How Do Oil Shocks Impact Energy Consumption? A Disaggregated Analysis for the U.S.

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ABSTRACT

This paper investigates the interaction between energy consumption and oil shocks in the U.S. from 1974 to 2018 using monthly data. Its contributions rely on the double disaggregation of energy consumption and oil shocks in a time-varying context. Oil shocks are disaggregated into oil supply, oil demand and aggregated demand shocks following the method of Kilian (2009). Energy consumption is disaggregated according to the production source in distinguishing between renewable and non-renewable energy consumption (hydropower, geothermal, wood, waste, coal, natural gas and petroleum). The impulse response function results show that renewable energy consumption responds the most to aggregate demand and oil supply shocks while for non-renewable energy consumption, it is oil demand shocks. The dynamic connectedness results show that oil supply and demand shocks spillover the most to hydropower consumption while aggregate demand shocks spillover the less. However, these relationships change over time and recommend the flexibility of energy policies.

Keywords: Disaggregated oil shocks, Disaggregated energy consumption, SVAR, Dynamic connectedness, U.S.

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1. INTRODUCTION

Due to the alarming economic and social issues related to energy security and environmental degradation, concerns have been advocated across the globe for energy sustainability and climate change mitigation. Debates in terms of conventional energy consumption reduction and shift to alternative energy sources have been at the forefront among the policy planners and research scholars. The option of renewable energy has been discussed at length in both developing and developed countries. Scholars like Moomaw et al. (2011) and Dogan and Sekar (2016) have advocated the adoption of renewable energy sources as a substitute to decarbonize the energy system and ensure the environmental protection.

In the U.S., the recent development of the renewable energy sector has put the country at the 3rd place in the list of the most attractive countries in terms of renewable *Energies* worldwide (Ernest & Young report in 2017). In the meanwhile, the U.S. is also the biggest oil producer in the world (U.S. Energy Information Administration 2017 report). In this context, an important issue is

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how oil shocks impact the consumption of renewable energy in the U.S. In the present study, we aim to answer this question. On the other hand, to have a global view of the energy market in the U.S., we also include non-renewable[1] energy consumption for comparison. To consider the specificity of each energy source, we disaggregate them into different sources with hydropower, geothermal, wood and waste for renewable energy consumption; and coal, natural gas and petroleum for non-renewable energy consumption. We also disaggregate oil shocks into different components which are from oil supply, oil demand and the aggregate demand of the economy. For that, we follow the SVAR approach established by Kilian (2009) and Kilian and Park (2009). This distinction of oil shocks is important because each of them can impact the economic system differently (Kilian 2009, Fattouh et al. 2013) and it has been investigated in several previous studies focusing on oil shocks, such as Mutuc et al. (2011), Antonakakis et al. (2017), and Basher et al. (2018).

On the other hand, the disaggregation of energy consumption in function of the production source is also very important because numerous studies already showed that each energy source behaves differently to economic and political events. Therefore, each energy source potentially responds differently to oil shocks. For example, Wise et al. (2014) found that a widespread of biomass in the U.S. would lead to its imports and limiting biomass imports would modify the balance of trade in agricultural products. On the other hand, Hirth (2015) found that the optimal long-term wind share should be 20% of the energy mix in Northwestern Europe. Regarding the importance to distinguish between different oil shocks and different energy sources, this double disaggregation is an important contribution of our study. To the best of our knowledge, the interaction between oil shocks and energy consumption has not been investigated at a disaggregated level for the U.S. in the previous literature.

As for the methodological framework, we rely on a complementary analysis based on impulse response functions and the dynamic connectedness measure proposed by Diebold and Yilmaz (2014) to examine the impact of different oil shocks on different components of renewable and non-renewable energy consumption. These two methods are complementary because the first one allows analyzing the response of energy consumption to an unanticipated variation of oil shocks while the second focuses on how oil shocks' variation is transmitted to energy consumption. An additional methodological contribution lies in the computation of time-varying impulse response functions and dynamic connectedness measures. This allows us to investigate the impact of time in the relationship between oil shocks and energy consumption.

Besides the contribution to the academic literature, our study provides important information to policy makers regarding the energy mix strategy in the U.S. In the context of the Energy Modeling Forum EMF 24[2] related to "U.S. Technology Transitions under Alternative Climate Policies", the results of this study are helpful to policy makers while considering the impact of oil shocks on renewable non-renewable energy consumption at a disaggregated level. Our findings show that wood and waste energy consumption respond the most to oil shocks while petroleum energy consumption responds to oil supply and demand shocks only. All energy consumption responds the most to oil specific demand shocks. Furthermore, oil shocks spillover the most hydropower consumption while aggregate demand shocks spillover the less to energy consumption. On the other hand, hydropower, waste, coal and petroleum consumption have the highest dynamic connectedness

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[1] We would like to thank an anonymous referee for suggesting the inclusion of non-renewable energy consumption.

[2] The EMF, established at the Stanford University in 1976, seeks to improve the use of energy and environmental policy models for making important corporate and government decisions. EMF 24 focused on the interaction between climate policies' architectures and advanced energy technology availabilities in the U.S. (Fawcett et al. 2014). See Sands et al. (2014) or Clarke et al. (2014) for more information.

with oil shocks. Finally, in a sensitivity analysis based on a time-rolling window approach, we show that the above results are time-varying. It is thus necessary to consider the changing economic and energy context to adapt the proposed policies in each period.

The rest of the paper is organized as follows. Section 2 presents a review of the academic literature regarding the oil-related determinants of renewable and non-renewable energy consumption. Section 3 presents the methodology framework and the data used. Section 4 analyzes the empirical findings for the whole period while Section 5 focuses on a time-varying analysis. Section 6 concludes with an extended analysis of policy implications and some perspectives for future research.

2. LITERATURE REVIEW: HOW DOES OIL INFLUENCE ENERGY CONSUMPTION?

Many studies have been conducted to examine the factors influencing energy consumption (e.g., Kiraly and Lovei 1985, Bhatia 1988, Moroney 1989, Leth-Petersen 2007, Onuonga et al. 2008, Sovacool 2009, Apergis and Payne 2010, Joyeux and Ripple 2011, Aroonruengswat et al. 2012, Salim and Rafiq 2012, Liddle 2013, Zhang et al. 2016, Acheampong 2018, Borozan 2018, Lawley and Thivierge 2018, Mahalingam and Orman 2018, Topca and Payne 2018, and Zhang and Bai 2018). Since we focus on how oil shocks influence energy consumption, the literature review will concentrate on previous studies including oil as a determinant factor of renewable and non-renewable energy consumption.

Regarding oil-related determinants of renewable energy consumption, Henriques and Sadorsky (2008) reported the existence of a unidirectional Granger causality from oil prices to the stock prices of alternative energy companies. Similarly, Sadorsky (2009) reported that oil price hikes affect renewable energy consumption only marginally but inversely in G7 countries. Popp et al. (2011) reported that fossil fuel production has no impact on renewable energy in 26 OECD countries. Managi and Okimoto (2013) found a direct association between oil and clean energy prices after they identified structural breaks, and an identical market response is observed for both clean energy and technology stock prices. In a panel of 64 countries, Omri and Nguyen (2014) documented that oil price hikes affect the renewable energy consumption aversely in middle-income countries and the whole panel. Omri et al. (2015) found a weak influence of oil prices on renewable energy consumption. Khan et al. (2017) found no impact of oil price declines on the renewable energy sector, while the latter is found to be increasingly cost competitive with the traditional fossil fuel energy. Using the ARDL methodology, Brini et al. (2017) reported a direct impact of oil price hikes on the renewable energy consumption in Tunisia. Lin et al. (2017) found a positive impact of oil price hikes and financial development on the size and share of non-hydro renewable electricity generation in a panel of 46 countries. Shah et al. (2018) investigated the impact of oil prices and macroeconomic factors on the renewable energy market in Norway, the UK and the U.S. from 1960 to 2015. Their results showed that there is a strong relationship between oil and renewable energy in Norway and the U.S. while there is no relationship between them in the UK. The main reason is related to the oil import-export profile of the country. Finally, Troster et al. (2018) studied the causal relationship among renewable energy, oil prices and economic activity in the U.S. from 1989 to 2016 using a quantile approach. Their results showed that there is a lower-tail dependence from changes in oil prices to changes in renewable energy consumption.

Regarding oil-related determinants of non-renewable energy consumption, Lee and Chiu (2011a) found that nuclear energy and oil are substitutes in the U.S. and Canada while they are complementary in France, Japan and the UK over the 1965–2008 period. Furthermore, the authors indicated that there is a unidirectional causality from real oil prices to nuclear energy consumption, except for the U.S., and a causality from oil consumption to nuclear energy consumption in Canada, Japan and the UK. In the long run, the impact of real oil prices is larger than that of real income on nuclear energy consumption in Canada, Germany, Japan and the US. Lee and Chiu (2011b) examined the short-run and long-run relationship among nuclear energy consumption, oil prices, oil consumption and economic growth for a panel of developed countries from 1971 to 2006. They found that in the long run, oil prices have a positive impact on nuclear energy consumption. However, real income has a higher impact on nuclear energy than oil prices in the long run. Furthermore, there is a unidirectional causality from oil prices to nuclear energy consumption. Adom (2015) used the fully modified OLS and canonical cointegration regressions (CCR) to examine the drivers of energy intensity in Nigeria. The study reported a negative impact of crude oil prices, FDI and trade openness on the energy intensity while the industry structure is a positive contributor to energy intensity. Bloch et al. (2015) studied the relationship between the production and consumption of coal, oil and renewable energy in China from 1977 to 2013 (for the supply side) and from 1965 to 2011 (for the demand side). Their results showed that making coal both absolutely and relatively expensive compared to oil and renewable energy can help shift from coal to oil and renewable energy. Applying a nonlinear iterative partial least squares (NIPALS) methodology, Sarkodie and Adom (2018) reported the significance of crude oil prices, population density, urbanization and renewable *Energies* from hydro sources in achieving the energy demand reductions in Kenya (total, fossil and electricity). The authors however found the income, climate change and population as the positive contributors to energy consumption. Sarwar et al. (2017) analyzed the relationship between economic growth, electricity consumption, oil price, gross fixed capital formation and population on a panel of 210 countries over the 1960–2014 period. Their results showed that countries using non-renewable sources for electricity generating, such as coal and oil, the electricity consumption has a negative relationship with economic growth.

From the above literature survey, we note that there has been a high number of studies investigating the determinants of renewable and non-renewable energy consumption in various countries. We also notice that there is a higher number of studies on the oil-related determinant factors of renewable energy consumption than that of non-renewable energy consumption. This may be explained by the fact that oil is naturally considered as a determinant factor of non-renewable energy consumption while the relationship is less clear for renewable energy consumption. On the other hand, most of the previous studies have been interested in macroeconomic determinants of renewable energy, such as GDP, financial development, labor force, trade openness, gross fixed capital formation and FDI, or pollutant emissions. Fewer studies included oil factors when studying the determinants of energy consumption. Overall, previous results show that the impact of oil prices on energy consumption is mixed. It can be insignificant, negative or positive depending on the choice of the sample period and country. However, we have not found any study analyzing the impact of disaggregated structural oil shocks on the consumption of seven different categories of energy (from hydropower, geothermal, wood, waste, coal, natural gas and petroleum) for the U.S. in a time-varying context as we do in this study. Given this lack in the literature, the results of our study allow drawing new insights on the impact of different facets of oil shocks (supply and demand) on the consumption of renewable and non-renewable energy produced from various sources.

3. METHODOLOGY AND DATA

The first sub-section focuses on our methodology framework while the second sub-section presents the data sample used.

3.1. Methodology

To examine the impact of oil price shocks on the consumption of renewable and non-renewable energy, we start with a decomposition of different types of oil shocks following the structural vector autoregression model (SVAR) proposed by Kilian (2009) and Kilian and Park (2009). As a second step, we estimate the impulse response functions of energy consumption to oil shocks based on this SVAR model. Indeed, this method allows us to know how energy consumption responds to an unanticipated increase of oil shocks and thus help energy policies and energy consumers adapt their behavior. To complement our analysis, in the third step, we further study the spillover from oil shocks to energy consumption based on the approach of Diebold and Yilmaz (2014). This method is complementary to the impulse response method because it shows how oil shocks participate to the forecast error variance of energy consumption through the variance decomposition analysis. Finally, to check the robustness of our results, we estimate time-varying values of these two methods in numerous sub-periods based on a time-rolling window process. As the SVAR model and the dynamic connectedness measure are in the heart of our empirical estimations, the two sub-sections below detail them.

