Energy Policy 106 (2017) 536–546

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Prices versus policy: An analysis of the drivers of the primary fossil fuel mix

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ARTICLE INFO

JEL Classification:
C68
E30
E37
Q43
Q48

Keywords:
Energy transition
Fossil fuel mix
Relative prices
DSGE modeling
Prices vs policy

ABSTRACT

Energy policymakers often attempt to shape their countries' energy mix, rather than leave it purely to market forces. By calibrating and simulating a Dynamic Stochastic General Equilibrium (DSGE) model, this paper analyzes the primary fossil fuel mix in the USA and compares it to Germany and the UK, given the different evolution of the mixes and the different roles played by relative prices and policy in North America and Europe. It is found that the model explains well the evolution of the primary fossil fuel mix in the USA for the period 1980–2014, suggesting that relative fossil fuel prices generally dominated in determining the mix during this time. However, this is not the case for Germany and the UK. For both countries, the model performs well only for the period after the market-oriented reforms in the 1990s. Additionally, the volatility of private consumption and output for the pre- and post-reform periods is evaluated for Germany and the UK and it is found that the liberalized energy markets brought about a transition from coal to natural gas, but with increased macroeconomic volatility.

1. Introduction

Policy makers see fuel price volatility as a risk to their economies. Consequently, they often attempt to use energy policies to shape an energy mix that leaves their economies less vulnerable to energy price shocks. Environmental concerns also add pressure in favor of a ‘cleaner’ energy mix. Accordingly, the observed energy mix is generally the result of the interaction of fuel prices, available technologies, and energy policies. In other words, the energy mix is determined by the relative costs of fuels, but also by local policies that address security, environmental, economic, and social aspects of the energy system. This paper aims to explain the role of fossil fuel prices relative to energy policy in driving the primary fossil fuel mix.

Fig. 1 illustrates the evolving primary fossil fuel shares for the USA, Germany, and the UK[1] from 1980 to 2014 and shows that the fossil fuel mix in the two European countries has changed far more than in the USA. From the beginning to the end of the period, the USA's oil share fell slightly from 46% to 42%, while the gas share increased from 30% to 34% and the coal share hardly changed (although it did increase slightly and then fall back again at the end of the period). In Germany, although the oil share did not change dramatically from the beginning to the end of the period (from 43% to 45%), the gas and coal shares did – from 15% to 25% and from 41% to 30%, respectively. A similar pattern emerged in the UK, with the oil, gas, and coal shares changing over the period from 42% to 43%, from 21% to 38%, and from 37% to 17%, respectively.

Generally, the USA had a relatively stable primary fossil fuel mix over the period 1980–2014, although there was an increase in the share of gas and a fall in the share of coal towards the end of the period (Fig. 1). This, by all accounts, was due to the development of shale gas in the USA; according to Joskow (2015), the share of shale gas in USA gas production increased from 7% in 2007 to 40% in 2015. In contrast, the primary fossil fuel mixes in Germany and the UK gradually shifted toward natural gas over the whole period, although from about 2010 onwards, it appears to decrease.

Therefore, it is interesting to analyze why the primary fossil fuel mix evolved so differently in the USA compared to Germany and the UK and to assess the factors behind the difference. In particular, are the differences the result of market forces and, hence, chiefly driven by relative fossil fuel prices? Alternatively, are the differences the result of

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[1] The spike in the UK fossil fuel shares in 1984 is due to the miners’ strike that took place that year and into 1985 (see, for example, BBC, 2004).

http://dx.doi.org/10.1016/j.enpol.2017.03.060
Received 20 October 2016; Received in revised form 16 February 2017; Accepted 27 March 2017
Available online 14 April 2017
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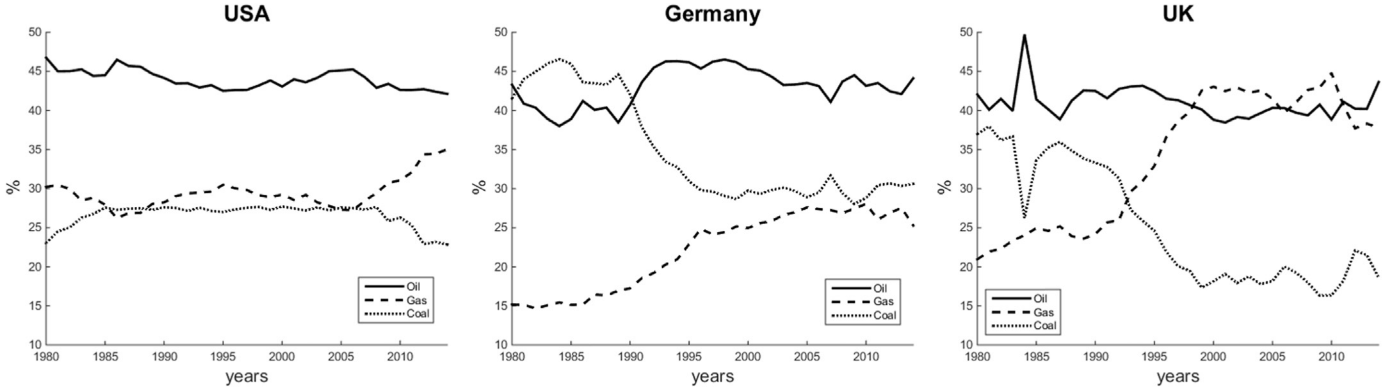

Fig. 1. Primary fossil fuel energy mix (relative shares).

the various energy policies of the countries considered in the analysis?[2] It is also interesting to analyze the impact of the changing primary fossil fuel mix on the two European countries' economies. In particular, are the German and British economies more or less volatile after the energy reforms of the 1980s and 1990s?

The analysis is undertaken by developing a Dynamic Stochastic General Equilibrium (DSGE) model for the USA and then simulating the model to assess the impact of relative prices on the primary fossil fuel mix over the period 1980–2014.[3] As a first step, we analyze the stability of the calibrated energy related parameters for the USA and compare them to those from similar production functions for Germany and the UK, where policy intervention is believed to have had a greater impact on primary fossil fuel demand. Furthermore, the DSGE models for all three countries are simulated in order to assess the importance of relative prices and policy in driving the primary fossil fuel mix. Additionally, the DSGE model is used to analyze the volatility of private consumption and output for the pre- and post-reform periods in Germany and the UK to assess the impact of the reforms on these economies.

Calibrated dynamic, either stochastic or deterministic, general equilibrium models have been at the core of macroeconomic analysis for the last few decades. Regarding energy, these models have mainly been used to analyze the macroeconomic effects of energy price shocks, particularly oil shocks (such as, Kim and Loungani (1992), Rotemberg and Woodford (1996)). More recently, DSGE models have been used to analyze optimal energy taxation (De Miguel and Manzano, 2006; Golosov et al., 2014), the behavior of the oil market (Nakov and Nuño, 2013), and the macroeconomic impact of the shale oil revolution (Mănescu and Nuño, 2015).

However, a DSGE model is used here for a different purpose. After initially analyzing the effects of fossil fuel prices and energy policies on the changes in the primary fossil fuel mix in the US, Germany, and the UK, we study the impact of the changing mix on the economic volatility of the two European countries.[4] Although some previous research has considered the energy mix (such as Dassisti and Carnimeo (2012) for Europe; Carraro et al. (2014) for the European power sector; Vidal-Amaro et al. (2015) for the Mexican power sector), this is, to our knowledge, the first attempt to analyze the drivers of the primary fossil fuel mix in this way. Moreover, the literature on analyzing the impact of fuel price shocks has focused on the impact of oil prices on economic activity (see for example, Hamilton (1983, 2003), Kilian (2008, 2009), De Miguel et al. (2003), Kesicki (2010), Herrera et al. (2015)). As far as we know, this is the first attempt to analyze the impact of fossil fuel prices on the fossil fuel mix and the consequences for the economy.

