Dirk Jan van de Ven and Roger Fouquet

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Historical energy price shocks and their changing effects on the economy☆

Dirk Jan van de Ven [a], Roger Fouquet [b,*]

[a] Basque Centre for Climate Change, Edificio Sede 1-1, Parque Científico de UPV/EHU, 48940 Leioa, Spain
[b] London School of Economics, Houghton St, London WC2A 2AE, United Kingdom

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ABSTRACT

The purpose of this paper is to identify the changes in the impact of energy shocks on economic activity — with an interest in assessing if an economy's vulnerability and resilience to shocks improved with economic development. Using data on the United Kingdom over the last three hundred years, the paper identifies supply, aggregate demand and residual shocks to energy prices and estimates their changing influence on energy prices and GDP. The results suggest that the impacts of supply shocks rose with its increasing dependence on coal, and declined with its partial transition to oil. However, the transition from exporting coal to importing oil increased the negative impacts of demand shocks. More generally, the results indicate that improvements in vulnerability and resilience to shocks did not progress systematically as the economy developed. Instead, the changes in impacts depended greatly on the circumstances related to the demand for and supply of energy sources. If these experiences are transferable to future markets, a transition to a diversified mix of renewable energy is likely to reduce vulnerability and increase resilience to energy price shocks.

1. Introduction

An economy's long run growth and development is highly dependent on its vulnerability and resilience to shocks (Balassa, 1986, Romer and Romer, 2004, Martin, 2012). Oil shocks have been seen as one of the main dampeners of economic growth since the Second World War. Especially since the 1970s oil crises, economists have sought to identify their effects on the economy (Hamilton, 1983, Kilian, 2008).

Early on in the debate, Nordhaus (1980a, 1980b) outlined some of the key avenues through which oil prices can constrain the economy[1]. A rising oil price increases energy expenditure (when the price elasticity of demand is low) which drives-up the price of goods produced and reduces goods consumed, thus, harming GDP, as well as harming the balance of payments (when oil is imported) and generating inflationary pressures. Hamilton (1983) estimated a statistically significant relationship between oil price hikes and economic recessions between 1948 and 1981. More recently, Kilian (2009) showed that the source (i.e. supply- or demand-driven) of an oil price hike is crucial to its impact on output and inflation. Despite major progress in our understanding of the macroeconomic impacts of oil shocks, most lessons from related studies tend to be limited to evidence gathered from short-run national or cross-sectional studies.

Instead, one might be interested to know whether individual economies have become less vulnerable to (i.e., the immediate impact) and more resilient from (i.e., the ability to bounce back) energy price shocks through time and as they have developed. For instance, one might expect that economic development – such as, the shift from an agrarian to an industrial to a knowledge economy – is enabling nations to become more capable of absorbing shocks. This might be because of a declining share of energy in production, more flexible labour markets or better monetary policies (Blanchard and Galí, 2010). Dhawan and Jeske (2006) found that, since 1986, developed economies have become less vulnerable to oil shocks. While some studies have focused on the impact in developing economies (Schubert and Turnovsky, 2011),

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* Corresponding author.
E-mail address: r.fouquet@lse.ac.uk (R. Fouquet).

[1] For recent broader discussions of the role of energy in influencing economic growth, see Kümmel et al. (2002), Ayres and Warr (2005), Allen (2009), Stern and Kander (2012).

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most of these studies, however, have been analysing the post-Second World War period in mature industrialized economies.[2]

To extend our understanding of a possible tendency towards declining vulnerability and possibly greater resilience, the primary purpose of this paper is to estimate the changing impacts of energy price shocks in the United Kingdom over the last three hundred years, and at different phases of economic development. It uses the rich data available for the United Kingdom on economic growth and energy prices (such as Broadberry et al., 2015 and Fouquet, 2011) to estimate the changing relationship. Thus, the main contributions of this paper to the literature are, first, to place current empirical evidence of declining impacts of oil shocks within a much broader historical context and, second, to assess what factors influence long run changes in the impacts of energy price shocks.

The results indicate that the impacts of shocks did not progress systematically as the British economy developed. Instead, the changes in impacts depended greatly on the circumstances related to the demand for and supply of energy sources — although energy markets may have been affected by the changing structure and energy intensity of the economy. At first, the transition from biomass to coal reduced the economy's vulnerability to supply shocks, increased its resilience to them, and led to greater gains from demand shocks, especially as coal was increasingly exported. However, by the early twentieth century, the economy's heavy dependence on coal made it highly sensitive to supply shocks. The partial transition to oil (and generally broader fuel mix) reduced the economy's immediate impacts of supply shocks, but also weakened its lagged response to these shocks and increased the negative impacts of demand shocks. Thus, energy markets, rather than levels of economic development, appear to be a key determinant of the effects of energy price shocks on the economy.

Given that the economy's increasing dependence on oil has been relatively recent compared to the dependence on coal and biomass,[3] this study considers energy more broadly. This broader perspective is also valuable given that the fuel mix in many economies is shifting towards natural gas and most recently renewable energy sources. Thus, a focus on oil at the expense of other energy sources might limit the value of these recent studies to interpret the vulnerability and resilience of future economies to natural gas (or even renewable energy-related) price hikes.

The following section reviews the literature on the impact of energy shocks on economic activity since the Second World War. The third section outlines the data used for this analysis. The fourth section explains the methodology used, based initially on Kilian (2008), and identifies the sources and size of the energy shocks over the last three hundred years. The subsequent section presents the evidence on how the impact of these shocks has changed over that time. The final section tries to draw the lessons from this historical experience for developing and developed economies.

2. The impact of oil prices shocks on the economy since 1948

The literature boom on the influence of oil prices on GDP was initiated by Hamilton (1983), who intended to measure the impact of oil prices on US macro-economic aggregates. Treating the oil price as an exogeneous variable, he found that oil prices had a significant impact on US GDP. Although Darby (1982) could not consistently confirm this negative impact of oil prices on GDP by testing the impact of the 1973–74 oil price shock on eight industrialized economies, several later studies that included the 1979–80 oil price shock confirmed Hamilton's (1983) finding. Burbridge and Harrison (1984), Gisser and Goodwin (1986), Mork (1989), Mork et al. (1994), Lee et al (1995), Ferderer (1996), Papapetrou (2001), Jimenez-Rodriguez and Sanchez (2005), Lardic and Mignon (2006) and Cunado and de Gracia (2005) found consistent negative impacts of oil prices on GDP for industrialized, industrializing, oil importing and oil exporting economies. Also, the effects seem to be surprisingly similar across developed countries.

Most studies concluded that the impact of oil prices on GDP declined strongly over time. Hamilton (1983, 1996) found a significant higher impact coefficient for the period 1948–1973 compared with the period after that. Blanchard and Galí (2010) found a reduced impact coefficient in the early 1980s, while Kilian (2008) and Baumeister and Peersman (2013a, 2013b) identified a strong decline in impact coefficients of oil prices on GDP in the mid-1980s. While Hamilton (1996) suggests that the reason for this declining impact is the higher level of overall inflation during the 1973–1980 period and rejects the idea that a structural break has taken place, McConnell and Perez-Quiros (2000), Baumeister and Peersman (2013b) and Kilian (2008) propose the existence of a structural break in the oil-GDP effect during the 1980s. Proposed explanations for this possible 'structural break' of the oil-GDP effect are the declining share of oil expenditures in GDP, declining wage ridigities, improved response of monetary policy (Blanchard and Galí, 2010; Bernanke, 2004), the sectoral composition of GDP (Maravalle, 2012), the terms of trade balance (Maravalle, 2013), differences in overall macroeconomic uncertainty (Robays, 2012), or a change in the origins behind an oil price surge (Kilian, 2008, 2009, Kilian and Murphy, 2012, 2014).

By looking at the different drivers of oil price surges, Kilian (2008) offered a new approach and stimulated a new line of research in the oil-GDP debate. While earlier work regarded oil price shocks to be exogenous and the result of supply distractions, Barsky and Kilian (2004) challenge this perception. Instead, Kilian (2008, 2009) proposed a three-variable endogenous model including oil production, real economic activity (using a business cycle indicator) and oil prices to disentangle three different shocks that could have an impact on oil prices:

- crude oil supply shocks (due to global oil production);
- aggregate demand shocks (for industrial commodities in the global market);
- oil-market specific demand shocks (that are specific to the global crude oil market, usually based on fear of future events that might cause oil prices to change; they are also known as precautionary demand or residual shocks).