3.1.1. The disaggregation of oil shocks

The Kilian and Park (2009) approach has two major benefits. First, it does not assume that oil prices are exogenous with respect to the global economy since global business cycle fluctuations also affect them (Hamilton 2008). Second, it provides a decomposition of the reduced form shocks into three different types of structural shocks since the previous literature has shown that the effects stemming from oil supply and demand shocks are both qualitatively and quantitatively different (Kilian 2009).

The underlying SVAR model is:

$$A_0 z_t = \alpha + \sum_{i=1}^{p} A_i z_{t-i} + \varepsilon_t, \tag{1}$$

where z_t represents a four-dimensional time series vector including (1) the growth rate of global crude oil production, (2) a global measure of real activity, (3) the real crude oil price, and (4) the change in energy consumption (REC). ε_t is a vector of serially and mutually uncorrelated structural shocks. Multiplying Eq. (1) by A_0^{-1} results in a reduced-form VAR model:

$$z_t = A_0^{-1}\alpha + \sum_{i=1}^{p} A_0^{-1} A_i z_{t-i} + A_0^{-1}\varepsilon_t \tag{2}$$

where the last term gives its innovations such that $e_t \equiv A_0^{-1}\varepsilon_t$. The key aspect is to derive the structural innovations ε_t from the reduced-form disturbances e_t. This is done by imposing exclusion restrictions on A_0^{-1} as given below:

$$e_t \equiv \begin{pmatrix} e_{1t}^{\Delta global\ oil\ production} \\ e_{2t}^{global\ real\ activity} \\ e_{3t}^{real\ price\ of\ \text{crude}\ oil} \\ e_{4t}^{\Delta REC} \end{pmatrix} = \begin{bmatrix} a_{11} & 0 & 0 & 0 \\ a_{21} & a_{22} & 0 & 0 \\ a_{31} & a_{32} & a_{33} & 0 \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix} \begin{pmatrix} e_{1t}^{oil\ supply\ shock} \\ e_{2t}^{aggregate\ demand\ shock} \\ e_{3t}^{oil-specific\ demand\ shock} \\ e_{4t}^{REC\ shock} \end{pmatrix}. \tag{3}$$

This proceeding allows us to trace back the fluctuations in the real crude oil price to three different types of structural shocks: First, ε_{1t} represents shocks to the global crude oil supply. Second, ε_{2t} denotes shocks to the global demand for all industrially used commodities driven by global economic activity (aggregate demand shock henceforth). Finally, ε_{3t} stands for crude oil specific demand shocks such as, for instance, changes in precautionary demand for crude oil (Alquist and Kilian 2010). In addition, ε_{4t} is the structural shock related to energy consumption (REC).

The identifying restrictions imposed in Eq. (3) are motivated by the following theoretical considerations: First, the change in global crude oil production will contemporaneously depend on oil supply shocks and not respond to demand shocks within the corresponding month. This is because shifts in the demand curve driven by both types of demand shocks affect the real crude oil price instantaneously but not the change in production due to high adjustment costs. Second, crude oil specific demand shocks will not contemporaneously affect the global real economic activity due to the sluggishness of the latter. Finally, the real crude oil price instantaneously responds to all the three types of shocks.

Having identified the three types of structural oil shocks, we follow with an impulse response analysis to examine the impact of the different types of oil shocks on renewable and non-renewable energy consumption.

3.1.2. Dynamic connectedness measures

To provide a deeper understanding on this impact, we follow Antonakakis et al. (2017) and make use of the dynamic connectedness approach proposed by Diebold and Yilmaz (2014) to analyze the spillover from oil shocks to renewable and non-renewable energy consumption. The dynamic connectedness approach is complementary to impulse response functions since it is based on a forecast error variance decomposition (FEVD) derived from the vector moving-average (VMA) representation of Eq. (2):

$$\Phi(L)z_t = A_0^{-1}\alpha + A_0^{-1}\varepsilon_t, \tag{4}$$

$$\text{Or } z_t = \Phi(L)^{-1} A_0^{-1}\alpha + \Phi(L)^{-1} A_0^{-1}\varepsilon_t, \tag{5}$$

where $\Phi(L)^{-1} \equiv \Theta(L) = \Theta_0 + \Theta_1 L + \Theta_2 L^2 + \ldots$ is the VMA matrix lag polynomial. $\Theta_{h,ij}$ is the (i,j)-element of the FEVD at horizon h. Then, the total directional connectedness from others to i is defined as follows:

$$C_{i\leftarrow *}^{h} = \sum_{\substack{j=1 \\ j\neq i}}^{N} \Theta_{h,ij} \tag{6}$$

and gives the share of the h-step FEVD of variable i coming from shocks in other variables. According to that, the total directional connectedness to others from j is given as:

$$C_{*\leftarrow j}^{h} = \sum_{\substack{i=1 \\ j\neq i}}^{N} \Theta_{h,ij} \tag{7}$$

and denotes the share of the h-step FEVD to other variables coming from a shock arising in variable j. We are interested in the intensity of the interdependence between the three different types of oil shocks mentioned above and energy consumption. Therefore, we rely on the net total effects. Thus, the net total directional connectedness measure for i is defined as the difference between "From others" to "To others", meaning Eq. (6) minus Eq. (7) as follows:

$$C_i^h = C_{i\leftarrow *}^h - C_{*\leftarrow j}^h . \tag{8}$$

The corresponding results are discussed in Section 4. Prior to this, the next sub-section presents the data sample on the disaggregated energy consumption (renewable and non-renewable) in the U.S. as well as the measures of oil shocks described above. It should be noted that before obtaining the final empirical results, we first correct the raw data from a seasonal effect by employing X-13ARIMA-SEATS Seasonal Adjustment Program.[3]

3.2. Data

The monthly data sample from January 1974 to February 2018 used in this study is composed of two different parts. The first part relates to energy consumption (renewable and non-renewable) produced from different sources such as water (hydropower),[4] heat (geothermal)[5] and biomass[6] (with wood and waste) for renewable energy; and fossil fuels such as coal,[7] natural gas[8] and petroleum[9] for non-renewable energy. The measure unit is trillion British thermal unit (Btu) or the amount of heat required to raise the temperature of 1 pound of liquid water by 1-degree Fahrenheit at a constant pressure of one atmosphere. These series are collected from the U.S. Energy Information Administration (EIA). The second part of our data is composed of oil-related variables, such as the world oil production, global real economic activity and real oil prices, to simulate the three considered oil shocks as defined in Eq. (3).

The monthly world oil supply (in millions of barrels per day) and the real oil price (in USD per barrel) measured by the U.S. refiner acquisition cost of crude oil deflated by the U.S. Consumer Price Index (CPI) are also collected from the EIA. The CPI was downloaded from the website of

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[3] X-13ARIMA-SEATS is a seasonal adjustment software produced, distributed, and maintained by the U.S. Census Bureau. Further details of the software and program are available at: https://www.census.gov/srd/www/x13as/. Please refer to Figure B in the Appendix for a graphical presentation of the raw data and the seasonal-adjusted data.

[4] The source of hydroelectric power is water. The volume of the water flow and the change in elevation (or fall) from one point to another determine the amount of available energy in moving water (Source: EIA).

[5] The word "geothermal" comes from the Greek words geo (earth) and thermal (heat). Geothermal energy is from the heat within the earth. This heat can be used as stream or as hot water to heat buildings or to generate electricity (Source: EIA).

[6] Biomass is organic material that comes from plants and animals. Biomass contains stored energy from the sun. Plants absorb the sun's energy in a process called "photosynthesis". When biomass is burned, the chemical energy in biomass is released as heat. Biomass can be burned directly or converted to liquid biofuels or biogas that can be burned as fuels. Biomass energy can come from wood, agricultural crops and waste materials, food, yard and wood waste in garbage, animal manure and human sewage (Source: EIA). It is important to make the difference between biomass and biogas. Biogas is also derived from organic and living matters. However, with biogas, the energy is created during the anaerobic digestion process to harness the methane gas which is burned to produce energy. For more information about biogas, please refer to the AgSTAR program initiated by the U.S. Environmental Protection Agency (EPA).

[7] Coal is a combustible black or brownish-black sedimentary rock with a high amount of carbon and hydrocarbons. Coal is classified as a non-renewable energy source because it takes millions of years to form. Coal contains the energy stored by plants that lived hundreds of millions of years ago in swampy forests (Source: EIA).

[8] Natural gas occurs deep beneath the earth's surface. Natural gas consists mainly of methane, a compound with one carbon atom and four hydrogen atoms. Natural gas also contains small amounts of hydrocarbon gas liquid and nonhydrocarbon gases. Natural gas is used as a fuel and to make materials and chemicals (Source: EIA).

[9] Petroleum products are produced from the processing of crude oil and other liquids at petroleum refineries, from the extraction of liquid hydrocarbons at natural gas processing plants, and from the production of finished petroleum products at blending facilities. Petroleum is a broad category that includes oil and petroleum products. Crude oil is a mixture of hydrocarbons that exists as a liquid in underground geologic formations and remains a liquid when brought to the surface. The terms oil and petroleum are sometimes used interchangeably (Source: EIA).

Table 1: The synthesis of energy consumption in the U.S. from January 1974 to February 2018 per source and per economic sector (source: EIA)

Energy / Sector	**Commercial**	**Industrial**	**Residential**	**Transportation**
Coal	4649,31	105451,23	980,68	2,80
% of total	*3%*	*11%*	*0,3161%*	*0,0003%*
Natural Gas	130369,01	378614,07	214290,91	29068,94
% of total	*72%*	*40%*	*69%*	*3%*
Petroleum	41321,14	383204,55	66869,92	1006363,27
% of total	*23%*	*40%*	*22%*	*95%*
Total fossil fuels	176339,45	868269,86	282141,52	1035435,00
% of total	*98%*	*91%*	*91%*	*98%*
Total non-renewable per sector	**176339,45**	**867269,84**	**282141,50**	**1035435,01**
% per sector	***7%***	***37%***	***12%***	***44%***
Hydroelectric power	27,41	1423,41		
% of total	*0,0152%*	*0,1495%*		
Geothermal energy	329,10	107,33	564,16	
% of total	*0,1821%*	*0,0113%*	*0,1818%*	
Solar energy	390,34	99,35	2116,71	
% of total	*0,2160%*	*0,0104%*	*1%*	
Wind energy	6,65	3,05		
% of total	*0,0037%*	*0,00032%*		
Biomass energy	3618,03	82213,08	25418,01	15848,53
% of total	*2%*	*9%*	*8%*	*2%*
Total renewable energy	4371,54	83846,21	28098,88	15848,53
% of total	*2%*	*9%*	*9%*	*2%*
Total renewable per sector	**8743,07**	**167692,43**	**56197,76**	**31697,05**
% per sector	**3%**	**63%**	**21%**	**12%**

Notes: This table presents a synthesis by the authors from statistics collected from the EIA website. The figures in this table are the sum of energy consumption from principal sources in four sectors (commercial, industrial, residential and transportation) from January 1974 to February 2018 in Trillion BTU. An empty cell means that there is no data provided. The % of total is the ratio between an energy source consumption within a sector and the total of all the energy sources consumed in the same sector. For example, the 3% in the first cell at the top on the left of the table means that in the commercial sector, coal represents 3% of the total energy consumption in the commercial sector.

the Federal Reserve Bank of St. Louis. A conventional index of global real economic activity is collected from the website of Professor Lutz Kilian and measured by the global index of dry cargo single voyage freight rates. This data set regarding oil shocks is very similar to that used by Kilian and Park (2009) and Kilian (2009).

To explain our choice of the above-mentioned energy sources, the following part presents an overview of energy consumption in the U.S. from 1974 to 2018.[10]

An overview of energy consumption in the U.S. from 1974 to 2018

In 2016, renewables represent 10.4% of the total energy consumption in the U.S. while coal accounts for 14.6%, natural gas for 29.2% and petroleum for 37% (2016 Renewable Energy Data Book, U.S. Department of Energy).[11] Compared to 2006, the same numbers are 6.7% for renewables, 22.6% for coal, 22.4% for natural gas and 40.1% for petroleum energy consumption. We can thus state the increase of renewables and the decrease of fossil fuels consumption. For more

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[10] We would like to thank an anonymous referee for this valuable suggestion.

