Electricity supply shocks and economic growth across the US states: evidence from a time-varying Bayesian panel VAR model, aggregate and disaggregate energy sources

Nicholas Apergis and Michael Polemis

Department of Banking and Financial Management, University of Piraeus, Department of Economics, University of Piraeus, Greece and Hellenic Competition Commission, Commissioner, Athens, Greece

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Nicholas Apergis[a] and Michael Polemis[b,c*]

[a] *Department of Banking and Financial Management, University of Piraeus, 80 Karaoli and Dimitriou Street, 185 34, Piraeus, Greece,* *napergis@unipi.gr*

[b,c] *Department of Economics, University of Piraeus, Greece and Hellenic Competition Commission, Commissioner, Athens, Greece,* *mpolemis@unipi.gr* *(corresponding author)*

Abstract

This paper investigates spillovers between electricity supply shocks and US growth, using monthly data from 48 US States, spanning the period January 2001-September 2016, while employs a novel strategy for electricity supply shocks based on a time-varying Bayesian panel VAR model. It accounts for the decomposition of electricity supply per fuel mixture and links its possible interactions with the US macroeconomic conditions. In that sense, the methodology models the coefficients as a stochastic function of multiple structural characteristics. The findings document that GDP growth increases after a positive electricity supply shock, irrelevant to the source of energy that generates it.

Keywords: Time-varying coefficient Bayesian panel VAR; electricity shocks; macroeconomic performance; impulse responses functions; US states.
JEL classifications: C33; O47; R11

1. Introduction

There is general consensus among researchers and practitioners that the electricity industry, with a net generation of 4,078 terawatt-hours (TWh) in 2015 and retail sales equal to 3,711 billion Kilowatt-hours (KWh), constitutes one of the most important energy sectors in the US (IEA, 2014). The industry is also crucial for the competitiveness and economic growth of the US economy since it has an impact on all other economic activities.

The reliability and quality of electricity supply is, however, vulnerable to shocks (disruptions) generated either from external factors, such as natural disasters (e.g., draughts, earthquakes), or human activity (e.g., nuclear accidents). Specifically, the nuclear power plant accident in Fukushima, initiated primarily by an earthquake in 2011, is a typical example of a natural disaster since immediately after the event, the active reactors automatically shut down their sustained fission reactions, causing extended power supply shortages. This resulted in persistent electricity price hikes, due to the shutdown of a large amount of the nuclear power plants. Moreover, the electricity crisis that hit Ecuador in 2009, stimulated by a severe drought that depleted water levels at hydroelectric plants, is another striking example of supply side electricity distortions, which lead to extensive brown outs and power supply cuts transmitted to the performance of the whole economy. Finally, one cannot fail to notice that California electricity crisis, dated back to 2000, constitutes another example of electricity supply shortage, triggered by market manipulations, shutdowns of pipelines by Enron, and capped retail electricity prices. This event generated a significant macroeconomic impact on the US economy, apart from market structure distortions, such as price spikes, capacity manipulation, and Megawatt laundering (Joskow 2001; Joskow and Kohn, 2002). Despite the fact that such shocks occur rather infrequently, they can cause considerable socio-economic costs and consequences across all the spectrum of economic activity (Pudineh and Jamasb, 2017; Levine et al, 2005). In other words, electricity supply interruptions result in shocks transmissions and spillover (cascading) effects to other sectors of the economy (Pudineh and Jamasb, 2017; Giulietti et al, 2010).

Although there is attention by policy makers and government officials on the impact of oil supply shocks on the main macro economic variables such as the level of economic growth or the level of employment (see for example Barsky and Kilian, 2002; Hamilton, 2003; Ramey and Vine 2011; Kilian, 2009a; Kilian, 2009b; Kilian 2008a, Kilian 2008b) little attention has been paid on the examination of the macroeconomic consequences of electricity supply shocks. This study tries to fill this gap in the literature by decomposing the main drivers of the electricity supply shocks broken down by type of fuel used in the generation process. Specifically, the issue of electricity supply shocks is researched recently especially in developing counties (i.e Chile, South Africa) where extended power cuts, load shedding especially in South Africa lead to serious and systematic power interruptions. This strand of literature is rapidly growing and calls for an in depth examination either from a theoretical or an empirical standpoint.

In a recent study, Pudineh and Jamasb (2017) apply an extensive (Leontief type) input-output model to primarily investigate the impact of electricity supply shocks on the performance of 101 sectors of the Scottish economy, in tandem with the estimation of the Societal Cost of Energy Not Supplied (SCENS), due to an interruption. They claim that inoperability corresponds to a heterogeneous level of economic losses across all the investigated sectors of the economic activity. In addition, the empirical findings postulate that SCENS varies with the duration of a power cut.[1]

Our approach deviates from the existing literature, focusing solely on the examination of electricity supply interruptions within a microeconomic perspective (Reichl et al., 2013; Nooij et al., 2007; Balducci, et al., 2002). Specifically, our study constitutes one of the very few attempts at modeling and estimating the determinants of possible electricity supply shocks on the macroeconomic performance of a large scaled economy, such as the US. More specifically, the empirical methodology adopted in this paper makes use of modelling GDP per capita growth across US states as time variation in VAR models by allowing the coefficients to stochastically vary, while they are also free to vary as a deterministic function of observable economic characteristics, such as total electricity supply or other economic controls, typically by pooling the data across US states and time in a panel VAR setup for that purpose.

The motivation of this paper is to investigate the relationship and the possible spillovers between electricity supply shocks and US macroeconomic performance since there is considerable evidence that this relationship has been unstable over time. Our analysis uses monthly regional data from the US states, spanning the period January 2001 to September 2016 and combines a novel identification strategy for electricity supply shocks based on inequality constraints with the estimation of a time-varying Bayesian panel VAR model (TVBPVAR). This methodology makes use of a Bayesian shrinkage estimator for panel VAR models which contrary to time series VAR modelling, also allows the coefficients to vary as a stochastic function of observable characteristics instead (Wieladek, 2016).

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[1] We have to stress out that the estimation of SCENS due to electricity interruptions is beyond the scope of this paper. However, a detailed presentation of interruption costs studies can be found in Toba (2007).

