Historical Energy Price Shocks and their Changing Effects on the Economy

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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 economy became more vulnerable to supply shocks with its increasing dependence on coal, and less vulnerable 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 vulnerability and resilience to shocks did not progress systematically as the economy developed. Instead, the changes in vulnerability and resilience depended greatly on the circumstances related to the demand for and supply of energy sources.

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1. Introduction

A nation's long run economic success is highly dependent on its vulnerability and resilience to shocks (Balassa 1986, Romer and Romer 2004). 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).

Nordhaus (1980) outlined some of the key avenues through which oil prices can constrain the economy[2]. Rising oil price increase energy expenditure (when price elasticities of demand are low) which raises 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. Mork (1989) argued that the impacts of oil price increases and decreases on GDP are asymmetric. However, 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 (i.e., the immediate impact) and more resilient (i.e., the ability to bounce back) to energy shocks through time and as they have developed. For instance, one might expect that economic development - for instance, 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 Gali 2009). Dhawan and Jeske (2004) 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), most of these studies, however, have been analysing the post-Second World War period in mature industrialised economies.

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 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 2013 and Fouquet 2011) to estimate the changing relationship. Thus, the main contributions of this paper to the literature are, therefore, first, to place current empirical evidence of declining vulnerability to oil shocks within a much broader historical context and, second, to assess what factors influence long run changes in vulnerability and resilience to energy price shocks.

The results indicate that vulnerability and resilience to shocks did not progress systematically as the British economy developed. Instead, the changes in vulnerability and resilience depended greatly on the circumstances related to the demand for and supply of energy sources. At first, the transition from

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[2] For recent broader discussions of the role of energy in influencing economic growth, see Kummel et al. (2002), Ayres and Warr (2004), Allen (2009), Stern and Kander (2012).

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 vulnerable to supply shocks. The partial transition to oil (and generally broader fuel mix) reduced the economy's vulnerability to supply shocks, but also weakened its resilience 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.

Naturally, given that the economy's increasing dependence on oil has been relatively recent (i.e., after the Second World War), 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 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) 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 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´s 1983 empirical study, which used a six-variable system for testing the influence of oil prices on macro-economic aggregates. He found that oil prices had a significant impact on GDP. These findings were confirmed by Burbidge and Harrison (1984), Gisser and Goodwin (1986), Mork (1989), and Ferderer (1996). Similar studies by Mork et al. (1994), Papapetrou (2001), Lee et al. (2001), Jiménez-Rodríguez and Sanchez (2005) and Lardic and Mignon (2006) for other major OECD countries and by Cunado and Gracia (2005) for six non-OECD Asian countries revealed that the negative oil price-GDP effect prevails in virtually all industrialized and industrializing economies, even in oil exporting countries (Mork et al. 1994) and Malaysia (Cunado and Gracia 2005). Also, the effects seem to be surprisingly similar across developed countries.

Moreover, Mork (1989, 1994) also tested for symmetry in the oil-GDP effect: since the negative response of GDP to oil price increases was of a significantly higher magnitude than the positive response of GDP to oil price decreases during the 1967-1992 period, Mork (1994) concluded that an asymmetric model is necessary to investigate the effect properly. Mory (1993) and Lee et al. (1995) confirmed the existence of asymmetry with the finding that oil price decreases had no impact on the US economy, while Lardic and Mignon (2006) determine that asymmetric cointegration is of major relevance in explaining the impact of oil price shocks in their twelve European sample countries.

Most studies concluded that the impact coefficient 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 Gali (2009) found a reduced impact coefficient in

the early 1980s, while Kilian (2008) and Baumeister and Peersman (2008, 2012) 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 (2008, 2012) and Kilian (2008) propose the existence of a structural break in the oil-GDP effect during the 1980s. The 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 Gali 2009, 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, Melolinna 2012) and the difference between the inflationary effects of these origins (Chen 2009).

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, Kilian (2008) 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 energy prices:

- crude oil supply shocks (due to primarily exogenous events);
- aggregate demand shocks (for most 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 2012, Melolinna 2012), the original breakdown proposed and continuously improved by Kilian (2008, 2009, 2012) and most recently in Kilian and Murphy (2012) remains the dominant approach to decompose oil shocks. His conclusions are that while oil prices are affected considerably by demand effects and to an even larger extent by speculation, the effects of supply shocks on oil prices are relatively low. The effects of supply shocks are a little more 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 (1983) conclusions and invalidating his methodologies that assume oil price variation to be exogenous. Edelstein and Kilian (2007) also rejected the hypothesis of asymmetry in the oil-GDP effect (Mork 1989, 1994; Mory 1993; Lee et al. 1995; Hamilton 1996, 2003), arguing that these studied failed to identify the influence of the 1986 US Tax Reform Act - it most probably offset the positive effects of the strong decline in oil prices.

The conclusion that the 2002-2008 oil price surge had been caused by aggregate demand rather than supply effects suggests why it was unexplained by earlier research which performed a direct VAR

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 negative correlation associated with the oil supply crises in the 1970s. Hamilton (2009) also proposed that speculation played an important role in the 2002-2008 oil price surge, while supply from the conventional oil exporters stagnated. Using a 'what-if' method, he states that, in absence of the oil shock, US GDP would have risen by 3% instead of fallen during the recession that occurred in late 2007.

Nearly all the literature came to the conclusion that the effect of an energy price increase on GDP has been significantly larger than would be expected given the share of energy expenditures in GDP. Economic theory has long struggled to explain this finding (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) mentions 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.

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 as a result, they are harder to predict. For these effects, an asymmetric response of GDP to energy price variation is likely, as given the risk-aversion of human nature, these effects are expected 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 1991). Second, the precautionary savings effect is in response to an energy price increase, consumers might smooth their consumption because they perceive a greater likelihood of future unemployment and the resulting income losses.

Using an economic growth model with capital, labor and energy as factors of production and integrating energy in the capital utilization formula, Finn (2000) found that an energy price shock can be considered as an adverse technology shock, since it causes capital (which embodies the technology) to produce at below capacity levels. According this model, an increase in energy prices would cause GDP to decrease 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). Thus, even when limiting ourselves to the actual function of energy in the economy, energy price shocks can be expected to affect GDP more than the share of energy in GDP would suggest.

The second category of transmission channels, related to the influence of risk-aversive human behaviour, could even strengthen the negative response of GDP resulting from rising energy prices offered by Finn (2000). For instance, postponed investments and consumption smoothing will aggravate this effect. Moreover, conclusions of 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 of investments as a result of energy price volatility in general rather than just energy price increases (although, as mentioned above, the significance of asymmetries can be questioned due to the 1986 US Tax Reform Act). Following this reasoning, some studies have used oil price volatility rather than oil price innovations as an explanatory variable for GDP in the US (Guo and Kliesen 2005) and several other oil-importing countries (Germany, Japan, India, South-Korea), as well as oil-exporting countries (Malaysia) (Rentschler 2013). For all countries, there seemed to be a significant negative impact of oil price volatility on GDP, which could also explain why even oil-exporting countries can suffer from oil price shocks as mentioned earlier. Given these findings, there are good reasons to believe that the effect of uncertainty has been of major influence concerning the influence of oil prices on GDP during the last few decades.