[11] For more information on the gas market in the U.S., refer to Makholm (2012).

details, Table 1 presents energy consumption in the four main economic sectors and allows drawing the following information. First, the part of renewable energy consumption (REC hereafter) is still small compared to that of non-renewable energy consumption (NREC hereafter), about 6% vs. 94%, for the 1974–2018 period. Second, the proportion of REC varies following the sector. The sectors with the highest part of REC are industrial and residential, both with 9% of REC. However, in the commercial and transportation sectors, this proportion is still very small, 2% only. Among the different renewable energy sources, biomass energy is the most consumed and constitutes the principal renewable energy source in the U.S. with about 90% of the total REC. This is followed by solar, geothermal and hydroelectric power energy. The latter is the most consumed in the industrial sector while solar energy is the most consumed in the residential sector. On the other hand, biomass energy is the most consumed in the industrial sector and the less consumed in the commercial sector.

The use of wind energy is still very small and is reported only for the commercial and industrial sectors. In this context, our analysis focuses on hydroelectric power, geothermal and biomass energy (from wood and waste). Wind and solar energy are not included in our analysis because their part in the REC is still very small and their data is available only from 1983 and 1984, respectively (our sample period starts in 1974). From these first statistics, we can conclude that REC still plays a minor role in the energy mix in the U.S., about 6% over the 1974–2018 period. Biomass energy remains the most used, followed by hydroelectric power and geothermal energy. The sector that consumes the most renewable energy is the industrial sector, followed by the residential sector, the transportation sector and finally the commercial sector. This shows that renewable energy is used in all the economic sectors though their part is still small. So, there are still high potentials for renewable energy in all the economic sectors and it is possible to find substitution solutions between renewable and non-renewable energy uses. This is possible if new technologies allow this transformation.[12] If this condition is satisfied, then we can hypothesize that there are high opportunities to use renewable energy in the residential and transportation sectors for which its consumption is still very small.

As for non-renewable energy, coal, natural gas and petroleum are the main fossil fuel sources. Petroleum is the most used with a proportion of 63%, followed by natural gas with 32% and coal with 5%. The transportation sector is the most energy-consumed sector, with 44% of the total NREC. Following the EIA, motor gasoline consumption averaged 391 million gallons per day in 2016. It is followed by the industrial sector with 37%, residential sector with 12% and finally by the commercial sector with 7%. So, petroleum is the fossil fuel the most consumed while the transportation sector consumes the most energy. Together with the analysis on renewable energy, we suggest that the industrial and transportation sectors represent the highest potentials of substitution between non-renewable and renewable energy. Furthermore, biomass and hydroelectric power are already widely used in the industrial sector. However, this energy transition needs to have adapted technologies. It is also important to note that fossil fuels are used in the electricity production from biomass.[13] Thus, the energy substitution based on biomass should consider this technical constraint. In the meanwhile, the U.S. is the biggest oil producer in the world and this may make the process to adopt renewable energy longer. On the other hand, this high capacity of oil production also raises an

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[12] For more information about the investment in renewable energy technologies, please refer to the Annual Renewable Energy Data Book published by the National Renewable Energy Laboratory (NREL), US Department of Energy (https://www.nrel.gov/).

[13] Source: National Academy of Sciences (2010), page 67. We would like to thank an anonymous referee for suggesting the inclusion of this information.

important question: How do variations in the oil supply and demand impact renewable and non-renewable energy consumption? In this paper, we seek to find the answer.

Descriptive statistics

In Table 2, we present the main descriptive statistics of the considered time series. In Part 1 on energy consumption, we find that on average, petroleum is the most consumed, with 2938 trillion BTU per month, followed by natural gas, coal, hydropower, wood, waste and geothermal energy. The standard deviation is the highest for natural gas consumption and the lowest for geothermal energy consumption. In general, the volatility of NREC is higher than that of REC. The skewness is negative in most cases implying that the distribution is skewed to the left, meaning the higher proportions of numbers below the average. However, this is not the case for hydropower, natural gas and petroleum. The kurtosis excess is positive for all energy sources. It means that the queues of the distributions (or the extreme values) are thicker than a normal distribution. The results of the Jarque-Bera test show that the distribution is not normal, which is usually the case for financial and economic data.

The results of the ADF test show that most of the series are not stationary, except for the hydropower consumption. This exception may be explained by the fact that hydropower has less energy policies changes' and is therefore more stable (as we can state from the IEA/IRENA Joint Policies and Measures Database).[14] Finally, the Perron (1989) unit root test also allows identifying the month in which there is a structural change in energy consumption.[15] For hydropower, it is May 2000 (with a strong decrease from 290.623 from the previous month to 256.913 Trillion BTU); for geothermal energy, it is July 1983 (with an increase from 4.518 to 7.404 Trillion BTU, compared to the previous month); for wood energy, it is May 1997 (with an increase from 189.865 to 200.871 Trillion BTU, compared to the previous month) and for waste energy consumption, it is January 1981 (with an increase from 0.125 to 7.476 Trillion BTU compared to the previous month.

These structural-break dates correspond to key dates in the renewable energy policies in the U.S. Indeed, green energy policies started with the PURPA era (Public Utilities Regulatory Policy Act) from 1978 to 1990 during which there was an increasing tendency in the renewable energy sector with pioneering states such as California, New York and Maine (Martinot et al. 2005, page 4). The PURPA era was then followed by a stagnation period starting in the 1990s. In the late 1990s, an increasing trend state-level policy was implemented thanks to the Production Tax Credit (PTC), ethanol tax credits and the reduction of renewable energy cost thanks to technology advances and economies of scale in production and learning. From Table 1 in the Appendix, we also notice that there was an increasing number of renewable energy policies between 2001 and 2009 with numerous policy tools such as research and development, fiscal and financial incentives, information and education, advice and aid in implementation, etc. We also notice that climate and renewable policies were numerous in 2009, the first presidential year of Barack Obama. Tables 2, 3 and 4 in the Ap-

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[14] IEA = International Energy Agency, IRENA = International Renewable Energy Agency. The related website is: https://www.iea.org/policiesandmeasures/renewableenergy/?country=United%20States. Please refer to Tables 1–4 in the Appendix for all details about the renewable energy policies in the U.S. from 1974 to 2016.

[15] It is worth noting that the exact definition and dating of structural breaks is difficult. The endogenously determined break dates within the Perron (1989) unit root test are found by minimizing the sum of squared residuals and it is often difficult to exactly match these with policy changes reported in Tables 1 to 4 in the Appendix due to forward looking behavior of agents as well as delayed effects of the conducted policies. Therefore, we interpret the structural breaks with caution and do not put a high weight for this part in our analysis. We would like to thank an anonymous referee for this valuable suggestion to explain the reason of each structural break date.

Table 2: Descriptive statistics

	Mean	Std. Dev.	Skewness	Kurtosis	J-B	ADF At level	Structural breaks
Part 1: Disaggregated non-renewable and renewable energy consumption							
A. Renewable energy							
Hydroelectric Power Consumption	238.19	44.42	0.239	2.447	11.84***	–5.21***	2000M05
Geothermal Energy Consumption	11.92	5.31	–0.632	1.917	61.28***	–3.43	1983M07
Wood Energy Consumption	185.19	26.35	–0.195	2.689	5.50*	–3.31	1997M05
Waste Energy Consumption	28.74	15.76	–0.762	2.238	64.19***	–3.98	1981M01
B. Non-renewable energy							
Coal Consumption	1538.69	290.16	–0.114	2.166	16.54***	–2.55	2014M03
Natural Gas Consumption	1843.82	454.27	0.587	3.048	30.54***	–1.28	1987M01
Petroleum Consumption	2938.39	250.49	0.102	2.513	6.16**	–3.48	1995M06
Part 2: Oil-related variables							
Oil production	65375.24	8548.82	0.247	1.871	33.54***	–2.509	1999M06
Global real economic activity	–0.56	26.67	0.168	4.289	39.18***	–4.788**	2013M12
Real oil prices	25.70	11.68	0.863	2.916	65.93***	–4.230**	2004M12

Notes: Std. Dev. denotes standard deviation, J-B is for the Jarque-Bera normality test, ADF denotes the Augmented Dickey-Fuller unit root test. The structural breaks' dates (Year-Month) are determined based on the Perron (1989) unit root test. ***, ** and * denote the rejection of the null hypothesis of a normal distribution (for the Jarque-Bera test) and of a unit root (for the ADF test) at 1%, 5% and 10% level of significance, respectively. Energy consumption is measured in trillion of British thermal unit (Btu). Oil production is measured in millions of barrels per day. The real oil price is measured in real USD and the global economic activity is measured by the dry cargo single voyage rates. More details are presented above.

pendix show that geothermal and biomass *Energies* have high policy supports starting in 1974 and 1980, respectively.

In Part 2 of Table 2, we find descriptive statistics of the three oil-related variables, as presented above. We notice that only the global economic activity has a negative mean while the oil production and the real oil price have positive means. To explain the negative average value of the global real economic activity, we refer to Kilian (2009) who measured it by the global index of dry cargo single voyage freight rates. Thus, an increase of the freight rate indicates a strong cumulative global demand pressures, and thus of economic activity. So, a negative mean value of the global real economic activity shows that over the 1974–2018 period, the dry cargo single voyage rate was in a decreasing trend in the most recent period and so the global economic activity (see Kilian (2009) for more information). On the other hand, the skewness is positive for all the variables, as well as the kurtosis excess. As usual, the distributions are not normal according to the Jarque-Bera. The ADF test shows that two out of the three series are stationary, except for the oil production.[16] Finally, the structural date is June 1999 for oil production, December 2013 for the global real economic activity and December 2004 for the real oil price. The structural break date in oil production (June 1999) may be due to the fact that Sudan started pumping oil through its pipeline linking the Heglig oil field in Western Kordofan province to Port Sudan on the Red Sea. The structural break of the global economic activity in December 2013 might be due to the exit from the global economic crisis. As for the real oil price, at the end of 2014, oil prices fell sharply to be at $59 per barrel in December because of the supply exceedance. Overall, the potential existence of structural breaks shows that a constant parameter analysis on the whole sample period may be inappropriate and that it is important to consider the time-varying character of the interaction between energy consumption and oil

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[16] It should be noted that statistics presented in Table 2 are obtained from the series in level. That is why oil production is not stationary. The series of change in oil production is however stationary. More details about the ADF test results on the change series are available upon request from the authors.

shocks. That is why our analysis will focus first on the full sample period (Section 4) before dividing it into numerous sub-periods determined by time-rolling windows (Section 5).

4. EMPIRICAL RESULTS: FULL SAMPLE

4.1. How does energy consumption respond to oil shocks?

4.1.1. Preliminary analysis: The response of oil prices to oil shocks

Before analyzing the responses of energy consumption to oil shocks, it is important to know how oil prices respond to each of the three oil shocks defined above. The objective of this preliminary step is to show that the three categories of oil shocks are closely related to the real oil price, usually used as a representative indicator of the oil market. For that, we estimate the responses of the real oil price over the 12 months following an unanticipated increase of one standard deviation on the oil supply, aggregate demand and oil-specific demand through the SVAR model presented in Section 3.1. The results are reported in Figure 1 and the red thick line shows the response of the real oil price over the 12 months following the three oil shocks separately. If this line is above 0, then the real price of oil increases and the amplitude of the response is related to the height of the line. If this line is below 0, then the real price of oil decreases after a positive oil shock. The dotted blue lines show the confidence intervals to make inference about the response. These confidence intervals are constructed as one standard-error bands. The impulse responses of the real oil price to oil shocks are statistically significant if the zero line is out of the confidence intervals. Finally, to underline more the time-varying aspect of the energy market, we reproduce Figure 1 for different sub-periods (from 1974 to 1981 for the oil-crisis period, from 1982 to 2006 for the pre-GFC period (with GFC = Global Financial Crisis), from 2007 to 2009 for the GFC period and from 2010 to February 2018 for the post-GFC period.[17] Figure 1A focuses on the supply shocks in the four mentioned sub-periods, while Figures 1B and 1C focus on the aggregate demand and oil-specific demand shocks, respectively.