Although several different approaches of this breakdown have been proposed in recent papers (e.g., Lutkepohl and Netsujanev, 2012; Melolinna, 2012), the original breakdown proposed and continuously improved by Kilian (2008, 2009), Kilian and Murphy (2012, 2014), Inoue and Kilian (2013) and Kilian and Lee (2014) remains the dominant approach to decompose oil shocks. His conclusions are that while oil prices are affected considerably by aggregate demand and speculative demand effects, the effects of supply shocks on oil prices are relatively low. The effects of supply shocks are predominantly disruptive for GDP during the first year after the shock, while oil-specific demand shocks and (highly significant) aggregate demand shocks are more disruptive for GDP after about two years. Aggregate demand shocks actually improve GDP during the first year as the positive effects on GDP offset the ensuing negative effects of the oil price increase. Kilian (2008) estimated the cumulative effect of oil supply shocks on oil prices since 1975 to be much smaller than those of aggregate and oil-specific demand shocks, rejecting Hamilton's (2003) conclusions and invalidating his assumption that oil price variations are exogenous.

The conclusion that the 2002–2008 oil price surge had been caused by aggregate demand rather than supply effects explains why it was unexplained by earlier research which performed a direct VAR (vector autoregressive) regression of oil prices on GDP. Hence, as it is likely that worldwide aggregate demand had a positive impact on both oil prices and GDP, a regression between the two would not capture the

[2] Huntington (2017) investigates the impact of energy price shocks before the Second World War in the US.

[3] The British economy was mainly dependent (over 50% of energy expenditures) on biomass until 1820, on coal from 1820 to 1950 and on oil from the 1950s onwards.

negative correlation associated with the oil supply crises in the 1970s. Furthermore, Kilian and Murphy (2014) and Hamilton (2009) found that price speculation also played a role in the 2002–2008 oil price surge.

Nearly all the literature came to the conclusion that the effect of an oil price increase on GDP has been significantly larger than would be expected given the share of oil expenditures in GDP. Economic theory has long struggled to explain this finding (Rotemberg and Woodford, 1996, Atkeson and Kehoe, 1999, Finn, 2000). Therefore, in parallel with the discussion about whether and to what extend oil prices have affected GDP, the channels of transmission regarding this causality have been investigated. Kilian (2008) identifies four different transmission mechanisms through which an increase in energy prices might affect GDP. We can roughly divide these four effects in two categories.

The first category has to do with the actual function of energy in the economy. These effects are likely to be symmetric in response to variation of energy prices, as they are relevant for both energy price increases and decreases. First, there is an operating cost effect: for durables that use oil as an energy input, their demand and usage is dependent on the operating costs defined by the price of oil (see Hamilton, 1988). There is also a discretionary income effect: as demand for most energy services nowadays is expected to be inelastic, changes in energy prices will have an effect on total income with consequences for consumption of other goods. Based on these effects, Finn (2000) found that energy price shocks, which can be considered as adverse technology shocks, could hypothetically cause GDP to decrease by more than twice the amount that would be expected given the energy share in GDP. Using Swedish GDP and energy data for the period 1800–2000, Stern and Kander (2012) concluded that whenever energy became scarce (hence, energy prices increased), the response of GDP relative to the share of energy expenditures in GDP was stronger than when energy was abundant (hence, cheap).

The second category consists of effects that have to do with human behaviour and expectations. Therefore, catching these effects in conventional economic models is more complicated and an asymmetric response of GDP to energy price variation is likely, as these effects are expected to be stronger in relation to energy price increases compared with energy price decreases. First, an uncertainty effect is associated with changing energy prices that may create uncertainty about the future path of the price of energy, causing consumers and producers to postpone irreversible investments (Bernanke, 1983, Pindyck, 1999). Furthermore, the precautionary savings effect is in response to an energy price increase, as consumers might smooth their consumption because they perceive a greater likelihood of future unemployment and the resulting income losses. Conclusions on an asymmetric response of GDP to oil prices (Mork, 1989, 1994; Mory, 1993; Lee et al., 1995; Hamilton, 1996, 2003) would suggest that the uncertainty effect is the dominant effect in the observations regarding the oil-GDP relationship, since this effect is based on the decline in investments as a result of energy price volatility in general rather than just energy price increases. Guo and Kliesen (2005) and Rentschler (2013) confirm the direct negative impact of oil price volatility on GDP in several countries.

As the discussion in this section shows so far, there is a lot of empirical literature on the impact of oil prices on GDP. Most of this literature however focuses on the last couple of decades. Since the purpose of this study is to estimate the impact of energy prices on British GDP since 1700, it is important to carefully choose the appropriate methodology for this task.

Especially in the last decade, economists have increasingly used historical or long run evidence in energy markets to provide insights that may be absent in contemporary data. For instance, many have focussed on energy transitions and the diffusion of technologies (Ray, 1983, Grübler et al., 1999; Gales et al., 2007, Batoletto and Rubio, 2008, Fouquet, 2008, Fouquet, 2010, Rubio and Folchi, 2012, Kander et al., 2013, Grubler and Wilson, 2014, Fouquet, 2016). A few have looked at long run fluctuations associated with resource abundance and scarcity reflected in energy prices (Hausman, 1996, Pindyck, 1999, Cashin and McDermott, 2002, Fouquet and Pearson, 2003, Fouquet, 2011, Muller, 2016). Some have investigated energy and energy service consumption patterns (Fouquet and Pearson, 1998, 2006, 2012, Fouquet, 2008, 2014). Others have looked at the important link between energy use and economic growth (Humphrey and Stanislaw, 1979, Ray, 1983, Ayres and Warr, 2005, Stern and Kander, 2012, Kander et al., 2013). These studies offer new approaches and new data sets for energy economists to exploit. They also raise questions about the external validity of these studies, and the lessons that can be learnt from them for understanding future behaviour and formulating policy. In particular, they highlight the need for theory to act as a bridge between historical experiences and relevant lessons.

While many of these studies are descriptive, a few offer analytical models and techniques that should be considered in the context of the current paper. Stern and Kander (2012) and Ayres and Warr (2005) build theoretical models in order to estimate the contribution of energy services to long run economic growth. Fouquet (2014) uses a VECM (vector error correcting) model to explore the long-term development of income and price elasticities, whereas Pindyck (1999) and Cashin and Mcdermott (2002) employ stochastic models in order to detect trends in the long run evolution of energy prices. None of these methods are, however, suitable to measure the impact of endogenously related stochastic variables, such as energy prices and GDP growth. More recently, however, VAR models have been applied to analyse long-term stochastic data (Rathke and Sarferaz, 2010; Stuermer, 2016). The benefit of the VAR method is that the user only has to prescribe the assumptions to identify shocks in the variables of the model and can be ambivalent or agnostic of the long-run causality of the relationship. This is important for the purpose of this study, given the endogeneity of the relationship between energy prices and GDP.

In an attempt to analyse the effects of energy prices on the long term, this paper therefore applies the method of separating price changes presented in Kilian and Murphy (2012) to British annual energy prices during for the period 1700–2010 to identify supply, demand and residual price shocks over time. As a next step and following Kilian (2008), we test the impact of these identified shocks on British GDP during the same period. We chose to apply this breakdown of the analysis in two phases over using a TVP-VAR model as in Baumeister and Peersman (2013a). The major reason for this choice is the possibility to explicitly review the identified shocks before continuing with their time-dependent impact on GDP. This intermediate result is not only an interesting output of the model, but it is also essential to check whether the identified shocks correspond with historical events in order to confirm whether the identification process makes sense. To take into account the potential time-varying relationship between the input variables, we applied a simplified modification to the identification process, which is further explained in Section 4. But before reviewing the method used, the next section will go into detail about the data used for this approach.

3. Data

To study the historical impact of United Kingdom energy prices on economic activity at different phases of economic development, it is necessary to gather statistical information on different energy prices and GDP for the period 1700–2008, as well as indicators for supply and demand in the energy market in order to reproduce Kilian's (2009) breakdown of oil price changes. The following is a summary of the sources and methods - more detail of the sources can be found in Fouquet (2008, 2011).

It is important to note that we focus on a wide set of commodities that contribute to the provision of energy services. These include provender (i.e., fodder for horses), wood, coal, petroleum and natural gas. Although food contributed significantly to the provision of power in the eighteenth and nineteenth century economy (up to 28% of power and

14% of total energy use in the early eighteenth century - Fouquet, 2008), we did not include it in this analysis as demand for food (and, therefore, its price) is driven by much more than just its calorific value.

United Kingdom GDP is based on pulling together data from Broadberry et al. (2015), Mitchell (1988) and ONS (2010). The consumer price index data available from Allen (2007) enables GDP and prices to be broadly comparable across time and expressed in real terms for the year 2000. The price data, and indiciators of supply and demand will be presented in the following three sub-sections.