As an attempt to analyse the effects of energy prices on the long term, this paper applies the breakdown of price innovations presented in Kilian and Murphy (2012), which built on Kilian (2008), to British annual energy prices during for the period 1700-2010. We chose to replicate this method, not only because this line of research remains the domiant concensus in research on the relationship between oil prices and GDP, but also because its methodology is more applicable for long-term annual data and it gives an insightful overview of the timing and relative magnitude of different shocks during the last 310 years of British history. Also, given that the 2002-2008 oil price surge is not the only case, over the past three centuries, where aggregate demand simultaneously boosted energy prices and GDP, a direct regression of energy prices on GDP would be invalid. With this in mind, the next section will go into detail about the data used for this approach, and Section 4 outlines the method used.

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 fuel prices and GDP for the period 1700-2008, as well as indicators for supply and demand in order to reproduce Kilian's (2009) breakdown of oil price innovations. The following is a summary of the sources and methods - more detail of the sources can be found in Fouquet (2008, 2011).

United Kingdom GDP is based on pulling together data from Broadberry et al. (2013), 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 used in this topic are composed from a variety of data sources. All of the original price series for energy fuels are discussed in Fouquet (2011) and can be seen in Figure 1, along with trends in

GDP. To replicate the existing oil price-GDP literature in this paper, however, we are interested in an aggregate price series for all different energy fuels. To calculate these series, we first created index numbers for the fuel prices of every different service[3] and weighted them using the expenditures on fuels of every service. We chose to use index numbers instead of taking an average of real fuel prices (weighted on expenditures), since different fuels can be of completely different values that are not directly comparable. For example, provender was about 12 times more expensive per energy unit than coal in the 19th century. Weighting the average values of primary fuels, a 5% decrease in the provender price would then overweigh a 20% increase of the coal price in the same year, even when expenditures on both provender and coal are equal (hence, with equal weights, the decrease in the coal price should outweigh the increase of provender price by a factor of four). Using index numbers however, the percentage change in prices is measured instead of the absolute change, resolving this problem.

After this step, we followed Kilian's (2008) approach, weighting the prices by the share of total energy expenditures in total GDP. Resulting is 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 deviations rather than the evolution of these price index series.
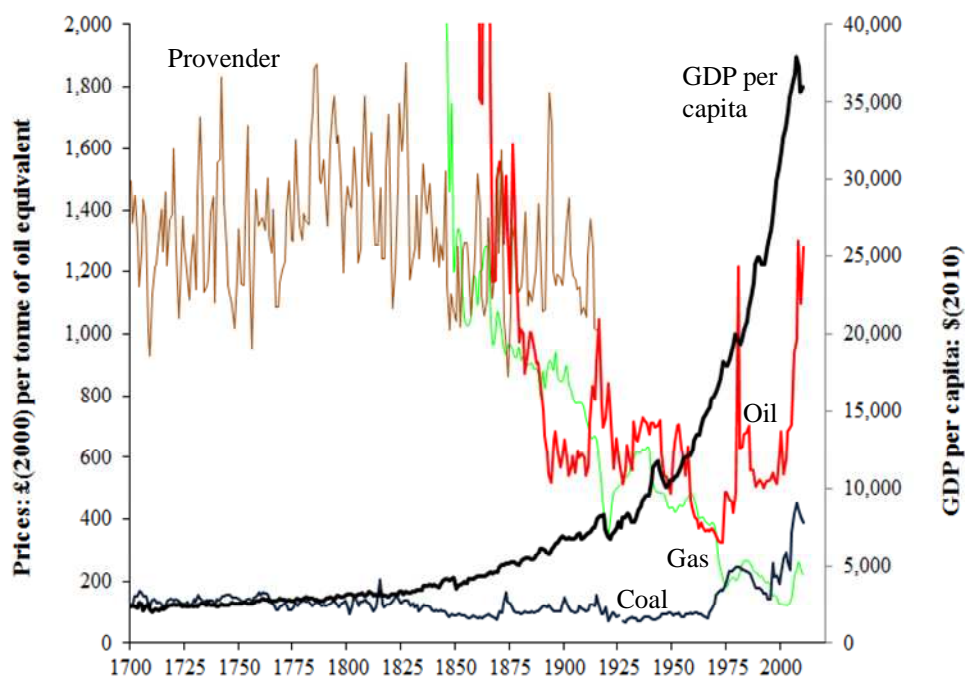
Source: Broadberry et al (2013), Fouquet (2011)

Figure 1. United Kingdom Energy Prices and GDP per capita (1700-2010)

3.2. Supply Data

The supply index series in this paper was constructed using a variety of sources for each different fuel type. Per fuel type, the weight for the final indicator is based upon the share of expenditures on this fuel

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

relative to the total expenditures on energy fuels. The expenditures are calculated by multiplying consumption with the 10-year moving averages[4] of the prices of each fuel.

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 (2013), 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 for 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.

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

Coal: For the period until 1981, we only use estimates of coal production within the United Kingdom. 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 1981. 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.

Petroleum: For the complete time series, we used the world oil production data from the JODI database[5]. Doing this, we assume that since oil is a relatively easy-to-transport energy source, production numbers throughout the world are relevant for the UK.

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. 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 measure of relevant economic activity is subject to a lot of discussion. In his papers, Kilian (2008, 2009) and Kilian and Murphu (2012) use worldwide dry cargo shipping rates as an indicator for economic activity. His reasoning is that since the supply of shipping is very price-inelastic, the variance in the price of shipping is a good indicator for the worldwide business cycles. In an upwards cycle, oil prices are expected to go up, but the negative effects of these higher oil prices on GDP could be offset by the positive effects that are initiated by the worldwide business cycle. This choice, however, has not

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[4] Ten-year moving averages were used in the calculation of fuel expenditures to remove most of the influence of price volatility in the weighting procedure.
[5] Available at http://www.jodidata.org/.

gone unnoticed and it already received some criticism. Melolinna (2012), for example, argues that shipping freight rates are positively related to oil prices, while Kilian assumes a negative influence of oil prices on economic activity. In any case, we do not have data on worldwide shipping rates back to 1700.