Overall, Figure 1 shows that the real oil price responds significantly to the three structural oil shocks because the zero lines are all outside the confidence intervals. Furthermore, Figure 1 also shows that the real oil price reacts differently to each category of oil structural shocks, which basically confirms the findings by Kilian (2009). Indeed, any unanticipated increase in the oil supply (Panel A, Figure 1) causes a decrease in the real oil price during the first three months before being stabilized in the following months. This is intuitive since a higher supply is associated with a lower price. On the opposite, any unanticipated increase in the aggregate demand (Panel B, Figure 1) causes an increase of the real oil price over the 12 following months. This result is also in line with the theory since a rise in the aggregate demand also increases the demand of oil due to its importance in the production and consumption process. This mechanism is even sharper in the case of oil-specific demand shocks since the amplitude of the responses is much higher (Panel C, Figure 1). In this case, an unanticipated increase in the oil demand causes a sharp increase in the real oil price during the first four months before the amplitude of the reaction decreases. This may be explained by the fact that once the oil demand shock is over, economic agents stabilize their oil consumption causing a smaller increase in the real oil prices than that in the first months after the shock.

Figure 1A shows the impact of oil supply shocks on the real oil price in the four sub-periods and displays that the responses vary over time. In the first sub-period, from 1974 to 1981 with

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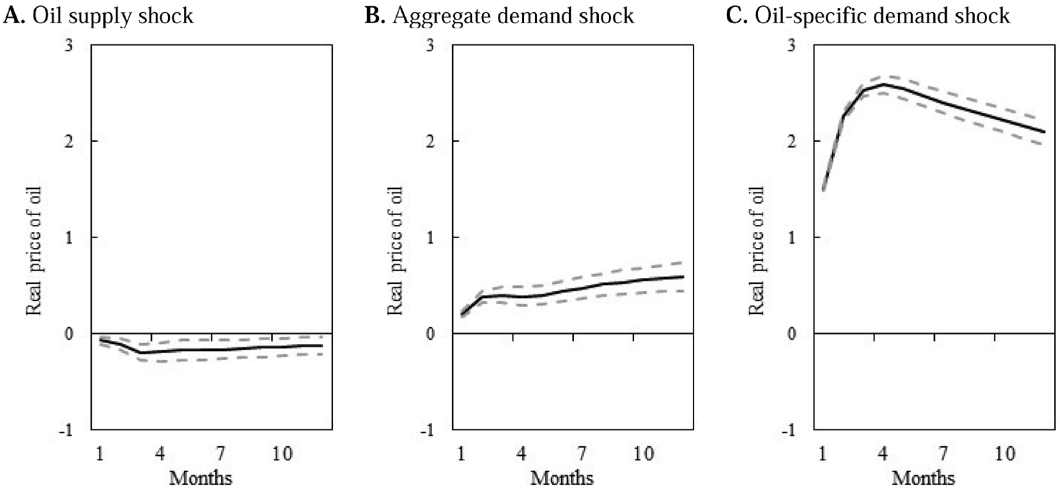
[17] We would like to thank an anonymous referee for this valuable suggestion.

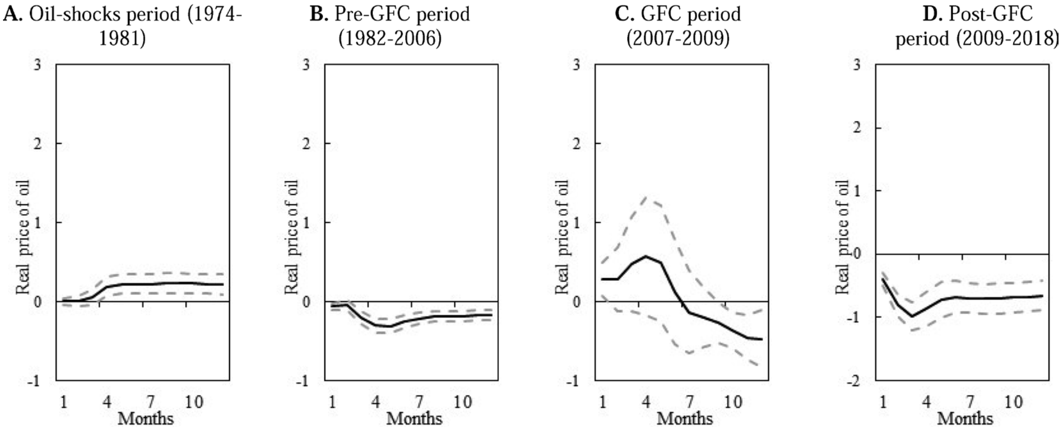
Figure 1: Impulse response functions of the real price of crude oil to one standard-deviation structural oil shocks *(SVAR models, point estimates with one standard-error bands)—Whole sample analysis*



A. Oil supply shock **B.** Aggregate demand shock **C.** Oil-specific demand shock

Notes: Estimates are based on the SVAR model described in Section 3.1. The thick line presents the responses of the real oil price to an unanticipated increase of 1 standard-deviation variation in oil shocks. The dashed lines present the confidence intervals with one standard-error bands, constructed using a recursive-design wild bootstrap (please refer to Goncalves and Kilian 2004). The vertical axis (the y axis) represents the amplitude and the sign of the impulse responses. The horizontal axis (the x axis) represents the 12 months following an unanticipated increase of 1 standard-deviation of oil shocks.

Figure 1A: Impulse response functions of the real price of crude oil to one standard-deviation structural oil supply shocks *(SVAR models, point estimates with one-standard error bands)—Sub-sample analysis*

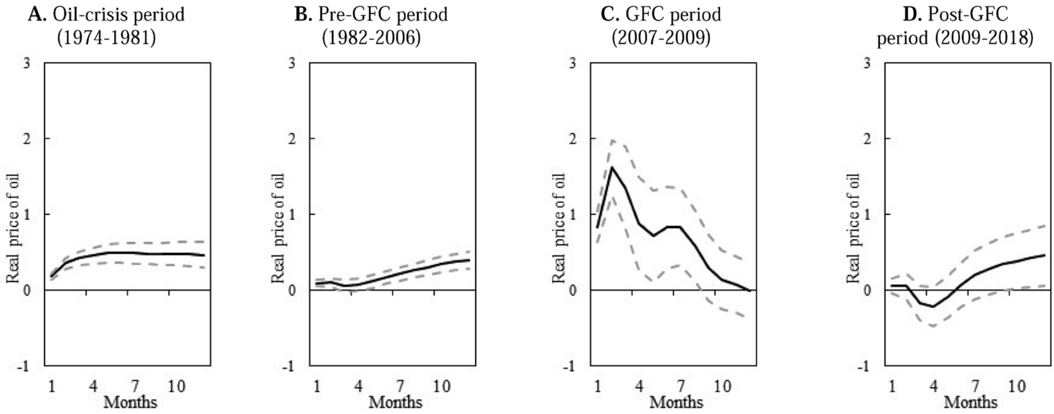


A. Oil-shocks period (1974-1981) **B.** Pre-GFC period (1982-2006) **C.** GFC period (2007-2009) **D.** Post-GFC period (2009-2018)

See notes of Figure 1.

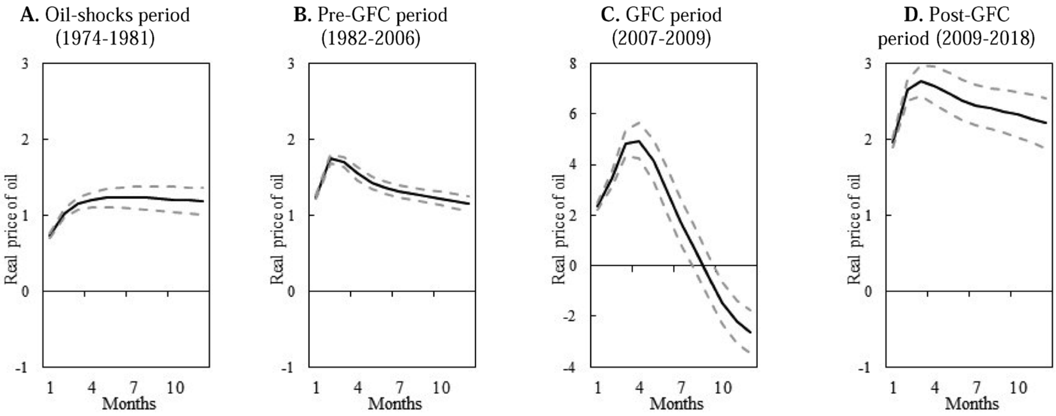
the two oil crises peaked in 1974 and 1979, the response of the real oil price to an oil supply shock is positive. However, during the 1982–2006 period, the effect is significantly negative. During the GFC period (2007–2009), the response of the real oil price to an oil supply shock is not statistically significant, except for a longer horizon of more than 10 months. However, in the post-GFC period, the response is significantly negative. In this case, the exceptional period is the oil-crisis period from

Figure 1B: Impulse response functions of the real price of crude oil to one standard-deviation structural aggregate demand shocks *(SVAR models, point estimates with one-standard error bands)—Sub-sample analysis*


A. Oil-crisis period (1974-1981)
B. Pre-GFC period (1982-2006)
C. GFC period (2007-2009)
D. Post-GFC period (2009-2018)

See notes of Figure 1.

Figure 1C: Impulse response functions of the real price of crude oil to one standard-deviation structural oil-specific demand shocks *(SVAR models, point estimates with one-standard error bands)—Sub-sample analysis*


A. Oil-shocks period (1974-1981)
B. Pre-GFC period (1982-2006)
C. GFC period (2007-2009)
D. Post-GFC period (2009-2018)

See notes of Figure 1.

1974 to 1981 in which the real oil price responds positively to an increase of oil supply. This might be because this period was affected by the Yom Kippur war and the Iranian revolution.

Figure 1B shows the response of the real oil price to an increase in the aggregate demand of the economy in the four considered sub-periods, which is significantly positive in all cases, except for the post-GFC period in which the response is mostly insignificant. We also note that the amplitude of the response is much higher in the GFC period than in the other periods. This may be because during the crisis, there has been a high increase of the aggregate demand and thus the price of oil. Finally, Figure 1C shows the response of the real oil price to oil-specific demand shocks in the four sub-periods. We note that the results are like with aggregate demand shocks but with a higher amplitude in the response of the real oil price. The negative response for the horizon from 8 to 12 during the GFC period can be explained by the large swings in the real oil price during this period.

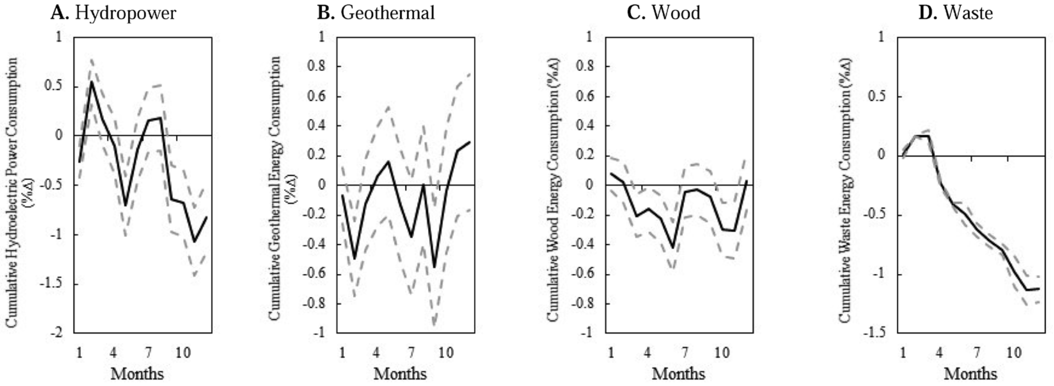
The next two sub-sections will focus on the impact of oil shocks on renewable and non-renewable energy consumption.

4.1.2. The response of renewable energy consumption to oil shocks

Having analyzed the responses of real oil prices to oil shocks, we now examine the responses of renewable energy consumption to oil shocks. The corresponding results are presented in Figures 2A, 2B and 2C corresponding to the three kinds of oil shocks.

Figure 2A shows that biomass energy consumption responds significantly and negatively to oil supply shocks (except for short-term horizons of 1 and 2 months for waste energy consumption when the reaction is positive and for wood energy consumption when the effect is not statistically significant). For hydropower and geothermal energy consumption, the sign of the response to oil supply shocks changes several times but is mostly negative. However, for geothermal energy consumption the impact is not statistically significant for most horizons because the zero line is

Figure 2A: Impulse response functions of renewable energy consumption to one standard-deviation structural oil supply shocks *(SVAR models, point estimates with one standard-error bands)*



See notes of Figure 1.