The contribution of this paper is three-fold. First and foremost, it is the first study that links the electricity supply shocks decomposed by fuel mix (i.e., nuclear, coal, renewable energy sources, natural gas, etc) with the US macroeconomic performance. Given that the electricity system is comprised of generation (different sources), transmission, and distribution (end-user), fuel mix may be substantially important as it addresses electrical power (measured by nameplate capacity and plant utilization), while electrical energy is the produced product and is essentially a commodity (and thus perfectly substitutable). In that sense, this study controls for shocks that may have differential effects because plant utilization (for given nameplate capacity) differs dramatically by source (for example, it is much less for wind and solar than it is for a natural gas electricity generation plant). A finding that source (fuel mix) shocks do not differ suggests that the system is operating (near) optimally in that transmission and distribution are not disrupted by where the shock started. Thus, it is the increased electrical supply that matters for macro growth. In this way, we attempt to shed some light on the mechanism of electricity supply shocks and how these shocks have changed over time. Second, the empirical model allows for time-varying heteroskedasticity in the VAR innovations that accounts for changes in the magnitude of structural shocks and their immediate impact on the US macroeconomic performance. Third, it goes beyond the existing literature in that it uses a particularly long panel of 48 US states on a monthly basis over the period January 2001-September 2016. Finally, in contrast to the existing empirical studies which assume that the variables are not correlated across the panel dimension (cross sectional independence) we perform appropriate techniques in order to deal with this issue. This is a common phenomenon appeared in macro-level data resulting in low power and size distortions of tests that assume cross-section independence (Pesaran, 2004). The latter may arise due to common unobserved effects generated by changes in the US states legislation (i.e., taxation, currency regulatory restrictions, import quotas, etc).

The rest of the paper is organized as follows. Section 2 describes the electricity industry in the USA focusing on the supply and demand conditions across the regions (states) along with the existing regulatory and competitive framework. Section 3 describes the data and performs the necessary preliminary testing (i.e cross-section dependence test, unit toot and cointegration testing). Section 4 presents the empirical methodology, while Section 5 portrays the empirical findings. Section 6 performs the necessary robustness checks to strengthen the validity of the empirical findings. Lastly, Section 7 concludes the paper providing some policy recommendations.

2. The electricity industry in the US

The electricity industry in the US is made up of over 3,000 public, private and co-operative utilities, including more than 1,000 independent power producers (IPPs), three regional synchronised power grids, eight electricity reliability councils, some 150 control-area operators, and thousands of separate engineering, economic, environmental, and land-use regulatory authorities (IEA, 2014). Power supply is generated from a diverse fuel mix. Specifically, fossil fuels (i.e., coal, natural gas, and petroleum liquids) account for 67 percent of U.S. electricity generation and 89 percent of installed capacity (IEA, 2014). Generation capacity also varies by state and can be dependent upon the availability of the fuel resources. Coal and gas power plants are more common in the Midwest and Southeast, whereas the West Coast is dependent upon high-capacity hydroelectric power, as well as gas-fired power plants (IEA, 2014). Power generation fuels have also a supply chain of their own. Coal, natural gas, uranium, and oil must all be extracted, processed into useable fuels, and delivered to the generation facility. Vast infrastructure networks of railroads, pipelines, waterways, highways, and processing plants all support the delivery of these resources to generating facilities, and many rely on electric power to operate.[2] (U.S. Department of Energy, 2015).

Over the last ten years, the proportion of renewables in the energy mix has also been increased. Nevertheless, fossil fuels - primarily oil, natural gas, and coal – are still the predominant sources of energy consumption in the country. It is expected that renewable capacity will continue to increase under pressure from the public concerned with climate change and improvements in renewable technologies and costs (IEA, 2014).

It is worth mentioning that the electricity industry is regulated by both State and Federal regulatory bodies (i.e., FERC, NERC). The Federal Energy Regulatory Commission (FERC) enjoys exclusive jurisdiction over the transmission of electricity in interstate commerce, over the sale of electric energy at wholesale in interstate commerce, and over all facilities for such transmission or sales of electric energy (IEA, 2014). FERC has also jurisdiction over wholesale transactions, where there is no crossing of state boundaries. Specifically, FERC regulates both the wholesale electricity markets and interstate transmission services (i.e., market structure, transmission planning and cost allocation, bulk power system reliability, etc). In contrast, state utility commissions regulate issues, such as retail rates and distribution services, distribution rates across all states, supply rates (integrated states) or default service procurements and retail choice rules (restructured states), resource

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[2] The United States Electricity Industry Primer provides a high-level overview of the U.S. electricity supply chain, including: i) the generation, transmission, and distribution process, ii) markets and ownership structures, including utilities and regulatory agencies, and iii) system reliability and vulnerabilities.

planning/adequacy, generation and transmission siting, demand-side resources and distribution reliability.

On the other hand, the North American Electric Reliability Corporation (NERC) is a regulatory authority whose mission is to assure the reliability and security of the bulk power system in North America (US, Canada, Mexico). Specifically, NERC develops and enforces Reliability Standards; it annually assesses seasonal and long-term reliability; monitors the bulk power system through system awareness. NERC is the electric reliability organization for North America, subject to oversight by the (FERC) and governmental authorities in Canada. NERC's jurisdiction includes users, owners, and operators of the bulk power system, which serves more than 334 million people.

Most U.S. states follow a "*regulated*" model, but many are "*restructured*" (Figure 1). Specifically, in regulated states, utilities are vertically integrated and prepare integrated resource plans to serve their load. Supply and distribution rates are set through economic regulation. In restructured states, generation is deregulated and supply rates are set by markets. Distribution services are still fully regulated and distribution rates are set through economic regulation. It is worth mentioning that restructured utilities do not prepare integrated resource plans, but states retain some authority onto direct generation and demand-side resources. Overall, the (de)regulation of the electricity industry still varies by state.

<Insert Figure 1 about here>

Finally, the electricity industry in the US includes industry players that provide a wide range of services, both privately and publicly owned. Generally, in the Southeast, the Southwest, and the Northwest states, electric utilities are responsible for the operation and the maintenance of the electricity system, providing retail customers with electricity power. The majority of these utilities are vertically integrated, where they own the systems responsible for the generation, transmission, and distribution of electricity. The large majority of utilities are publicly owned, with about ten federal utilities.

3. Data and preliminary empirical testing

3.1. Data description

Our empirical analysis is based on a large panel dataset of 9,072 monthly observations, spanning the period from January 2001 to September 2016 (N = 48 and T = 189). The selected sample includes 48 US states, with Alaska and Hawaii being omitted. The starting date for the study was dictated by energy data availability, while the final date observation (September 2016), represents the last month for which data mostly regarding the US Energy Information Administration (EIA) were available at the time the research was conducted.