Also, it is not desirable to use a worldwide estimate of economic activity for the full period of our project, as activity outside the UK had little influence on energy prices and other economic aggregates in the UK for the majority of our sample. For that reason, we used four different gross demand indicators, dependent on the relevant region for a certain fuel during a certain period. The four regions and their assumed relevance in sense of fuel demand (influencing UK aggregates) 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 an 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 ubefore 1965.

A variety of different variables were tried as an indicator of economic activity. The most important feature of this indicator should be that it shows the ups and downs of the business cycle. For that reason, we finally decided using GDP data (aggregated for each country block) and used the Hodrick-Prescott Filter (using $\lambda = 100$, following Backus and Kehoe (1992)) to filter out the business cycle from this GDP data. Taking these four business cycle series together, weighted correctly on the relevant energy sources consumed in the UK, a final business cycle indicator was created, which is a relevant indicator for a aggregate economic activity.

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

Regions: _Fuels:_	UK	Europe	Europe + Western offshoots	Oil- consuming world	Coal- consuming world
Biomass	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.

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 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 analyzed period from 1700 to 2010. The method used for disentangling these shocks is similar to that of Kilian & Murphy (2012), but with one important change 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 of 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 innovations to the model depend on each other. Since we are looking at shocks over 310 years and, therefore, aware that these relationships between innovations (i.e., the residuals of the VAR model of energy production, economic activity and energy prices) change over time, we use a moving average (rather than a single matrix as is traditionally done for short run analysis) in orthogonalizing Ω and identify shock matrix called P_k, such that $\Omega_k = P_k{'}P_k$ and $e_{t+n} = P_k\varepsilon_{t+n}$.

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

Here, n describes the number of years inside 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 innovations and also that real activity cannot respond to oil price innovations 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), in which different assumptions are made. 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 logical 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 innovations in real activity could be positive or negative. 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 innovations 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 with the data we use in the model.

Table 2. Sign restriction from impulse responses

	Energy supply shock	Aggregate demand shock	Residual shock
Energy production	-	+/-	+
Economic activity	+/-	+	-
Energy price	+	+	+

These restrictions do not identify the shocks uniquely, but result in a large set of admissible shock matrices. Therefore, 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 innovations in energy prices, as done in Kilian and Murphy (2012). Since we are working with annual instead of monthly data, our boundaries cannot be as restrictive. Thus, we only assumed that, within one year, supply must be inelastic in response to energy price shocks.[6]

Finally, we calculated our identification matrices based on a moving average of 60 years. 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, 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. We select this unique shock matrix by searching the closest-to-median matrix..[7]

Since the method above, introduced by Kilian (2008, 2009) and developed in Kilian and Murphy (2012), is initially designed for analyzing monthly data, there might be doubts about the robustness of our results on annual data. However, even with monthly 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 Lütkepohl 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 identified shocks are actually a coincidence is even bigger with annual data.

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[6] 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.

[7] 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.

On the other hand, there might be some advantage in using annual instead of monthly data for the shock identification results. In his final results, Kilian (2008, 2009) finds a surprisingly low impact of supply shocks on oil prices and a very large impact of specific oil demand shocks (residual shocks). However, shocks in specific oil demand might in some cases catch effects that are actually related to supply shocks, through the role of precautionary demand and storage that occur when a supply disruption is expected as a 'news shock'. Rizvanoghlu (2012) investigated this 'news shock' using a theoretical model. He concludes that a 'news shock' is always followed by a strong price increase and GDP decrease, while the long-term effects depend on whether the 'news shock' is followed by an actual supply disruption. If it is, the effects on prices (upwards) and GDP (downwards) are persistent and strong, while if it is not, the response of prices and GDP first overshoots the steady state level in a backward direction and within three months, GDP and energy prices are back to their steady state levels. Since the 'news shock' and the actual supply disruption often occur in different months (but with a high probability during the same year), the chance that an actual supply disruption is captured by a 'residual shock' instead of a 'supply shock' is smaller using annual data than when using monthly data.

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 Figure 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 Figure 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 – in 1980-1984.
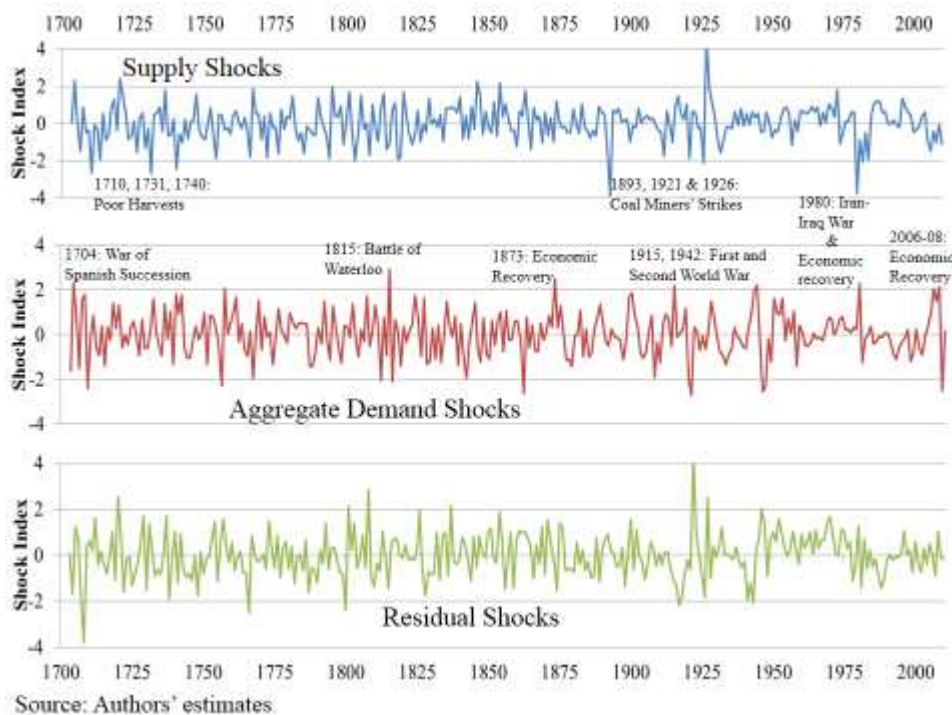
Figure 2. Energy Price Shocks by Factor (1700-2010)

Table 3 provides an overview of all supply shocks with an absolute value of two or higher grouped by their probable cause - the average shock had a magnitude of 0.75. Two well-known shocks (the oil crisis of 1973-4 and the coal miners' strike of 1984) are included in grey, because they were below an absolute value of two.