Figure 2B: Impulse response functions of renewable energy consumption to one standard-deviation structural aggregate demand shocks *(SVAR models, point estimates with one standard-error bands)*

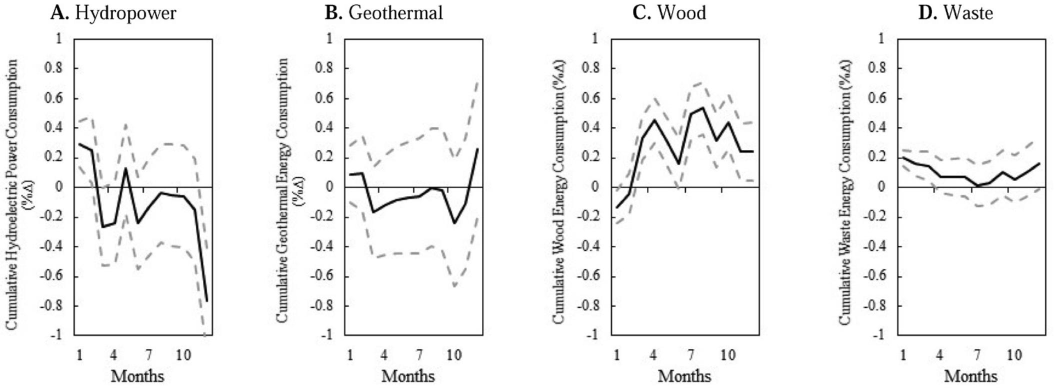
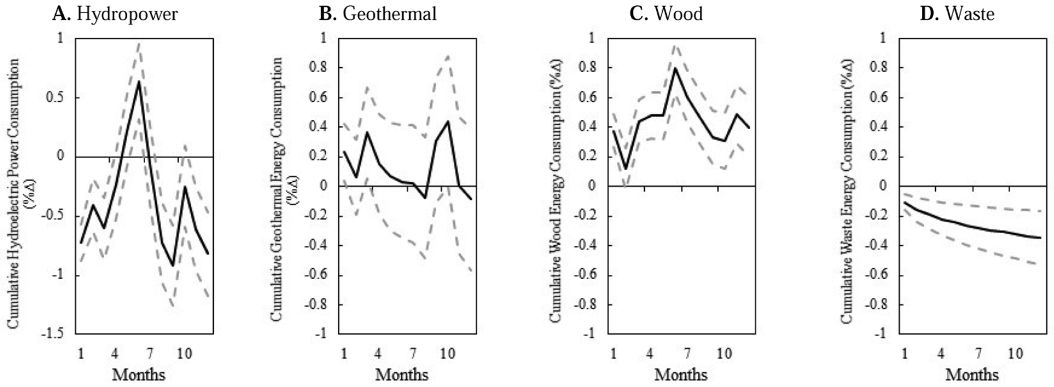


Figure 2C: Impulse response functions of renewable energy consumption to one standard-deviation structural oil-specific demand shocks *(SVAR models, point estimates with one standard-error bands)*



A. Hydropower **B.** Geothermal **C.** Wood **D.** Waste

Notes: see notes to Figure 2A.

inside the confidence intervals. Overall, the results indicate that biomass energy consumption has the strongest reaction to oil supply shocks. Indeed, an increase in the oil supply conducts to a decrease in the consumption of biomass energy. On the other hand, Figure 2B shows that wood energy consumption responds significantly and positively to aggregate demand shocks, which can also be observed for hydropower and waste consumption but solely in the short run. Finally, Figure 2C indicates that again, wood and waste energy consumption have the most significant reaction to oil-specific demand shocks while hydropower also responds significantly with different signs for several horizons. Wood energy consumption responds positively while waste energy consumption responds negatively to oil demand shocks.

Overall, the results show that biomass energy consumption is the most sensitive to the three oil shocks. However, within biomass energy, wood and waste behave differently. On the contrary, geothermal energy consumption responses to the three oil shocks are insignificant in most cases while hydropower consumption responds significantly, especially to oil-specific demand shocks. Thus, we conclude that biomass energy is the most influenced by oil shocks and geothermal is the less one. This may be explained by the fact that oil is used in the electricity production process using biomass.[18]

Regarding the hydropower potential, a report of the U.S. Department of Energy published in 2016 showed an increasing tendency following more than 50 potential scenarios of new hydropower capacity growth between 2017 and 2050 (Hydropower Vision, Chapter 3, page 4). In Chapter 2 of this report (page 82, Table 2–5), it was shown that there are 20 hydrologic regions in the U.S. (such as Great Lake, Ohio, Missouri or Pacific Northwest) which provide a total capacity of 65,493 MW and a total generation of 347,280 MWh per year. However, the development of hydropower can have some difficulties to face social and environmental constraints such as water rights, water availability, adverse effects on river systems and species (Hydropower Vision, Chapter 1, page 7). On the other hand, the report also indicates that hydropower has numerous social, economic and environmental benefits such as limitation of air pollutants and greenhouse gas emissions, low and

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[18] Source: Page 67 in a book published by the National Academies of Sciences Engineering Medicine in 2010 entitled "Electricity from renewable resources". Available at: https://www.nap.edu/nap-cgi/skimchap.cgi?recid=12619&chap=i%E2%80%93xviii

stable operational costs (not subject to market-driven fuel price fluctuations) and is easily foreseeable with long-term electricity storage services (Chapter 1, Hydropower Vision).

4.1.3. The response of non-renewable energy consumption to oil shocks

Figures 3A, 3B and 3C present the results of the impulse responses of non-renewable energy consumption (coal, natural gas and petroleum) to the oil supply, aggregate demand and oil demand shocks, respectively. Figure 3A shows that natural gas and petroleum consumption respond significantly and positively to oil supply shocks. For coal consumption, this is also the case but only for the first 3 months following the shock (with the zero line outside the confidence intervals). Figures 3B and 3C show that coal and natural gas consumption respond significantly and positively to aggregate and oil demand shocks while it is not the case for petroleum consumption. This result is

Figure 3A: Impulse response functions of non-renewable energy consumption to one standard-deviation structural oil supply shocks *(SVAR models, point estimates with one standard-error bands)*

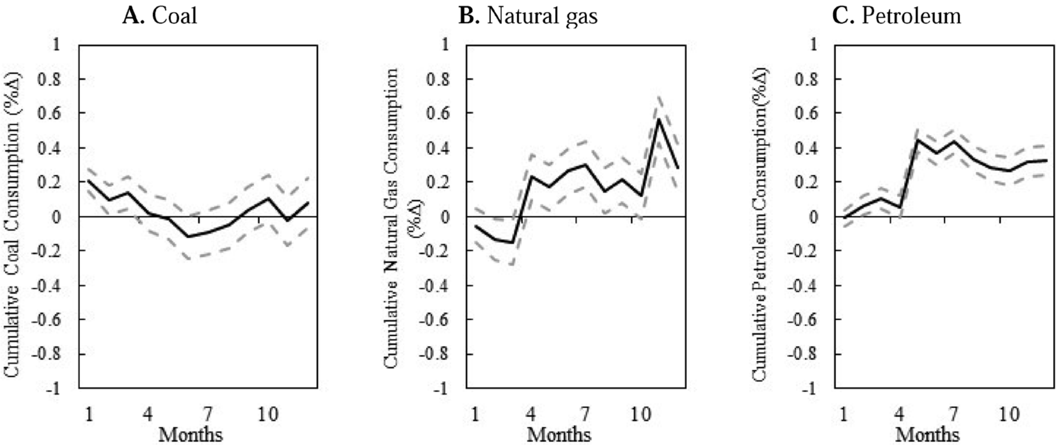

A. Coal **B.** Natural gas **C.** Petroleum

Figure 3B: Impulse response functions of non-renewable energy consumption to one standard-deviation structural aggregate demand shocks *(SVAR models, point estimates with one standard-error bands)*

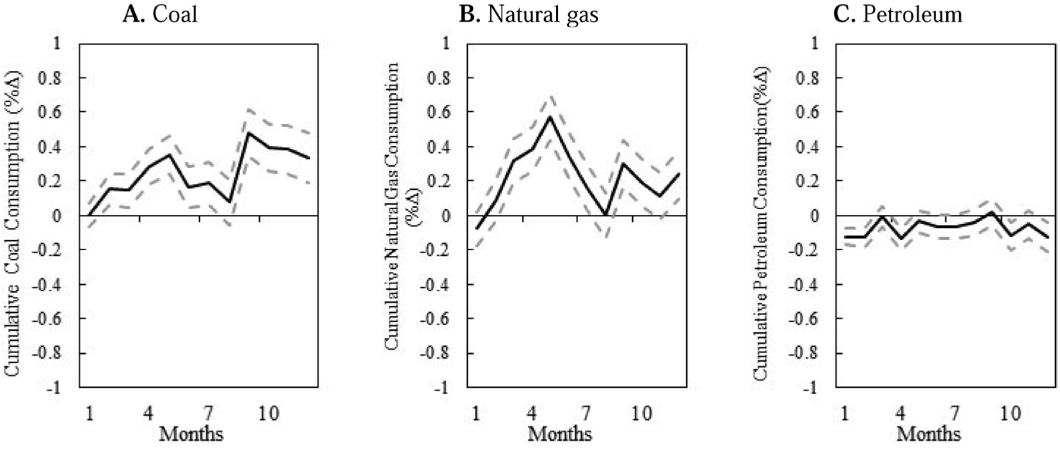
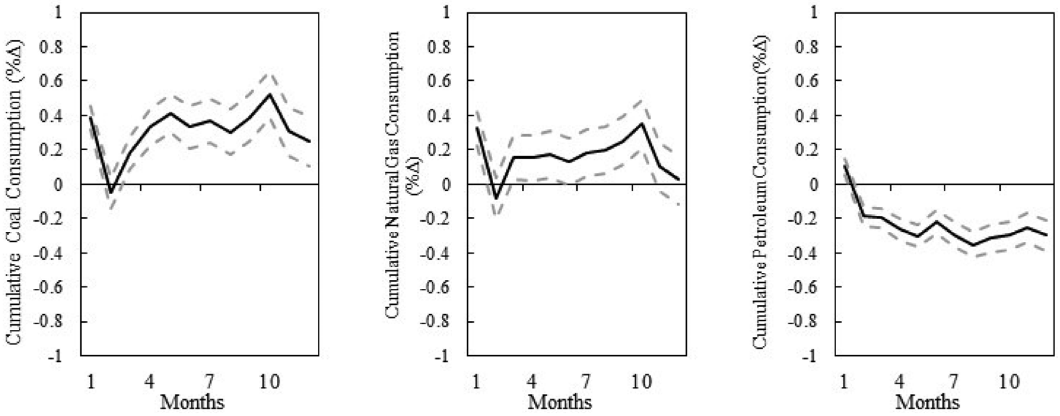

A. Coal **B.** Natural gas **C.** Petroleum

Figure 3C: Impulse response functions of non-renewable energy consumption to one standard-deviation structural oil-specific demand shocks *(SVAR models, point estimates with one standard-error bands)*



A. Coal **B.** Natural gas **C.** Petroleum

plausible because when demand increases, energy consumption increases, and so for coal and natural gas. For petroleum consumption, demand shocks have significant and negative impacts for most of the horizons. This result is also plausible since petroleum is produced from crude oil and especially an oil-specific demand shock increases the price of oil (shown in Section 4.1.1) and therefore reduces petroleum consumption. In this case economic agents tend to substitute it by other energies, such as coal, natural gas or wood (see Figure 2C) to satisfy the energy demand. Overall, the results indicate that an unanticipated increase in the demand raises the consumption of coal and natural gas and lowers the consumption of petroleum.