3.1. Price data

The price series are based on residential UK energy prices from a variety of data sources (Fouquet, 2011) and can be seen in Fig. 1, along with trends in GDP. To replicate the price series in the oil price-GDP literature, however, we create an aggregate energy price series. To calculate the series, we created indices for the energy prices of each different end-use service[4] and weighted them using the expenditures on energy of every service.

After this step, we followed Kilian's (2008) approach, weighting the prices by the share of total energy expenditures in total GDP. This creates an index series that represents the accumulation of expenditure-weighted changes in energy prices over time. Since we want to measure the economic effects of energy price 'shocks' in this paper, we are interested in the annual variation rather than the trend in these price index series.

3.2. Production data

The supply index series in this paper is constructed using a variety of sources for each different energy type. The different energy types are weighted by their relative share of total energy expenditures. The expenditures are calculated by multiplying consumption with the 10-year moving averages[5] of the prices of each type of energy. We are interested in production statistics of relevance for UK energy supply. Therefore, it can differ between energy sources and between periods whether we use national or international production statistics, depending on whether we are looking at locally or globally traded energy commodities.

3.2.1. Provender for working animals

Consumption of provender (i.e., fodder for horses) can easily be estimated using working horse population estimates. However, production data is harder to obtain. Due to extensive documentation by Broadberry et al. (2015), it was possible to obtain an annual estimate for agricultural production in Great Britain for the period 1700–1870. In their data, they report an estimate of agricultural GDP in which price variation is filtered out. Using this index, it was implicitly assumed that the production trend is similar for Northern Ireland and that on average, variation in the annual production and price estimates is equally spread between the food and provender sector. For the period after 1870, production growth data is extrapolated. However, the share of provender in the total energy mix had already lost most of its significance by 1870. Provender imports are not taken into account, as these were not very significant until 1870.

3.2.2. Woodfuel

For simplicity, we keep woodfuel production equal to wood consumption over the whole period. Since woodfuel production has not been very significant in the British energy mix since 1700, the assumption that woodfuel demand was met might be quite realistic for the UK. Consumption data is obtained from Fouquet (2008).

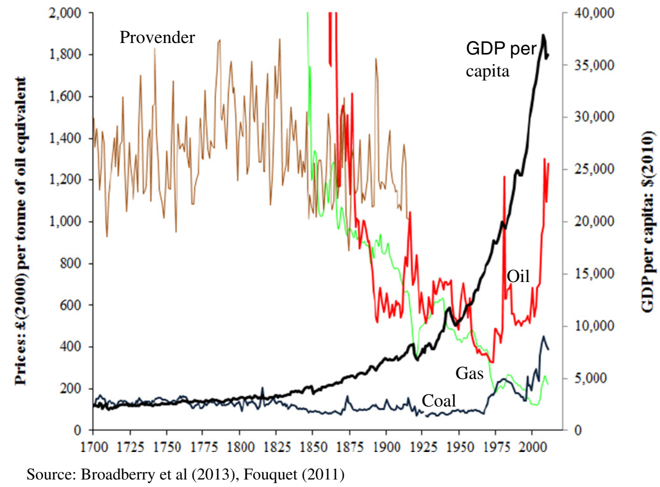

Fig. 1. United Kingdom energy prices and GDP per capita (1700–2010).

3.2.3. Coal

For the period until 1981, we only use the sum of coal production estimates within the UK and coal imports into the UK. The latter were however limited until the 1980s[6]. Even though coal is an internationally tradable commodity, accurate world coal production estimates are absent for the pre-1981 period. Also, the UK was a net exporter of coal until 1984, so mainly homeland production was relevant for British coal supply until the 1980s. For the period after 1981, world coal production estimates are used as the worldwide market became important for UK supply purposes. This data is obtained from the BP (2011) Statistical Review.

3.2.4. Petroleum

For the complete time series, we used the world oil production data from the JODI database[7]. Doing this, we assume that since oil is a relatively easy-to-transport energy source, world oil production is relevant for the UK.

3.2.5. Natural gas

Until 1970, nearly all gas consumed in the UK was obtained from coal in the form of 'town gas'. Since the production of town gas from coal is an industrial process, we use coal production as a proxy for town gas production.[8] From 1970 onwards, however, when natural gas use increasingly replaced town gas use in the UK, we use the natural gas production estimates of the UK for the share of natural gas in the total gas mix (100% from 1976 onwards). For most of the period since 1970, the UK was nearly producing all its natural gas within its borders. The data on natural gas production in the UK are again obtained from the BP (2011) Statistical Review.

3.3. Economic activity data

The most important feature of the indicator for economic activity should be that it shows the ups and downs of the business cycle. Following Baumeister and Peersman (2013a) whose research objective comes close to the one of this paper, we decided to use a mix of GDP data for

[4] As we divide the energy prices indices by the service end-use, we measure the prices paid by final users (after taxes) and thus not the prices of primary energy.

[5] Ten-year moving averages were used in the calculation of energy expenditures to remove most of the influence of price volatility in the weighting procedure.

[6] Apart from a few years with strong coal production cuts, when the total effect of these cuts were partly offset by increased imports.

[7] Available at *http://www.jodidata.org/*.

[8] We only use production estimates of primary energy commodities and not intermediate energy commodities in order avoid estimation errors due to interdependence of different energy commodities in our energy production index.

the UK (Broadberry et al., 2015) and for other regions[9] and used the Hodrick-Prescott Filter (using $\lambda = 100$, following Backus and Kehoe, 1992) to filter out the business cycle from this GDP data.

By using GDP data as an indicator of economic activity, we do not follow Kilian (2008, 2009) and Kilian and Murphy (2012), who use a transformation of worldwide dry cargo shipping rates as an indicator for economic activity. Their reasoning for using shipping rates is that since the supply of shipping is relatively flat when demand for shipping is low and very steep when demand for shipping is high, the variance in the price of shipping is a good indicator for the worldwide business cycles. They argue that using national GDP or industrial production data would require a complex weighting procedure between different countries in order to create a global index that correctly represents the evolution in relevant economic activity. Although shipping rates are available for the full period of interest for this study (1700–2010), we do not adopt these as our indicator for real activity for two main reasons: there may exist a reverse causality of energy prices on shipping rates for which this relationship cannot assumed to be non-positive for annual data back to 1700[10] and shipping rates have historically been heavily influenced by factors other than economic activity, such as increased risk premiums durings wars.

Given the choice of GDP as an indicator of economic activity, it is important to take the spatial relevance of economic activity to UK energy prices into account in order to create an index that correctly represents the evolution in relevant economic activity. For example, economic activity in China had essentially zero impact on UK provender prices in 1700, whereas they had a major impact on UK petroleum prices in 2010. For that reason, we used five different gross demand indicators, dependent on the relevant region for a certain energy commodity during a certain period. The five regions and their assumed relevance to energy demand (influencing energy prices in the UK) are given in Table 1. Most of the splits in the data between regions are already clarified above in the supply data. Besides these clarifications, we used a real activity indicator for Europe and Western offshoots together for the oil part until 1965, since an oil-consuming world indicator could only be constructed from 1965 onwards and the big majority of oil demand came from Europe and North-America before 1965. Taking the business cycle series of these five regions together - weighted correctly on the relevant energy commodities consumed in the UK - a final business cycle indicator was created, reflecting relevant economic activity for the UK energy market.

4. The shock analysis

As explained in the introduction, we will use our data to distinguish shocks in the supply of energy, shocks in aggregate demand for commodities and shocks in the price of energy not explained by either supply or aggregate demand shocks. In making this distinction, we can test the correlation between these resulting shocks on other variables like energy prices and GDP.

4.1. Methodology to identify shocks

The first step in our approach was to define all the supply, demand and residual shocks through the analysed period from 1700 to 2010. The method used for disentangling these shocks is similar to that of Kilian and Murphy (2012), but with one important difference to make the method more appropriate for long-term data.