Since an aggregate indicator of energy is used in this study, the supply of energy is dependent on the weighted growth rates of each source of energy used. During the last three centuries, different energy sources have dominated at different times (Fouquet 2008). Figure 3 shows the distribution of total expenditures on primary energy sources in the UK since 1700. During the eighteenth century, provender was the most dominant source of energy, which was used for power. By 1700, coal had become the main source of heating, especially for domestic heating, although not yet for iron production. Coal became the main source of power during the nineteenth 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 fuel. This has tended to create three different types of supply shocks, as visible in Table 3.
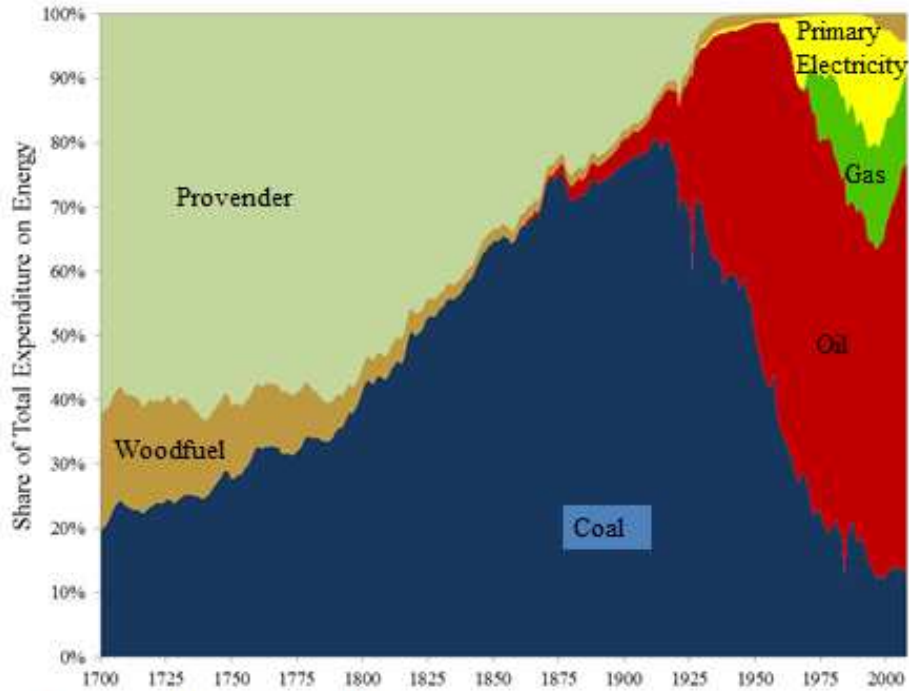
Source: Fouquet (2008), Fouquet (2011)

Figure 3. Share of Primary Energy Expenditure in the United Kingdom (1700–2010)

During 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. 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 a large disruption of energy supply. Subsequently, the strikes in 1921 and 1926 also led to strong shortages (Church 1987). 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 a considerable supply shock in 1974 and a very large one in 1980.

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.

Aggregate demand shocks experienced a broadly opposite experience. Except for a few major shocks (i.e. close or greater than two in Figure 2) in the early 1700s and then in 1815, important aggregate demand surges were very infrequent until the 1870s. At the beginning of the twentieth century, major shocks were relatively common and, throughout the century, on average, the shocks were considerably stronger than before. However, the second half of the twentieth century only experienced one major aggregate demand shock, in 1980.

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 though 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 sources (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 Figure 2). There were also periods of civilian economic growth (1873, 1980 and 2008) that appear to have fed through into pressures on resources and increasing energy prices.

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.

Finally, residual shocks are estimated as the change in price not explained by changing supply or 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.

Due to the moving average structure of our model to identify shocks, the timing of events has an important influence on the strength of a shock. In other words, an event that strongly disrupts energy supply or boosts energy demand will cause a much stronger supply or demand shock when occuring during a relatively stable period. This 'surprise' effect is the reason that the 1893 coal miner strike and the 1980 Iran-Iraq war caused stronger supply shocks than the coal miner strikes in 1921 and 1926, even though supply disruptions were weaker in real terms. Similarly, economic recoveries in 1873,

1980 and 2008 caused relatively large demand shocks as they occurred during periods with few demand surges (e.g., times of relative peace).

5. The Trends in Shock Effects

The purpose of this paper is to analyze 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 analyze 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

Figure 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[8]. 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 analyze 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[9]. 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. [10]

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[8] 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 innovations: the positive and negative effects of demand shocks on fuel prices are strongly overestimated, since increased consumption leads to rising fuel 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 fuel 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.

[9] 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.

[10] 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.
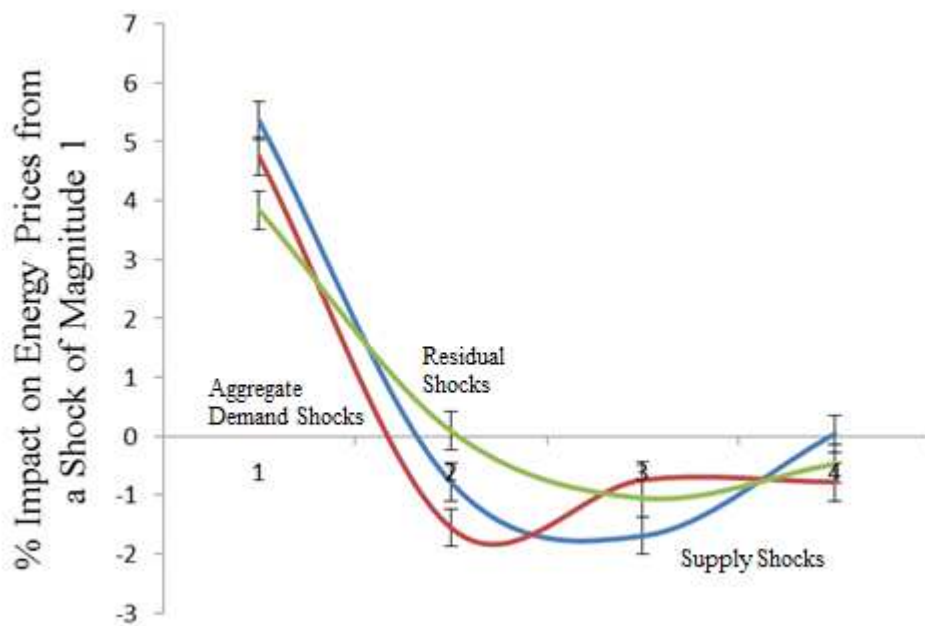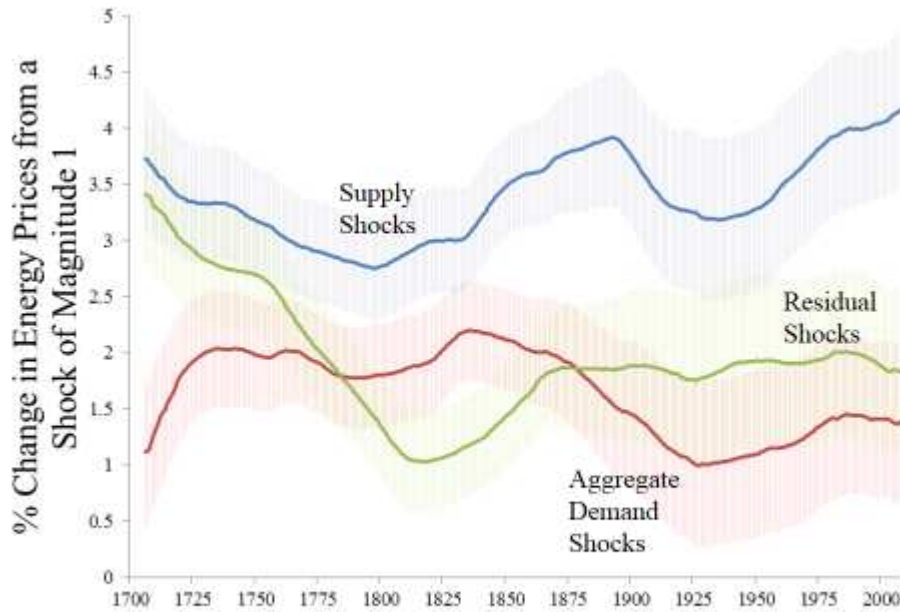
Source: Authors' estimates