4.2. How do oil shocks spillover to energy consumption?

As mentioned in Section 3.1., the dynamic connectedness measure proposed by Diebold and Yilmaz (2014) is used to analyze spillovers from oil shocks to energy consumption based on a forecast error variance decomposition (FEVD). The corresponding results shown in Tables 3A and 3B (for renewable and non-renewable energy consumption, respectively) are obtained from a forecast of 12-months-ahead. Table 3A is composed of four panels: Panel A on hydropower energy consumption (HPC), Panel B on geothermal energy consumption (GEC), Panel C on wood energy consumption (WEC), Panel D on waste energy consumption (WsEC). Table 3B is composed of three panels corresponding to coal energy consumption (CC, Panel A), natural gas consumption (NGC, Panel B) and petroleum consumption (PC, Panel C). In each panel, OSS, ADS, OSDS represent the three oil shocks (oil supply, aggregate demand and oil-specific demand shocks, respectively). The figures in each panel thus show the spillovers from the shocks in the corresponding row to those in each column. For example, in Panel A of Table 3A the spillover from oil supply shocks (OSS) to hydropower consumption (HPC) is 4.51%. In other words, this is the share of the FEVD of oil-supply shocks to shocks arising in hydropower consumption.

The last column of each panel, entitled "**From others**", measures the total spillovers received from all the other shocks. For example, in Panel A of Table 3A, the total spillover from oil supply shocks, aggregate demand shocks and oil-specific demand shocks to hydropower consumption is 11.1%. On the opposite, the row entitled "**To others**" provides the total spillovers from one

Table 3A: Dynamic connectedness between oil shocks and renewable energy consumption

A. Hydroelectric Power Consumption (HPC)

	From *(j)*				
To *(i)*	OSS	ADS	OSDS	HPC	From others
OSS	95.80	1.37	1.22	1.62	4.20
ADS	1.77	87.15	10.04	1.04	12.85
OSDS	1.89	13.23	83.58	1.29	16.42
HPC	**4.51**	**1.79**	**4.80**	88.90	11.10
To others	8.18	16.39	16.05	3.96	Total Connectedness:
Net	3.97	3.54	–0.37	–7.14	**11.14%**

B. Geothermal Energy Consumption (GEC)

	From *(j)*				
To *(i)*	OSS	ADS	OSDS	GEC	From others
OSS	95.13	1.51	1.16	2.20	4.87
ADS	2.15	88.23	9.46	0.16	11.77
OSDS	2.08	15.71	82.15	0.07	17.85
GEC	**1.44**	**0.33**	**0.68**	97.55	2.45
To others	5.67	17.55	11.30	2.42	Total Connectedness:
Net	0.80	5.78	–6.55	–0.03	**9.23%**

C. Wood Energy Consumption (WoEC)

	From *(j)*				
To *(i)*	OSS	ADS	OSDS	WoEC	From others
OSS	96.76	1.47	0.80	0.96	3.24
ADS	1.75	88.20	8.97	1.07	11.80
OSDS	2.44	14.15	80.58	2.83	19.42
WoEC	**1.26**	**1.37**	**1.65**	95.73	4.27
To others	5.45	16.99	11.42	4.86	Total Connectedness
Net	2.22	5.20	–8.00	0.59	**9.68%**

D. Waste Energy Consumption (WsEC)

	From *(j)*				
To *(i)*	OSS	ADS	OSDS	WsEC	From others
OSS	95.43	1.13	1.17	2.26	4.57
ADS	3.36	85.99	8.44	2.22	14.01
OSDS	2.03	15.18	81.69	1.10	18.31
WsEC	**5.01**	**1.19**	**0.99**	92.80	7.20
To others	10.40	17.50	10.61	5.58	Total Connectedness
Net	5.83	3.49	–7.71	–1.61	**11.02%**

Notes: Results in this table are from the own calculations of the authors. This table shows the connectedness measures given by Eq. (4) to (8) and calculated from variance decompositions based on 12-step-ahead forecasts (see Section 3.1. for more details). The total connectedness is measured by Eq. (6) for "From others" and by Eq. (7) for "To others". The net connectedness is measured following Eq. (8) which is Eq. (6)—Eq. (7). OSS, ADS, and OSDS indicate the oil supply shock, aggregate demand shock, and oil-specific demand shock, respectively. Please refer to Eq. (3) in Section 3.1. for more details. Please refer to Eq. (3) in Section 3.1. for more details.

Table 3B: Dynamic connectedness between oil shocks and non-renewable energy consumption

A. Coal Consumption (CC)

	From *(j)*				
To *(i)*	OSS	ADS	OSDS	CC	From others
OSS	94.96	1.43	1.03	2.58	5.04
ADS	2.22	87.44	6.88	3.45	12.56
OSDS	2.22	14.85	80.29	2.64	19.71
CC	**1.16**	**2.42**	**4.57**	91.84	8.16
To others	5.60	18.70	12.49	8.67	Total Connectedness:
Net	0.56	6.14	–7.22	0.52	**11.36%**

B. Natural Gas Consumption (NGC)

	From *(j)*				
To *(i)*	OSS	ADS	OSDS	NGC	From others
OSS	96.04	1.59	0.75	1.61	3.96
ADS	1.62	89.20	8.83	0.35	10.80
OSDS	2.10	15.18	81.40	1.33	18.60
NGC	**1.87**	**1.43**	**1.61**	95.09	4.91
To others	5.59	18.20	11.19	3.29	Total Connectedness:
Net	1.63	7.40	–7.41	–1.62	**9.57%**

C. Petroleum Consumption (PC)

	From *(j)*				
To *(i)*	OSS	ADS	OSDS	PC	From others
OSS	92.98	1.28	1.24	4.51	7.02
ADS	1.56	88.99	9.10	0.34	11.01
OSDS	3.76	15.40	79.47	1.36	20.53
PC	**2.89**	**1.39**	**1.88**	93.84	6.16
To others	8.21	18.07	12.22	6.22	Total Connectedness
Net	1.19	7.07	–8.31	0.05	**11.18%**

Notes: Results in this table are from the own calculations of the authors. This table shows the connectedness measures given by Eq. (4) to (8) and calculated from variance decompositions based on 12-step-ahead forecasts (see Section 3.1. for more details). The total connectedness is measured by Eq. (6) for "From others" and by Eq. (7) for "To others". The net connectedness is measured following Eq. (8) which is Eq. (6)—Eq. (7). OSS, ADS, and OSDS indicate the oil supply shock, aggregate demand shock, and oil-specific demand shock, respectively. Please refer to Eq. (3) in Section 3.1. for more details. Please refer to Eq. (3) in Section 3.1. for more details.

specific shock to all the others. For example, in Panel A of Table 3A, the total spillovers from oil supply shocks to all the others is 8.18%. In other words, this is the share of the FEVD of oil-supply shocks to shocks arising in the three others. The last row in each panel, entitled "Net", is the difference between "To others" and "From others". If it is positive (negative), the component in that column is a shock transmitter (receiver). This also means that the higher the value of "Net", the higher the impact of that component to the others. Finally, the "Total connectedness" presented in the last cell of each panel is simply the sum of all the connectedness measures between all possible pairs in each panel. Given our objective to study the spillover from oil shocks to energy consumption, our analysis will focus on the spillovers from oil supply shocks (OSS), aggregate demand shocks (ADS) and oil demand shocks to shocks (OSDS) of each energy consumption component. Thus, our focus are the rows entitled HPC, GEC, WoEC, WsEC (Table 3A) as well as CC, NGC and PC (Table 3B) because it shows the spillovers from the three oil shocks to each energy consumption.

Table 3A shows that for hydropower energy consumption (HPC, panel A), the spillover from oil supply shocks is 4.51%, from aggregate demand shocks is 1.79% and from oil-specific shocks is 4.8%. Thus, the variance spillover from oil-specific demand shocks to the variance of hydropower energy consumption is the highest, followed by oil supply shocks. For geothermal energy consumption (GEC, panel B), the highest spillover is from oil supply shocks (1.44%), followed by oil demand shocks (0.68%) and aggregate demand shocks (0.33%). Wood energy consumption (WoEC, panel C) receives the highest effect from oil demand shocks (1.65%), followed by aggregate demand shocks (1.37%) and oil supply shocks (1.26%). For waste energy consumption (WsEC, panel D), the highest influence is from oil supply shocks (5.01%), followed by aggregate demand shocks (1.19%) and oil supply shocks (0.99%).

Overall, these results show that it is important to make a double disaggregation for both energy consumption and oil shocks because the impact of each oil shock to each energy consumption is different. The impact of the oil shocks on hydropower consumption is the highest, followed by waste, wood and geothermal energy consumption. Oil supply shocks impact the most on renewable energy consumption while the aggregate demand and oil demand shocks impact differently in function of the energy source. Table 3B on non-renewable energy consumption shows that in general, the impact of oil supply shocks on non-renewable energy is weaker than that on renewable energy consumption. Coal consumption is the most impacted by oil shocks, followed by petroleum and natural gas consumption. Oil demand shocks spillover the most on coal while oil supply shocks impact the most on petroleum consumption.

The above results are valid for the whole period. However, the potential existence of structural breaks in the time series (as addressed in Table 2) raises the question about the time-varying character of the interaction between energy consumption and oil shocks in the U.S. That is why we proceed to the time-rolling window analysis in the next section.

5. ARE THE RESULTS TIME-VARYING?

In this section, we perform the analysis on impulse response functions and dynamic connectedness over numerous sub-periods within a continuous basis. Indeed, each sub-period is composed of 200 months[19] and is rolling with a gap of 1 month. This procedure is called the time-rolling window analysis in which the impulse response function and the spillover effect are measured for each time window. We then present these measures in a graph to examine their variation over time. To make the results' presentation clearer, sub-section 5.1 focuses on renewable energy consumption

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[19] With the window size of 200 months, the first estimation is for August 1990.

while sub-section 5.2 focuses on non-renewable energy consumption. In each sub-section, the first figure presents the time-varying impulse response function of energy consumption to oil shocks and the second one presents the time-varying spillovers from oil shocks to energy consumption.

5.1. Time-varying analysis on renewable energy consumption

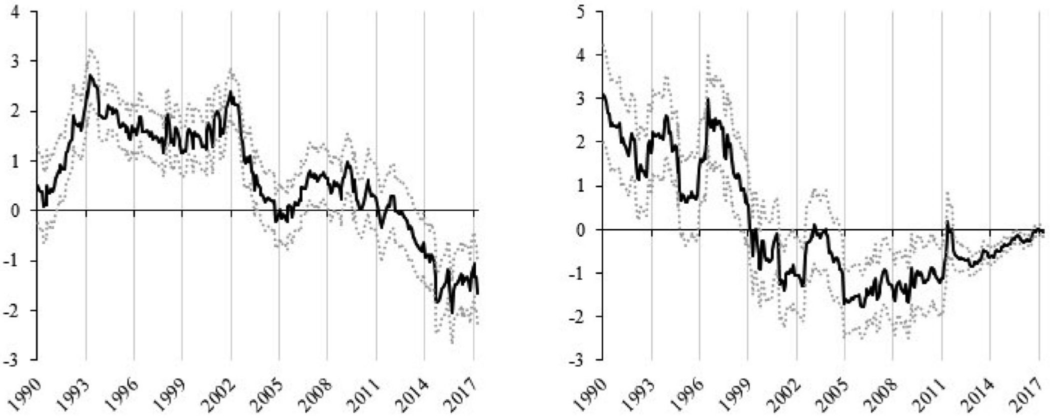
5.1.1 Time-varying impulse responses of renewable energy consumption to oil shocks

Figure 4A presents the time-varying impulse responses of renewable energy consumption to a one standard deviation shock in the oil supply over the 1974–2018 period. Each point on the curve is the impulse response for a time window of 200 months. The dotted lines represent the

Figure 4A: Time-varying impulse responses of renewable energy consumption to one standard-deviation structural oil supply shocks *(SVAR models, point estimates with one-standard-error band)*