In summary, this paper uses a macroeconomic approach to assess the relative importance of fossil fuel prices and policy in determining the primary fossil fuel mix. This is undertaken initially for the USA, and then Germany and the UK where, *a-priori*, we expect policy to play a greater role than prices given the different energy policies in the USA and the European countries. The remainder of the paper is organized as follows. Section 2 presents the DSGE model followed by Section 3 that discusses the calibration of the model parameters and the simulation of the model for the USA. Section 4 presents the calibration of the parameters and simulation of the model for Germany and the UK, compares them to those for the USA, and considers the impact of the change in the fossil fuel mix on the volatility of private consumption and output. Section 5 presents a summary and conclusion.

2. The model

The economies of the USA, Germany, and the UK can each be represented by a stylized DSGE model. The models consist of an infinitely lived representative household and a representative firm producing final output. Given that the analysis aims to assess the effect of fossil fuel prices (relative to policy) on the primary fossil fuel mix, not the determination of prices, fossil fuel prices are assumed exogenous and stochastic.

2.1. The representative household

The representative household's preferences are characterized by a utility function:

$$U(c_t) = \frac{c_t^{1-\sigma}}{1-\sigma} \tag{1}$$

where c_t is consumption at time t and σ is the inverse of the intertemporal elasticity of substitution of consumption. Given the analysis focuses on primary energy use, c_t is assumed to represent all

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[2] In addition, technological change can increase the efficiency of the use of a primary energy source, potentially changing the fuel mix toward the fuel that has experienced the technology improvement. However, since there are technology diffusion flows among developed economies, technology should not play a major role in explaining differences in the energy mix among countries.

[3] The models were simulated using the software program DYNARE, a freely available software platform at http://www.dynare.org/.

[4] The focus of the paper is to assess the impact of international prices relative to energy policy on the primary fossil fuel energy mix, so renewable and nuclear energy are not taken into account. In the past, the deployment of energy from renewables and nuclear has generally been the result of governmental strategy pursuing objectives such as energy security, greenhouse emissions reduction, economic competitiveness, industrial development or even green jobs (see Dassisti and Carnimeo (2012) for a discussion concerning the European Union). Additionally, there are no ‘international prices’ for nuclear and renewable energy; hence, it is not possible to include them in the analysis. We considered the Levelized Cost of Electricity (LCOE) as a proxy for the international price of renewable or nuclear technology; however, this was not deemed appropriate given that the LCOE depends on factors such as leverage, the discount rate, taxes, cost of land, administrative permissions, etc. Therefore, LCOE does not allow for a homogeneous comparison.

consumption. Therefore, the model does not distinguish between consumption of energy by households and firms.[5] The household maximizes an intertemporal expected discounted flow of utility subject to the budget constraint and capital accumulation:

$$max_{c_t,k_{t+1}}E_0\sum_{t=0}^{\infty}\beta^t\frac{c_t^{1-\sigma}}{1-\sigma} \tag{2}$$

subject to:

$$c_t+k_{t+1}-(1-\mu)k_t=w_tn_t+r_tk_t \tag{3}$$

where, the variable k_t is capital, r_t is the interest rate, w_t are wages and n_t is the quantity of labor, all at time t. The parameter β is the discount factor and μ is the capital depreciation rate. The first order conditions that define optimal household behavior are:

$$\frac{\partial U}{\partial c_t}=\beta E_t\frac{\partial U}{\partial c_{t+1}}(1-\mu+r_{t+1}) \tag{4}$$

$$c_t+k_{t+1}-(1-\mu)k_t=w_tn_t+r_tk_t \tag{5}$$

Eq. (4) is the Euler condition that governs the intertemporal substitution of consumption and Eq. (5) represents the budget constraint. In addition, the transversality condition for capital is:

$$lim_{t\to\infty}\frac{\partial U}{\partial c_t}k_t=0 \tag{6}$$

2.2. The representative firm

It is assumed that there is one competitive and representative firm that produces ‘final goods and services.’ The firm uses labor, capital, and three primary fossil fuels as inputs according to a production function with constant returns to scale. Moreover, the production function is assumed to be a Constant Elasticity of Substitution (CES) function for a composite fossil fuel source (consisting of natural gas and coal), which is nested within a CES function with oil, which is further nested within a Cobb-Douglas (CD) function with capital and labor; as follows:

$$Y_t=n_t^{\alpha}k_t^{\phi}\left(ae_{O_t}^{\delta}+(1-a)(be_{G_t}^{\gamma}+(1-b)e_{C_t}^{\gamma})^{\frac{\delta}{\gamma}}\right)^{\frac{1-\alpha-\phi}{\delta}} \tag{7}$$

where Y_t is final output, n_t is labor, k_t is capital, e_{O_t} is oil, e_{G_t} is natural gas, and e_{C_t} is coal at time t. The chosen specification of technology is similar to that used in Blazquez et al. (2017), but here it is assumed that the elasticities of substitution between natural gas and coal and between oil and the composite fossil fuel source (consisting of natural gas and coal) are different. This is because oil is generally refined to produce oil products that are heavily used in the transportation sector, whereas the vast majority of coal and natural gas is used to produce electricity and thus compete against each other as fuel sources for power.

The first order conditions for the final goods firm to maximize profits are:

$$w_t=\alpha n_t^{\alpha-1}k_t^{\phi}\left(ae_{O_t}^{\delta}+(1-a)(be_{G_t}^{\gamma}+(1-b)e_{C_t}^{\gamma})^{\frac{\delta}{\gamma}}\right)^{\frac{1-\alpha-\phi}{\delta}} \tag{8}$$

$$r_t=\phi n_t^{\alpha}k_t^{\phi-1}(ae_{O_t}^{\delta}+(1-a)(be_{G_t}^{\gamma}+(1-b)e_{C_t}^{\gamma})^{\frac{\delta}{\gamma}})^{\frac{1-\alpha-\phi}{\delta}} \tag{9}$$

$$\begin{aligned}P_{O_t} &= (1-\alpha-\phi)an_t^{\alpha}k_t^{\phi}e_{O_t}^{\delta-1}\\ &\quad\times\left(ae_{O_t}^{\delta}+(1-a)(be_{G_t}^{\gamma}+(1-b)e_{C_t}^{\gamma})^{\frac{\delta}{\gamma}}\right)^{\frac{1-\alpha-\phi}{\delta}-1}\end{aligned} \tag{10}$$

$$\begin{aligned}P_{G_t} &= (1-\alpha-\phi)(1-a)bn_t^{\alpha}k_t^{\phi}e_{G_t}^{\gamma-1}(be_{G_t}^{\gamma}+(1-b)e_{C_t}^{\gamma})^{\frac{\delta}{\gamma}-1}\\ &\quad\times\left(ae_{O_t}^{\delta}+(1-a)(be_{G_t}^{\gamma}+(1-b)e_{C_t}^{\gamma})^{\frac{\delta}{\gamma}}\right)^{\frac{1-\alpha-\phi}{\delta}-1}\end{aligned} \tag{11}$$

$$\begin{aligned}P_{C_t} &= (1-\alpha-\phi)(1-a)(1-b)n_t^{\alpha}k_t^{\phi}e_{C_t}^{\gamma-1}(be_{G_t}^{\gamma}+(1-b)e_{C_t}^{\gamma})^{\frac{\delta}{\gamma}-1}\\ &\quad\times\left(ae_{O_t}^{\delta}+(1-a)(be_{G_t}^{\gamma}+(1-b)e_{C_t}^{\gamma})^{\frac{\delta}{\gamma}}\right)^{\frac{1-\alpha-\phi}{\delta}-1}\end{aligned} \tag{12}$$

where w_t, r_t, P_{O_t}, P_{G_t}, and P_{C_t} are the prices of labor, capital, oil, natural gas, and coal at time t. The price of the aggregate good is normalized to one, so that all prices in the economy are real prices. The quantity of labor is also normalized to one to simplify the analysis. Eqs. (8)–(12) imply that input prices are equal to the respective marginal productivities.