The electricity supply variables are seasonally adjusted and include both total electricity generation (per capita), as well as power production by specific energy source (coal, nuclear, natural gas, oil, hydroelectric, biomass, wind and solar). The reason for decomposing electricity generation by fuel is to investigate whether different patterns of electricity supply shocks prevail in the industry and, thus, affecting the overall macroeconomic performance of the US economy. All the above variables are taken from the EIA and especially from the electricity data browser.[3] The level of economic growth is proxied by per capita real GDP across US states, measured in 2009 USD. The latter which is drawn from the Regional Economic Accounts of the Bureau of Economic Analysis (BEA), provides the market value of goods and services

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[3] https://www.eia.gov/electricity/data/browser/

produced by the labor and property located in a US state.[4] In other words, real GDP by state is an inflation-adjusted measure that is based on national prices for the goods and services produced within each state. Total employment (full-time and part-time) is used as a proxy for the labor force. The aforementioned variable, which is also taken from BEA, includes wage and salary jobs, sole proprietorships, but not unpaid family workers nor volunteers per US state, over the sample period. School enrolment is used as a proxy for human capital and includes secondary school enrolment. This variable is drawn from the US Department of Education and especially from the National Center for Education Statistics. Gross fixed capital formation includes land improvements; plant, machinery, and equipment purchases; and the construction of roads, railways, and the like, including schools, offices, hospitals, private residential dwellings, commercial and industrial buildings and finally net acquisitions of valuables. This indicator is measured in constant 2010 USD prices per US state and is extracted from the Datastream database. Moreover, we use the public deficit variable, which is drawn from the US Census Bureau and especially from the Federal, State and Local Governments database of the US Department of Commerce.[5]

For the case of the US states the analysis also uses the following variables: trade openness, defined as the ratio of the sum of exports and imports to GDP (with data obtained from BEA), the total population of the state (mid-year estimate) with data sourced from the US Census Bureau, urbanization, defined as the percent of population living in urban areas with data also coming from the US Census Bureau, the shares of total earnings earned in ‘Farm’ and ‘Other Agriculture’ industries (in thousands, while it includes net farm proprietors' income and the wages and salaries, pay-in-kind, and supplements to wages and salaries of hired farm laborers), in ‘Manufacturing’ industries (in thousands, while it includes establishments engaged in the mechanical or

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[4] https://www.bea.gov/regional/index.htm

[5] https://www.census.gov/govs/

chemical transformation of materials or substances into new products; these establishments are usually described as plants, factories, or mills and characteristically use power driven machines and materials handling equipment; establishments engaged in assembling component parts of manufactured products are also considered manufacturing if the new product is neither a structure nor other fixed improvement; also included is the blending of materials, such as lubricating oils, plastics resins, or liquors.), and in ‘Services’ industries (in thousands, while it includes establishments primarily engaged in providing a wide variety of services for individuals, business and government establishments, and other organizations; hotels and other lodging places; establishments providing personal, business, repair, and amusement services; health, legal, engineering, and other professional services; educational institutions; membership organizations, and other miscellaneous services, are also included), with all data being obtained from BEA.

Table 1 reports a set of descriptive statistics for all the variables used in the empirical analysis. From the relevant table, it is evident that the data are well behaved, showing limited variability in relation to the mean of the population since the coefficient of variation do not exceed 50% in all of the cases. In contrast, the variables as expected do not follow the normal distribution, since the relative values of the skewness and kurtosis measures are not zero and three respectively.

<Insert Table 1 about here>

3.2. Preliminary testing for cross-section dependence and unit roots

In the first step of empirical analysis, we examine the unit root properties in the data through advanced panel unit root tests. Panel unit root tests of the first-generation can lead to spurious results (because of size distortions), if significant degrees of positive residual cross-section dependence exist and are ignored. Consequently, the implementation of second-generation panel unit root tests is desirable only when it has been established that the panel is subject to a significant degree of residual cross-section dependence. In the cases where cross-section dependence is not sufficiently high, a loss of power might result if second-generation panel unit root tests that allow for cross-section dependence are employed. Therefore, before selecting the appropriate panel unit root test, it is crucial to provide some evidence on the degree of residual cross-section dependence.

The cross-sectional dependence (CD) statistic by Pesaran (2004) is based on a simple average of all pair-wise correlation coefficients of the OLS residuals obtained from standard augmented Dickey-Fuller regressions for each variable in the panel. Under the null hypothesis of cross-sectional independence, the CD test statistic follows asymptotically a standard normal distribution. The test is based on the estimation of the linear panel model of the form:

$$y_{it} = \alpha_i + \beta_i' x_{it} + u_{it}, \quad i = 1,..N; T = 1,..T \tag{1}$$

where T and N are the time and panel dimensions respectively, α_i the provincial-specific intercept, and x_{it} a kx1 vector of regressors, and u_{it} the random disturbance term. The null hypothesis assumes the existence of cross-section correlation: $\mathrm{Cov}(u_{it}, u_{jt}) = 0$ for all t and for all $i \neq j$. This is tested against the alternative hypothesis that $\mathrm{Cov}(u_{it}, u_{jt}) \neq 0$ for at least one pair of i and j.

The results reported in Table 2 uniformly reject the null hypothesis of cross-section independence, providing evidence of cross-sectional dependence in the data given the statistical significance of the CD statistics regardless of the number of lags (from 1 to 4) included in the ADF regressions.

<Insert Table 2 about here>

A second-generation panel unit root test is employed to determine the degree (order) of integration in the respective variables. The Pesaran (2007) panel unit root test (known also as "*CIPS*" test) does not require the estimation of factor loading to eliminate cross-sectional dependence. Specifically, the usual Dickey-Fuller regression is augmented to include the lagged cross-sectional mean and its first difference to capture the cross-sectional dependence that arises through a single-factor model. The null hypothesis is a unit root for the Pesaran (2007) test. The *CIPS* test is based on the cross-section Augmented Dickey-Fuller (ADF) test as follows:

$$\Delta y_{it} = \alpha_i + \rho_i y_{i,t-1} + \beta_i \overline{y}_{t-1} + c_i \Delta \overline{y}_t + u_{it} \tag{2}$$

where $\overline{y}_{t-1} = n^{-1}\sum_{i=1}^{n} y_{i,t-1}$ and $\Delta y_t = n^{-1}\sum_{i=1}^{n} \Delta \overline{y}_t$ are used as a proxy for the effect of the unobserved common factor. The *CIPS* test statistic is simply the average t-statistic of the OLS estimate for ρ_i for the individual sections. The null hypothesis that $\rho_i = 0$ for all i is tested against the alternative that only fractions of the series are stationary. The results are reported in Table 3 and support the presence of a unit root across all variables under consideration. In other words, our sample variables are integrated of order one I(1).

