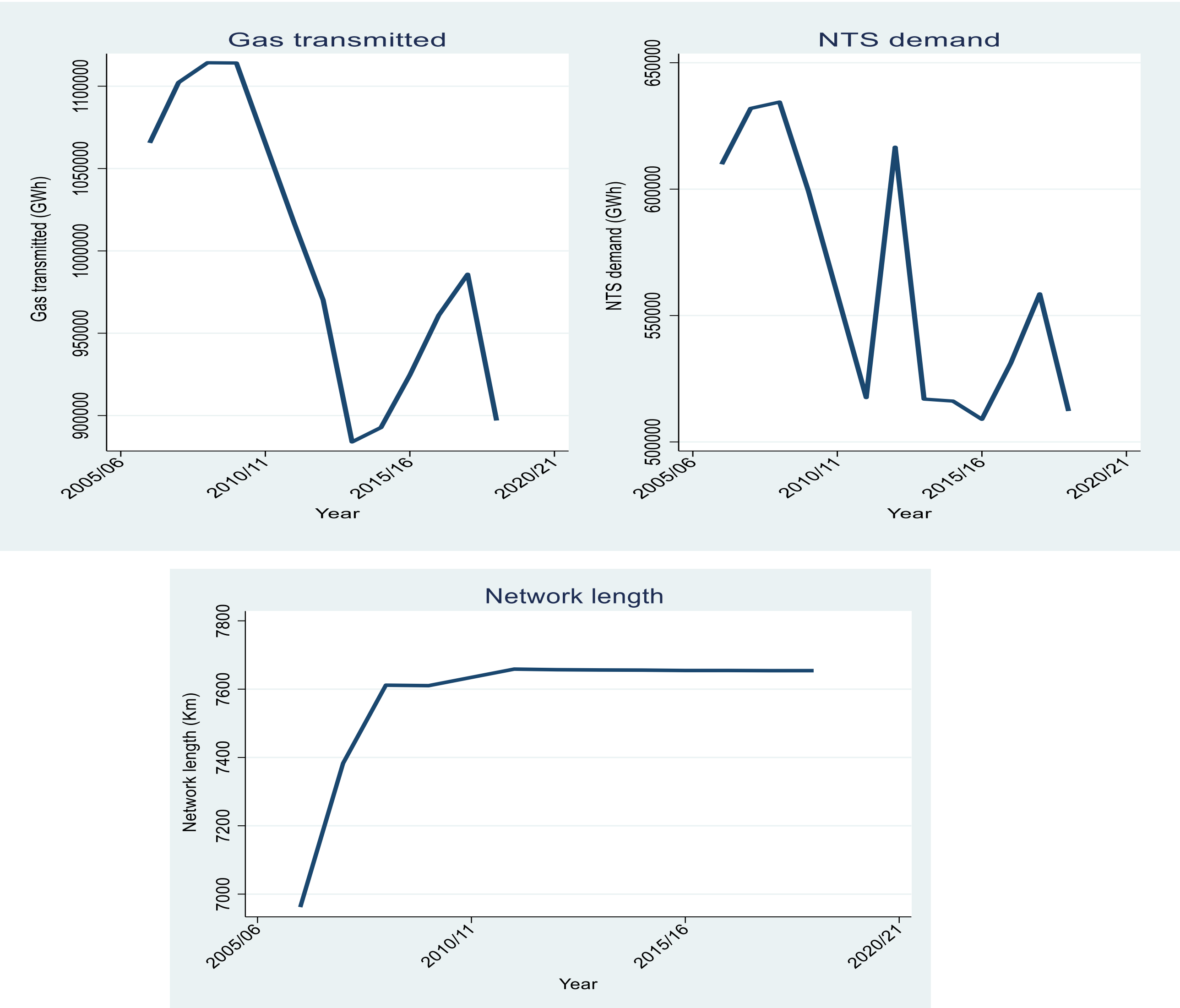
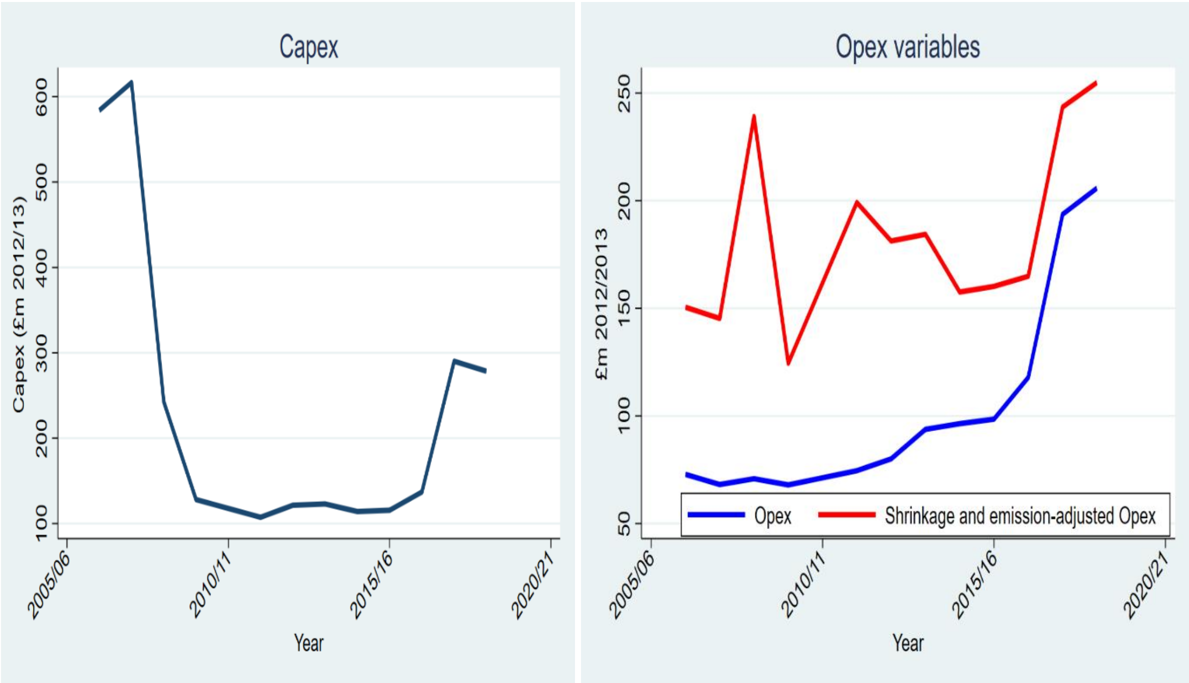


Fig. 2: Annual evolution of inputs for gas transmission sector

---

"Updated short term traded carbon values for UK public policy appraisal" in the link below: https://www.gov.uk/government/publications/2012-update-to-carbon-valuation-methodology-for-uk-policy-appraisal. Although gas distribution utilities are not subject to the EU ETS, so this could be an underestimate. See Appendix II for the calculation of the emission costs.



4.2 Model specification

In terms of models, we specify three different 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.

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 gas transmission utilities. The model considers two inputs (Opex and Capex) and three outputs that correspond to the standard components of Ofgem's composite size variable (gas transmitted, gas NTS demand and network length), covering 12-year sample period, 2006/2007–2018/19[14].

Model 2 (Model 1 with opex adjusted for shrinkage)

Model 2 extends the Ofgem's base model to incorporate value of gas shrinkage, an important quality variable for gas transmission. With the cost of gas shrinkage included in the opex, Model 2 specifies three outputs and two inputs.

Model 3 (Model 1 with Opex adjusted for shrinkage and carbon emission)

[14] Our analysis does not include year 2010/2011 as there was no available data for the year. Hence the TFP indices was adjusted to account for the missing year.

Model 3 is a variant of Model 2 but with a further adjustment made to Opex to account for carbon emission cost. The carbon emission variable by TSO is valued using social price of carbon and added to shrinkage-adjusted opex in Model 2. Thus, we specify three outputs and two inputs in Model 3. The sample period remains the same across the three model. Table 1 summarises the three models used in our transmission network TFP analysis.

Table 1: *Overview of Models for Gas Transmission*

Model	**Model 1**	**Model 2**	**Model 3**
Output:			
Gas transmitted	✓	✓	✓
Gas NTS demand	✓	✓	✓
Network length	✓	✓	✓
Input:			
Capex	✓	✓	✓
Opex	✓		
Shrinkage-adjusted Opex		✓	
Shrinkage-and emission-adjusted Opex			✓

4.2 *Transmission results and discussion*

The Malmquist productivity index is based on the DEA model and its decomposition is calculated for each year relative to the previous year as specified in equation (4). 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. We only discuss the total factor productivity change (TFPC) as no decomposition can be achieved in the case where there is only one firm to analyse and all change in TFPC is attributable to technical change. Hence, it cannot be decomposed as there is no efficiency boundary being the sole DMU in the DEA model. Therefore, we compute the TFP from the estimated DEA model by employing a Malmquist productivity index over the period 2006/2007–2018/2019 for three alternative models. This computation is equivalent to the geometric mean of output and input ratios. Index values higher than 1 indicate productivity improvement while values lower than 1 represent productivity regress.