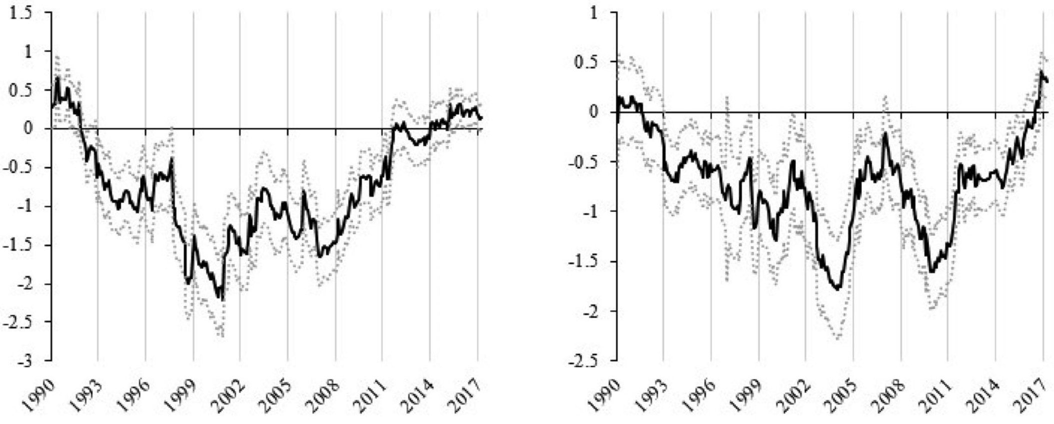
A. Hydroelectric Power Consumption

B. Geothermal Energy Consumption



C. Wood Energy Consumption

D. Waste Energy Consumption



Notes: The impulse response functions (IRFs) are computed using the SVAR estimation on a rolling sample of 200 months with a lag of 1 month between two consecutive windows. The IRFs are indexed by the end dates of each time window in the rolling SVARs and the IRFs at the horizon of 6 months are plotted. 6-month horizon is chosen for the short-run impact of oil because the maximum effect occurs 6 months after the shock. The thick line represents the responses of energy consumption to a 1 standard-deviation variation in oil shocks. The dashed lines represent the confidence intervals with one standard-error bands which were constructed using a recursive-design wild bootstrap (please refer to Goncalves and Kilian 2004).

confidence intervals. Panel A in Figure 4A shows that hydropower consumption responds significantly and positively to oil-supply shocks from 1990 to 2003, insignificantly from 2004 to 2014, and significantly and negatively from 2014 to 2018. The time-varying character of the impact of oil shocks on energy consumption may be partly explained by the most popular renewable *Energy Policy*, the Renewable Portfolio Standard (RPS hereafter) which was initiated in 1997. This policy follows a voluntary approach and each state can choose to enact the standard or not. Under the RPS, retail electricity suppliers are required to purchase a growing amount or percentage of renewable energy over time. Massachusetts was one of the first states to enact an RPS in 1997, followed by Connecticut and Wisconsin in 1998, Maine, New Jersey and Texas in 1999, Arizona, Hawaii and Nevada in 2001, California and New Mexico in 2002, Minnesota in 2003, Colorado, Maryland, New York, Pennsylvania and Rhode Island in 2004, District of Columbia in 2005 (Martinot et al. 2005). In 2017, 29 states plus the District of Colombia adopted an RPS, according to the report of Barbose (2017) from the Lawrence Berkeley National Laboratory. Following this report, the application of the RPS impacts 59% of total electricity retail sales in 2017. So, as and when the RPS is enacted in different states, the proportion of renewable energy consumption changes and thus its relationship with oil shocks.

Panel B in Figure 4A shows the response of geothermal energy consumption to oil supply shocks from 1990 to 2018. It is significantly positive from 1990 to 1999, insignificant from 2000 to 2005, and significantly negative from 2006 to 2018. For wood and waste energy consumption (panels C and D), the behavior is different because their response to oil supply shocks is significantly negative during the whole period, except for 1990–1992 and 2015–2018. These results thus show again that biomass energy consumption is different from other renewable *Energies* like hydropower and geothermal. When oil supply increases, the consumption of biomass energy decreases while the response can be negative or positive for hydropower and geothermal energy consumption in different time periods. This difference may be due to the use of oil in the electricity production from biomass (as we explained above) while it is not the case for hydropower and geothermal energy.

Figure 4B shows the responses of renewable energy consumption to an unanticipated increase of 1 standard deviation in the aggregate demand. First, we note that the amplitude of the response is lower compared to that for oil supply shocks. This suggests that the aggregate demand has a lower influence on renewable energy consumption than oil supply shocks. Second, the response of renewable energy consumption to aggregate demand shocks is more time-varying. For hydropower, it is mostly significantly positive from 1990 to 2011 and significantly negative from 2012 to 2018.

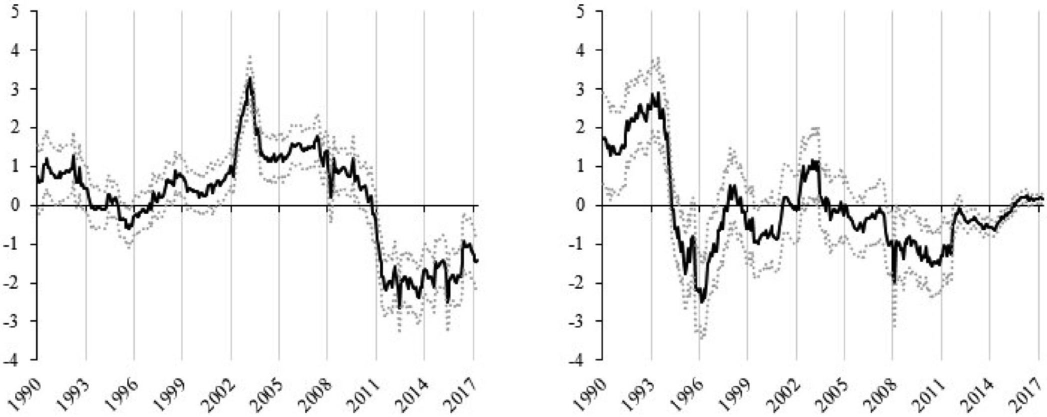
For geothermal energy consumption, it is significantly positive from 1990 to 1994, significantly negative from 1994 to 1997, insignificant from 1998 to 2008, and significantly negative from 2009 to 2016.For wood energy consumption, it is significantly negative most of the time (1999–2008) and significantly positive at the beginning and at the end of the sample period. For waste energy consumption, the behavior is different from wood energy consumption because it is significantly positive from 1990 to 1997, insignificant from 1998 to 2008, significantly negative from 2009 to 2014, and significantly positive from 2015 to 2018. We also notice that there are structural changes in waste energy consumption in 1997 and in 2008. These two dates correspond to the launch of the Renewables Portfolio Standard (RPS) policy in 1997 and the launch of the "Food, Conservation and Energy Act" in 2008 which has a direct impact on the waster energy production (See Table 1 in the Appendix for more details).

Figure 4C shows the impulse responses of renewable energy consumption to oil demand shocks. In most of the time, renewable energy consumption increases after an increasing shock in the oil demand. The highest response amplitude is observed for geothermal energy consumption,

Figure 4B: Time-varying impulse responses of renewable energy consumption to one standard-deviation structural aggregate demand shocks *(SVAR models, point estimates with one-standard-error band)*

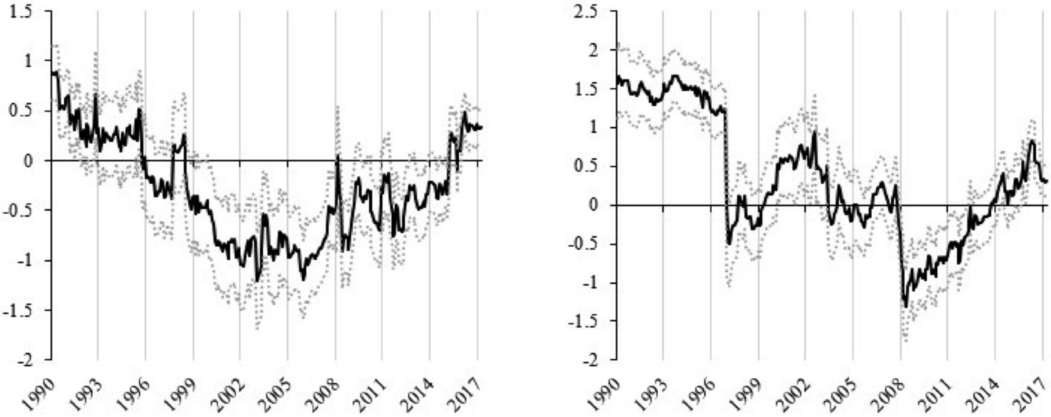
A. Hydroelectric Power Consumption

B. Geothermal Energy Consumption



C. Wood Energy Consumption

D. Waste Energy Consumption



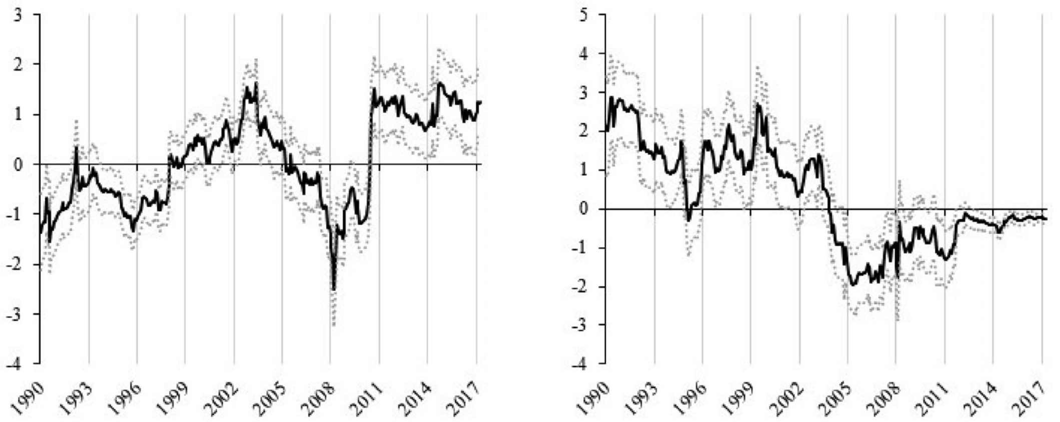
Notes: see notes to Figure 4A.

which is significantly positive from 1990 to 2004 and significantly negative from 2005 to 2018. For hydropower, the reaction is substantially time-varying, showing some periods of positive and negative effects. For biomass energy consumption, the response is mostly positive for wood energy consumption and changing for waste energy consumption (positive from 1990 to 2003 and negative from 2004 to 2018). Overall, the results indicate a substantially time-varying character of energy consumption reaction to oil shocks. This underlines the importance to adapt energy policies to each period.

Figure 4C: Time-varying impulse responses of renewable energy consumption to one standard-deviation structural oil-specific demand shocks *(SVAR models, point estimates with one-standard-error band)*