Figure 4. Immediate and Lagged Responses of Energy Prices in the United Kingdom to Shocks of Magnitude 1 (average over 1700-2010), with Standard Deviations.

Figure 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 Figure 4). The immediate impact of supply shocks on prices increased until the early ninetheenth century, when biomass was the dominant source of energy, then decreased during the age of coal until the First World War, and finally increased again with the transition to petroleum and electricity. The corrective effect of supply shocks (i.e., the sum of the three lags) mirrored the immediate impact, dampening the full effect of supply shocks on energy prices over the whole period (since a larger corrective effect reduces the total effect.

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 got dominated by a single source of energy (1830-1900 for coal and 1940-2010 for petroleum, see Figure 3). This effect indicates that realistic opportunities of fuel switching have a stabilising effect on the response of energy prices to events that disrupt supply of the initially dominant fuel.

Figure 5. Accumulated Response of United Kingdom Energy Prices to Shocks, with 95% Confidence Intervals (1700-2010)

The immediate impact of aggregate demand shocks declined strongly from 6% around 1700 to 3% in the early twentieth century, and has been 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. Figure 6 combines the estimated shocks (Figure 2) and their period-dependent effects on energy prices (Figure 5) to give an indication of the causes of energy price fluctuations since 1700. The figure shows that except for some periods with large shocks (coal strikes, world wars and oil crises), the average magnitude of energy price innovations declined significantly through 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. Figure 6 also shows that different shocks were dominant during different periods and that residual shocks indeed occurred simultaneously with supply and/or aggregate demand shocks in most cases.
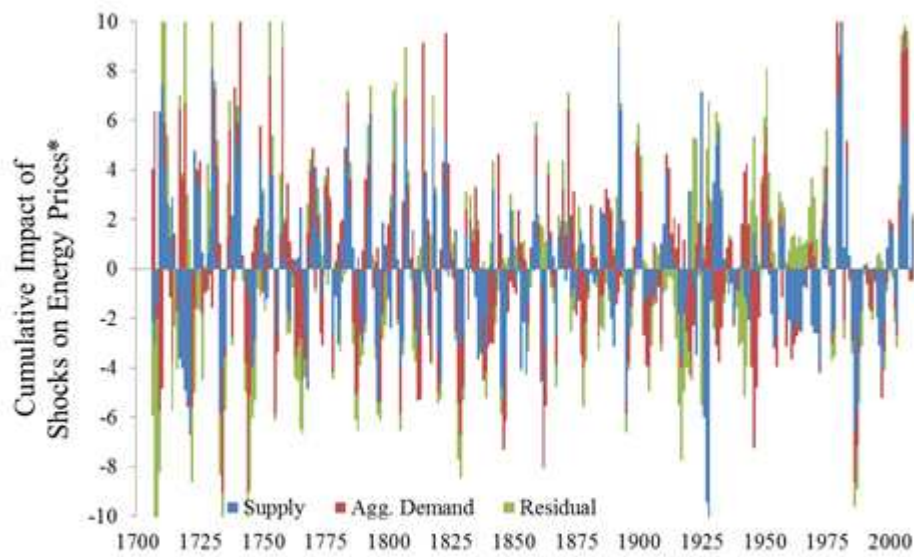
Figure 6. United Kingdom Energy Price Variation Explained by Supply, Aggregate Demand and Residual/Residual Shocks, 3-year average (1700-2010)

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 Figure 7). As with the regression on energy prices (see Figure 4), both means and confidence intervals are estimated using least-squares methods.
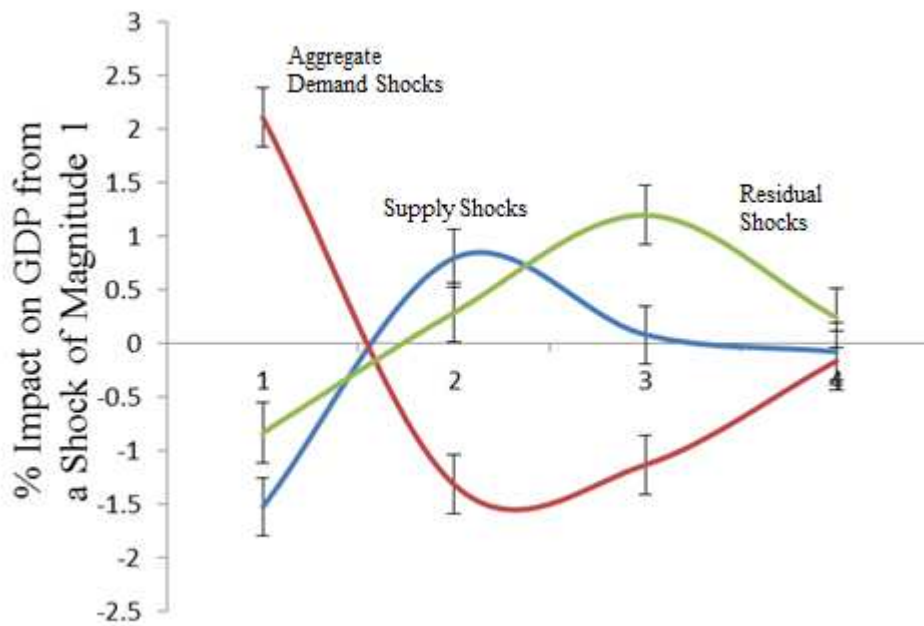
Source: Authors' estimates

Figure 7. Immediate and Lagged Responses to Shocks of Magnitude 1 on United Kingdom GDP (average over 1700-2010), with Standard Deviations.