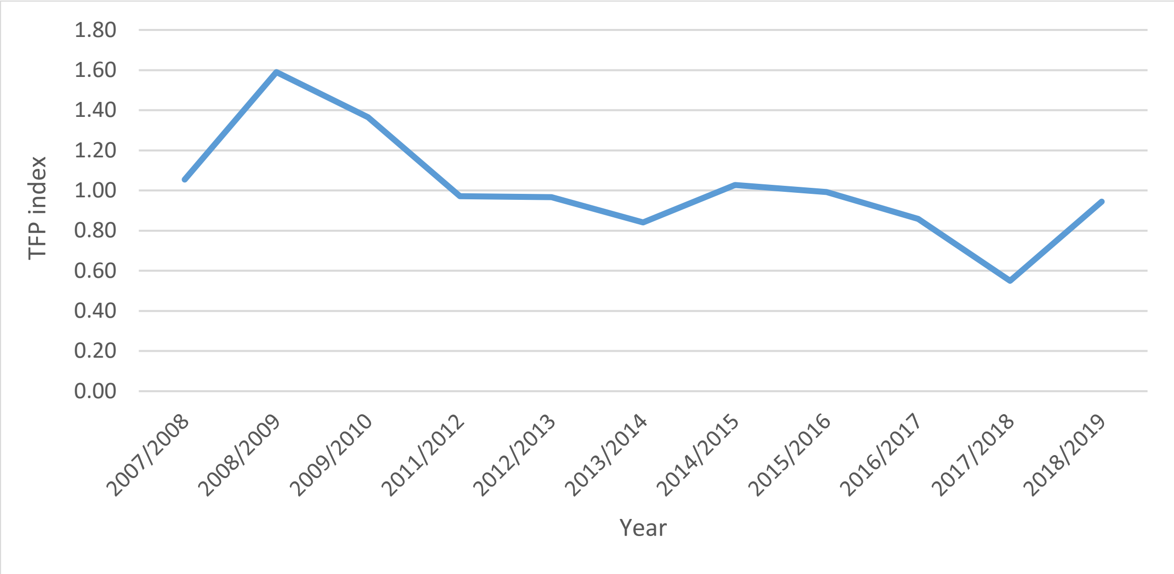
Table 2: Transmission Total Factor Productivity Change Models 1-3

Year	Model 1	Model 2	Model 3
2007/2008	1.054	1.037	1.037
2008/2009	1.590	1.264	1.264
2009/2010	1.365	1.854	1.854
2011/2012	0.972	0.805	0.805
2012/2013	0.967	1.051	1.051
2013/2014	0.841	0.908	0.902
2014/2015	1.028	1.128	1.128
2015/2016	0.993	0.998	0.996
2016/2017	0.858	0.93	0.925
2017/2018	0.550	0.578	0.58
2018/2019	0.944	0.947	0.952
Mean	**0.984**	**1.006**	**1.005**

Model 1= gas transmitted, NTS demand, network length, Capex and Opex
Model 2= gas transmitted, NTS demand, network length, Capex and shrinkage-adjusted Opex
Model 3= gas transmitted, NTS demand, network length, Capex and shrinkage-and emission-adjusted Opex

The average annual total factor productivity for Models 1-3 is reported in Table 2 The Malmquist index summary of annual geometric means when the year 2006/2007 is set as the base period to be the reference point for observing the annual changes. Due to missing data, the year 2010/11 is omitted from the analysis. We begin our discussion with Model 1 which is the baseline model that considers only the conventional measures of TFP without adjusting for improvements in quality and reduction in environmental emission variables using the standard inputs and output. The result reveals that the sector recorded productivity regress, with an average annual in TFP growth rate of -1.6% p.a. over the whole sample period. The trend of average annual productivity growth for Model 1 is displayed in Fig. 3. shows that the productivity growth rate has been sloping downward for nearly the entire sample period. The TFP growth reached the peak between 2007/08 and 2008/09, growing at about 59%. This period coincides with early stage of TPCR4 when there are significant reductions in RPI-X and P0 (Ofgem, 2009).

Fig. 3: Average Annual Total Factor Productivity Change in Models 1



The inclusion of the monetised shrinkage value to opex in Model 2 to control for quality slightly increased the overall productivity to an average annual TFP growth of 0.6% p.a. This result suggests that the ability of transmission firms to sufficiently reduce shrinkage can occur when gas transmission utilities consume gas within their transportation systems to fuel gas compressors as well as when gas is stolen or accounted for could enhance their productivity. Apparently, the shrinkage scheme which incentivises the transmission company to reduce the cost of gas shrinkage associated with NTS operation have implications for the productivity growth of the transmission utility. In practice, the shrinkage scheme rewards NGG for cost savings against the target cost level and penalises the utility with additional cost in the event that the company exceeds the target cost level. However, the average annual TFP growth somewhat remain similar at 0.5% p.a. when emission variable by network firm is valued using social price of carbon.

We carefully separate the results based on transmission price control reviews to gain more insights into the impact of incentives on productivity into TPCR4 and RIIO-GT1 we present the TFP results in accordance with transmission price control reviews in Table 3.

Table 3: Annual Total Factor Productivity Change by Price Control Models 1-3

TPCR	Model 1	Model 2	Model 3
TPCR4	1.136	1.128	1.128
RIIO-GT1	0.852	0.897	0.896
Whole Period	**0.984**	**1.006**	**1.005**

Table 3 reports that much of the growth in the sample period across Models 1-3 was recorded in the previous transmission price control review (TPCR4), averaging between 12.8% p.a. to 13.6% p.a. productivity growth. Various incentives mechanisms introduced in TPCR4 in could have promoted productivity growth in this period. For instance, revenue drivers were implemented to drive capacity investment funding and this was complemented by the strengthening of capex efficiency incentive to the tune of 25% earned as benefits or incurred as cost arising from differences between allowed capex and actual capex (Ofgem, 2009). The current price control witnesses a dismal growth across the three models, averaging -10.3% p.a. to -14.8% p.a. This marks the period when the special focus on the delivery of environmental targets has increasingly accelerated, with NGGT undertaking many future oriented projects such as those placing greater importance on different uses of hydrogen in the transmission segment (Ofgem, 2021). However, in Model 1, the TFP growth of 13.6% in TPCR4 in was not sufficient to offset the productivity regress of -14.8% p.a. experienced in the current price control period (RIIO-GT1), thereby culminating in the overall TFP growth of -1.6% p.a. in Model 1. Despite the negative TFP growth in RIIO-GT1 in Models 2-3, the overall TFP growth for the whole period still maintains a positive TFP growth in both models, at least to 2019. The RIIO-GT1 price control ran for a further 2 years beyond the end of our dataset.

5. Gas distribution network

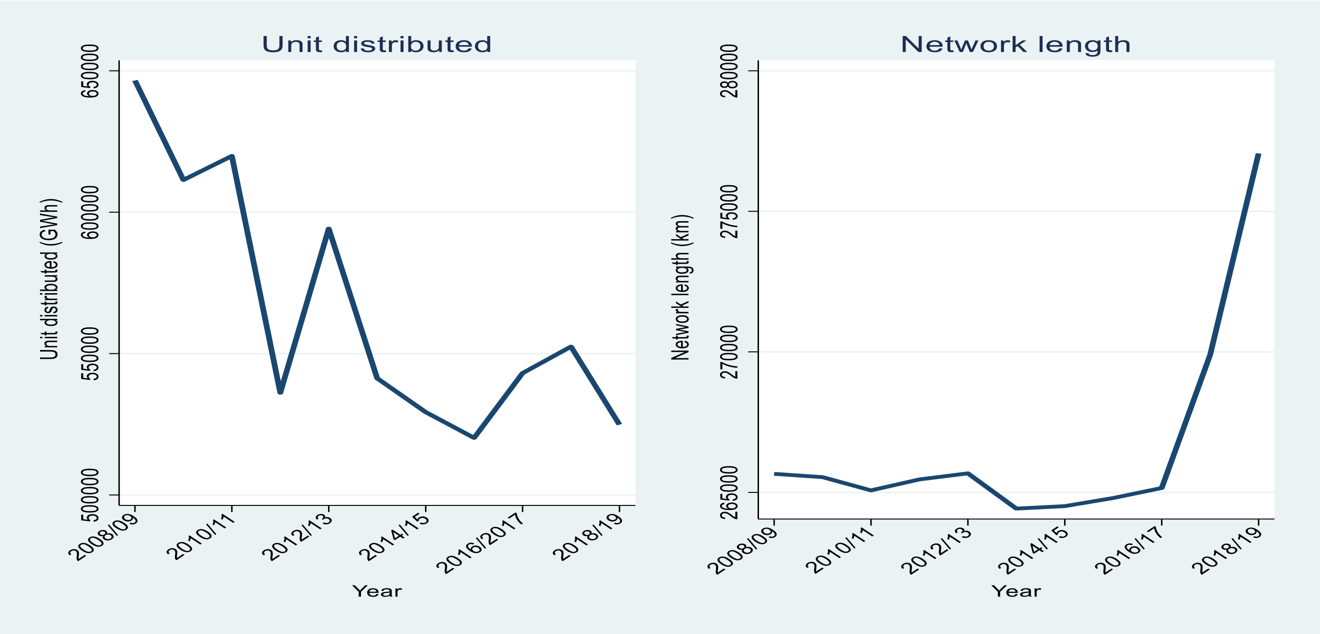
5.1 Distribution data

Our 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. Output variables used for the gas distribution network productivity analysis are units of gas distributed, number of customers and network length. Gas is distributed to final consumers through 8 regional gas distribution networks (GDNs). The units of gas distributed is measured in GWh and network length measured in km. The data are obtained from Ofgem for the 8 gas distribution network operators in Great Britain for the 2008/2009–2018/2019 period. The distribution networks are North West, London, West Midlands and East of England, Wales and West Distribution Network, North of England Distribution Network, Northern Gas Networks, Southern England Distribution Network and Scotland Distribution Network.