<Insert Table 3 about here>

4. Empirical methodology

The literature has recorded a number of studies in estimating VAR models with time-varying coefficients. Such studies explore the transmission mechanism of monetary (see for example Cogely and Sargent, 2005) and fiscal policy (Perreira and Lopes, 2010) to shocks on output and inflation while other studies make use of these methods (i.e Bayesian time varying VECM and seasonal ARIMA models) to forecast electricity demand (Grasso, 2010). Moreover, Hurn et al. (2016) employ a smooth transition logit model to detect the presence of potential structural changes in the electricity industry stemmed from deregulation. The model allows the timing of any change to be endogenously determined and also market participants' behaviour to change gradually over time. The main empirical findings indicate the presence of a structural change, consistent with the process of deregulation in Australia. Most papers in this literature assume that coefficients evolve stochastically according to a slowly moving random walk, implying that changes in the coefficients can reflect permanent structural changes. However, this is not possible to infer why such structural changes occur.

A different strand of the literature has related changes in the transmission of shocks to certain observable economic characteristics (Mertens, 2008; Olivei and Teynero, 2007 and 2008). In addition, Assenmacher-Wesche and Gerlach (2010) and Calza et al. (2013) estimate panel VARs on a set of countries with more and less developed financial markets to infer the impact of mortgage market development on the monetary policy transmission mechanism. If the economic characteristic in question can be observed both over time and in the cross-section, it might, of course, be more desirable to estimate a model that exploits all of the variation across both of these dimensions. However, no study has applied this methodological approach to explore the link between economic growth and electricity supply across the US states. Let's assume the following time-varying coefficient panel VAR model:

$$\boldsymbol{Y}_{\boldsymbol{c}\mathrm{t},} = \boldsymbol{X}_{\boldsymbol{c}\mathrm{t},}\, \boldsymbol{B}_{\boldsymbol{c},} + \boldsymbol{E}_{\boldsymbol{c}\mathrm{t},} \text{ with } \boldsymbol{E}_{\boldsymbol{c}\mathrm{t},} \sim (\mathbf{0},'_{\boldsymbol{c},\boldsymbol{\tau}}\boldsymbol{\Sigma}_{\boldsymbol{c}}\boldsymbol{A}_{\boldsymbol{c},\boldsymbol{\tau}}) \qquad (3)$$

where Y_{ct} is and $1xN$ matrix of N endogenous variables for state c at time t, containing the lags of Y_{c}, and a constant term. Based on the work by Wieladek (2016) (the mathematical details of the model can be found there), it is assumed that these coefficients vary as a function of observables:

$$\boldsymbol{\beta}_{\boldsymbol{c},} \mid \boldsymbol{y}_{\boldsymbol{c}\mathrm{t},}, \boldsymbol{X}_{\boldsymbol{ct}}, \boldsymbol{\alpha}_{\boldsymbol{c\tau}}, \boldsymbol{\Sigma}_{\boldsymbol{c}} \sim \boldsymbol{N}(\boldsymbol{D}_{\boldsymbol{c\tau}}\boldsymbol{\delta}_{\boldsymbol{B}}, \boldsymbol{\Lambda}_{\boldsymbol{B}\mathrm{C}}) \tag{4}$$

$$\boldsymbol{\alpha}_{\boldsymbol{c},} \mid \boldsymbol{y}_{\boldsymbol{c}\mathrm{t},}, \boldsymbol{X}_{\boldsymbol{ct}}, \boldsymbol{\beta}_{\boldsymbol{c\tau}}, \boldsymbol{\Sigma}_{\boldsymbol{c}} \sim \boldsymbol{N}(\boldsymbol{D}_{\boldsymbol{c\tau}}\boldsymbol{\delta}_{\boldsymbol{A}}, \boldsymbol{\Lambda}_{\boldsymbol{A}\mathrm{C}}) \tag{5}$$

where $\boldsymbol{\delta}_{\boldsymbol{B}}$, $_{\boldsymbol{\delta}}\boldsymbol{A}$ is a matrix of pooled coefficients across states, which relate the weakly exogenous variables $\boldsymbol{D}_{\boldsymbol{ct}}$ to the individual state coefficients $\boldsymbol{\beta}_{\boldsymbol{c\tau}}$, $\boldsymbol{A}_{\boldsymbol{c\tau}}$, with the variances $\boldsymbol{\Lambda}_{\boldsymbol{B}\mathrm{C}}$, $\boldsymbol{\Lambda}_{\boldsymbol{A}\mathrm{C}}$ determining the tightness of these priors (Liu et al, 2017; Hong and Lian, 2012). For the purposes of our empirical analysis, we estimate this model by repeatedly drawing from the posteriors of the Gibbs sampling chain 150,000 times, discarding the first 50,000 draws as burn-in and retaining every 100th of the remaining draws for inference.

5. Baseline results and discussion

The next step of the baseline empirical analysis involves bivariate time-varying panel VAR modeling in which the GDP per capita and the total supply of electricity are the two endogenous variables involved. Panel VARs are built with the same logic of standard VARs and they can be regarded as a much more powerful tool to address interesting policy implications (Canova and Ciccarelli, 2013, Polemis, 2016). In a panel-VAR framework all variables are treated as endogenous and interdependent, both in a dynamic and in a static sense. Furthermore, one of its major advantages is that it examines the underlying dynamic relationships compared to static results generated by fixed effects models (Mamatzakis et al, 2013). The Bayesian panel-VAR framework allows the examination of the impact of electricity supply shock innovations (total electricity generation or decomposed by certain fuel mix) on the US macroeconomic performance (proxied by the GDP/capita growth indicator) in more detail and is included in this study in order to perform a sensitivity analysis. However, Kilian and Murphy (2010) argue that it is important to identify the potential simultaneous impact of electricity supply and electricity demand shocks on economic growth through the imposition of certain quantity restrictions. To this end, we impose that the relevant individual-state output is positive if faced with an electricity-supply shock and negative if an electricity-demand shock prevails.

In particular, the baseline analysis uses a bivariate identification scheme with GDP per capita growth ordered first. Within this methodological framework it is possible to examine how the coefficients of GDP per capita growth (and the implied impulse responses), are affected by total electricity in the following manner: first, evaluate the structural characteristic of interest, i.e. total electricity supply, at a high value (defined as the 90th percentile of values realized in the sample) to obtain draws of $\boldsymbol{\beta}_{\boldsymbol{c},\boldsymbol{\tau}}^{\text{total electricity supply-1}}$ and $\boldsymbol{\alpha}_{\boldsymbol{c},\boldsymbol{\tau}}^{\text{total electricity supply-1}}$ and the associated distribution of impulse responses. Next, we repeat the previous step, but this time with a low value of total electricity supply (defined as the 10th percentile) to obtain draws of $\boldsymbol{\beta}_{\boldsymbol{c},}^{\text{total electricity supply-2}}$ and $\boldsymbol{\alpha}_{\boldsymbol{c},\boldsymbol{\tau}}^{\text{total electricity supply-2}}$. A comparison of these two distributions, subject to the same size shock, allows us to infer the effect of total electricity supply on GDP per capita shocks.