Figure 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 Figure 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.

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 Figure 7 is partly a self fulfilling prophecy[11].

The response to residual shocks is also interesting: while Figure 4 indicates that the corrective effect of energy prices after a residual shock was relatively low, Figure 7 shows that the corrective effect of GDP was remarkably high and long-lasting. There are two possible explaiations 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

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

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. A fuel switch that uses different technology, say, might have an increasing effect on energy prices, but might have a positive effect on GDP as the new technology becaomes more efficient or yields other qualitative advantages.

The more interesting question however is how the effects of supply and demand shocks changed over time. Figure 8 shows the change of this effect over time, separately for the immediate and the lagged response (sum of the three lags, see Figure 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 (Figure 5) [12].

The immediate response of GDP to supply shocks (i.e., vulnerability) decreased strongly (in absolute terms; i.e. become 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 vulnerability has continued into the twenty-first century, supporting the observation made by Dhawan and Jeske (2006) and Kilian (2008) that vulnerability to oil price shocks has decreased during the last decades. However, these results place their observations within a broader historical trend of increased vulnerability 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.
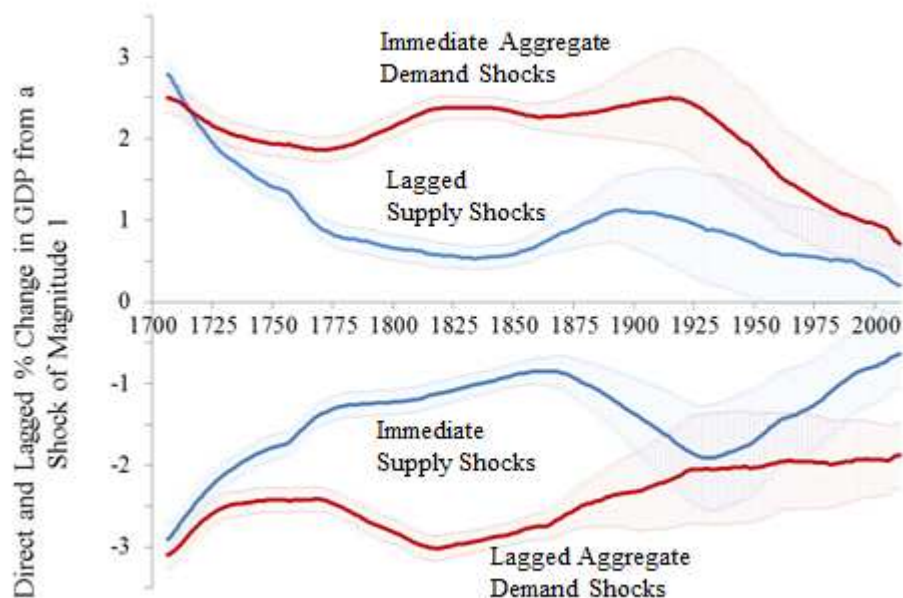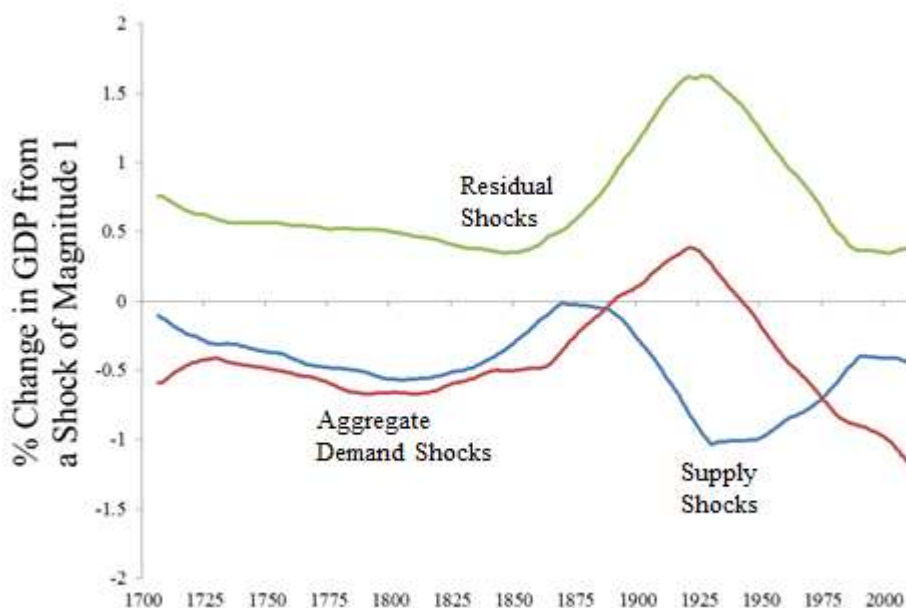

Source: Authors' estimates

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[12] 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.

Figure 8. Accumulated Response of United Kingdom GDP to Shocks, with 95% Confidence Intervals (1700-2010)

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, an economy appears to develop levels of resilience commensurate with its vulnerability.

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 fuels 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.

Source: Authors' estimates

Figure 9. Immediate and Lagged Response of United Kingdom GDP to Shocks (1700-2010)

Just as was done for energy prices (i.e., by summing up the responses of the four estimated lags), Figure 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 characterised as a Ɛ-shape curve rotated 90° anti-clockwise: 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.

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 Figure 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 caused the immediate positive effect of demand shocks on GDP to decrease. Lagged effects also declined (in absolute terms), yet far less than immediate effects, implying increasingly negative total effects of aggregate demand shocks on GDP throughout the twentieth century.