Fig. 4 shows the annual evolution of the output variables: units distributed, number of customers and network length. While units distributed has been going down continuously over the sample period, network length has been rising in the recent years and customer numbers has been steadily increasing too. Input variables are operating expenditure (Opex) and capital expenditure (Capex), and they are treated separately as inputs. They are measured in million pounds 2012/13 prices and deflated annually using capital good index and wage index obtained from the ONS database. Fig. 5 shows the total annual evolution of the input variables which reveals that capex has experienced a sharp increase in recent years while opex has fluctuated. We consider the continuity dimension of quality by applying quality of service variables such as total customer minutes lost and customer satisfaction. These are measures of security of supply and availability of supply. We scale the measure of customer satisfaction in order to include it as output in the DEA models[15]. Customer minutes lost and higher values of customer satisfaction, ceteris paribus, are expected to improve productivity growth. Total customer minutes lost did not show marked sector-wide improvement due to the differences in quality-of-service performance of networks companies. For instance, Wales and West Distribution recorded a significant improvement in total customer minutes lost during the sample period but London performed poorly with an upsurge in total customer minutes. However, there were notable rises in customer satisfaction in all the gas network companies during the sample period. We also include business carbon footprint to control for environmental quality and adjust operating expenditure with the cost equivalents of the variable. Cost of business carbon footprint is calculated in a way similar to transmission network, covering the RIIO-GD1 period. The descriptive statistics for the gas inputs, outputs, and quality data are given in Appendix I on Table A4.

[15] We multiply customer satisfaction and customer minutes lost by number of customers to obtain the scaled measure.

Fig. 4: *Total annual evolution of outputs for the gas distribution sector*



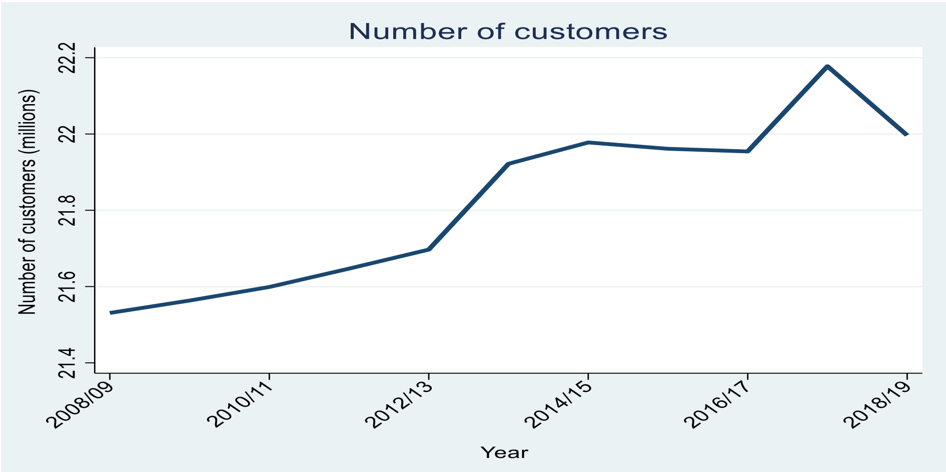
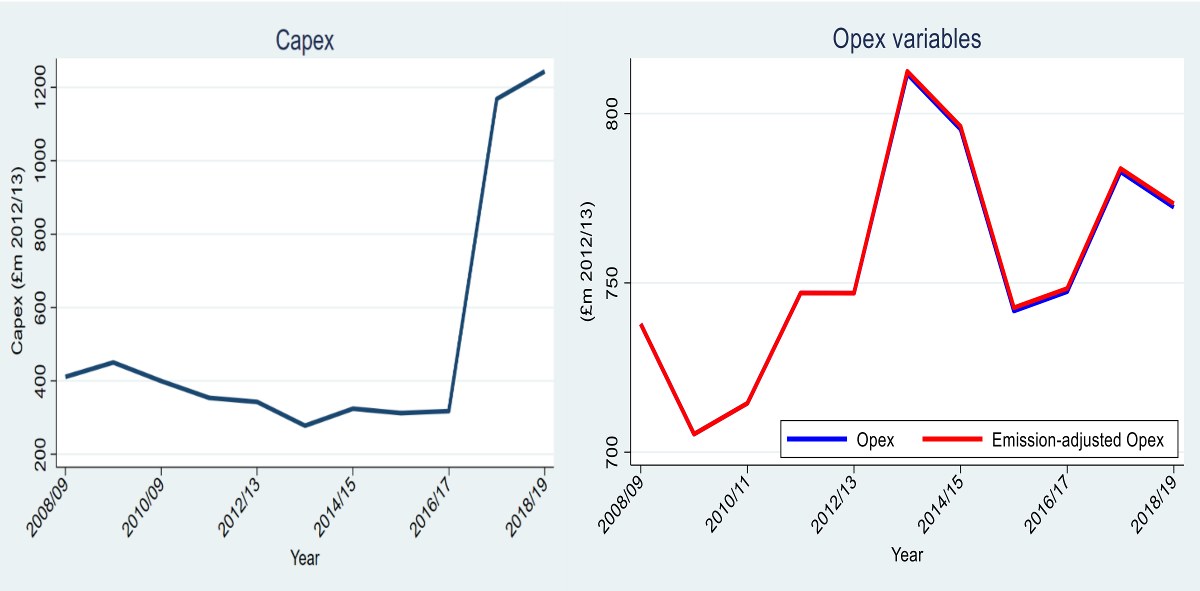


Fig. 5: Total annual evolution of inputs for the gas distribution sector



We adjust Opex using the monetised values of quality variables and are treated as inputs, meaning that ceteris paribus, a reduction in their values would increase their productivity. In order to include customer satisfaction in a DEA model, we multiply the values by the number of customers, to make the variables scalable and treat as input. Fig. 5 shows the total annual evolution of the input variables.

5.2 Model specification -gas distribution

We specify a progressively comprehensive set of DEA models analogous to transmission network. Four different types of DEA models are considered using some combinations of input, output and quality variables of gas distribution data. This approach enables us to uncover the impact of regulatory policy as it relates to the productivity of GDNs. The sample period remains the same across the four models, spanning 2008/2009–2018/19. The models are as briefly discussed below, and Table 1 presents the overview the four models used in our gas distribution network TFP analysis.

Model 1: Base model

Model 1 is the base model and does not account for the inclusion of quality variables. The specification is identical to Ofgem's COLS model used in benchmarking of gas distribution utilities. The model considers two inputs -Opex and Capex- and three outputs -units distributed, number of customers and network length.

Model 2 (Model 1-CML)

Model 2 extends Ofgem's base model to incorporate important quality variable measured by customer minutes lost and it is treated as an input in the model[16]. The model's outputs and sample period remain the same as Model 1.

Model 3 (Model 1-CML-Customer satisfaction)

Model 3 extends Ofgem's base model but in addition to customer minutes lost , we also account customer satisfaction model which is treated as output in the models. Therefore, Model 3 contains four outputs and three inputs.

[16] We would have valued CML but we couldn't get data on incentive rates. However, the gas network is has very low levels CML and these change only marginally (44 mins per customer in 2008-09 to 38 mins in 2018-19) over the period. The changes are very small compared to the change observed in electricity distribution (discussed in Ajayi et al., 2021).

Model 4 (Model 3 with Opex adjusted for emission)

Model 4 is an extension of Model 3 but with an adjustment made to Opex to account for carbon emission cost. The GDNs' carbon emission variable is monetised using social price of carbon and added to Opex input in Model 4. Thus, we specify four outputs and three inputs like Model 3.

Table 4: Overview of Models for Gas Distribution

Model	Model 1	Model 2	Model 3	Model 4
Output:				
Unit distributed	✓	✓	✓	✓
Customer number	✓	✓	✓	✓
Network length	✓	✓	✓	✓
Input:				
Capex	✓	✓	✓	✓
Opex	✓	✓	✓	
Emission costs adjusted Opex				✓
Quality variable:				
Customer minute lost		✓	✓	✓
Customer satisfaction			✓	✓

5.3 Distribution results and discussion

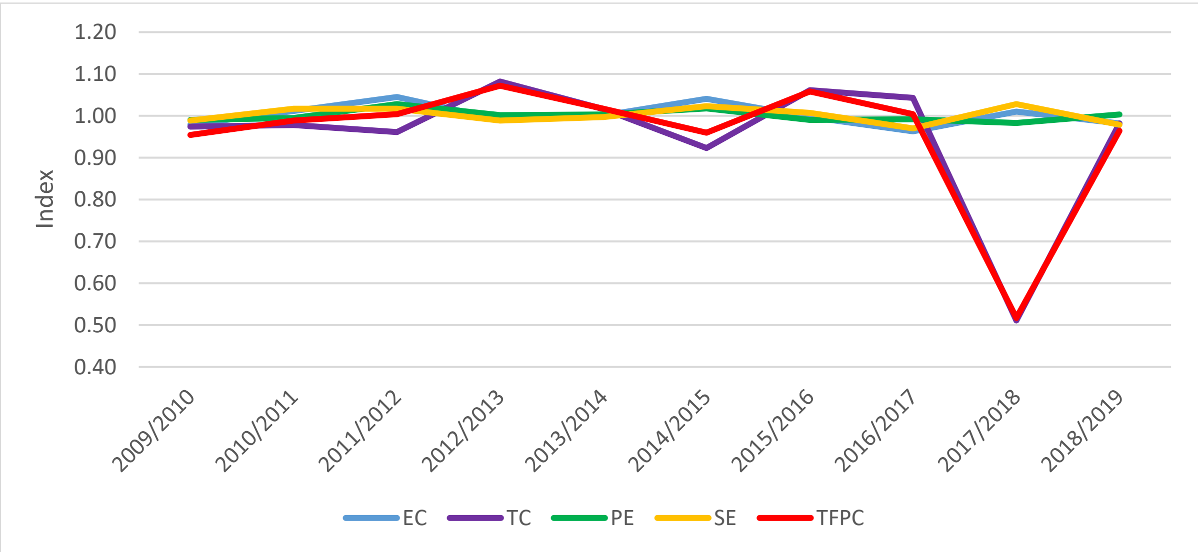
We compute the gas distribution TFP and its components from the estimated DEA model using a Malmquist productivity index as specified in equation (4) across there models over the period 2008/2009 –2018/2019. Table 5 reports the Malmquist index summary of annual geometric means, and the Malmquist index are decomposed into efficiency change (EC), technical change (TC), pure efficiency change (PEC), scale efficiency change (SEC), and total factor productivity change (TFPC). The year 2008/2009 is set as the base reference point for observing the annual changes. Turning to Model 1 which is the baseline model, the results indicate that gas distribution network companies experienced a negative average annual TFP growth rate of -6.2% p.a. over the whole sample period. The indices for average productivity growth show that average efficiency changes i.e., catch-up effects grew at 0.2% p.a. while technical change i.e., the shift in technological frontier, regressed over the sample period, averaging -6.4% p.a., thereby resulting in negative overall TFP growth in Model 1.