Figure 2 shows Impulse Responses Functions (IRFs) for GDP per capita growth to shocks in total electricity supply (bivariate model), at the 10th percentile of total electricity supply and at the 90th percentile. These results illustrate that GDP per capita growth increases following a positive electricity supply shock (across all three distributions), which is a result consistent with a number of time series and panel data studies in the literature (see among others Narayan et al., 2010; Lorde et al., 2010; Bildirici et al., 2012; Solarin and Shahbaz, 2013; Jakovac and Vlahinic Lenz, 2016).

[Insert Figure 2 about here]

Figure 2 also illustrates IRFs for GDP per capita growth to shocks in electricity generated by different fuel mix (i.e coal, nuclear, natural gas, oil, hydro, biomass, solar, wind). The new empirical findings clearly support that decomposed electricity shocks exert a robust positive impact on GDP per capita growth, indicating that all sources of energy seem to be conducive to GDP per capita growth in the case of the US states. However, a closer inspection of Figure 2 reveals several differences between the IRFs for each electricity fuel source.

Specifically, in the case of electricity generated from coal (see first row, second column of the diagram), it is emphasised that the innovations generated by a one standard deviation shock are positive but statistically insignificant within the first ten years (125 months approximately) showing an increasing rate of return. Subsequently, the confidence bands become narrow, making the response of GDP per capita growth to electricity from coal shocks after this time period significant. This outcome reveals the low penetration of coal in the electricity generation in the US compared to other alternative fuels such as nuclear and natural gas, where the confidence bands are much narrower from the beginning of the simulated time period.

It is also interesting to note that the speed of adjustment toward the long-run equilibrium portrays a slightly different pattern among the different categories of electricity supply shocks. To be more specific, in the case of electricity from oil, the innovations generated by a one standard deviation shock are strongly positive for the first five years after the initial shock (approximately 55 months) turning into negative (but still statistically significant) thereafter. Similarly, the response of GDP/capita growth to an electricity shock in the Renewable Energy Sources (RES) such as biomass, solar and wind turns to be negative after the first five (simulated) years of study. However, we must bear in mind that the negative effect is more elastic in the case of electricity generated by biomass compared to electricity from solar revealing that GDP/capita growth stabilises at a faster pace than the latter response after the initial (positive) shock.

Contrary to the above findings, we argue that the response of GDP growth to a one standard deviation shock stemmed from the electricity generation from hydro is positive for the first 2.5 years (nearly 30 months) and negative across the rest of the period (ten years) confirming that the positive effect of GDP/growth to an electricity supply shock is evident only in the short-run (short-lived).

Based on the above findings we argue that knowledge of the actual causality direction between electricity shocks and economic growth has important implications for modeling *inter alia* suitable environmental policies. Specifically, if the causality runs from electricity supply shocks to economic growth, then environmental policies for combating emissions focusing on promoting green energy technologies may not enhance energy switching. On the other hand, if the causality is reversed, then environmental policies aimed at restricting industrial output and thus emissions may negatively affect the level of efficiency in the industry.

6. Robustness check

In order to check for the robustness of our findings, we re-estimate our basic model which is accordingly adjusted for the presence of additional control variables (covariates) that the theoretical literature has exemplified as important determinants of economic growth, while retaining the restrictions posed in the bivariate analysis.

In particular, based on both neoclassical and endogenous growth theories, the analysis considers gross capital formation (Romer, 1986; Young, 1991), the labor force (Lucas, 1988; Azariadis and Drazen, 1990; Young, 1995; Klenow and Rodriguez-Clare, 1997), school enrollment as a proxy for human capital (Lucas, 1988; Rebelo, 1991), budget deficits/surpluses as percentage of GDP (Barro, 1990; Kneller et al., 1999; Zagler and Durnecker, 2003; Gomez, 2007), trade openness (Frankel and Romer, 1999; Irwin and Terviö, 2002; Karras, 2008), state population (Dawson and Tiffin, 1998; Thornton, 2001; Bucci and La Torre, 2007), urbanization (Reed, 2009; Turok and McGranaham, 2013), industrial diversity (Reed, 2009; Pede, 2013), the share of total revenues from agricultural activities (Weber et al., 2015), the share of total revenues from manufacturing activities (Ulku, 2004; Szirmai, 2012), the share of total revenues from services (Reed, 2009; Tarr, 2012), the percentage of years that both the Governor and the Legislation were Democrats, and the percentage of years that both the Governor and the Legislation were Republicans (Alesina and Roubini, 1997; Faust and Irons, 1999; Santa-Clara and Valkanov, 2003; Reed, 2009) across the US states as the additional controls for economic growth. In terms of the methodology used in this paper, these additional drivers are considered in their median of their distribution, while retaining the same assumptions for the electricity supply variables.

We now turn our attention to the examination of IRFs drawn from the multivariate model (Figure 3). More specifically, the relevant diagram presents the new IRFs of GDP per capita growth to both aggregate and decomposed electricity supply shocks. This figure shows the typical speed of response to fluctuations to electricity generation and underscores the point that the responses of GDP growth may differ substantially, depending on the time period of the electricity supply shocks.

[Insert Figure 3 about here]

The upper panel of Figure 3 shows the IRFs of the GDP growth to the transmission of electricity supply shocks (total, coal and nuclear). Specifically, it is evident that the effect of one standard deviation shock of the total electricity generation on the US macroeconomic performance when all the covariates enter the model is positive and significant only in the short-run (three years after the initial shock). Subsequently, the graph reveals that an increase in the electricity generation all else equal would cause a non-transitory downward trend within the next month which stabilizes thereafter. Lastly, the cumulative peak response of GDP growth to total electricity innovations occurs three years after the initial shock and is estimated to be approximately 5% which is higher than the relevant response of the bivariate model (approximately 3,5%). Moreover, as it can be easily observed, the results display a similar behavior across all forms of electricity supply (as well as across all three distributions), confirming the important role of electricity (irrelevant to the source of energy that generates it) for economic growth across the US states.