First, we consider a fully structural oil market VAR model of the form

$$y_t = \alpha + \sum_{i=1}^{2} B_i y_{t-j} + e_t$$

where e_t is a vector of residuals and $y_t = (\Delta prod_t, \Delta rea_t, \Delta rpe_t)$ contains annual data on the percent change in energy production ($prod_t$), the index of real economic activity representing the relevant business cycle (rea_t) and the percent change in real energy prices (rpe_t). We use Ω, the variance–covariance matrix of e_t, to identify how the structurally independent changes to the model depend on each other. Since we are looking at shocks over 310 years and, therefore, aware that these relationships between changes (i.e., the residuals of the VAR model including energy production, economic activity and energy prices) develop over time, we use a moving average (rather than a single matrix as is traditionally done for short run analysis) to orthogonalize Ω and identify the shock matrix P_k, such that $\Omega_k = P_k{}' P_k$ and $e_{t+n} = P_k \varepsilon_{t+n}$.

$$e_{t+n} \equiv \begin{pmatrix} e_{t+n}^{\Delta prod} \\ e_{t+n}^{rea} \\ e_{t+n}^{\Delta rpe} \end{pmatrix} = \begin{bmatrix} p_{k11} & p_{k12} & p_{k13} \\ p_{k21} & p_{k22} & p_{k23} \\ p_{k31} & p_{k32} & p_{k33} \end{bmatrix} \begin{pmatrix} \varepsilon_{t+n}^{supply-shock} \\ \varepsilon_{t+n}^{demand-shock} \\ \varepsilon_{t+n}^{residual-shock} \end{pmatrix}$$

Here, n describes the number of years in the moving average and k identifies a set of years $t + n$ for which a separate shock matrix P_k is identified. The vector ε_t consists of a supply shock, a shock to aggregate demand in the economy and a residual shock to energy prices not explained by variation in supply or demand, which we call the residual shock.

In his initial version of the model, Kilian (2008, 2009) fixes the values of b_{12}, b_{13} and b_{23} to zero, as he postulates a vertical short-run supply curve for crude oil. In other words, he assumes that oil supply do not respond to aggregate demand and oil price changes and also that real activity cannot respond to oil price changes within one month. Although these assumptions are reasonable on a monthly basis, they are not realistic for annual data. That is why we used the method described in Kilian and Murphy (2012). Instead of fixing b_{12}, b_{13} and b_{23} to zero, a method of sign-identification is introduced to identify supply, demand and residual shocks based on logical economic reasoning. In addition, Kilian and Murphy (2012) imposed bounds on the oil supply elasticity to limit the amount of resulting admissible models, based on historically observed maximum values of these (monthly) elasticities.

Table 2 gives the sign-identification scheme that we used to identify energy supply shocks, aggregate demand shocks and residual shocks in our analysis. These sign restrictions are based on assumptions on the movements of the different variables as a response to the three different shocks. Thus, an energy supply shock is identified if, over the year, energy production declines and energy prices increase. For this shock, the sign of changes in real activity does not matter. An aggregate demand shock is identified if during one year real activity increases and energy prices increase as well. Hence we are agnostic about the sign of changes in energy production in the identification of aggregate demand shocks. Since we assume that residual shocks are shocks in the price of energy that are not the result of declines in energy production or increases in real activity, we identify them when energy prices increase, real activity decreases and energy production increases during the same year. In other words, these shocks measure increases in energy prices that are not explainable by the model.

These restrictions do not identify the shocks uniquely, but result in a large set of admissible shock matrices. To minimize the level of uncertainty regarding the actual shock matrix, the main task is to limit the number of admissible matrices based on theoretical expectations. Therefore, when using the sign identification matrix in Table 2, we also impose restrictions on the levels of supply elasticity related to changes in energy prices, as done by Kilian and Murphy (2012). Since we are working with annual instead of monthly data, our boundaries cannot be too restrictive. Thus, we

[9] The Maddison-Project, http://www.ggdc.net/maddison/maddison-project/home.htm, 2013 version.

[10] Kolodzeij and Kaufmann (2014) suggest that the impact of oil prices on shipping rates can also not be assumed to be non-positive for Kilian's (2009) data (1975–2007), but Kilian suggests that the contemporaneous correlation between bunker shipping rates and bunker fuel is essentially zero and therefore assumes that shipping rates do not correspond to changes in oil prices within the same month.

Table 1
Split of demand data into different regions by relevance for UK consumption.

Regions: *Energy:*	UK	Europe	Europe + Western offshoots[1]	Oil-consuming world	Coal-consuming world
Provender and Wood	Full period		–	–	–
Coal	Until 1983	Until 1983, for export share			From 1983 onwards
Petroleum			Until 1965	From 1965 onwards	
Natural gas	Full period				

Source: see text.
[1] Western offshoots include: USA, Canada, Australia and New-Zealand. The term stems from the source data (The Maddison-Project, http://www.ggdc.net/maddison/maddison-project/home.htm) that we use for these GDP estimates.

only assumed that, within one year, supply must be inelastic (i.e. ΔSupply / ΔPrice < 1) in response to energy price shocks.[11]

Finally, we calculated our identification matrices based on a moving average of 60 years (n = 60). We chose sixty years to balance-out higher flexibility in the results and lower levels of uncertainty. For each period k, all the resulting admissible matrices are theoretically equally viable. However, imposing stronger restrictions narrows down the set of admissible matrices. Ultimately, we want to determine only one shock matrix per set of moving-average time series in order to identify a unique set of shocks per period. This unique shock matrix is selected by finding the closest-to-median matrix.[12]

Since the method above, introduced by Kilian (2008, 2009) and developed in Kilian and Murphy (2012), is initially designed for analysing monthly data, there might be doubts about the robustness of our results on annual data. There can be a situation in which energy prices increase simultaneously with a decrease in energy production, while the actual cause of the energy price increase is not the decrease in production. In such a situation, an energy supply shock is identified, while it might be a coincidence. As Lutkepohl and Netsunajev (2012) point out, there may be an omitted variables problem if only those variables are included in the empirical model that are described in the theoretical model. The chance that an identified shock is based on a coincidence is not absent with monthly data, but bigger with annual data. Thus, this is a limitation of all studies using this approach, and kept in mind when analysing the results.

4.2. Overview of shocks

Average shock values for every year can be calculated as an intermediate result. Here, the shock value of a particular year represents the moving average (i.e., the average of the estimated shock values of that year identified by all shock matrices valid for that year). An overview of these supply, aggregate demand and residual shocks can be seen in Fig. 2.

There has been a distinct evolution in the nature of supply shocks. From 1700 to 1820, there was roughly one major shock (i.e., near or below minus two) per decade. The transition away from biomass towards coal (see Fig. 3) ushered in a period of stable supply (with less frequent and, on average, weaker shocks in the nineteenth and twentieth centuries). However, by the end of the nineteenth century, a series of very strong supply shocks were experienced. The post-Second World War era was one of supply stability interrupted only by one period of distinct supply shocks — between 1980 and 1984.

Since an aggregate indicator is used, the supply of energy is dependent on the weighted growth rates of each source of energy used. Over the last three centuries, different energy sources have dominated at different times (Fouquet, 2008). Fig. 3 shows the distribution of total expenditures on primary energy sources in the UK since 1700. During the eighteenth century, provender was the dominant source of energy for power. With the diffusion of steam engines, coal became the main source of power during the nineteenth century. Coal had already become the main source for residential heating by 1700, and then for iron production by the end of the eighteenth century. In the twentieth century, oil became dominant for transportation and more recently natural gas for heating. Therefore, energy supply shocks are usually caused by a shock in the supply industry of the most dominant energy source. This has tended to create three different types of supply shocks. Table 3 provides an overview of all supply shocks of two standard deviations (or more) grouped by their probable cause - the average shock consisted of 0.75 standard deviations. Two well-known shocks (the oil crisis of 1973–4 and the coal miners' strike of 1984) are included in italics, because they were below two standard deviations.

In the eighteenth century, agricultural factors like crop failures had an important impact on provender supply and, therefore, on total ‘energy’ supply. During that century, three of these events generated major supply shocks (Broadberry et al., 2015). As the energy market changed, so did the events causing supply disruptions. Since most of the British economy was dependent on coal by the end of the nineteenth century, the first big coal miners' strike in 1893 led to the largest disruption of energy supply in three hundred years. Subsequently, the strikes in 1921 and 1926 also led to strong shortages (Church, 1865). In 1984, when the economy was dependent on oil for transportation and natural gas for heating, the coal strike had a substantially weaker impact, but still influenced average energy prices, as coal generated most of the UK's power. Meanwhile, the oil crises associated with unrest in the Middle-East led to an important one in 1974 and, in 1980, the second largest supply shock in more than three hundred years.

Aggregate demand shocks were driven by completely different factors. Indeed, the type of energy source used did not matter much for the existence of aggregate demand shocks, although which energy source used might determine whether the aggregate demand shock fed through into a price increase. Instead, the state of the economy was the driver of these shocks.

Significant demand shocks were observed in times of warfare, as they generated unusual and intensified demands for energy (see Table 4). The wars that had the most significant effects on aggregate demand were the War of Spanish Succession (especially, 1704–5) and the Second World War (here, 1943–4). The Seven Years' War in combination with three simultanuous colonian wars against France (in North-America, India & Ghana) in 1757, the Battle of Waterloo in 1815, the second Boer War in 1900 and the First World War (particularly 1915) also appear to have been important (see also Fig. 2). There were also periods of civilian economic growth that fed through into pressures on

Table 2
Sign restriction from impulse responses.