Table 5: *Total Factor Productivity Change and its Components- Model 1*

Year	EC	TC	PEC	SEC	TFPC
2009/2010	0.979	0.974	0.990	0.989	0.954
2010/2011	1.012	0.978	0.995	1.017	0.989
2011/2012	1.045	0.961	1.028	1.017	1.004
2012/2013	0.991	1.082	1.002	0.989	1.072
2013/2014	1.001	1.016	1.003	0.997	1.017
2014/2015	1.041	0.923	1.018	1.023	0.960
2015/2016	0.997	1.061	0.990	1.007	1.058
2016/2017	0.963	1.043	0.992	0.970	1.004
2017/2018	1.010	0.511	0.983	1.028	0.517
2018/2019	0.982	0.982	1.003	0.979	0.964
Mean	**1.002**	**0.936**	**1.000**	**1.002**	**0.938**

Fig. 6 illustrates the evolution of total factor productivity change and its components for Model 1. The index decomposition shows that TFP oscillated steadily between positive and negative growth for the most part of the sample period, until a huge plunge in TFP growth between 2016/2017 and 2017/2018, amounting to about -48.3% p.a. This negative growth in TFP was driven mainly by technical change which recorded a growth of -48.9% p.a. during the same period. This was a period when capex rose sharply. Incidentally, the TFP growth of 1.7% p.a. was achieved between 2012/2013 and 2014/2015 which happened to occur at the end of the last price control period (GDPCR1) and the beginning the current price control period (RIIO-GD1).

Fig. 6: *Total Factor Productivity Change and its Components*



Gas distribution was initially part of aggregate gas network price controls which were put in place to cater for both gas transmission and distribution since privatisation, and subsequently an aggregate 2002 GDN price control review. Effectively, GDPCR1 was implemented in 2008/2009 and represented the first full separate gas distribution price control review period of the separate GDNs. The current price control period, RIIO-GD1, began in 2013/2014, being the second gas distribution price control period. Therefore, we look into how changes in the incentives mechanism have influenced the GDNs' productivity by presenting our results for the average of both price control periods as sub-periods i.e. 2008/2009 -2012/13 and 2013/14-2018/2019. There were differences between the gas transmission price control and the GDN price control. Gas transmission had a weighted revenue driver whereby half of revenue was fixed and the remaining half varied according to the volume of gas transported. Gas distribution had no volume driver under GDPCR1 (Ofgem, 2009). Also, the opex rolling incentive was implemented under GDPCR1 was such that the GDNs could retain, for a fixed period of five years, any efficiency improvements savings, and benchmarking of capex between GDNs was first carried out under GDPCR1 (Ofgem, 2009).

The most recently completed network price control (RIIO-GD1) ran for eight years from 2013-2021. RIIO-GD1 is an output based framework which provides incentives for GDN companies to innovate and deliver cost-effective services. RIIO-GD1 introduces a broad set of outputs that GDNs companies are required to deliver such as social obligations, customer satisfaction, safety, and reliability, and are linked with different incentive mechanisms which reward (or penalise) utilities for their output performance[17] (Ofgem, 2012). Therefore, taking the geometric average over all the 8 GDNs and price control sub-periods, the result from Model 1 is reported in Table 6.

Table 6: *Distribution Price Control Review Period Model 1*

DPCR	EC	TC	PEC	SEC	TFPC
GDPCR1	1.006	0.998	1.004	1.003	1.004
RIIO-GD1	0.999	0.897	0.998	1.000	0.896
Whole Period	**1.002**	**0.936**	**1.000**	**1.002**	**0.938**

The TFP growth gas distribution network was 0.4% p.a. during the first price control period and average productivity decline of -10.4% p.a. during the second distribution price control

[17] For more comprehensive review of the price control period for gas networks see Ofgem (2009) and Ofgem (2012).

review period, which was lower than the average annual productivity growth for the whole period of -6.2% p.a. While the growth rate of technical change was rather depressing in both sub-periods, no appreciable growth in efficiency change was recorded for either price control periods. Furthermore, we report the TFP growth of the alternative models in Table 7 to show how the TFP growth of the baseline model is changing with the inclusion of quality variables and emission costs. Controlling for quality of service in the gas distribution network, we incorporate customer minutes lost in Model 2. Table 7 reports that the distribution networks also experienced productivity regress with a TFP growth rate of -5.4% p.a. over the whole period. Although the finding reveals a marginal improvement in TFP growth when compared with base model, Model 1 with TFP growth of -6.2% p.a. This slight productivity improvement arises from the relative inclusion of quality of service variable to Model 2. Adjusting for customer satisfaction in Model 3 leaves the productivity growth with a growth rate of -5.0% p.a., implying that the inclusion of customer satisfaction as output raises the productivity growth in the Model 3, which is a slight improvement compared to the productivity growth of Model 1 and Model 2. The TFP growth in Model 4 largely remains the same with Model 3 despite incorporating emission cost in Model 4. In general, the finding reinforces that quality of service could somewhat improve productivity performance.

Table 7: Distribution Total Factor Productivity Change Models 1-4

Year	Model 1	Model 2	Model 3	Model 4
2009/2010	0.954	0.896	0.900	0.900
2010/2011	0.989	1.051	1.051	1.051
2011/2012	1.004	1.021	1.039	1.039
2012/2013	1.072	1.073	1.074	1.074
2013/2014	1.017	1.036	1.047	1.046
2014/2015	0.96	0.950	0.953	0.953
2015/2016	1.058	1.052	1.057	1.057
2016/2017	1.004	1.018	1.019	1.019
2017/2018	0.517	0.544	0.542	0.542
2018/2019	0.964	0.974	0.974	0.974
Mean	**0.938**	**0.946**	**0.950**	**0.950**

Model 1= gas distributed, customer number, network length, capex and opex
Model 2= gas distributed, customer number, network length, customer minutes lost, , capex and opex
Model 3= gas distributed, customer number, network length, customer satisfaction, customer minutes lost, capex and opex
Model 4= gas distributed, customer number, network length, customer satisfaction, customer minutes lost, , capex and emission-adjusted opex

Table 8 presents the TFP results based on distribution price control reviews. We observe positive TFP growth across the models in the first price control period (GDPCR1). It is intriguing, however, that the RIIO-GD1 experienced negative productivity growth in the four models. The findings seem congruent with the increasing regulatory pressure on network companies in the RIIO-GD1 and underscore the fact that regulatory targets might be achieved at the expense of measured TFP.

Table 8: *Gas Distribution Price Control Review Period Model 1-4*

DPCR	Model 1	Model 2	Model 3	Model 4
GDPCR1	1.004	1.008	1.014	1.014
RIIO-GD1	0.896	0.907	0.910	0.910
Whole Period	**0.938**	**0.946**	**0.950**	**0.950**

6. Gas network corporate productivity

The GB gas distribution has been traditionally linked to gas transmission, and this trend continued under British Gas after privatization as a wholly integrated company, thereby constituting a threat of competition contained. However, a series of events were initiated and implemented by the GB government to in a bid to foster competition into the industry. In particular, the Gas Act in 1995 heralded competition in the residential market which was included in the privatization Act (Price, 1997). Following the demerging of British Gas in 1997 to produced two listed firms; Centrica plc and BG plc, which held ownership of Transco, there have been chains of corporate reorganisations in the gas industry. Table 9 shows overview these historical events in the gas industry since privatisation in 1986.

Table 9: Historical events in the gas industry post-privatisation.