2.3. Prices of fossil fuels

Fossil fuel prices are assumed to be exogenous and follow stochastic processes:

$$lnP_{O_t}=(1-\rho_O)lnP_O^{ss}+\rho_O lnP_{O_{t-1}}+\varepsilon_t^O, \tag{13}$$

$$lnP_{G_t}=(1-\rho_G)lnP_G^{ss}+\rho_G lnP_{G_{t-1}}+\varepsilon_t^G, \tag{14}$$

$$lnP_{C_t}=(1-\rho_C)lnP_C^{ss}+\rho_C lnP_{C_{t-1}}+\varepsilon_t^C, \tag{15}$$

where P_O^{ss}, P_G^{ss} and P_C^{ss} represent the steady state values for the price of oil, natural gas, and coal, respectively – around which each price fluctuates. The variables ε_t^O, ε_t^G and ε_t^C represent innovations in the stochastic processes. These variables are assumed to follow a normal multivariate process:

$$\begin{bmatrix}\varepsilon_t^O\\ \varepsilon_t^G\\ \varepsilon_t^C\end{bmatrix}\sim N\left(\begin{bmatrix}0\\0\\0\end{bmatrix},\begin{bmatrix}\sigma_O^2 & & \\ \sigma_{OG} & \sigma_G^2 & \\ \sigma_{OC} & \sigma_{GC} & \sigma_C^2\end{bmatrix}\right) \tag{16}$$

2.4. The competitive equilibrium

The competitive equilibrium for this economy is a set of allocation and price paths that satisfy the following conditions:

i) $\{c_t, k_t\}$ solve the household's problem given prices $\{r_t, w_t\}$.
ii) $\{n_t, k_t, e_{O_t}, e_{G_t}, e_{C_t}\}$ maximize the profits of the firm that produces the aggregate ‘good’ given input prices $\{w_t, r_t, P_{O_t}, P_{G_t}, P_{C_t}\}$.
iii) All markets clear.

In summary, the theoretical model above is characterized by:

- a representative household with rational expectations that maximizes consumption over time;
- a representative firm that produces final goods and services with a constant returns to scales production function and maximizes profits in a competitive environment; and
- exogenous stochastic fossil fuel prices.

This theoretical model is nonlinear and stochastic; hence, it is not

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[5] The model used here therefore differs to that introduced by Dhawan and Jeske (2008) (who distinguish between energy use by firms and consumers) and to that introduced by Plante (2014) (who distinguishes between oil and oil products use by firms and consumers, respectively). However, Dhawan and Jeske's (2008) model is used to analyze energy price shocks on the macro economy and Plante's (2014) model is used to analyze how monetary policy should respond to changes in oil prices. Therefore, given the focus of the analysis in this paper (similar to Golosov et al. (2014)), it is assumed that consumers maximize utility with respect to c_t only in order to simplify the analysis.

possible to obtain analytical solutions. Therefore, the model is solved numerically and calibrated values for the parameters are required. The sections below describe the calibration and econometric estimation for the USA, Germany, and the UK.

3. The USA

3.1. USA model calibration

3.1.1. Final goods firm

The elasticity of substitution measures how factors of demand vary as relative factor prices change. The assumptions about these elasticities are vital for the calibration of the model introduced in Section 2 and the outcome of the analysis since they determine the shape and behavior of the production function, Eq. (7). For the top-level relationship between labor, capital, and the total composite fossil fuel a CD technology is assumed; hence, the partial elasticity of substitution between each pair of factors is unity. However, this is not the case for the nested relationships between the different fossil fuels, where a CES technology is assumed. Thus, it is important to consider the assumptions for the interfuel elasticities of substitution that measure how fuel demand varies as relative fuel prices change.

There is a long history of research attempting to estimate measures of interfuel substitutability. This is summarized by Stern (2012) who undertakes a meta-analysis using almost 50 primary studies that include results for the USA, Germany, and the UK. However, although Stern (2012) identifies a number of key drivers that determine the results for a range of interfuel elasticities, the paper does not supply obvious values for the key interfuel elasticities of substitution required for Eq. (7); namely, between natural gas and coal and between oil and the composite fossil fuel (from natural gas and coal). Moreover, when considering the individual studies included in Stern (2012), they were found not to be applicable here.[6] For example, many of the studies are now dated (being from the 1970s) and often did not report the actual estimated interfuel elasticities of substitution. Furthermore, primary fossil fuels at the whole economy level are considered here and it would appear that many of the previous studies used secondary energy consumption at a sectoral level – again rendering them not appropriate for our analysis.

Instead, therefore, the USA interfuel elasticities of substitution used here are based on the estimates from Serletis et al. (2010). These estimates were chosen given they are for the national level and use annual data for the estimation (in line with the data frequency used in the analysis here[7]). Therefore, the appropriate averages of the estimated (asymmetric) Morishima elasticities of substitution from Table 6 of Serletis et al. (2010; p. 742) are used here. This gives, for the USA, assumed interfuel elasticities of substitution of 0.38 for coal and natural gas and 0.24 for oil and the composite fossil fuel (consisting of natural gas and coal) – which implies that δ and γ in Eq. (7) are equal to −3.16 and −1.65, respectively.

Given the δ and γ assumptions and using actual USA data[8] for the period 1980–2014, Eqs. (8)–(12) allow for the calibration of the parameters α, ϕ, a, and b. For the key energy related parameters (a and b) the averages for various sub-periods were considered to ensure the stability of the calibrated values, which are given in Table 1; in addition the annual figures for a and b are illustrated in Fig. 2[9] (along with $1\text{-}b$[10]). These show that over the whole period the calibrated energy related parameters are relatively stable for the USA, with no noticeable difference across time. Moreover, as shown in Table 1, the coefficient of variation for a is relatively small at 4% but it is slightly larger for b at 11%. However, both a and b are regarded as being relatively stable for the USA; hence, the average calibrated values from the whole sample (1980–2014) are used when running the simulations discussed below. Table 2 therefore gives all the USA calibrated production function parameters averaged over the whole period, derived from Eqs. (8)–(12).

Table 1
USA calibrated energy related production function parameters (for different periods).

Period	a	b
1980–1990	0.89	0.62
1991–2000	0.84	0.63
2001–2010	0.87	0.67
2011–2014	0.91	0.71
Mean (1980–2014)	0.87	0.65
Standard deviation	0.03	0.07
Coefficient of variation	0.04	0.11

3.1.2. The household

Following the meta-analysis of Havranek et al. (2015), we assume an intertemporal elasticity of substitution of 0.5, implying that σ is equal to 2. Using standard values from the macroeconomic literature (see for example, Prescott, 1986), the parameter β is assumed to equal 0.96 and μ is assumed to equal 0.1.

3.1.3. Fossil fuel prices

Table 3 presents the correlation coefficients between the real prices of crude oil, natural gas, and coal. The price of coal is relatively strongly correlated with the price of oil, but the correlation of the price of natural gas with both oil and coal is less strong. This is consistent with the view that in the USA, natural gas prices ‘decoupled’ from oil prices following the emergence of shale gas (see Joskow (2015)), given that for the period 1980–2006 the correlation between the oil price and natural gas was 0.63 compared to 0.40 over the whole period.

Given the relatively strong correlations between prices, it would be wrong to assume that the residuals of the stochastic processes given in Eqs. (13)–(15) are independent. On the contrary, the high correlations suggest that energy prices are affected by the same shocks. Prices are therefore modeled using the Seemingly Unrelated Regression (SUR) method, allowing the shocks on the three fossil fuel prices to be contemporaneously correlated (see Green (2012)). Table 4 presents a summary of the estimation results. Furthermore, Table 5 shows the covariance matrix of the residuals from the estimated equations, which imply that oil shocks, natural gas shocks, and coal shocks are not independent in the model.