This steep decline should again be interpreted carefully, as the relevance of economic activity for energy prices shifts from the UK towards the rest of the world during the twentieth century (as explained in Section 3.3). Therefore, an aggregate demand shock in early periods is measured as a business cycle peak in the UK itself and so logically has a more positive impact on British GDP than a business cycle peak in the rest of the world. The declining response of GDP to aggregate demand shocks might therefore be partly or completely caused by a shift in the relevant real activity. Although this might be interesting by itself, such as when fuel 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 entended 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 Figure 10). However, the major force behind this decrease seems to be smaller shock magnitudes (see Figure 2) rather than particularly declining vulnerability or greater resilience to energy price shocks (see Figures 8 and 9).
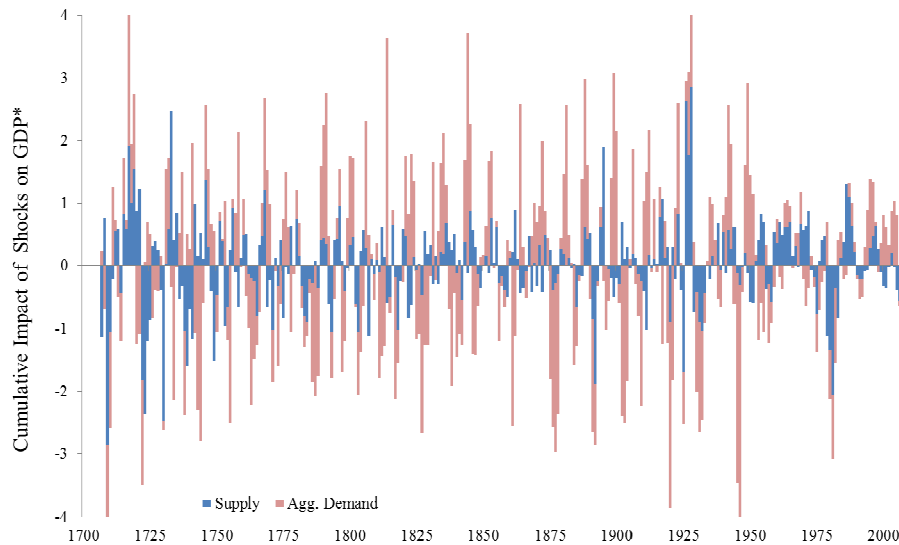
* Here, a negative supply shock is positive to sum shock effects on prices (conversely to Figure 2).
Source: Authors' estimates

Figure 10. United Kingdom GDP Variation Explained by Supply and Aggregate Demand Shocks, 3-year average (1700-2010)

6. Conclusion

The purpose of this paper was to analyze 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 and Murphy (2012) was used to disentangle supply, aggregate demand and residual shocks. For the method to be more suitable on 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 Figure 9). The economy experienced a decline in the total impact from supply shocks associated with early industrialisation and transition to coal. In fact, the results suggest that, between 1800 and 1870, the total impact of supply shocks was approaching zero, mainly due to a lower immediate impact of supply shocks (see Figure 8). However, from the 1870s, the economy's vulnerability (i.e., the immediate impact) to supply shocks increased strongly. Then, from the 1920s, vulnerability appears to have started to decrease. This supports the Dhawan and Jeske (2006) and Kilian (2008) conclusions that vulnerability to energy supply shocks has 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 industrialised 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 Figure 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 Figure 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 (2014) 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 the ability to adjust to higher prices. Especially during the accelerated transition to coal in the late ninetheenth century, price elasticities decreased 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 Figure 2 and 10).

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

In this paper, the findings concerning the effects of aggregate demand shocks on GDP (strongly positive immediate impact and strong negative corrective effect) might be partly based on a self-fulfilling prophecy: as real activity - the major indicator for aggregate demand shocks - is typically measured by a business cycle indicator, a shock in aggregate demand largely reflects a business cycle peak. Business cycle peaks logically occur together with increasing GDP, followed by a decline in GDP in the years after the business cycle peak.

Also, the consequence of analyzing the effects over more than three hundred years 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 is inevitable that the resulting shocks are less 'pure' than those identified from monthly data. Also, using the median matrix from the set of admissible shock matrices is not theoretically correct, since the method imposes that every admissible shock matrix is 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 shock magnitudes since 1948 has created an illusion of declining impacts on the British economy (as shown in Figure 2). Future research might investigate in more detail the cause of these weaker shocks, and changing vulnerabilities and resiliences associated with the transitions to coal and to oil, as well as potential transitions to natural gas, nuclear power or renewable energy sources.

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Appendix A

By using the sign identification matrix in Table 2, on average 6,8% of all randomly generated rotation matrices turned out to be admissible to derive a shock-matrix. This percentage is the result of multiplying 100,000 orthonormal rotation matrices with the recursively identified lower-triangular Cholesky decomposition of the variance-covariance matrix of the VAR model residuals (e_t) using MatLab, leaving on average around 6,800 admissible rotation matrices after filtering for the sign restrictions in Table 2. This method is explained in detail by Kilian and Murphy (2012). Throughout, we impose restrictions on the levels of supply elasticity associated with innovations in energy prices to further drive down the percentage of admissible shock matrices. These extra restrictions cancel out all matrices for which the values of P_{k12} and P_{k13} are smaller than the values of P_{k32} and P_{k33} respectively. This extra restriction drives down the amount of admissible shock matrices towards 3.5% on average. Figure A1 shows the percentage of admissible rotation matrices for our moving average periods of 60 year. Note that, to avoid strange results on the borders of our estimates, we reduced the moving average period towards 50 years at the edges of our sample (i.e., 1700-1750, 1700-1751, … , 1700-1760, 1701-1761 etc).
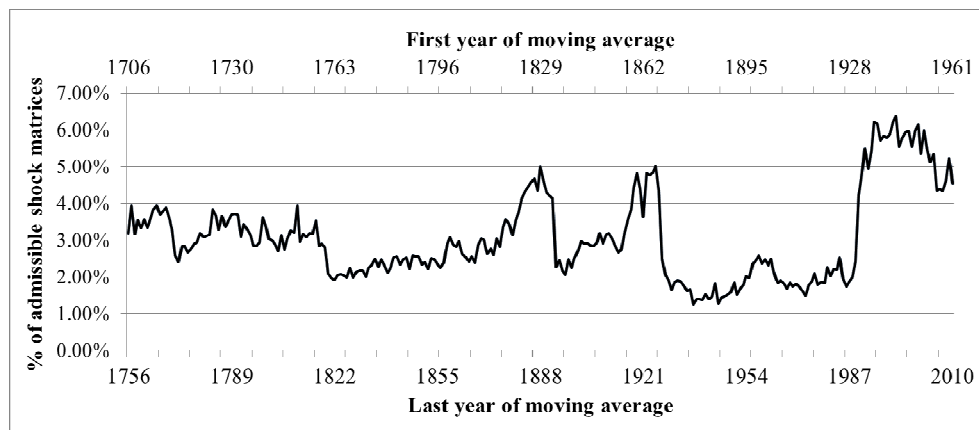
Figure A1: Percentage of resulting admissible shock matrices after sign and supply elasticity restrictions for our moving average sets of time-series

For every period, we finally choose one single closest-to-median matrix. This matrix requires the conditions to be a viable shock matrix. Table A1 shows the values of all our selected closest-to-median matrix. In brackets are the standard deviations of these matrix values, calculated on basis of all entry values from the admissible matrices in a particular period.