Year	Main events
1986	Gas Act: privatization of integrated monopoly with statutory monopoly for supplies below 25,000therms p.a.
1987	Referral monopolies and Merger Commission (MMC) on price discrimination in the contract market
1989	Introduction of price schedules for contract market and gas carriage
1991	New price cap agreed for tariff market.
1992	‘Monopoly threshold’ reduced to 2,500 therms p.a.
1993	MMC recommends breaking up BG before liberalizing entire market
1994	Full liberalization confirmed in Queen’s Speech
	BG restructured into five business unit
	Transco responsible for transportation and storage of gas
1995	Gas Act allowing competition in the residential market
1996	First phase of competition in the south-west of England
1997	Competition extended to 2m consumers in the south of England
	BG Group (including Transco) and Centrica demerge
1998	Full competition throughout Great Britain
2000	BG Group created Lattice Group
2002	Twelve Local Distribution Zones (LDZs) reduced to eight regional gas distribution network companies
	Merger between National Grid and Transco, a subsidiary of Lattice Group, to create National Grid Transco
2005	Third party acquired four distribution firms from National Grid Transco
	National Grid Transco plc changed its name to National Grid plc
2016	Cadent acquired the remaining four distribution firms from National Grid

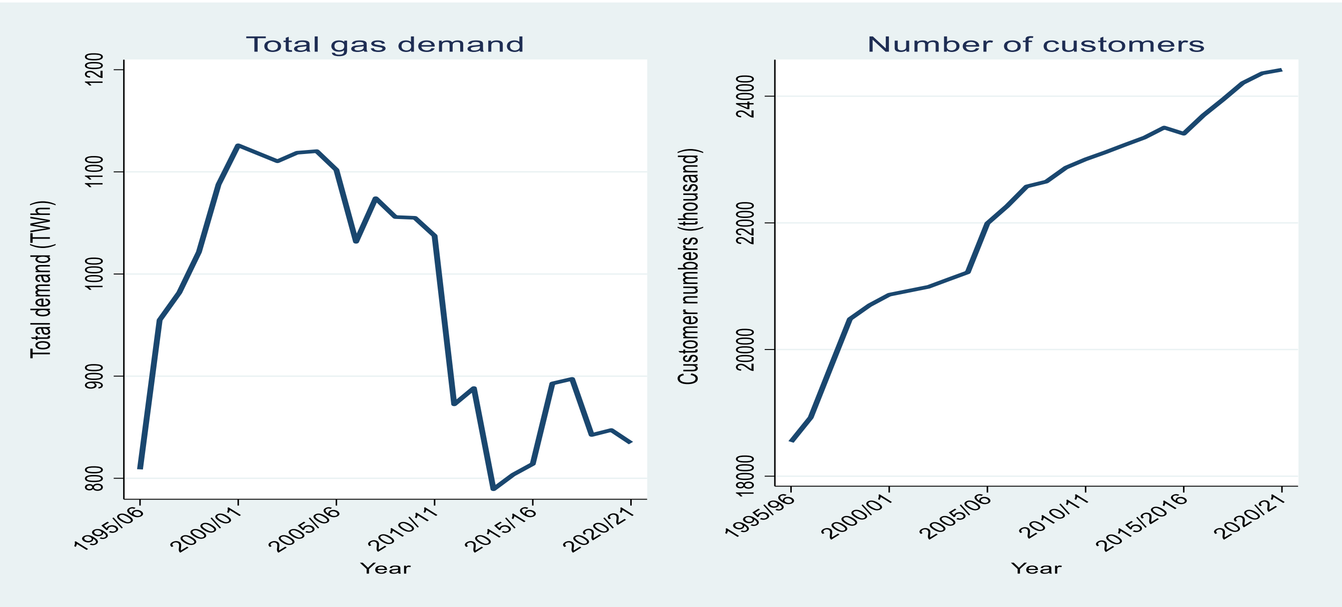
Source: Adapted from Price (1997) and updated by the authors.

6.1 Gas network corporate data

To assess the gas corporate productivity growth, we put together financial accounting data by aggregating several distribution companies and national grid transmission network to form a single entity for our analysis in order to give another perspective to the productivity trend in the gas industry. National Grid Gas remains the sole transmission operator (TO) for the gas National Transmission System. Following several changes, there are eight gas distribution networks, each covering a separate geographical region of Great Britain. The distribution networks are North West, London, West Midlands and East of England which were previously owned and managed by National Grid but acquired by Cadent in 2016/2017. The remaining four of the eight gas distribution networks under the control of National Grid Transco which were sold to private investors are Wales and West Distribution Network, owned by Wales and West Utilities, North of England Distribution Network owned by Northern Gas Networks, Southern England Distribution Network and Scotland Distribution Network, jointly owned and managed by Scotia Gas Networks[18].

We use total gas demand and number of customers as our measure of outputs as obtained from the UK Department for Business, Energy and Industrial Strategy (BEIS)[19]. To ensure consistency with gas industry fiscal year, we adjust total demand using quarterly data. Total gas demand the measured in GWh and number of customers is expressed in thousand. Fig. 7 shows the annual trend of output variables, with total gas demand seen to have been plummeting over the sample period whereas number of customers has been rising consistently over the same period.

Fig. 7: Annual evolution of outputs for gas network corporate data



We collect input variables are opex and capex for these companies using the corporate accounts filed by these distribution companies and National Grid transmission on the UK Company

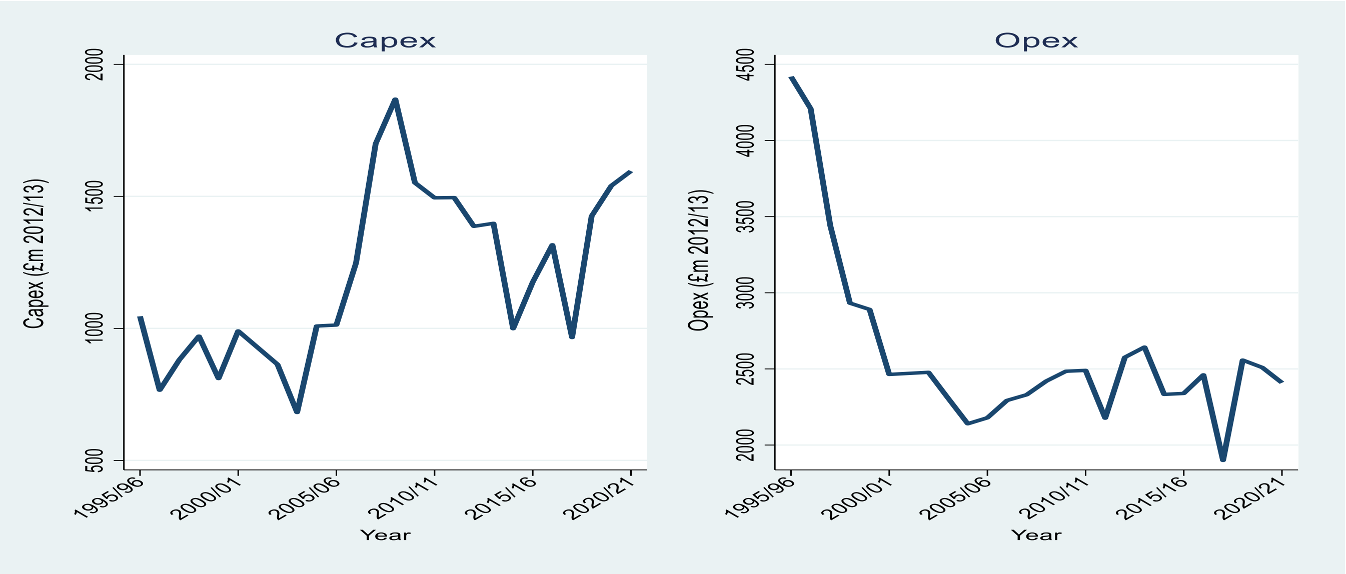
[18] The original twelve Local Distribution Zones that preceded the present eight distribution companies are Scottish Gas Board, Northern Gas Board, North Western Gas Board, North Eastern Gas Board, Wales Gas Board, West Midlands Gas Board, East Midlands Gas Board, South Western Gas Board, North Thames Gas Board, Eastern Gas Board, Southern Gas Board, and South Eastern Gas Board.

[19] The total gas demand may include some Northern Irish data.

House website. They are measured in million pounds and capex is deflated annually using capital good index while opex is deflated using wage index. The summary statistics for the corporate data used are reported in Appendix I, Table A5. Fig. 8 reveals the evolution of the input variables, with opex experiencing much more downward trend while capex has been oscillating for most of the period. The data used for the corporate productivity are available for the period 1995/1996–2020/2021[20].

The data trend is indicative and there may be productivity effects from non-network business inclusion (e.g. some consultancy services or commercial contracting) and from inter-business trading which increases following the break-up of the integrated Transco. Both of these might bias measured productivity growth, but are likely to be small as the core business of the companies is network provision and inter-business trading is limited (their primary customers are users of their networks).

Fig. 8: Annual evolution of inputs for gas corporate account

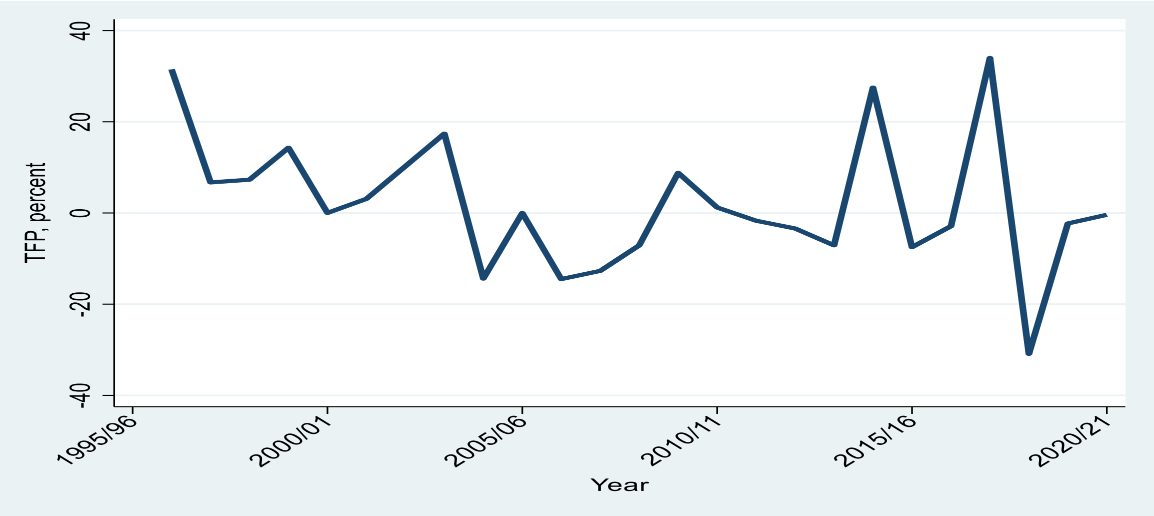


[20] 2001/2002 is omitted from the analysis as there is no data available due to a change of accounting year to fiscal year.