3.2. USA results

The calibrated parameters from above are applied in order to assess the stability of the primary fossil fuel mix in the USA during the period 1980–2014. Fig. 3 compares the actual fossil fuel shares for oil, natural gas, and coal with the predicted shares from the model simulation. The results ‘predict’ the actual shares relatively well, including the impact of large fossil fuel price fluctuations. For example, from 2000 the price of oil increased relative to the prices of natural gas and coal, which is reflected in the results and the actual shares, both showing a sharp increase in the share of natural gas and a decline in the share of oil in the primary fossil fuel mix. However, a more stable evolution of coal's share in the fossil fuel mix than actually occurred is predicted, suggesting that coal should represent around 26% of the fossil fuel mix during the period 1980–2014, which is not consistent with the

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[6] See Table 1 in Stern (2012; pp. 309–314) for a full list of the previous studies.

[7] Unlike Golosov et al. (2014) that used a 10-year data frequency in their analysis.

[8] See the Appendix A for a detailed description of the data.

[9] The range of the vertical axes for the USA charts are the same as those presented below for Germany and the UK to aid comparison.

[10] Note the discussion of the calibration focusses on the energy related parameters of the production function a and b; however, the parameter $1\text{-}b$ is also shown in Fig. 2 (as well as Figs. 4 and 5 below) to aid clarity.

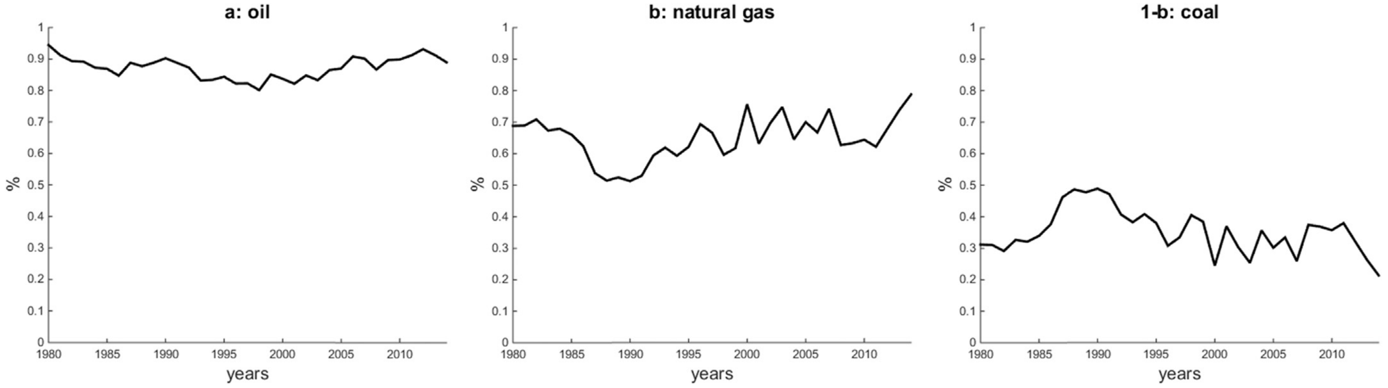

Fig. 2. USA Calibrated energy related production function parameters.

Table 2
USA calibrated production function parameters (used for analysis).

Period	α	ϕ	a	b
1980–2014	0.60	0.34	0.87	0.65

Table 3
Real fossil fuel prices correlation coefficients for the USA (1980–2014).

	Oil	Natural Gas	Coal
Oil	1	0.40	0.80
Natural Gas		1	0.59
Coal			1

Table 4
Seemingly Unrelated Regression (SUR) for price models.

	Coefficient	Std. Error
ρ_O	0.86	0.07
ρ_G	0.71	0.10
ρ_C	0.68	0.12

Table 5
Covariance matrix for the errors.

	ε_t^O	ε_t^G	ε_t^C
ε_t^O	0.05	0.02	0.02
ε_t^G		0.07	0.02
ε_t^C			0.04

actual data for the period. The larger share of coal consumption during those years probably reflects the response to the 1970s oil embargo, when power generation in the USA switched from oil to coal for energy security reasons (see EIA (2012)), rather than in response to a change in the relative price of coal. In addition, the model does not pick up the sharp decline in the share of coal since 2008 that may be due to the implementation of new energy policies. According to the IEA/IRENA (n.d.), 27 new policies on climate change entered into force in the USA 2009 and 2010 following President Obama's electoral pledge. However, the evolution of the natural gas share is very well captured by the model, suggesting that prices mostly explain the increase in natural gas consumption since 2008 and the rise of its share in the primary fossil fuel mix.

In summary, the model does a good job in explaining how the USA's primary fossil fuel mix evolved over the period 1980–2014, suggesting that relative fossil fuel prices generally dominated in determining the USA's mix. The next section considers Germany and the UK, to analyze whether such a model can explain the primary fossil fuel mix evolution as successfully in countries where there has been more structural change and where energy policy was more active.

4. Germany and the UK

4.1. Germany and the UK model calibration

4.1.1. Representative firm

Unlike for the USA, we could not find any recent papers that included appropriate interfuel elasticity of substitution estimates for Germany and the UK. Therefore, for Germany and the UK the same values as those used for the USA from Serletis et al. (2010) were assumed for both European countries. This implicitly assumes that the same energy-using technologies in the USA were available in Germany

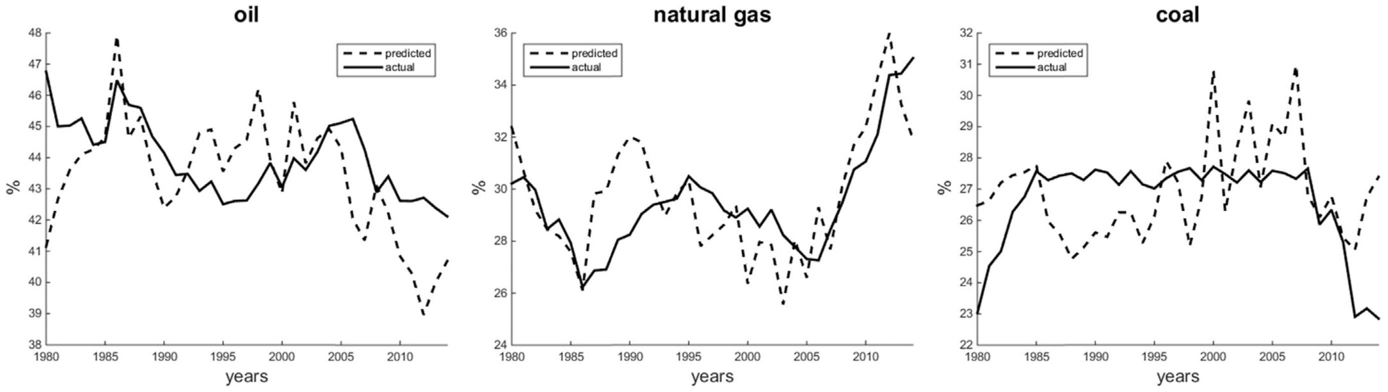

Fig. 3. Actual and predicted USA primary fossil fuel energy shares.

and the UK – which should not be an unreasonable assumption given they are all western developed economies. Nonetheless, to ensure that the results are robust, a sensitivity analysis around the assumptions for the key interfuel elasticity of substitution was undertaken, and although there are some small differences in the quantitative results, there are no discernable differences in the qualitative results.[11]

Similar to the analysis for the USA, the stability of the calibrated energy related parameters for Germany and the USA was investigated. Therefore, the average calibrated parameters (a and b) for the two European countries using Eqs. (8)–(12), over various sub-periods within the period 1980–2014 are given in Table 6 (with summary statistics) along with the annual figures for Germany and the UK illustrated in Figs. 4 and 5, respectively. Unlike for the USA, however, the key calibrated energy related parameters for Germany and the UK are relatively unstable over the period considered. Both calibrated energy related parameters for both European countries show much greater variation than for the USA. The coefficients of variation for a are 14% for Germany and 74% for the UK, both higher than the 4% value for the USA. This is also the case for b, with coefficients of variation of 60% for Germany and 92% for the UK compared to 11% for the USA.[12] These variations, highlighted by differences across the sub-periods, likely reflect the change in energy structure that accompanied German reunification in 1990 and the liberalization of the UK energy sector during the 1980s and the 1990s. In other words, structural change and policy factors appear to dominate the impact of changing relative prices.