	Energy supply shock	Aggregate demand shock	Residual shock
Energy production	−	+/−	+
Economic activity	+/−	+	−
Energy price	+	+	+
		$\succ P_{12}$	$\succ P_{13}$

[11] Further details on the method and the admissible shock matrices over time can be found in Appendix A. We would like to thank Danny Quah for this advice regarding this method.
[12] For the resulting shock matrix, most of the entry values were statistically significant over time. For more details on the selected matrices over time, see Appendix A.

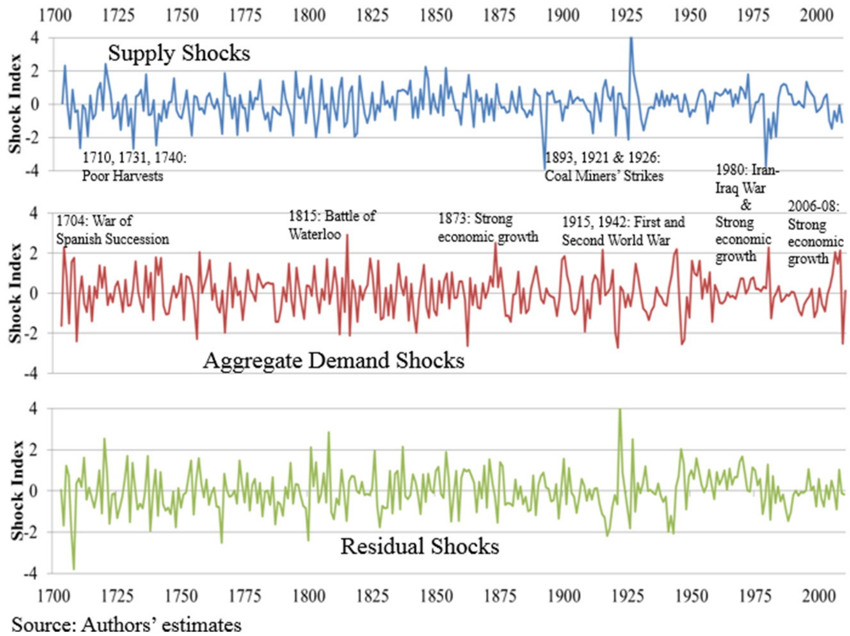

Fig. 2. Energy price shocks by factor (1700–2010).

resources, 'overheating' and increasing energy prices, culminating in economic downturns, often coinciding with financial crisis (1873, 1980 and 2008).

Finally, residual shocks are estimated as the change in price not explained by changing supply or aggregate demand. Often, these are described as shocks associated with precautionary demand in which consumers or speculators hoard energy in the anticipation of future supply shortages (Kilian, 2008). Major positive and negative residual shocks generally coincide with supply or aggregate demand shocks. This indicates that they do reflect some form of extended reaction to other 'fundamental' shocks.

5. The trends in shock effects

The purpose of this paper is to analyse the economic effects of energy price shocks from a long-term perspective. As these energy price shocks can be caused by different factors (i.e. energy supply, aggregated demand or speculation) and since GDP responds differently depending on the mechanism behind the shock, we chose to analyse the economic effects by breaking down the energy price shocks into three different types, as explained in the previous section.

5.1. Influence of shocks on prices

Fig. 4 presents the average values (for the full period of 310 years) of the immediate and lagged response of energy prices to each of the average shocks, using least-squares methods, presented in Section 4.2. It shows that the immediate response of energy prices to all three shocks is similar.[13] That is, there is an initially large response to the shock and then, in later years, some response in the opposite direction. In other words, for all shocks, there tends to be overshooting or correction to the shock in the first period.

While this average graph shows the result over a total period of 310 years, we are interested in how this response changed over time. To analyse that, we performed similar estimates for every set of shocks identified by the same shock matrix (see Section 4.1). The final estimate of the response of UK energy prices to shocks in a particular year will be the 60-year moving average (i.e., the average of all responses estimated where that year was included — see Fouquet and Pearson, 2012). All the results were estimated using the least-squares method, and the standard deviations resulting from the same method.[14] We used periods of 60 years as it seemed to be the optimal length to ensure both a high flexibility in the resulting point estimates and low uncertainty levels.[15]

Fig. 5 shows the resulting moving average of the effect of shocks to energy prices. These results represent the sum of the immediate impact and the three lags following these shocks (see Fig. 4). Interestingly, supply shocks tended to have lower impacts on energy prices during transition periods (1780–1830 for biomass to coal and 1900–1940 for coal to petroleum) compared with periods during which the energy mix was dominated by a single source of energy (1830–1900 for coal and 1940–2010 for petroleum, see Fig. 3). This effect indicates that realistic opportunities of energy switching have a stabilizing effect on the response of energy prices to events that disrupt supply of the initially dominant energy source.

The immediate impact of aggregate demand shocks declined strongly from 6% around 1700 to 3% in the early twentieth century, and has been relatively stable since then. This decline during the transition of biomass to fossil fuels suggests that fossil fuel (i.e., coal and later oil and gas) producers could respond more easily to a sudden increase in demand than farmers, toning-down the final effect on energy prices.

Fig. 6 combines the estimated shocks (Fig. 2) and their period-dependent effects on energy prices (Fig. 5) to give an indication of the causes of energy price fluctuations since 1700. The figure shows that

[13] Section 3.1 explained that, for the price series used in the model, we weighted the prices by the percentage of energy expenditures in total GDP. While this is a necessary condition inside the model to estimate the shocks correctly, this method causes a somewhat misleading series of energy price changes: the positive and negative effects of demand shocks on energy prices are strongly overestimated, since increased consumption leads to rising energy prices and weights of these prices. On the other hand, if price increases due to supply shocks are followed by a strong decline in energy consumption (which occurs in many cases throughout the time series), this also decreases the weight of energy prices, dampening these price increases. Therefore, weighting the price changes on energy expenditures strongly underestimates the effects of supply shocks. Since we want to see the effects of shocks on actual changes in energy prices rather than on those influenced by the consumption level, we used unweighted real energy price changes as an dependent variable in the regression of shocks on energy prices.

[14] As the results are presented as the sum of the effect over several years, we used the standard deviation of the immediate response as the standard deviation for this sum, as this generally has the largest standard deviation. In the few cases that the lags have higher standard deviations, we use the average standard deviation of the lags.

[15] Robustness checks of these estimates with respect to the choice of the median shock identification matrices can be found in Table B1 in Appendix B.

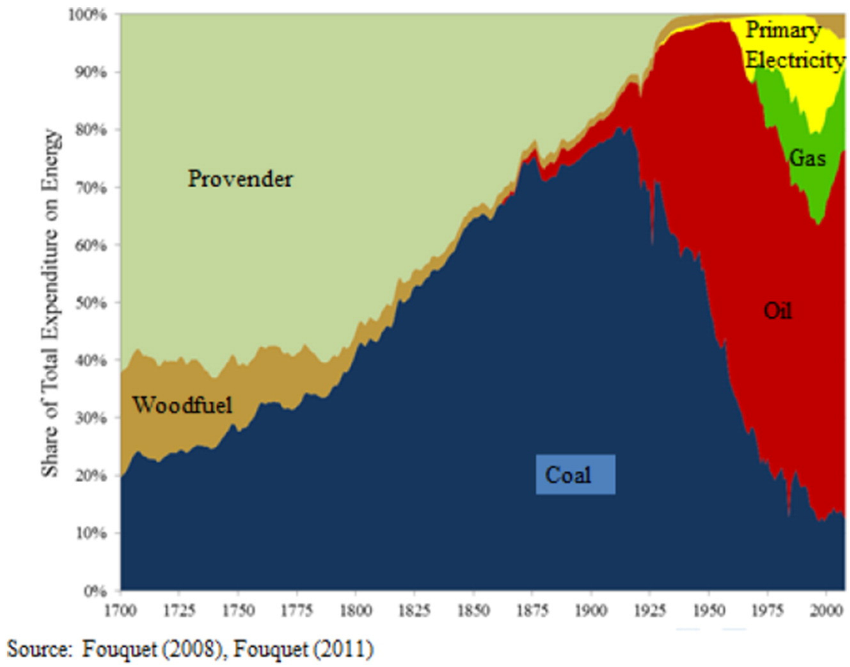

Fig. 3. Share of primary energy expenditure in the United Kingdom (1700–2010).

except for some periods with large shocks (coal strikes, world wars and oil crises), the volatility of energy prices declined significantly over time. In the eighteenth century, shocks causing a 10% increase or decrease of energy prices were frequent. After the 1920s, such shocks were rare. Declining prices in the 1950s and 1960s were driven by excess supply. However, the energy supply shocks in the 1970s and 2000s occurred simultaneously with aggregate demand shocks, causing strong price shocks when adding up both effects, confirming Kilian's (2008) results.