6.2 Gas corporate productivity results and discussion

The total factor productivity for corporate accounting data is reported in Table 10. We present the Malmquist index as annual change rather than cumulative for ease of discussion. Having adjusted for the missing year in 2001, the result shows that British corporate gas companies experienced an average annual in TFP growth rate of 1.0% p.a. over the whole sample period. The trend of annual change in productivity is displayed in Fig. 9. shows that the productivity growth rate has been mostly wandering over the sample period.

Fig 9: Annual change in gas network corporate TFP



Productivity reached its peak in 2017/2018, growing at about 34%. This was the following year after the NGG reorganised its operations by selling off its four distribution businesses to Cadent. Productivity appears to fall after this. It is intriguing to notice a significant productivity growth of 17.4% in 2003/2004 after the merging of Transco and National Grid Group to create National Grid Transco in October 2002. However, the productivity growth was not sustained.

Table 10: *Total Factor Productivity Change – corporate accounts*

Year	TFP
1996/1997	31.5
1997/1998	6.7
1998/1999	7.3
1999/2000	14.3
2000/2001	0.01
2001/2002	3.1*
2002/2003	3.1
2003/2004	17.4
2004/2005	-14.4
2005/2006	-0.01
2006/2007	-14.5
2007/2008	-12.7
2008/2009	-7.1
2009/2010	8.8
2010/2011	1.2
2011/2012	-1.7
2012/2013	-3.4
2013/2014	-7.1
2014/2015	27.5
2015/2016	-7.5
2016/2017	-2.9
2017/2018	34
2018/2019	-30.9
2019/2020	-2.3
2020/2021	-0.4
Mean	**1.0**

*2001/2002 missing year interpolated.

One interesting insight from the results is that the timing of the improved corporate productivity gains in the gas industry is coincidental to the period of major reorganisations. For instance, the year following full liberalisation of the industry and the introduction of first phase of competition experienced a productivity growth of 31% in 1996/97. This suggests that corporate changes seemingly provided the main boost of productivity following a major organizational change in the gas industry. We separate our data into before and after our Ofgem regulatory data period to enable comparison with the productivity growth obtained using the Ofgem regulatory data used in the previous two sections. It also marks the pre-and-post restructuring period when the distribution network was first separated from the transmission network. The corporate productivity change of before and after the Ofgem regulatory data period is reported in Table 11. The finding shows that most of the years prior to our Ofgem regulatory data period has positive productivity, with an average annual productivity change of 6.2% p.a. We observe a TFP change of -2.4% p.a. for the aggregated corporate data for transmission and distribution compared with the comparable (Model 1) individual productivity growth of transmission and distribution using Ofgem physical data of -1.6% and -6.2% p.a. respectively.

This suggests the corporate data productivity is broadly in line with our regulatory data for the shared later period and that there may have been much higher productivity growth in earlier years when corporate reorganisation activity was high.

Table 11: Before and after Ofgem regulatory restructuring.

Before regulatory restructuring		After regulatory restructuring	
Year	**TFP**	**Year**	**TFP**
1996/1997	31.5	2006/2007	-14.5
1997/1998	6.7	2007/2008	-12.7
1998/1999	7.3	2008/2009	-7.1
1999/2000	14.3	2009/2010	8.8
2000/2001	0.01	2010/2011	1.2
2001/2002	3.1*	2011/2012	-1.7
2002/2003	3.1	2012/2013	-3.4
2003/2004	17.4	2013/2014	-7.1
2004/2005	-14.4	2014/2015	27.5
2005/2006	-0.01	2015/2016	-7.5
Mean	**6.3**	2016/2017	-2.9
		2017/2018	34
		2018/2019	-30.9
		2019/2020	-2.3
		2020/2021	-0.4
		Mean	**-2.4**

*2001/2002 missing year interpolated.

7 Conclusions

We undertake two separate analyses for the productivity growth of the gas networks in GB using DEA. First, we set out different models for the TFP analysis for gas transmission and distribution networks, beginning with a basic model and extending to general models where we include quality variables to examine how changes in incentive mechanism have influenced the measured TFP. In the second analysis, we construct a combined single series for distribution and transmission using financial data to unveil what has been happening to distribution and transmission, particularly to get a new perspective in the years before and after restructuring.

We find a negative TFP growth of -1.6% p.a. for gas transmission over a period of (2006/07-2018/19), which immediately follows a major restructuring of the sector. Although, this is reversed once quality is included. For gas distribution, we actually find productivity regress at -6.2% p.a. (for the period 2008/09-2018/19), with this negative TFP trend observed across all the models, despite the inclusion of quality variables. This is driven by sharp increase in distribution capex figures from £317 million in 2016/2017 to £1.24 billion (2012/2013 prices) in 2018/2019. However, gas transmission saw a large fall in investment (capex) over the short period for which we have data (2006/07-2018/19), thereby attenuating the TFP regress. However, we find a slightly higher TFP growth of 1% using corporate accounts. The period before the final separation of transmission and distribution networks has very positive productivity growth.

The slowing of productivity growth in gas networks coincides with decreasing levels of outputs, particularly in terms of units of gas distributed and transmitted. Gas demand has equally been falling substantially since around 2005 and is much lower in 2019 than in 2005. Conversely, other outputs such as network length and number of customers have been experiencing a steady rise over the sample period. Arguably, this is a recipe for slowdown in productivity posing challenging conditions for productivity growth in industry. The inclusion of service quality in both gas transmission and gas distribution shows different outcomes on the impact of incentive regulation on network productivity, but the monetised carbon emission variable makes no difference to measured productivity for both networks. The addition of shrinkage as a quality variable in gas transmission network helps improve measured productivity while adding customer minutes lost as quality variables does not improve measured productivity growth in distribution network. In fact, the productivity gains arising from the improvements in quality of service in transmission is relatively high. However, no such effect is observed for distribution networks.

Finally, due to the shorter period of our analysis which spans only two price control periods, we could not find any marked improvement during the most recently completed RIIO price control period. If anything, productivity seemed slower in this period than the previous price control period. Hence, our analysis could not find a productivity improvement due to the move from RPI-X to RIIO.

References

Agrell, P.J., Bogetoft, P. and Trinkner, U., 2016. Benchmarking European Gas Transmission System Operators. http://www.sumicsid.com/reg/papers/pe2gas_R2_main_141231ver4.pdf.

Agrell, P.J. and Bogetoft, P., 2018. Theory, techniques, and applications of regulatory benchmarking and productivity analysis. *The oxford handbook of productivity analysis*.

Aigner, D., Lovell, C.K. and Schmidt, P., 1977. Formulation and estimation of stochastic frontier production function models. *Journal of Econometrics*, *6*(1), pp.21-37. https://doi.org/10.1016/0304-4076(77)90052-5

Aivazian, V.A., Callen, J.L., Chan, M.L. and Mountain, D.C., 1987. Economies of scale versus technological change in the natural gas transmission industry. *The Review of Economics and Statistics*, pp.556-561. https://doi.org/10.2307/1925549

Ajayi, V., Anaya, K. and Pollitt, M., 2021. *Incentive regulation, productivity growth and environmental effects: the case of electricity networks in Great Britain* EPRG Working Paper 2126 and Working Paper No. 012, The Productivity Institute.

Alaeifar, M., Farsi, M. and Filippini, M., 2014. Scale economies and optimal size in the Swiss gas distribution sector. *Energy Policy*, *65*, pp.86-93. https://doi.org/10.1016/j.enpol.2013.09.038

Amirteimoori, H., Amirteimoori, A. and Karbasian, M., 2020. Performance measurement of gas companies with fixed-sum inputs: a DEA-based model. *Journal of Economic Studies*. https://doi.org/10.1108/JES-06-2019-0285

Burns, P., Jenkins, C., Riechmann, C. and Mikkers, M., 2006. The role of the policy framework for the effectiveness of benchmarking in regulatory proceedings. *Competition and Regulation in Network Industries*, *1*(2), pp.287-306. https://doi.org/10.1177%2F178359170600100208

Capece, G., Costa, R. and Di Pillo, F., 2021. Benchmarking the efficiency of natural gas distribution utilities in Italy considering size, ownership, and maturity. *Utilities Policy*, *72*, p.101277. https://doi.org/10.1016/j.jup.2021.101277

Carrington, R., Coelli, T. and Groom, E., 2002. International benchmarking for monopoly price regulation: The case of Australian gas distribution. *Journal of Regulatory Economics*, *21*(2), pp.191-216. https://doi.org/10.1023/A:1014391824113

Casarin, A.A., 2014. Productivity throughout regulatory cycles in gas utilities. *Journal of Regulatory Economics*, *45*(2), pp.115-137. https://doi.org/10.1007/s11149-013-9239-2

Caves, D.W., Christensen, L.R. and Diewert, W.E., 1982. The economic theory of index numbers and the measurement of input, output, and productivity. *Econometrica: Journal of the Econometric Society*, pp.1393-1414. https://doi.org/10.2307/1913388

Charnes, A., Cooper, W.W. and Rhodes, E., 1978. Measuring the efficiency of decision making units. *European Journal of Operational Research*, *2*(6), pp.429-444. https://doi.org/10.1016/0377-2217(78)90138-8

Choi, I.S., Do, B.S., Park, C.S. and Park, J.G., 2009. A Comparative Analysis on Productivity in Gas Distribution Industry Between Korea and Japan. *Journal of the Korean Institute of Gas*, *13*(2), pp.14-22.