It is interesting to consider the possible reasons for the greater variability in the energy related calibrated parameters (a and b) for Germany and UK than the USA. For Germany, b is found to be very small during the 1980s, reflecting the relatively low consumption of natural gas and oil and the importance of coal in the primary fossil fuel mix – which is likely to be the outcome of policies implemented by both East and West Germany during that period. In 1991, following German reunification, energy policy changed dramatically as the eastern part of the country shifted towards a more market-oriented system. For the UK, in the 1980s, the parameter b is found to be substantially smaller than for the remainder of the period – which is likely to be due to the (then publically owned) UK electricity industry having to buy and use coal produced by the UK's (then publically owned) coal company.[13] However, for the UK, b changed markedly from the early 1990s following the government's liberalization and privatization policies, when both the electricity and coal industries were re-structured and sold to the private sector and the subsequent shift from coal- to gas-fired power production.[14]

In Germany, 1991–2002 was a period of transition. Coal progressively lost market share relative to oil and natural gas. This transition might have been explained by a systematic increase of coal prices relative to natural gas prices; however, the actual path of relative prices was the opposite. For the UK, 1991–1998 was a period of transition and, as in Germany's transition period, the evolution of relative fossil fuel prices was not consistent with the increase in natural gas consumption. Thus, for these two European countries, changes in the relative prices of natural gas, coal, or oil cannot explain the transition from coal to natural gas. Lauber and Mez (2004) suggest that in Germany a change in energy policy towards a more clean and sustainable energy mix drove the transition toward natural gas. In the UK, an institutional change drove the transition, as the electricity system moved from a state controlled and effectively vertically integrated system to an unbundled, privatized, liberalized, and deregulated market system (as discussed in Green (1991)).

Table 6
Germany and UK calibrated energy related production function parameters (for different periods).

	Germany		UK	
	a	b	a	b
1980–1990	0.66	0.10	0.80	0.34
1991–2000	0.86	0.35	0.73	0.70
2001–2010	0.86	0.58	0.59	0.93
2011–2014	0.89	0.59	0.74	0.92
1998–2014			0.67	0.93
2003–2014	0.86	0.59		
Mean (1980–2014)	0.80	0.36	0.71	0.68
Standard deviation	0.11	0.22	0.11	0.27
Coefficient of variance	0.14	0.60	0.74	0.92

Given this variability, when simulating the model for Germany, the values for a and b are the averages for 2003–2014, since they are relatively stable over this period. For the UK, the model is calibrated using data for 1998–2014, given that a and b are relatively stable through this period. Table 7 therefore presents all the calibrated parameters for the production function parameters for both Germany and the UK, derived from Eqs. (8)–(12).

4.1.2. *Household*

The parametrization of the households for Germany and the UK are identical as the one used for the USA.

4.1.3. *Fossil fuel prices*

Table 8 presents the correlation coefficients between the real prices of crude oil, natural gas, and coal for Germany and the UK. The correlation between the price of oil and the price of natural gas for both Germany and the UK is much higher than that for the USA. No ‘shale gas revolution’ has occurred in Europe, arguably the main reason behind the decoupling of prices in the USA. In addition, the high correlation could be caused by long-term natural gas contracts in Europe that are linked to oil prices, as Stern (2009) points out. Similarly, the correlation coefficient between the price of natural gas and the price of coal is about 0.8 for both Germany and the UK compared to about 0.6 for the USA. Unlike in the USA, natural gas prices in Germany and the UK do not appear to have ‘decoupled’ from oil prices. Nonetheless, as in the USA, there is relatively strong correlation between the fossil fuel prices in Germany and in the UK, suggesting that the prices are affected by the same shocks. Therefore, models for the fossil fuel prices in Germany and the UK are also estimated using the SUR method. Table 9 presents the main estimation results for both European countries. Finally, Table 10 shows the covariance matrix for the residuals of the regressions. As in the USA, the results suggest that oil shocks, natural gas shocks, and coal shocks are not independent.

4.2. *Germany results*

The results for Germany are generated for the whole period, but using the calibrated parameters for the period 2003–2014, as explained above. Fig. 6 represents the actual German fossil fuel energy mix for the whole period compared to that predicted by using the

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[11] The sensitivity analysis involved varying the German and British elasticity of substitution assumptions by a half, both negatively and positively. Therefore, the natural gas and coal elasticity of substitution of 0.38 was varied by ± 0.19 and the oil and composite fossil fuel elasticity of substitution of 0.24 was varied by ± 0.12; thus, giving a total of four comparator models to benchmark the central model against. The charts illustrating the sensitivity analysis for both European countries (and for the USA that was also undertaken for completeness) are available from the authors on request.

[12] The implicit parameter (*1-b*, that represents coal) also displays greater variability for Germany and the UK (as can be seen by comparing the final right hand diagrams of Figs. 4 and 5 with Fig. 2).

[13] The public Central Electricity Generating Board was established in 1957, but was restructured and privatized in the late 1980s and early 1990s.

[14] See Green (1991) for an explanation and discussion about the impact of privatization on the structure of the UK electricity market.

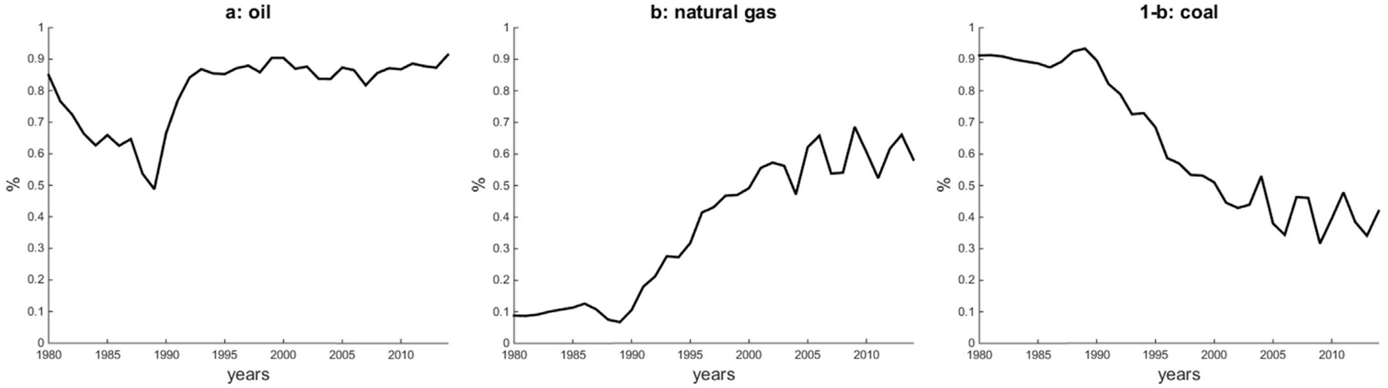

Fig. 4. Germany calibrated energy related production function parameters.