Finally, if we try to compare the IRFs between the two models (bivariate and multivariate), some interesting results emerge. First, in the multivariate model the response of GDP growth per capita to electricity supply shocks is more abrupt than the bivariate responses since the relevant peak response within the short run time span is greater in the former model than the latter. However, both models exhibit a decreasing trend nearly three years on average after the shock stabilising thereafter. This finding reveals the absence of a sluggish adjustment mechanism, which may reflect weak competition and significant market power (SMP) by the incumbents in the electricity industry. Moreover, an electricity shock in both models is short-lived. Specifically, the rate of response of GDP growth per capita to electricity supply shocks, gives an indication that a market power effect prevails in the electricity industry.

7. Conclusion and policy implications

The goal of this paper was to investigate the relationship and the possible spillovers between electricity supply shocks and macroeconomic performance in the US. The analysis used monthly seasonally adjusted regional data across 48 US states and combined a novel identification strategy for electricity supply shocks based on inequality constraints with the estimation of a time-varying Bayesian VAR model. The main novelty of this paper was that it used for the first time in the empirical literature a TVBPVAR model accounting for the decomposition of electricity supply per fuel mixture and linking its possible interactions with US macroeconomic conditions.

The empirical findings clearly illustrated that the US macroeconomic performance improved following a positive electricity supply shock (regardless of the energy source it originated). These findings survived a robustness check based on a multivariate model that identified a number of economic drivers for growth. These results could be important for policy makers, academic researchers and government officials. More specifically, they call for the need to strengthen the effectiveness of energy generating agencies by ensuring systematic replacements of worn-out equipment and necessary tools in order to drastically reduce power losses. Any electricity outages are expected to have spillovers from distorted macroeconomic performance that affect both domestic and global welfare.

US energy policy makers should design and implement efficient electricity conservation policies without adversely affecting economic growth. Such policies aim at reducing the wastage of electricity, such as demand-side management and efficiency improvement measures. Therefore, to ensure the security of supply to meet the demand of electricity, it is important for them to emphasize primarily alternative sources of electricity, such as renewable energy sources that were also shown to exert a positive impact on economic growth. The overall findings validate that electricity supply stimulates economic growth across US states. Intuitively, improvements in electricity supply are a necessity for the enhancement of the economy. Hence, policy makers should put in place any necessary policies that could restructure the electricity supply industry.

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Table 1: Summary statistics for the sample variables.

Variable	**Mean**	**Standard Deviation**	**Min**	**Max**
Per capita GDP	43,648.3	13,279.9	29,957	70,918
Total electricity supply	6,384.4	5,759.3	25	44,280
Electricity from coal	2,943	2,963	-6	15,815
Electricity from nuclear	1,315.5	1,715.9	-26	8,871
Electricity from natural gas	1,428.2	2,647.5	0	22,893
Electricity from oil	97.1	329.9	-18	5,296
Electricity from wind	139	380	0	5,670
Electricity from solar	9.58	80.6	0	2,190
Hydroelectric electricity	429.3	1,078.4	-248	11,209
Biomass electricity	43.7	70.4	-1	640
Labour force	5,955,590	425,580.1	330,154	46,257,210
Gross capital formation	718.7	82.0	586.2	862.4
Public deficit	12.2(%)	0.0045	11.4(%)	13.1(%)
School enrolment	958,965	94,142.1	68,681	6,742,400
Trade openness	26.5	4.39	22.4	33.9
State population	6,201,127	179,466.7	564,513	39,250,017
Urbanization (%)	84.5	5.9	77.6	88.9

Share of total earnings from Agriculture	609,747	242,848	529,365	8,500,946
Share of total earnings from Manufacturing	9,106,320	344,216	33,593	13,099,461
Share of total earnings from Services	1,145,682	339,895	70,591	27,890,673

Table reports summary statistics for the 48 US states in the sample over the period Jan 2001 to Sep 2016. All variables are used in the econometric analysis as natural logarithms (when appropriate).

Table 2 Cross dependence tests

	Lags			
Variables	1	2	3	4
Per capita GDP	[0.00]***	[0.00]***	[0.00]***	[0.00]***
Electricity supply	[0.00]***	[0.00]***	[0.01]***	[0.01]***
Labor force	[0.00]***	[0.00]***	[0.00]***	[0.01]***
Gross capital formation	[0.00]***	[0.00]***	[0.00]***	[0.00]***
School enrolment	[0.00]***	[0.00]***	[0.01]***	[0.02]**
Public deficit	[0.00]***	[0.00]***	[0.00]***	[0.00]***
Electricity from coal	[0.00]***	[0.00]***	[0.01]***	[0.02]**
Electricity from nuclear	[0.00]***	[0.00]***	[0.01]***	[0.02]**
Electricity from natural gas	[0.00]***	[0.00]***	[0.00]***	[0.01]***
Electricity from oil	[0.00]***	[0.00]***	[0.00]***	[0.00]***
Electricity from wind	[0.00]***	[0.01]***	[0.02]**	[0.04]**
Electricity from solar	[0.00]***	[0.00]***	[0.01]***	[0.01]***
Hydroelectric electricity	[0.00]***	[0.01]***	[0.02]**	[0.02]**
Biomass electricity	[0.00]***	[0.02]**	[0.04]**	[0.04]**
Trade openness	[0.00]***	[0.00]***	[0.00$^{]***}$	[0.01]***
State population	[0.00]***	[0.00]***	[0.00]***	[0.00]***
Urbanization	[0.00]***	[0.00]***	[0.00]***	[0.01]***
Share of total earnings from Agriculture	[0.00]***	[0.00]***	[0.01]***	[0.02]**
Share of total earnings from Manufacturing	[0.00]***	[0.00]***	[0.00]***	[0.00]***
Share of total earnings from Services	[0.00]***	[0.00]***	[0.01]***	[0.03]**

Under the null hypothesis of cross-sectional independence the CD statistic is distributed as a two-tailed standard normal. Results are based on the test of Pesaran (2004). Figures in parentheses denote p-values. ***:$p \leq 0.01$, **:$p \leq 0.05$.