Coelli, T.J., Rao, D.S.P., O'Donnell, C.J. and Battese, G.E., 2005. *An introduction to efficiency and productivity analysis*. springer science & business media. https://doi.org/10.1007/b136381

Cunningham, M., Lawrence, D. and Fallon, J., 2020. Frontier Shift for Dutch Gas and Electricity TSOs. Available at: https://www.acm.nl/sites/default/files/documents/rapport-economic-insights-frontier-shift-for-dutch-gas-and-electricity-tsos.pdf. Assessed on 16 May 2022.

Ertürk, M. and Türüt-Aşık, S., 2011. Efficiency analysis of Turkish natural gas distribution companies by using data envelopment analysis method. *Energy Policy*, *39*(3), pp.1426-1438. https://doi.org/10.1016/j.enpol.2010.12.014.

Fabbri P, Fraquelli G, Giandrone R. Costs, technology and ownership of gas distribution in Italy. Managerial and Decision Economics. 2000 Mar;21(2):71-81. https://doi.org/10.1002/1099-1468(200003)21:2%3C71::AID-MDE972%3E3.0.CO;2-Y

Färe, R., Grosskopf, S. and Roos, P., 1995. Productivity and quality changes in Swedish pharmacies. *International Journal of Production Economics*, *39*(1-2), pp.137-144. https://doi.org/10.1016/0925-5273(94)00063-G

Färe, R., Grosskopf, S., Norris, M. and Zhang, Z., 1994. Productivity growth, technical progress, and efficiency change in industrialized countries. *The American economic review*, pp.66-83.

Farrell, M.J., 1957. The measurement of productive efficiency. *Journal of the Royal Statistical Society: Series A (General)*, *120*(3), pp.253-281. https://doi.org/10.2307/2343100

Farsi, M., Filippini, M. and Kuenzle, M., 2007. Cost efficiency in the Swiss gas distribution sector. *Energy Economics*, *29*(1), pp.64-78. https://doi.org/10.1016/j.eneco.2006.04.006.

Giannakis, D., Jamasb, T. and Pollitt, M., 2005. Benchmarking and incentive regulation of quality of service: an application to the UK electricity distribution networks. *Energy policy*, *33*(17), pp.2256-2271. https://doi.org/10.1016/j.enpol.2004.04.021

Goncharuk, A.G. and lo Storto, C., 2017. Challenges and policy implications of gas reform in Italy and Ukraine: Evidence from a benchmarking analysis. *Energy Policy*, *101*, pp.456-466. https://doi.org/10.1016/j.enpol.2016.10.037.

Granderson, G., 2000. Regulation, open-access transportation, and productive efficiency. *Review of Industrial Organization*, *16*(3), pp.251-266. https://doi.org/10.1023/A:1007884704252

Granderson, G. and Linvill, C., 1996. The impact of regulation on productivity growth: an application to the transmission sector of the interstate natural gas industry. *Journal of Regulatory Economics*, *10*(3), pp.291-306. https://doi.org/10.1007/BF00157674.

Gugler, K. and Liebensteiner, M., 2019. Productivity growth and incentive regulation in Austria's gas distribution. *Energy Policy*, *134*, p.110952. https://doi.org/10.1016/j.enpol.2019.110952

Haney, A.B. and Pollitt, M.G., 2009. Efficiency analysis of energy networks: An international survey of regulators. *Energy policy*, *37*(12), pp.5814-5830. https://doi.org/10.1016/j.enpol.2009.08.047

Hollas, D.R., Macleod, K.R. and Stansell, S.R., 2002. A data envelopment analysis of gas utilities' efficiency. *Journal of Economics and Finance*, *26*(2), pp.123-137. https://doi.org/10.1007/BF02755980

Jamasb, T., & Pollitt, M., 2000. Benchmarking and regulation: international electricity experience. *Utilities policy*, *9*(3), 107-130. https://doi.org/10.1016/S0957-1787(01)00010-8

Jamasb, T., and Pollitt, M., 2005. Electricity market reform in the European Union: review of progress toward liberalization & integration. *The Energy Journal*, *26* (Special Issue). https://doi.org/10.5547/issn0195-6574-ej-vol26-nosi-2.

Jamasb, T., and Pollitt, M., 2007. Incentive regulation of electricity distribution networks: Lessons of experience from Britain. *Energy Policy*, *35*(12), 6163-6187. https://doi.org/10.1016/j.enpol.2007.06.022.

Jamasb, T., Pollitt, M. and Triebs, T., 2008. Productivity and efficiency of US gas transmission companies: A European regulatory perspective. *Energy Policy*, *36*(9), pp.3398-3412. https://doi.org/10.1016/j.enpol.2008.05.001

Kim, T.Y. and Lee, J.D., 1995. Cost analysis of gas distribution industry with spatial variables. *The Journal of Energy and Development*, *20*(2), pp.247-267.

Kim, T.Y., Lee, J.D., Park, Y.H. and Kim, B., 1999. International comparisons of productivity and its determinants in the natural gas industry. *Energy Economics*, *21*(3), pp.273-293. https://doi.org/10.1016/S0140-9883(99)00007-9

Kumbhakar, S. C., Wang, H., and Horncastle, A. P., 2015. *A practitioner's guide to stochastic frontier analysis using Stata*. Cambridge University Press. https://doi.org/10.1017/cbo9781139342070.

Lowry, M. N., and Getachew, L. 2009. Econometric TFP targets, incentive regulation and the Ontario gas distribution industry. *Review of Network Economics*, *8*(4). https://doi.org/10.2202/1446-9022.1183.

NG, 2005. From privatisation to Transco (part of BG Plc). Available at: https://extranet.nationalgrid.com/GasArchive/privatisation1.htm. Accessed on: March 24, 2022.

Nieswand, M., Cullmann, A. and Neumann, A., 2010. Overcoming data limitations in Nonparametric Benchmarking: Applying PCA-DEA to natural gas transmission. *Review of Network Economics*, *9*(2). https://doi.org/10.2202/1446-9022.1209

Ofgem, 2009. Regulating energy networks for the future: RPI-X@20 Principles, Process and Issues, London: Ofgem.

Ofgem, 2012. RIIO-T1/GD1: Initial Proposals – Real price effects and ongoing efficiency appendix. Consultation-appendix. Office of Gas and Electricity Markets, Jul. 2012.

Price, C.W. and Weyman-Jones, T., 1996. Malmquist indices of productivity change in the UK gas industry before and after privatization. *Applied Economics*, *28*(1), pp.29-39. https://doi.org/10.1080/000368496000000004

Price, C.W., 1997. Competition and regulation in the UK gas industry. *Oxford Review of Economic Policy*, *13*(1), pp.47-63. https://doi.org/10.1093/oxrep/13.1.47

Romano, T., Cambini, C., Fumagalli, E. and Rondi, L., 2022. Setting network tariffs with heterogeneous firms: The case of natural gas distribution. *European Journal of Operational Research*, *297*(1), pp.280-290. https://doi.org/10.1016/j.ejor.2021.05.019.

Rossi, M.A., 2001. Technical change and efficiency measures: the post-privatisation in the gas distribution sector in Argentina. *Energy Economics*, *23*(3), pp.295-304. https://doi.org/10.1016/S0140-9883(00)00067-0

Sadjadi, S.J., Omrani, H., Abdollahzadeh, S., Alinaghian, M. and Mohammadi, H., 2011. A robust super-efficiency data envelopment analysis model for ranking of provincial gas companies in Iran. *Expert Systems with Applications*, *38*(9), pp.10875-10881.

Shephard, R.W., 1953. Cost and production functions. Princeton University Press. Princeton, NJ.

Sickles, R.C. and Streitwieser, M.L., 1992. Technical inefficiency and productive decline in the US interstate natural gas pipeline industry under the Natural Gas Policy Act. In *International Applications of Productivity and Efficiency Analysis* (pp. 115-129). Springer, Dordrecht.

Tovar, B., Ramos-Real, F.J. and Fagundes de Almeida, E.L., 2015. Efficiency and performance in gas distribution. evidence from Brazil. *Applied Economics*, *47*(50), pp.5390-5406. https://doi.org/10.1080/00036846.2015.1047093

Waidelich, P., Haug, T. and Wieshammer, L., 2022. German efficiency gone wrong: Unintended incentives arising from the gas TSOs' benchmarking. *Energy Policy*, *160*, p.112595. https://doi.org/10.1016/j.enpol.2021.112595.

Zorić, J., Hrovatin, N. and Scarsi, G., 2009. Gas distribution benchmarking of utilities from Slovenia, the Netherlands and the UK: an application of data envelopment analysis. *South East*

European Journal of Economics and Business, *4*(1), pp.113-124. http://dx.doi.org/10.2478/v10033-009-0008-1.