Table A1: 25-year averages of shock matrix entries for the different moving average periods. In brackets the relevant standard deviations based on the total selection of matrix entry values

Start year	End year	(1,1) - Energy supply on supply shocks	(1,2) - Energy supply on demand shocks	(1,3) - Energy supply on residual shocks	(1,4) - Economic activity on supply shocks	(1,5) - Economic activity on demand shocks	(1,6) - Economic activity on residual shocks	(1,7) - Energy prices on supply shocks	(1,8) - Energy prices on demand shocks	(1,9) - Energy prices on residual shocks
1706-1720	1756-1779	4.54	2.29	3.04	2.20	2.22	-0.94	-12.95	10.29	11.38
		(0.6)	(1.128)	(1.08)	(0.476)	(0.54)	(0.66)	(2.96)	(3.648)	(3.42)
1721-1745	1780-1804	3.38	1.91	2.09	1.24	1.72	-0.60	-12.36	10.15	9.97
		(0.496)	(0.864)	(0.812)	(0.4)	(0.34)	(0.432)	(2.936)	(3.42)	(3.632)
1746-1770	1805-1829	3.29	1.49	1.94	1.21	2.03	-0.63	-12.43	7.81	7.91
		(0.36)	(0.764)	(0.728)	(0.38)	(0.3)	(0.532)	(2.156)	(2.652)	(3.032)
1771-1795	1830-1854	2.98	1.34	1.69	1.23	2.32	-0.69	-13.25	7.29	7.51
		(0.308)	(0.696)	(0.644)	(0.42)	(0.308)	(0.596)	(2.028)	(2.616)	(3.068)
1796-1820	1855-1879	2.60	1.11	1.57	0.90	2.39	-0.65	-13.22	7.05	7.01
		(0.3)	(0.624)	(0.6)	(0.44)	(0.296)	(0.568)	(2.012)	(2.54)	(3.008)
1821-1845	1880-1904	2.52	1.08	1.64	0.79	1.98	-0.54	-11.06	7.00	6.98
		(0.3)	(0.62)	(0.6)	(0.412)	(0.256)	(0.484)	(2.008)	(2.4)	(2.752)
1846-1870	1905-1929	3.81	1.29	2.43	0.86	1.96	-0.75	-9.50	6.64	8.45
		(0.396)	(0.876)	(0.868)	(0.364)	(0.316)	(0.528)	(1.952)	(2.616)	(2.552)
1871-1895	1930-1954	8.03	1.63	3.60	1.44	2.13	-1.50	-6.70	6.66	10.15
		(0.416)	(1.36)	(1.412)	(0.272)	(0.648)	(0.768)	(1.448)	(3.364)	(2.524)
1896-1920	1955-1979	8.03	1.59	3.38	1.29	2.25	-1.78	-4.72	6.20	9.73
		(0.408)	(1.304)	(1.364)	(0.288)	(0.724)	(0.768)	(1.388)	(3.136)	(2.348)
1921-1945	1980-2004	4.40	1.24	2.71	0.92	1.91	-1.20	-9.70	6.37	8.86
		(0.412)	(0.94)	(0.956)	(0.344)	(0.476)	(0.62)	(1.844)	(3.108)	(2.476)
1946-1970	2005-2010	2.34	0.93	1.88	0.31	1.11	-0.46	-12.44	6.71	8.09
		(0.34375)	(0.6375)	(0.63125)	(0.2375)	(0.175)	(0.275)	(2.2)	(2.95625)	(3.00625)

Appendix B

We are interested in the robustness of the final regressions of shocks to energy prices and GDP with respect to the choice of our identified shock matrices. To check robustness, we first estimated the 68% confidence interval with respect to our median matrices and select the two matrices within that interval

with the highest difference compared to our selected median matrix. These matrices should be different from the median matrix by about one standard deviation. Since it is impossible to systematically rank these matrices in sense of an upper and lower limit matrix for each period, we compare the outcomes of the total effect estimated by shocks that are derived by the median matrix (as visualized in Figure 5 and 8 for energy prices and GDP respectively) with the outcomes of the total effect estimated by these robustness matrices. We show the average mean values of the total effect derived by the median matrix in 25-year intervals and compare these with the maximum average distance from those mean total effect values estimated by the robustness matrices for the regression on energy prices and GDP in Table B1 and Table B2 respectively. While the maximal distance is, mostly for aggregate demand shocks, quite large in some periods, the evolution on the effects keeps robust regardless these distances.

Table B1: Robustness check for the outcomes of the total effect of Shocks on Energy Prices

Shocks on Energy Prices	Supply shocks		Aggregate demand shocks		Residual shocks	
Average of years:	*median*	*max distance*	*median*	*max distance*	*median*	*max distance*
1710-1735	3.4067	0.8856	1.7853	1.63	2.9958	1.2593
1735-1760	3.2142	0.8339	2.003	1.2712	2.6865	1.3424
1760-1785	2.9256	0.6705	1.9253	1.008	2.1092	1.0466
1785-1810	2.8004	0.8084	1.8001	1.2132	1.419	0.5697
1810-1835	2.9783	1.1333	2.0015	1.496	1.0732	0.4257
1835-1860	3.3833	1.355	2.1273	1.4413	1.386	0.6286
1860-1885	3.7079	1.1433	1.9485	1.1692	1.793	0.8151
1885-1910	3.7587	0.7312	1.4846	0.9034	1.8663	0.6452
1910-1935	3.2708	0.2227	1.0801	0.7563	1.8021	0.2876
1935-1960	3.2801	0.3581	1.0879	0.9251	1.9064	0.3358
1960-1985	3.7473	0.6238	1.2961	1.124	1.9391	0.5496
1985-2010	4.0529	0.7494	1.4112	1.4508	1.9162	0.9044

Table B2: Robustness check for the outcomes of the total effect of Shocks on GDP

Shocks on GDP	Supply shocks		Aggregate demand shocks		Residual shocks	
Average of years:	*median*	*max distance*	*median*	*max distance*	*median*	*max distance*
1710-1735	-0.256	0.2297	-0.4546	0.3688	0.635	0.2251
1735-1760	-0.3531	0.1839	-0.4789	0.4151	0.5631	0.2151
1760-1785	-0.4657	0.1935	-0.5807	0.6075	0.5324	0.2011
1785-1810	-0.5423	0.3628	-0.6638	0.7599	0.5042	0.117
1810-1835	-0.5237	0.362	-0.6152	0.6028	0.4238	0.1313
1835-1860	-0.3253	0.2157	-0.5032	0.4199	0.367	0.1754
1860-1885	-0.0519	0.1386	-0.3005	0.2905	0.5678	0.161
1885-1910	-0.2284	0.3883	0.0837	0.4246	1.089	0.5234

1910-1935	-0.8208	0.6142	0.3053	0.8219	1.5684	0.8603
1935-1960	-0.9844	0.4416	-0.0787	0.945	1.3248	0.696
1960-1985	-0.7412	0.2359	-0.6145	0.6826	0.7609	0.4448
1985-2010	-0.4264	0.1785	-0.9568	0.391	0.3745	0.3436