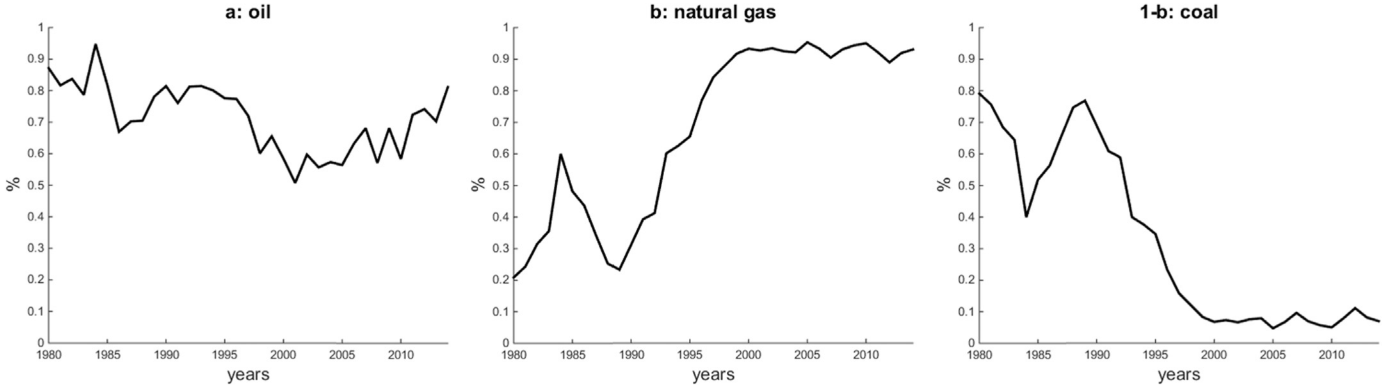

Fig. 5. UK calibrated energy related production function parameters.

Table 7
Germany and UK calibrated production function parameters (used for analysis).

	Period	α	ϕ	a	b
Germany	2003–2014	0.63	0.35	0.86	0.59
UK	1998–2014	0.65	0.32	0.67	0.93

Table 8
Real fossil fuel prices correlation coefficients for Germany and the UK (1980–2014).

	Germany			UK		
	Oil	Natural gas	Coal	Oil	Natural gas	Coal
Oil	1	0.87	0.80	1	0.85	0.76
Natural gas		1	0.83		1	0.78
Coal			1			1

Table 9
Seemingly Unrelated Regression (SUR) for price models.

	Germany		UK	
	Coefficient	Std. Error	Coefficient	St. Error
ρ_O	0.75	0.07	0.80	0.07
ρ_G	0.81	0.01	0.76	0.09
ρ_C	0.58	0.12	0.65	0.10

calibrated parameters for 2003–2014. This predicts the fossil fuel mix relatively well for the 2003–2014 period, suggesting that relative fuel prices were the main driver of the fossil fuel mix during that time. In particular, it captures the decline of the share of oil in the energy mix after 2008 while the shares of gas and coal were relatively stable.

Table 10
Covariance matrix for the errors.

	Germany			UK		
	ε_t^O	ε_t^G	ε_t^C	ε_t^O	ε_t^G	ε_t^C
ε_t^O	0.08	0.04	0.04	0.06	0.04	0.02
ε_t^G		0.05	0.03		0.08	0.04
ε_t^C			0.05			0.04

The price of fossil fuels appeared to predict adequately the USA's primary fossil fuel mix for the whole period, suggesting that the role of policy had a minor impact compared to the relative price drivers. However, a very different situation is observed for Germany. Fig. 6 illustrates the noticeable change in the German primary fossil fuel mix from 1990 onwards, likely driven by energy policy and the structural changes that followed German reunification. This clearly highlights that large shifts in energy policy accompanied by structural changes in energy marginalize the role of fossil fuel prices in determining the fossil fuel mix.

Given that the parameters for Germany are taken from a sub-period of the data, alternative model parametrizations were also analyzed. The reforms in Germany in the 1990s favored more liberalized markets, implying that fossil fuel prices should have a higher impact on the primary fossil fuel mix in the later part of the sample. In other words, given that prices drive the model, it should adjust better in the later part of the sample. The sample was therefore divided into three sub-periods: 1980–1990, 1991–2002 (the transition period), and 2003–2014. For each sub-period, we re-calibrated the energy related production function parameters and compared the actual fossil fuel mix with that predicted by using actual prices.

To compare the quality of the predictions, for each sub-period the

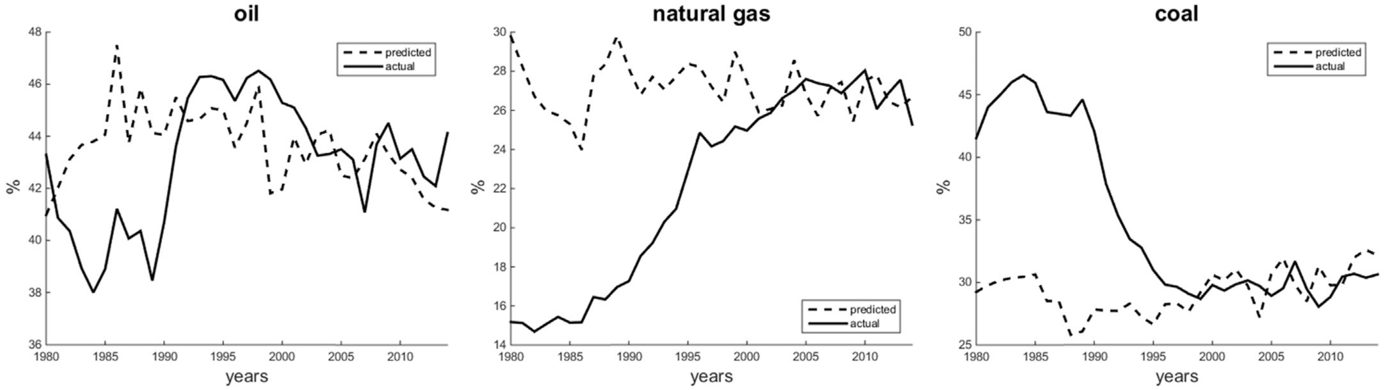

Fig. 6. Actual and predicted German primary fossil fuel energy shares.

Table 11
Average of the sum of quadratic errors for Germany.

	Oil	Natural Gas	Coal
Calibration 1980–1990	0.0007	0.0001	0.0005
Calibration 1991–2002 (transition period)	0.0002	0.0007	0.0011
Calibration 2003–2014	0.0002	0.0001	0.0003

average of the sum of the quadratic difference between the shares predicted and actual shares of the fossil fuel mix were calculated, i.e., the sum of quadratic prediction errors for each fuel share given by the formula $\left(\frac{\sum(Data - Predicted)^2}{n}\right)$. Table 11 shows that, as expected, the smallest prediction errors occur for oil, natural gas, and coal for the 2003–2014 sub-period – suggesting that the predictions are more accurate in this period. Although, in the case of oil these errors are similar to those of the transition sub-period 1991–2002 and in the case of natural gas these errors are similar to those of the first sub-period 1980–1990.

4.3. *UK results*

For the UK, the results were generated over the whole period using the calibrated parameters from 1998 to 2014, as discussed above and are shown in Fig. 7. This predicts the share of oil reasonably well for the whole period, but markedly over-predicts the gas share and under-predicts the coal share up until the late 1990s. This result is not surprising given that the nationalized coal and electricity industries in the UK were re-structured, liberalized, and privatized, with the full effect coming through in the mid to late 1990s. Moreover, during the publicly owned period and the initial few years of the privatized era, power producers were contracted to use a certain amount of UK coal. Unsurprisingly, the relative fossil fuel prices in the model over-predict the gas share but under-predict the coal share during this time.

As soon as the privatized electricity sector was released from such constraints in about the mid-1990s, the situation changed and relative fuel prices appear to affect the primary fossil fuel shares. From about the mid-1990s, the share of coal fell and the share of natural gas rose, reflecting the new Combined Cycle Gas Turbine (CCGT) stations that incumbent and new power producers built in the so-called ‘dash-for-gas’.[15] Therefore, as in Germany, the calibration replicates well primary fossil fuel energy mix, when the parameters are stable. This result is consistent with the periods when market forces, and hence relative prices, drove the primary fossil fuel mix.