Appendix I

Table A1: Gas transmission and distribution price control periods in Great Britain

Gas transmission

Period	Price control	X-factor	Incentive
1986-1992	TPRC0	RPI-2	Price control introduced Incentives essentially focused on raising economic efficiency and improving management skill.
1992-1997	TPCR1	RPI-5	Incorporation of gas costs incurred by BG within price control to encourage efficiency in gas purchase decision Cost of capital set at a level between 5% to 7%. Documentation of 'The Environment and Energy Efficiency' proposal on a code of practice on energy efficiency implementation
1997-2002	TPCR2	RPI-5	Price control changed to a weighted price cap Gas cost excluded from price control The RPI-5 is associated with significantly high level of immediate price cut. Incentives to invest meeting statutory obligations such as meeting reasonable demands, developing and maintaining an efficient system. Financial incentive to invest in which revenues are dependent on volume of gas transported.
2002-2007	TPCR3		The price control is essentially output-based in which explicit national transmission system (NTS) output measures such as entry capacity and exit capacity are essential component of TO price control. Efficient generation of agreed outputs formed basis for setting the allowed capital expenditure and operational expenditure. Guaranteed were provided for the allowed revenue under the price control for 5 years. Day-to-day System Operator incentives introduced. Long term investment incentive whereby Transco will sell entry and exit capacity o NTS customers and but it back in the event of unavailability of capacity. Exit capacity incentive which provided Transco with financial incentives to consider the most effective means of meeting customer demand, and could earn up to 50% of the savings, capped at £10m for 2002/ 03 from cheaper investment alternative to substitute pipeline investment.

2007-2013	TPCR4	RPI-0	Introduction of 'capex safety net' to trigger a review in case that cumulative under-spend reached a level that was more than 20% of the capex allowance. Reduction in underlying efficient opex by 3%. Strengthening of incentives on capex efficiency which set out a penalty of 25 % of the extra cost, or reward 25 % of the saving benefit arising from differences between allowed capex and actual capex. Innovation Funding Incentive (IFI) for all the TOs for technological improvements on environmental projects. A "vanilla‟ WACC return on the RAV was used and this was set at 5.05%.
2013-2021	RIIO-GT1		Based on various categories outputs which are linked to incentives. Safety obligations with a penalty/reward of 2.5% of the value of any over/under delivery of replacement outputs. Customer satisfaction survey with incentive of up to +/-1% of allowed revenue. Stakeholder engagement up to 0.5% of allowed revenue via a discretionary reward scheme. Increased funding for innovation under the NIA to 0.7 per cent of NGGT‟s allowed revenues. Increased funding for incremental capacity. Financial package comprises of cost of equity set at (post-tax real) 6.8%, notional gearing at 62.5% and vanilla WACC 4.4%. Reputational incentive to publish yearly Business Carbon Footprint (BCF) account.
			Gas distribution
2002-2008	2002PCR	RPI-2	Price control changed from an average revenue cap applicable to all of the GDNs to separate average revenue caps applicable to the specific circumstances of each of the individual GDNs which were owned by different entities. GDNs subjected to a weighted revenue driver whereby 65% of revenue was fixed and 35% varied in accordance with the volume of gas transported. Strong opex efficiency incentive to reduce costs below the assumed level.

			3.1% opex efficiency target was applicable to all the GDNs. Capex set according to an evaluation of historic and forecast capex
2008-2013	GDPCR1	RPI+2	Information Quality Incentive (IQI) introduced. Benchmarking of capex between GDNs was first carried. Significantly increased targets and stronger incentive to achieve quality of service incentive mechanisms. interruptions incentive on the costs related with upgrading of the distribution networks was introduced Flat and flexible capacity incentives were implemented. Implementation of environmental emissions incentive in which GDNs are exposed to the costs arising from carbon emissions. Innovation Funding Incentive (IFI) was introduced to spur investment in technologies that could drive environmental improvements projects and enhance sustainability. Losses Discretionary reward scheme (LDR) incentive was introduced aimed at lowering the impact of gas distribution, particularly to facilitate the reduction of reduced shrinkage, improve network extension or promoted gas safety. A vanilla WACC return on the RAV was used and this was set at 4.94%.
2013-2021	RIIO-GD1		RIIO-GD1 is based on outputs, incentives, and innovation. The RIIO -GD1 focuses on six set of output: safety; reliability; environmental; social; connections; and customer services. Safety risk reduction target of 40-60 per cent were set GDNs to reduce during RIIO-GD1. Expected reduction of gas transport losses by 15% to 20%, which accounts for 95% per cent of GDNs' carbon footprint. Significant customer satisfaction improvements to avoid a penalty and earn a reward. Changes to the treatment of opex-capex trade-offs, modelling of emergency service costs, and business support costs to limit cost efficiency reductions requirement from an industry average of 10 % to around 7%. Increased funding for safety and environmental outputs of about£1.5 billion or 12% of controllable costs. Financial packages that include an assumed cost of equity of 6.7 % (post-tax real), and a notional gearing level of 65%. An increase in allowed revenues of about 5% on average over the RIIO-GD1 period to limit the impact on customer bills.

Source: compiled from various Ofgem publications

Table A2: Summary of the literature on productivity analysis of gas networks

Authors	Method(s)[a]	Data	Variable used[b]	Main findings
		Gas	**Transmission Network**	
Granderson and Linvill (1996)	Econometric cost function	20 US interstate natural gas pipelines from 1977 to 1987	O: Volume of gas transmitted I: Total cost IP: labour price, price of capital, price of compressor capital and price pipeline capital	TFP grew at an average annual rate of 6.4% p.a
Kim et al. (1999)	Tornqvist productivity index	9 transmission companies and 19 integrated companies across 8 countries from 1987 to 1995	O: Total volume of supplied gas I: Number of Employees, capital costs , administration input	Productivity growth rate between 1%pa -36.9% p.a. for transmission companies' group and -2.3%pa -31.2% p.a. for integrated companies' group.
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% p.a.
		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% per annum.
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% per annum, which can be decomposed into technical change of 2.4% and technical efficiency of 0.4%.
Casarin (2014)	Econometric variable cost function and generalized index approach	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 % per year, whereas the index model suggests a marked decline in TFP of - 0.833 % per year.
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% p.a in the Austrian gas distribution sector in the period 2002–2013.

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

Table A3: Descriptive Statistics for Gas Transmission Network

	Variable	Unit	Mean	Std. Dev	Min	Max
Capex	Input	£m	238.19	181.86	107.36	616.51
Opex	Input	£m	103.37	47.56	67.96	205.80
Shrinkage-adjusted opex	Input	£m	182.19	41.68	124.48	252.25
Shrinkage-and emission-adjusted opex	Input	£m	183.76	42.24	124.48	254.87
Gas Transmitted	Output	GWh	994026.98	87676.18	883985.51	1114250.35
Gas NTS Demand	Output	GWh	562805.96	51472.90	508959.63	634447.46
Network Length	Output	km	7567.63	205.97	6961.93	7658.71

Table A4: Descriptive Statistics for Gas Distribution Network

	Variable	Unit	Mean	Std. Dev	Min	Max
Capex	Input	£m	94.35	24.23	60.52	163.75
Opex	Input	£m	63.65	49.47	18.01	267.79
Emission-adjusted opex	Input	£m	94.41	24.25	60.59	163.91
Unit Distributed	Output	GWh	70674.89	20617.63	43002.69	120219
Number of Customers	Output	Million	2.73	0.82	1.74	4.20
Network Length	Output	km	33332.6	10355.3	20224.58	51780.33
Customer Minute Lost	Quality variable	Million	112.60	85.37	20.36	376.70
Customer Satisfaction	Quality variable	Million	22.66	7.19	13.64	37.01

Table A5: Descriptive Statistics for Gas Corporate Accounts

	Variable	Unit	Mean	Std. Dev	Min	Max
Capex	Input	£m	1207.65	323.88	681.54	1868.30
Opex	Input	£m	2615.30	591.94	1898.99	4419.90
Total Demand	Output	GWh	562805.96	51472.90	508959.63	634447.46
Number of Customers	Output	Thousand	4818.56	1476.81	2670.00	7432.58

Appendix II

We deflate capital expenditure using gross fixed capital formation price deflator as capital index. The ONS variable code for the gross fixed capital formation price deflator is CDID:YBFU. We use wage index as proxy to deflate operating expenditure. We use the Average Weekly Earnings (AWE) statistics as a measure of wage index are reported by the ONS and consider the index for the whole economy with the ONS variable code CDID: K54U for the AWE. The indices are reported monthly, and we construct the annual series following the Ofgem annual regulatory fiscal year end in March for both capital index and wage index over our sample period.

Monetisation of emissions variables

Carbon emission cost

Emission variables data are recently being reported by Ofgem in the current price control period, RIIO-1, starting from 2013/2014, and their valuation only covers this period for both gas transmission and distribution networks. Therefore, we compute the cost of carbon emission from as follows.

Carbon emission cost = Business Carbon Footprint (tCO2e) × social price of carbon £/CO2[21]*).*

Cost of gas shrinkage

The valuation of gas shrinkage is obtained by multiplying gas transmission shrinkage in MWh by NBP gas prices expressed in £/MWh 2012/2013 prices, covering 2006/2007 to 2018/19. We adjust the wholesale gas prices following annual regulatory fiscal year end in March and deflate it using a wage index.

Cost of shrinkage = gas shrinkage (MWh) × NBP gas prices (£/MWh*)*

[21] The updated short term traded carbon values for UK public policy appraisal" can found in the link below: https://www.gov.uk/government/publications/2012-update-to-carbon-valuation-methodology-for-uk-policy-appraisal.