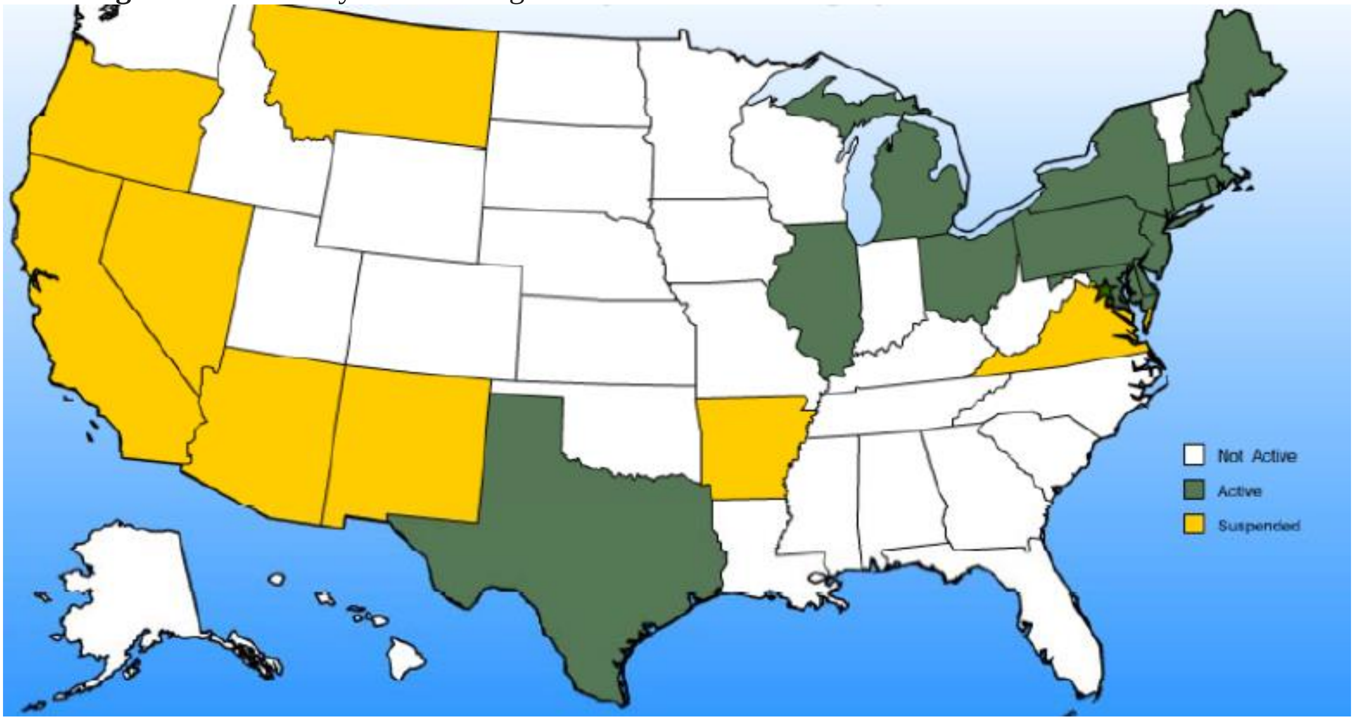
Table 3 : Panel unit root test.

Variable	**Pesaran (CIPS)**	**Pesaran (CIPS*)**
Per capita GDP	-1.28	-1.33
Δper capita GDP	-6.31***	-6.57***
Electricity supply	-1.38	-1.42
Δelectricity supply	-6.14***	-6.30***
Electricity from coal	-1.25	-1.34
Δelectricity from coal	-5.79***	-5.96***
Electricity from nuclear	-1.36	-1.40
Δelectricity from nuclear	-5.80***	-5.96***
Electricity from natural gas	-1.27	-1.33
Δelectricity from natural gas	-6.13***	-6.25***
Electricity from oil	-1.32	-1.38
Δelectricity from oil	-6.42***	-6.69***
Electricity from wind	-1.39	-1.44
Δelectricity from wind	-5.89***	-6.06***
Electricity from solar	-1.27	-1.35
Δelectricity from solar	-6.10***	-6.28***
Hydroelectric electricity	-1.36	-1.41
Δhydroelectric electricity	-5.84***	-6.01***
Biomass electricity	-1.36	-1.40
Δbiomass electricity	-5.92***	-6.10***
Labor force	-1.22	-1.29
Δlabor force	-6.27***	-6.39***
Gross capital formation	-1.25	-1.31
Δgross capital formation	-6.12***	-6.24***
Public deficit	-1.28	-1.36
Δpublic deficit	-6.19***	-6.30***
School enrollment	-1.33	-1.39

Δschool enrollment	-5.87***	-6.03***
Trade openness	-1.28	-1.35
ΔTrade openness	-5.68***	-5.93***
State population	-1.32	-1.39
ΔState population	-5.77***	-5.96***
Urbanization	-1.26	-1.34
ΔUrbanization	-5.94***	-6.25***
Share of total earnings from Agriculture	-1.31	-1.38
ΔShare of total earnings from Agriculture	-5.62***	-5.85***
Share of total earnings from Manufacturing	-1.26	-1.33
ΔShare of total earnings from Manufacturing	-5.83***	-6.17***
Share of total earnings from Services	-1.30	-1.38
ΔShare of total earnings from Services	-5.69***	-5.94***

Δ denotes first differences. A constant is included in the Pesaran (2007) tests. Rejection of the null hypothesis indicates stationarity in at least one country. CIPS* = truncated CIPS test. Critical values for the Pesaran (2007) test are -2.40 at 1%, -2.22 at 5%, and -2.14 at 10%, respectively. The results are reported at lag = 4. The null hypothesis is that of a unit root. ***: $p \leq 0.01$.