5.2. Influence of shocks on GDP

The final purpose of the shock identification method is to estimate the changing impact of different shocks on GDP. As Kilian (2008) has shown, supply and aggregate demand shocks are likely to impact GDP differently. Before investigating the changing impacts, to show the effects of different shocks, we ran a static linear regression of the average shocks and their 3-year lags on GDP over the entire 310-year period (see Fig. 7). As with the regression on energy prices (see Fig. 4), both means and confidence intervals are estimated using least-squares methods.

Fig. 7 confirms our expectations that the immediate response of GDP on aggregate demand shocks has been significantly positive, while it has been negative for supply shocks. The corrective effects of GDP from all shocks are much stronger than for energy prices in Fig. 4: for both supply and demand shocks, the sum of the lags generated slightly negative values; for residual shocks, they were positive.

For supply shocks, the majority of the negative immediate impact on GDP has been offset by a positive corrective effect during the first year following the shock. A supply shock (leading to a price increase) can be seen as a temporary adverse technology shock, reducing the amount of capital utilization (Finn, 2000). According to this theory of supply shocks, once the shock ends, capital utilization can return to its earlier level and so does GDP.

Table 3
Energy supply shocks and probable causes for these shocks.

Supply shocks	Probable cause
1710, 1731, 1740	Agricultural reasons / crop failures
1893, 1921, 1926, *1984*	Coal miners' strikes
1974, 1980	Oil crises

Source: Authors' estimates.

For aggregate demand shocks, the positive impact during the year of the shock led to a longer lasting negative corrective effect. However, one should take care in interpreting this result: as an aggregate demand shock is measured by an increase in energy prices that coincided with a business cycle peak, such a peak year in the business cycle was inevitably followed by a decline, so the response of GDP to aggregate demand shocks in Fig. 7 is partly a self fulfilling prophecy[16].

The response to residual shocks is also interesting: while Fig. 4 indicates that the corrective effect of energy prices after a residual shock was relatively low, Fig. 7 shows that the corrective effect of GDP was remarkably high and long-lasting. There are two possible explanations for this high corrective rate of GDP after a residual shock. First, in many cases, a residual shock represents the amount of overshooting in the response to supply and aggregate demand shocks. As it occurred in parallel with both kinds of shocks, a regression would typically estimate the impact in association with the effects of both supply and demand shocks. However, a price-induced technical efficiency improvement might be largely represented by a positive residual effect. Second, residual shocks might include any effects that could increase energy prices apart from the effect of supply and aggregate demand. An energy switch that uses a different technology, say, might have an increasing effect on energy prices, but might have a positive long term effect on GDP as the new technology becaomes more efficient or yields other qualitative advantages.

The more central question, however, is how the effects of supply and demand shocks changed over time. Fig. 8 shows the change of this effect over time, separately for the immediate and the lagged response (sum of the three lags, see Fig. 7) of either supply and aggregate demand shocks. Both the point estimates and the confidence intervals are calculated using the same method as used for energy prices (see Fig. 5)[17].

[16] The same effect would apply in Kilian (2008) as the aggregate demand indicator also measured the global business cycle using dry cargo shipping rates.

[17] Robustness checks of these estimates with respect to the choice of the median shock identification matrices can be found in Table B2 in Appendix B.

Table 4
Aggregate demand shocks and probable causes for these shocks.

Aggregate demand shocks	Probable cause
1704–5, 1757, 1815, 1900, 1915, 1943–4	Warfare
1873, 1980, 2008	Strong economic growth

Source: see text above.

The immediate response of GDP to supply shocks (i.e., an indicator of vulnerability) decreased strongly (in absolute terms; i.e. became less negative) during the first half or our time-series, when the dominance of agricultural products in the energy mix declined rapidly. It then increased until 1925 with the rapid transition to domestically produced coal and decreased again with the transition towards imported petroleum. This decreased impact has continued into the twenty-first century, supporting the observation made by Dhawan and Jeske (2006) and Kilian (2008) that immediate impacts of oil price shocks has decreased during the last decades. However, these results place their observations within a broader historical trend of increased immediate impacts during the Second Industrial Revolution (1870–1913) as the economy became increasingly dependent on coal for all economic activities and energy services, such as heating, power and transportation.

In broad terms, the corrective or lagged effect (i.e., resilience) of GDP to supply shocks mirrored the immediate effects. While the immediate effects followed an-inverse S-shape curve rotated 90° anti-clockwise, the lagged effects displayed a S-shape curve rotated 90° anti-clockwise. Thus, in general, the lagged effects of supply shocks seem to largely offset the immediate effect.

However, at specific times, these lagged effects did not mirror the immediate effects, leading to significant changes in total effects. For instance, the lagged effects declined at first rapidly then more gradually until 1830. Around 1850, they increased faster than the immediate effects implying that the total effects of supply shocks were negligible. Thus, the economy became more resilient to supply shocks with the early transition from biomass energy to coal during the third-quarter of the nineteenth century. However, its resilience to supply shocks appears to have decreased strongly with the increasing dependence on coal energy from the 1880s, partly supporting Jevons' (1865) hypothesis that increasing dependence of the British economy on coal energy would finally have a negative influence on economic growth due to the rising scarcity and costs of coal.

Just as was done for energy prices (i.e., by summing up the responses of the four estimated lags), Fig. 9 presents the moving average of the total effect that the three different shocks had on GDP from 1700 to 2010. This figure shows the change in the total effect of supply shocks on GDP since 1700. The effect can be characterized as a W-shape curve: the negative impact increased (in absolute terms) during the eighteenth century, became weaker during the the nineteenth century (with no estimated effect between 1870 and 1890), then it strengthened and, around 1940, it weakened again.

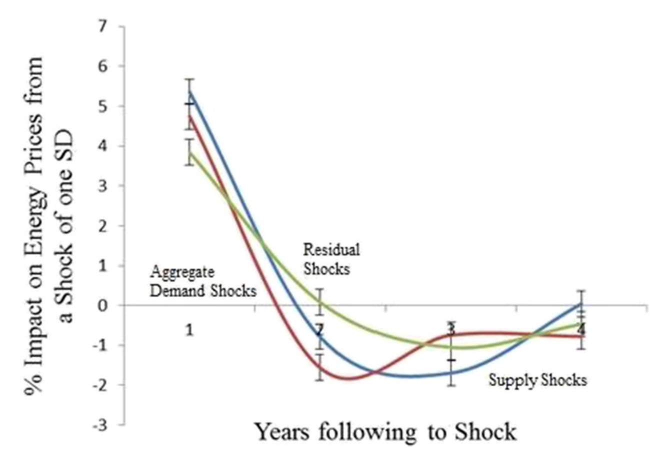

Fig. 4. Immediate and lagged responses of energy prices in the United Kingdom to shocks of one standard deviation (average over 1700–2010).

The total impact of aggregate demand shocks on GDP fluctuated around −0.5 until the mid-nineteenth century. The lagged negative effects (mostly associated wth the resource scarcity implications of an overheating economy) were a little greater (in absolute terms) than the immediate beneficial effects (see Fig. 8). However, from the 1870s, the rapid expansion of coal exports to Europe strengthened the immediate positive effect of demand shocks to GDP, while the transition from an agricultural to a fossil fuel based economy weakened the long-term negative effects caused by an 'overheating' economy.

From the 1920s, declining coal exports and strongly increasing dependence on imported petroleum implied that energy prices were increasingly impacted by global instead of national demand shocks, while the profits of higher energy prices started to flow out instead of into the UK. This increasing mismatch between the UK business cycle and demand-related energy price shocks caused the immediate positive effect of demand shocks on GDP to decrease. This decreasing response of GDP to aggregate demand shocks might, therefore, be partly or completely caused by a shift in the relevant real activity (see explanation in Section 3.3). Although this might be interesting by itself, such as when energy markets became more international, this also created a larger mismatch between domestic business cycle peaks and high energy prices caused by international business cycle peaks, making these shocks economically more painful.

For residual shocks, for which the positive effects on GDP seem to be strongly related with the share of coal exports from the UK, this evolution is almost completely driven by the variation of the positive lagged response of GDP to residual shocks. The explanation of the evolution of the residual shock seems obvious. Throughout the majority of the sample, residual shocks tend to represent some mix of amplified reactions of energy prices to supply and demand shocks. Therefore, the expected effect on GDP is slightly positive, representing the positive effects that energy prices might have on investment in energy efficient technology. However, in a ceteris paribus situation, an increase in energy prices would always positively affect GDP of an energy exporting country. Therefore, the boost in coal exports from the UK, peaking in the early twentieth century, is represented by an increased positive correlation between energy prices and GDP growth.