The UK model should perform well after the market-oriented reforms took effect. Therefore, as in Germany, different model parametrizations were analyzed by dividing the sample into three sub-periods: 1980–1990, 1991–1997 (the transition period) and 1998–2014. Again, we re-calibrated the energy related parameters for the production function for each sub-period to compare the actual fossil fuel mix with that predicted. Table 12 shows that the prediction errors for natural gas and coal are smaller in the 1998–2014 sub-period – although for oil, the prediction errors are smallest during the transition period – but overall the final 1998–2014 sub-period produces the most accurate UK results.

4.4. *The economic results of the energy reforms in Germany and the UK*

Germany and the UK reformed and liberalized their energy systems in the 1990s based on the premise that market-oriented economies allow for greater competition, which should improve efficiency, lower prices, increase final consumption, and increase social welfare. As already highlighted, these reforms resulted in a dramatic change in the primary fossil fuel mix, with the share of natural gas increasing and the share of coal decreasing while the share of oil remained more or less stable. This change potentially exposed the two economies to more volatile fossil fuel prices; in particular, more volatile natural gas prices compared to coal prices. As discussed in the introduction, policymakers perceive increased fuel price volatility as a risk (see, for example, the discussion about the volatility of oil prices on the economy in Kantchev (2015) and Klevnäs et al. (2015)). Nonetheless, how changes in the primary fossil fuel mix affect the vulnerability of the economic system remains, to our knowledge, unexplored; therefore, we also examine this question.

An initial approach to explore the impact of the primary fossil fuel mix shift on the volatility of the German and British economies is by analyzing the impulse-response functions associated with a shock to each fossil fuel price on output. These are shown in Fig. 8 for the parametrizations covering the 1980–1990 period for both countries, 2003–2014 for Germany, and 1998–2014 for the UK. This shows that an oil price shock has a similar impact on output for both calibration periods, pre and post-liberalization of electricity markets, and for both, Germany and the UK. Nevertheless, the results for coal and natural gas are different depending on the period used for the calibration. In both countries, Fig. 8 suggests that the macroeconomic impact of a coal price shock has decreased given that the impulse responses are higher for the 1980–1990 period calibrations compared to the shorter period. In contrast, the macroeconomic impact of a natural gas price shock has increased given that the impulse responses are lower for the 1980–1990 period calibrations compared to the shorter period. Therefore, for both countries it would appear that the liberalization of the energy markets reduced the exposure to of their economies to coal disruptions at the cost of greater exposure to natural gas disruptions.

However, this analysis does not reveal whether the shift in the fossil

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[15] Watson (1997) discusses the many factors that explain the fast uptake of CCGTs in the 1990s.

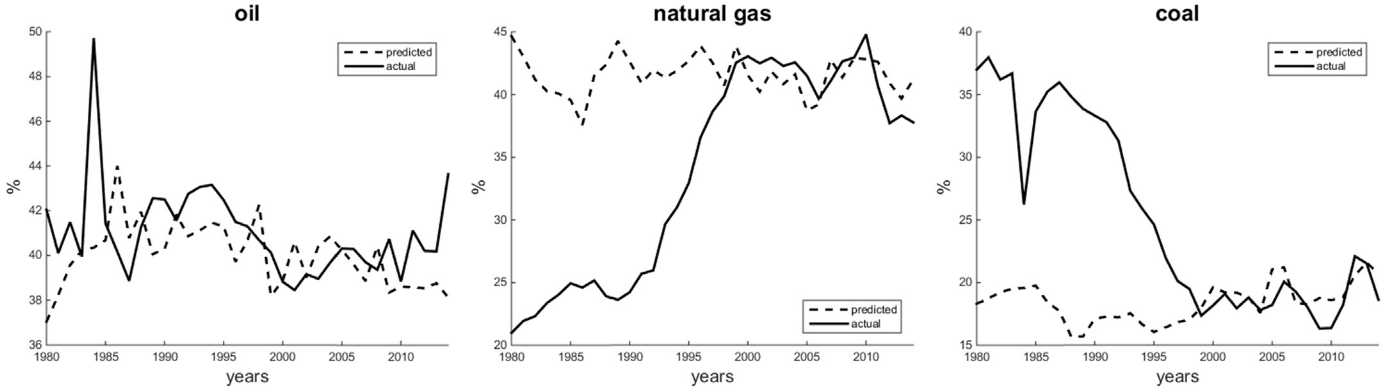

Fig. 7. Actual and predicted UK primary fossil fuel energy shares.

Table 12
Average of the sum of quadratic errors for the UK.

	Oil	Natural Gas	Coal
Calibration 1980–1990	0.0013	0.0007	0.0014
Calibration 1991–1997 (transition period)	0.0000	0.0015	0.0015
Calibration 1998–2014	0.0003	0.0004	0.0002

fuel mix created a more volatile economic environment. To do this the volatility of private consumption and output for Germany and the UK for both parametrizations are calculated and shown in Table 13. This suggests that as a result of the changes in the primary fossil fuel mix resulting from the reforms of the 1990s, private consumption is about 6% and 5% more volatile in Germany and the UK, respectively and output about 4% more volatile.

The prices of oil and natural gas, at least in Europe, are strongly correlated, as shown in Table 8 implying that oil price shocks are directly translated into natural gas price shocks of similar magnitude. Table 14 shows the coefficient of variation of real fossil fuel prices for both European countries, illustrating that coal is the least volatile fossil fuel price. Given the higher volatility of natural gas prices relative to coal, the reforms of the 1990s in both Germany and the UK and the resulting changes in the primary fossil fuel supply mix appear to have generated a more volatile economic environment. In summary, the German and British energy transitions towards natural gas as a consequence of a move to a more market orientated approach resulted in a ‘cleaner’ energy mix, but at the cost of increased economic volatility.

5. Conclusions and policy implications

The USA is one of the world's most market-driven economies. On the other hand, the two European comparator countries, Germany and the UK, have experienced significant structural and energy policy changes since the 1980s. The USA has experienced a relatively stable fossil fuel mix since 1980, while in Germany and the UK, the share of natural gas increased dramatically at the expense of coal. If market forces dominated, then the observed change in the fossil fuel mix in Germany and the UK would be consistent with an increase in the relative price of coal compared to natural gas. However, historical fossil fuel prices did not follow this trend, confirming that energy policy played an important role in the evolution of the fossil fuel mix in Germany and the UK.

This paper therefore analyzes the drivers of the fossil fuel mix in the USA and compares them to Germany and the UK, given the different evolution of the fossil fuel mix and the different roles that prices and policy have played in North America and Europe. To achieve this, a DSGE model is calibrated and simulated to explore the impact of relative prices on the primary fossil fuel mix over the period 1980–2014. We then compared the results using a similar analysis for Germany and the UK. In addition, the German and British models are used to evaluate the volatility of private consumption and output for the pre- and post-reform periods for both European countries to assess how changes in the primary fossil fuel mix affected these two economies.

For the USA, it is found that the calibrated production function explains well the evolution of the primary fossil fuel mix over the whole period 1980–2014, suggesting that relative fossil fuel prices and the market generally dominated the determination of the USA primary fossil fuel mix over the period. However, a different picture emerges for Germany and the UK, where dramatically changing shares of natural gas and coal cannot be explained by the calibrated production functions over the whole period. Instead, the production function for Germany is calibrated using data from the 2003–2014 period and for the UK using data for the 1998–2014 period. For both Germany and the UK, the calibrations perform well following the countries' transitional periods, when the allocation of resources in the energy sector became more market-oriented.[16]

Furthermore, given the dramatic increase in the shares of natural gas in Germany and the UK, the impact on the two economies is considered by analyzing the potential for increased volatility in private consumption and output. This analysis shows that, given the greater volatility of natural gas prices compared to coal prices, the move toward natural gas has generated a more volatile economic environment in both Germany and the UK. The German and British energy transitions towards natural gas have resulted in a ‘cleaner’ energy mix, but at the cost of increased economic volatility.

The analysis in this paper not only sheds light on the drivers of the primary fossil fuel mix, but also shows that the impact of natural gas price shocks could potentially be as important as previous oil price shocks. These issues, as far we know, have not been addressed empirically in the literature, where the focus has been the impact of oil price shocks on economic activity.