Figure 1: Electricity restructuring across US States



Source: FERC

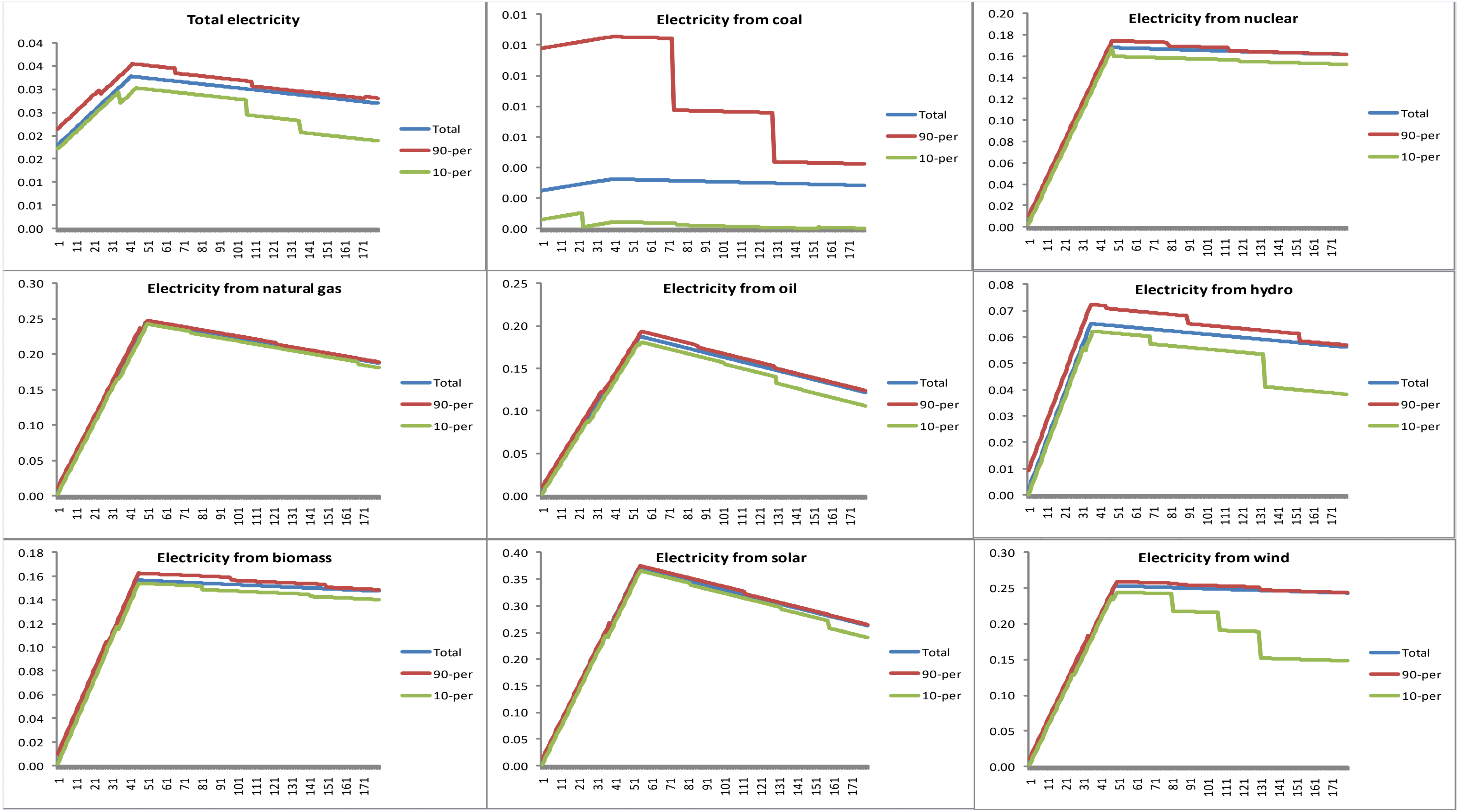


Figure 2: IRFs for the bivariate time-varying Bayesian panel VAR model

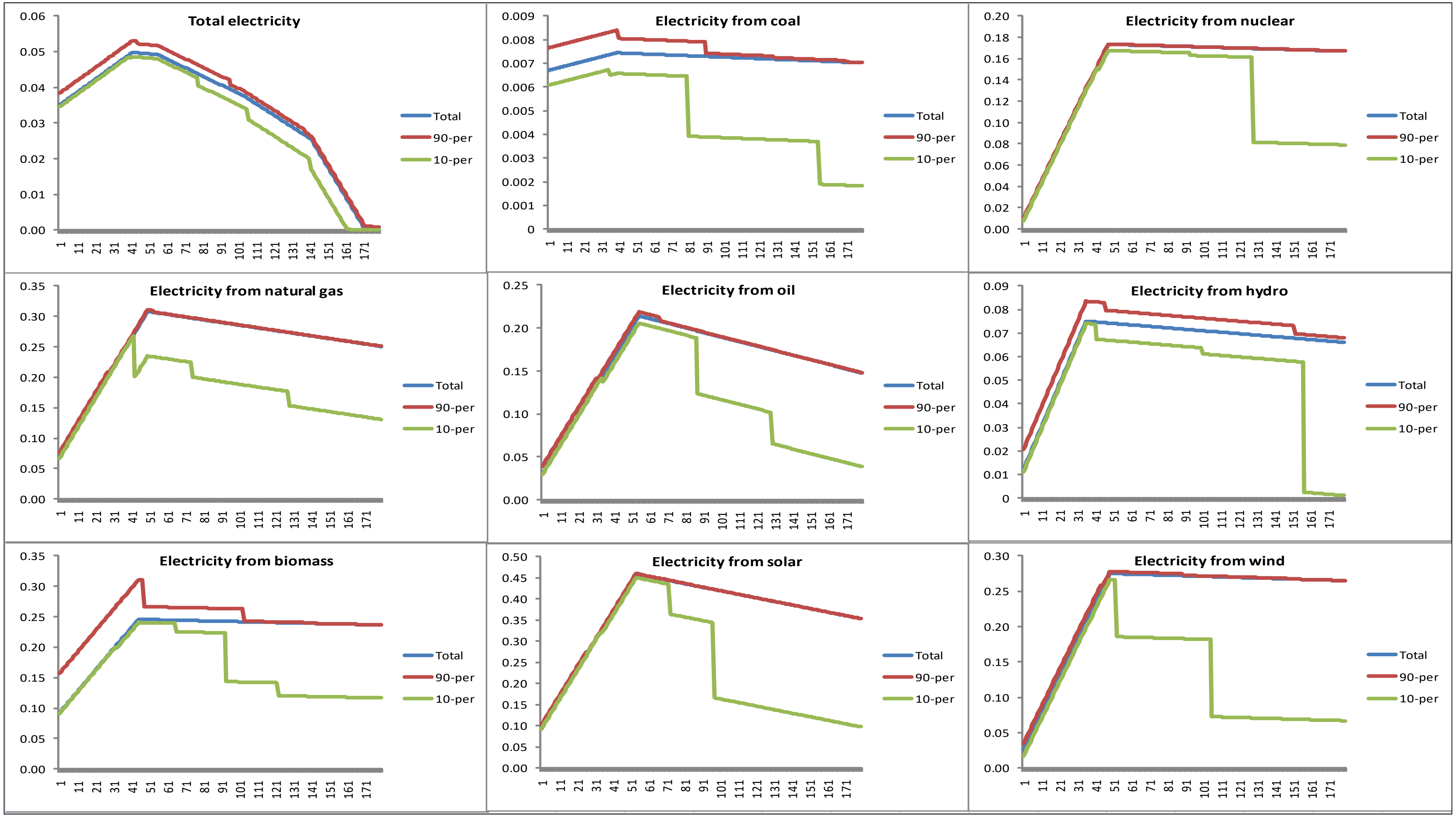


Figure 3: IRFs for the multivariate-time varying Bayesian panel VAR model