Finally, as a general point, there was a significant decrease in the actual impact caused by energy price shocks on GDP since the Second World War (See Fig. 10). However, the major force behind this decrease seems to be smaller shocks (see Fig. 2) rather than particularly declining impacts to energy price shocks (see Figs. 8 and 9).

6. Conclusion

The purpose of this paper was to analyse the effects of energy price shocks on GDP at different phases of economic development, by analysing United Kingdom data over the last three hundred years. To perform such an analysis, the method proposed by Kilian (2008) and developed further in Kilian and Murphy (2012) was used to disentangle supply, aggregate demand and residual shocks. For the method to be more suitable for long-term annual time series, we identified shocks using a moving average of the identification matrices. The average shocks were identified and discussed in the context of historical events, such as poor harvests, miners' strikes or wars, and the time-specific shocks were used as explanatory variables in influencing variation in real energy prices and GDP.

The results showed that there was considerable change in the effects of shocks on GDP over the past three hundred years (see Fig. 9). The economy experienced a decline in the total impact from supply shocks associated with early industrialisation and the transition to coal. In fact, the results suggest that, between 1800 and 1870, the total impact

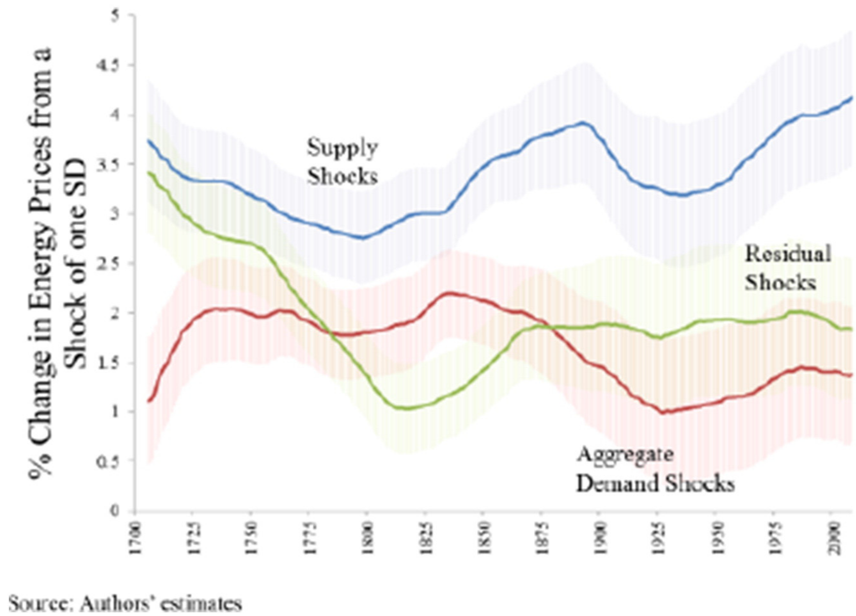

Fig. 5. Accumulated response of United Kingdom energy prices to shocks, with 95% confidence intervals (1700–2010).

of supply shocks was approaching zero, mainly due to a lower immediate impact of supply shocks (see Fig. 8). However, from the 1870s, the economy's immediate impact to supply shocks increased strongly. Then, from the 1920s, these immediate impacts appear to have started to decrease. This supports the Dhawan and Jeske (2006) and Kilian (2008) conclusions that the impacts of energy supply shocks have been decreasing since the transition to petroleum and places them within a broader historical trend.

Similarly, the negative total impact of aggregate demand shocks on GDP growth rates declined during the nineteenth century (as the economy industrialized and completed the transition to coal) and demand shocks became even positive when coal exports to Europe peaked in the early twentieth century. However, the economy appears to have become more sensitive with the transition to oil in the mid-twentieth century (see Fig. 9). In general, this type of shock could be interpreted as a cost of the economy accelerating too quickly and overheating. With the transition to oil, the overheating was experienced at an increasingly global level and, therefore, there was a decline in the immediate positive gains to the domestic economy (see Fig. 8).

One possible explanation for this change in sensitivity to supply and demand shocks could be associated with price elasticities of demand for energy and energy services. Fouquet and Pearson (1998) shows that there was a general increase (in absolute terms) in price elasticities of demand for energy services until the 1870s, followed by a decline until the 1920s and relatively stable elasticities since then. Higher price elasticities in the nineteenth century implies that consumers had higher substitution effects and/or higher income effects, and an ability to adjust to higher prices. Especially during the accelerated transition to coal in the late ninetheenth century, price elasticities decreased

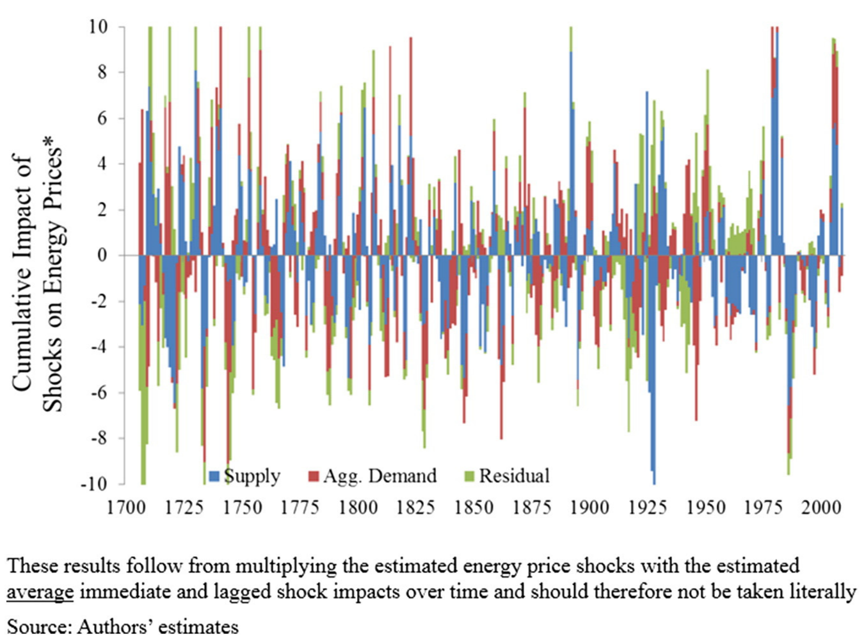

Fig. 6. United Kingdom energy price variation explained by supply, aggregate demand and residual/residual shocks, 3-year average (1700–2010).

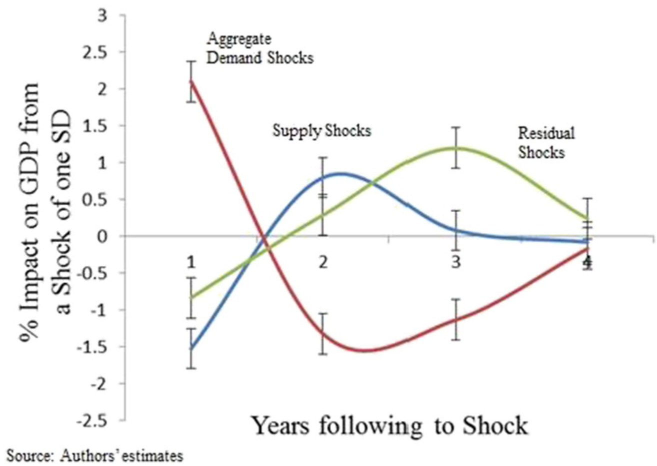

Fig. 7. Immediate and lagged responses to shocks of one standard deviation on United Kingdom GDP (average over 1700–2010).

strongly, causing the market to be less adaptable and, thus, more vulnerable to price shocks.

More generally, however, the major reason why the economy has been less affected by supply and demand shocks since Second World War is simply that, apart from the price hike in 1980 and more modestly between 2006 and 2008, the shocks themselves have decreased significantly in strength (see Figs. 2 and 10).

The most straightforward reason why shocks could have decreased significantly in strength since the Second World War is that the scale of energy markets has increased significantly since then. Decreasing shipping prices and global trade agreements implied that energy commodities have been traded on a rapidly increasing scale since the end of the Second World War. Disruptive local events that would significantly impact energy prices in a situation with isolated markets will be easily dampened in a global market. Indeed, prior to the Second World War, bad harvests, coal miner strikes and regional conflicts caused major energy price shocks. However, the only events that caused significant shocks in UK energy prices after the Second World War were important global events, such as tensions and wars specifically in the region that supplied most the world's exported oil (1973/74 and 1979/80) and an unprecedented rapid increase in the global economy (2002–2008).