Finally, the past ‘energy transitions’ in both Germany and the UK considered in this paper came about due to a combination of political and structural changes. In Germany, the transition came about mainly from the reunification of the old East and West Germany and the subsequent move away from the heavily centrally planned coal-fired power system. In the UK, the transition was driven by the 1980s Thatcher government's agenda to reduce the role of the state and increase efficiency by deregulating, liberalizing, and privatizing the different parts of the energy industry. Both transitions, however,

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[16] It is worth noting that one factor that could play a role in the evolution of the mix of fossil fuels in Germany and the UK is taxes given international prices are used in the modeling. However, it would appear that there were no obvious structural changes in fuel taxes in the two European countries that would have altered relative domestic fuel prices enough in order to drive the change in the observed fossil fuel mix.

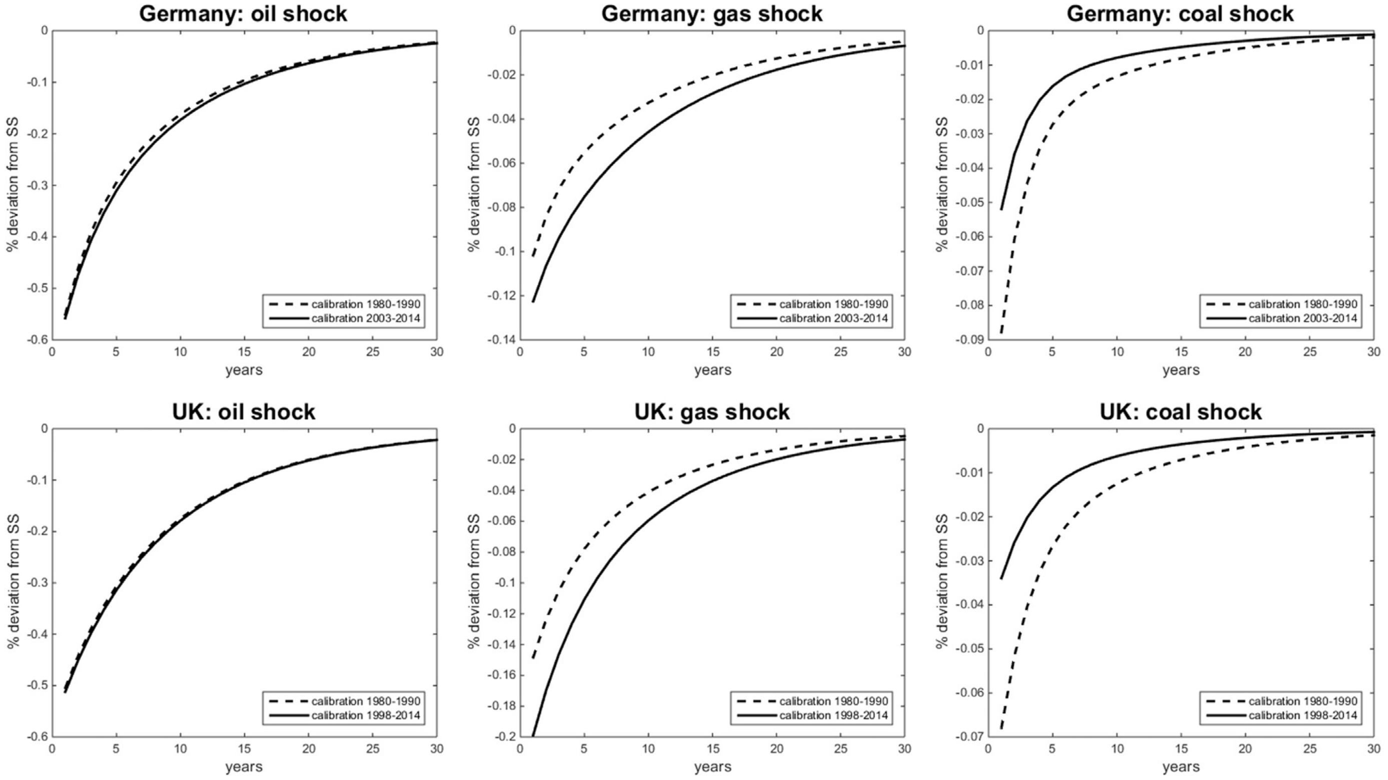

Fig. 8. Output impulse response functions to primary fossil fuel price shocks.

Table 13
Standard deviation according to the Germany and the UK models.

Germany	Private consumption	Output
Calibration 1980–1990	0.0080	0.0157
Calibration 2003–2014	0.0085	0.0163
Percent Difference	6.3	3.8

UK	Private consumption	Output
Calibration 1980–1990	0.0079	0.0145
Calibration 1998–2014	0.0083	0.0151
Percent Difference	5.1	4.1

Table 14
Coefficient of variation of real fossil fuel prices.

	Oil	Natural gas	Coal
Germany	0.53	0.46	0.30
UK	0.51	0.46	0.29

resulted in de-regulated market driven energy systems where the fuel mix was driven predominantly by market determined relative fuel prices – more akin to that in the USA. Furthermore, although this resulted in a ‘cleaner’ fuel mix – as the share of gas increased at the expense of the share of replaced coal – neither transition was instigated by the environmental agenda and the need to reduce carbon emissions. However, Europe is now in a new ‘energy transition’ era given the environmental constraint, with a move to increase significantly the proportion of renewables by introducing command and incentive policies to bring about a different energy mix to what would ensue if left purely to the market. It will therefore be interesting to see the impact this has and how the energy mix evolves over the next couple of decades in Europe compared to that in the USA.

Acknowledgments

Baltasar Manzano acknowledges financial support from Spanish Ministerio de Economía y Competitividad (ECO2015-68367-R). Early work for this paper was presented at the KAPSARC Workshop on Energy Vulnerability in March 2015 in Riyadh, Saudi Arabia and at the 39th International Association for Energy Economics (IAEE) 2016 International Conference in Bergen, Norway, and we are grateful to participants for their comments and suggestions. We are also grateful to anonymous referees for their comments and suggestions that have helped to improve considerably the paper; nonetheless, we are of course responsible for all errors and omissions. Furthermore, the views expressed in this paper are those of the authors and do not necessarily represent the views of their affiliated institutions.

Appendix A. Description of the data

The primary energy consumption data for the three fossil fuels (oil, natural gas, and coal) for the three countries (the USA, Germany, and the UK) were all obtained from BP (2016). Data for international oil prices were also obtained from BP (2016), with the Brent used as the representative price of crude oil for Germany and the UK and West Texas Intermediate for the USA.

Coal prices were generated differently, with the Central Appalachian coal spot price used as the reference coal price for the USA from 1980 to 2014. For Germany and the UK, for 1987–2014 the Northwest Europe marker coal price was used as the representative coal price and for 1980–1986 the sea-borne USA Central Appalachian coal spot price was used as a reference for price movements in the two countries – assuming that both series have similar annual rates of growth.

In the case of natural gas, for the USA the Henry Hub spot price for the years 1987–2014 was used and the USA spot wellhead gas price obtained from EIA (n.d.) for the preceding years. The average import price were used as the German benchmark price for 1984–2014 and for the preceding period 1980–1983, the German price was reverse-constructed by assuming similar growth rates to the USA spot wellhead gas price obtained from the EIA (n.d.). In the case of the UK, the National Balancing Point (NBP) price for the period 1996–2014 was used and for the preceding period 1980–1995, the UK gas price was reverse-constructed by assuming similar growth rates to the German gas prices.

All three fossil fuel prices were converted to real terms using country-specific deflators. The USA, Germany, and the UK Gross Domestic Products (GDPs), in both real and nominal terms, were taken from World Bank (n.d.), complemented by data on the share of labor as a percentage of GDP taken from the European Commission database (AMECO n.d.).

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