Compared to Kilian (2009), this study found, over the entire period, a similar immediate impact and corrective effect from supply shocks to GDP (see Fig. 7). The average negative lagged effects of demand shocks caused by an 'overheating' economy were weaker than Kilian's estimates, although our estimates come close to those of Kilian during the later subset of our sample (see Fig. 8). For residual shocks, our results show opposite effects to the oil-market specific demand shocks presented by Kilian's (2009) study. Compared to Kilian's estimates, our resulting effects of shocks on energy prices tend to be significantly stronger for supply shocks while weaker for demand shocks. An important difference, however, is that Kilian used weighted energy prices for this analysis, while we used unweighted energy prices as we think that weighting energy prices by expenditures underestimated the true effects that supply disruptions have on the real price of energy, while overestimating the true effects of increased demand for energy.

The consequence of analysing the effects over this long timespan is that it was necessary to use annual data, while the methodology was initially designed for monthly data. Although a combination of a sign-identification matrix and supply elasticity bounds was used to overcome the problem of a biased identification of the different shocks (similar to Kilian and Murphy, 2012), it was inevitable that the resulting shocks were less 'pure' than those identified from monthly data. Also, using the median matrix from the set of admissible shock matrices was not theoretically correct, since the method imposed that every admissible shock matrix was equally likely. It is hoped that the reader will also agree with the authors that the benefits gained from this historical perspective outweigh these limitations.

Altogether, the analysis offers novel findings about the effects of energy price shocks. As current literature has only focused on the post-Second World War period and usually only on oil, this paper puts those results in a broader and historical perspective. Indeed, the results indicate that resilience of the British economy to shocks has changed following energy transitions, but does not appear to have been systematically improved by economic development. The trend of decreasing energy price shocks since 1948 has created an illusion of increasing resilience of the British economy (as shown in Figs. 2 and 10).

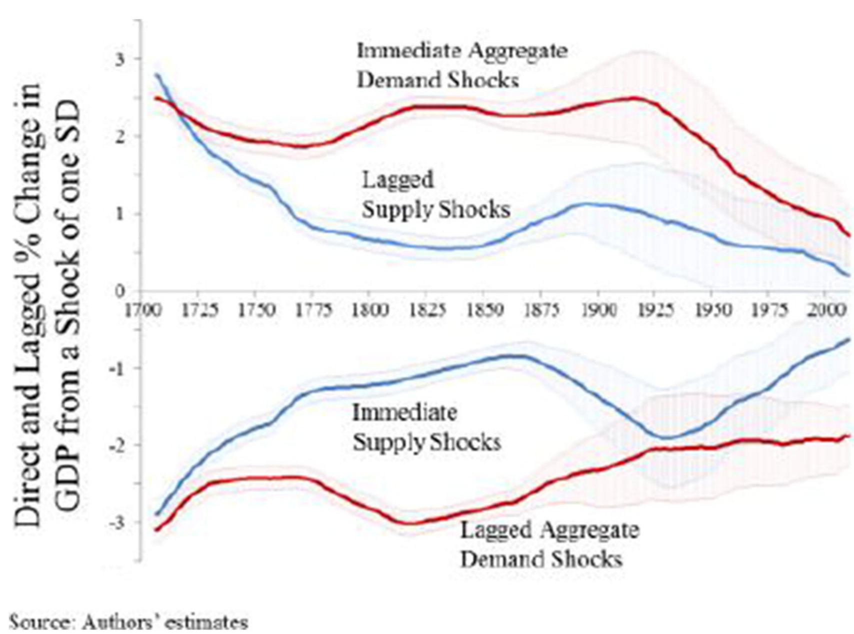

Fig. 8. Immediate and lagged response of United Kingdom GDP to shocks, with 95% confidence intervals (1700–2010).

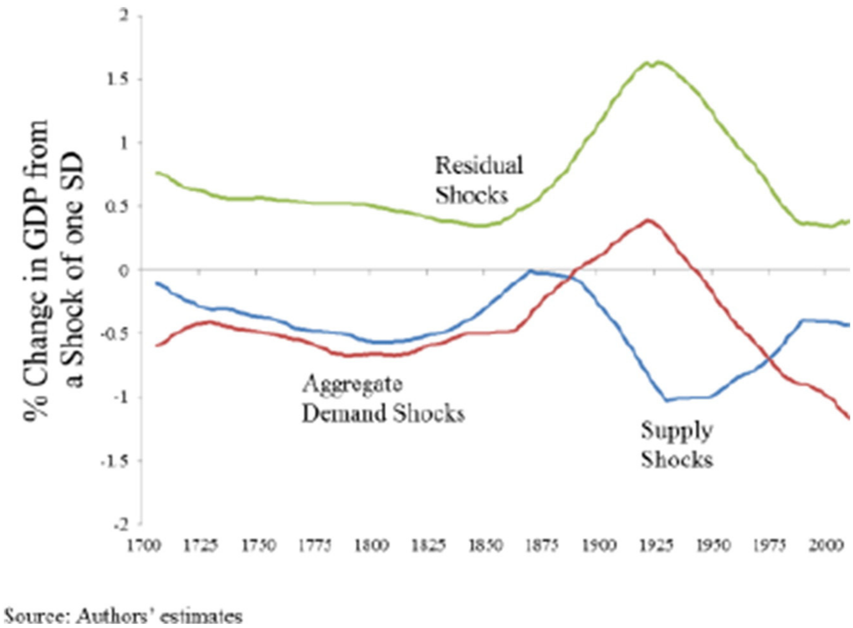

Fig. 9. Accumulated response of United Kingdom GDP to shocks (1700–2010).

A continuing globalization of energy markets, spurred by developments in the natural gas may further decrease the probability of large energy price shocks. However, this development increases the vulnerability of every individual economy to non-domestic macroeconomic events such as the economic boom in 2002–2008 that caused energy prices to increase to levels unprecendented in the last century (see Fig. 1). On the other hand, a transition towards renewable energy may reverse this trend, and care should be taken to learn from the lessons from earlier periods – in particular, that integrating individual national markets can dampen volatility, ensure a mix of energy sources and avoid overheating the economy.

An important conclusion that can be drawn from the results - that vulnerability and resilience to energy price shocks are related to energy markets rather than economic development - is that developing countries that depend on globally traded energy resources should not expect to become more resilient to energy price shocks over time. Instead, the highest resilience against energy price shocks was observed between 1850 and 1880 when the British economy depended on a diversified mix of domestically produced energy sources (coal, provender and wood). Such an energy mix implies that the impact of supply shocks was limited due to high substitutability between energy sources, whereas the negative impacts of aggregate demand shocks were offset by the positive impacts of a growing economy (that caused the shock). If this conclusion can be applied to the future, then, particularly during a transition to renewable energy sources, economies will become less vulnerable and more resilient to energy price shocks. Future research should investigate in more detail the changing vulnerabilities and resiliences associated with the transitions to low carbon economies to confirm this hypothesis.

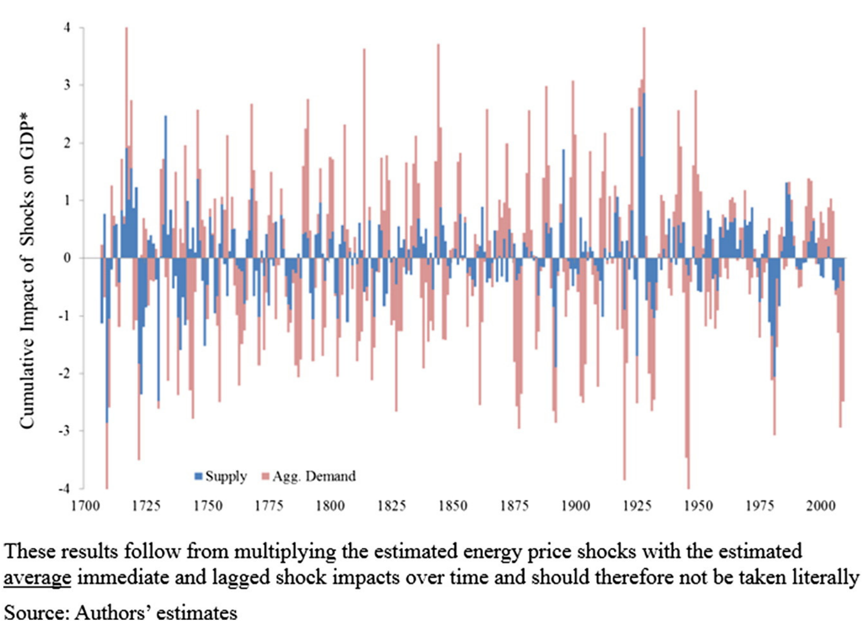

Fig. 10. United Kingdom GDP variation explained by supply and aggregate demand shocks, 3-year average (1700–2010).

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.eneco.2016.12.009.

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