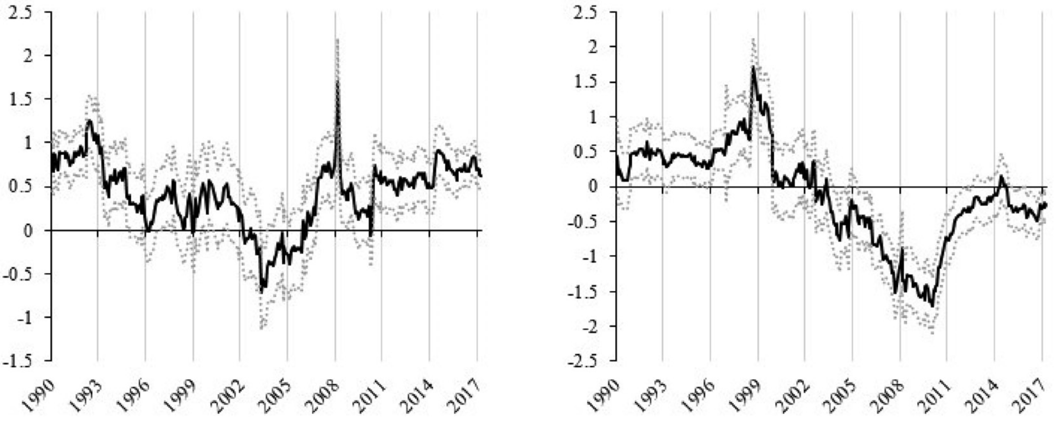
A. Hydroelectric Power Consumption

B. Geothermal Energy Consumption



C. Wood Energy Consumption

D. Waste Energy Consumption



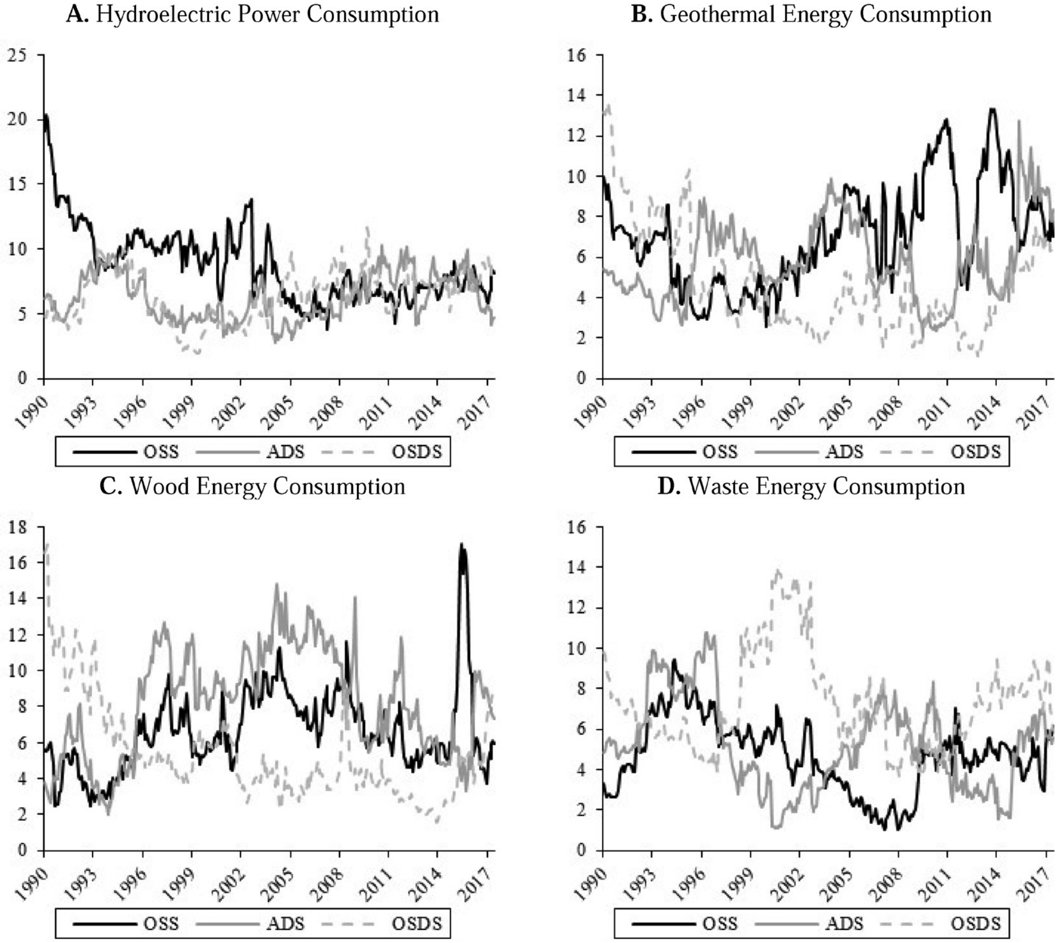
Notes: see notes to Figure 4A.

5.1.2 Time-varying spillovers from oil shocks to renewable energy consumption

Figure 5 presents the time-varying directional spillovers from the three disaggregated oil shocks to renewable energy consumption.

Panel A shows that oil supply shocks contribute the most to the variation of hydropower energy consumption with the highest impact from 1990 to 2004. Panel B shows that oil supply shocks also have the highest influence on geothermal energy consumption with a higher impact from 2005 to 2018. Wood energy consumption is mainly influenced by the aggregate demand shock while waste energy consumption is strongly affected by the oil demand.

Figure 5: Time-varying spillovers from oil shocks to renewable energy consumption



Notes: The directional spillovers are calculated from variance decompositions based on 12-step-ahead forecasts using SVAR estimation (see Section 3.1. for more details) on a rolling sample of 200 observations. The values are indexed by the end dates of the subsamples used in the rolling SVARs. OSS, ADS and OSDS stand for oil supply shocks, aggregate demand shocks and oil-specific demand shocks.

5.2. Time-varying analysis on non-renewable energy consumption

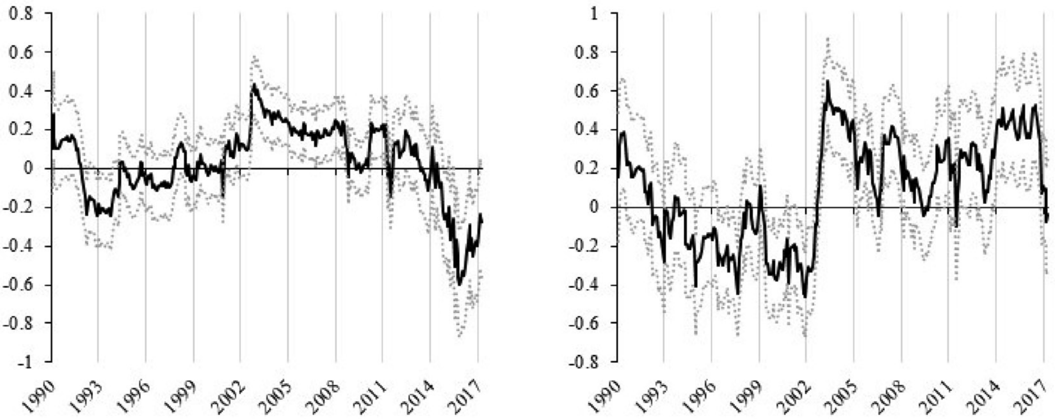
5.2.1. Time-varying impulse responses of non-renewable energy consumption to oil shocks

Figure 6A shows the impulse responses of non-renewable energy consumption to oil supply shocks.

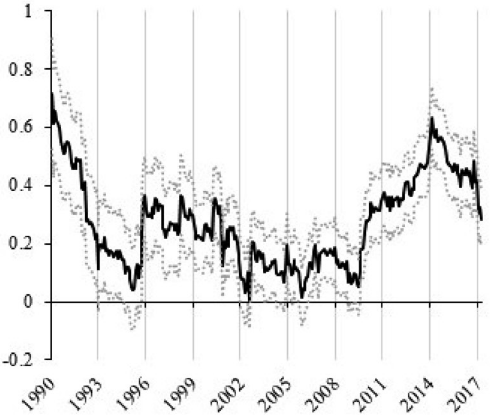
Panel A in Figure 6A shows that the response of coal consumption to oil supply shocks is significant only from 2002 to 2009 and from 2015 to 2017 while the impact is positive in the former period and negative in the latter. For natural gas consumption, the effect is mostly significantly positive from 2002 to 2018. However, for petroleum energy consumption, its response to oil supply shocks remains significant and positive for the whole period. This may be explained by the fact that petroleum is produced from crude oil. Furthermore, we notice that the amplitude of the response of non-renewable energy consumption is smaller than that of renewable energy consumption. This

Figure 6A: Time-varying impulse responses of non-renewable energy consumption to one standard-deviation structural oil supply shocks *(SVAR models, point estimates with one-standard-error band)*

A. Coal Consumption **B.** Natural Gas Consumption



C. Petroleum Consumption



Notes: see notes to Figure 4A.

shows that renewable energy reacts the most to oil shocks because it is considered as an alternative energy source.

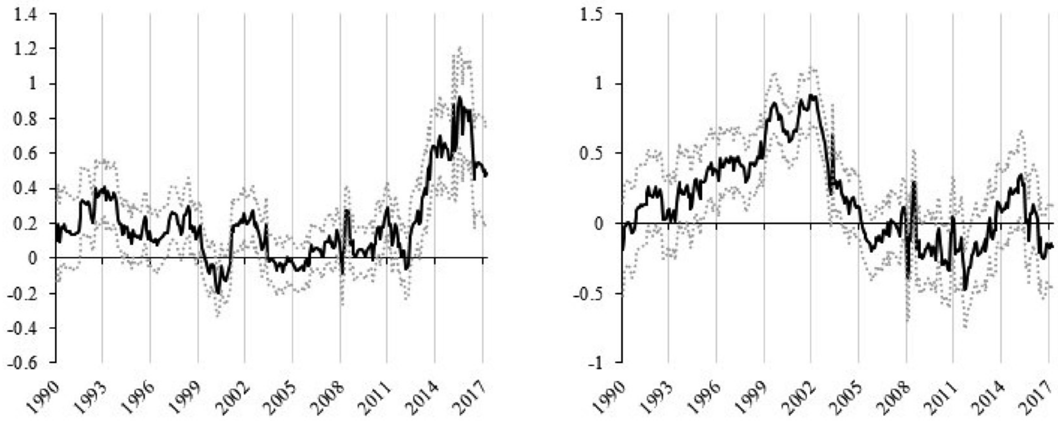
Figure 6B shows the impulse responses of non-renewable energy consumption to aggregate demand shocks. Natural gas consumption responds the most to aggregate demand shocks with a significant and positive value from 1995 to 2004. However, after this period, it is not significant. For coal consumption, the response is also positive but is significant only in two periods, from 1990 to 1999 and from 2012 to 2018. For petroleum, the response is insignificant most of the time, except from 2002 to 2009.

Figure 6C shows that oil-demand shocks affect the most non-renewable energy consumption with significant responses most of the time and a higher amplitude in the response. For coal consumption, the response is significantly positive from 1996 to 2003 and from 2008 to 2018. For natural gas consumption, the response is significant most of the time while being positive from 1990 to 2003 and negative from 2004 to 2011. For petroleum consumption, the reaction to oil demand shocks is significant and negative nearly for the entire sample period. This negative effect may be

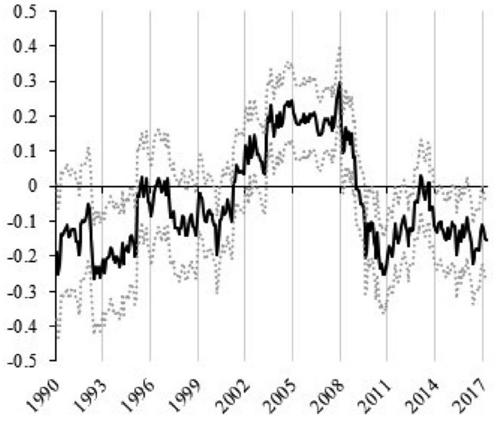
Figure 6B: Time-varying impulse responses of non-renewable energy consumption to one standard-deviation structural aggregate demand shocks *(SVAR models, point estimates with one-standard-error band)*

A. Coal Consumption

B. Natural Gas Consumption



C. Petroleum Consumption



Notes: see notes to Figure 4A.

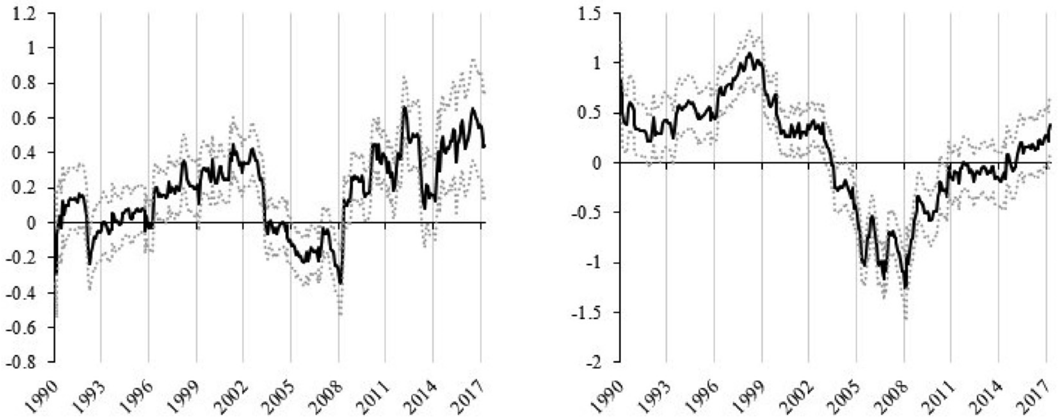
because an unanticipated increase in the oil demand also increases the oil price and this in turn decreases the petroleum consumption, which tends to be substituted by other renewable energy sources (as shown in sections 5.1).

5.2.2 Time-varying spillovers from oil shocks to non-renewable energy consumption

Figure 7 shows the share of the variance of non-renewable energy consumption explained by oil shocks. Panel A shows that oil-specific demand shocks impact the most strongly coal consumption from 1990 to 2010 while the aggregate demand influences it the most from 2011 to 2018. The forecast error variance of natural gas consumption is mostly explained by aggregate demand and oil-specific demand shocks while oil supply shocks mainly influence the variance of petroleum energy consumption, especially in the period from 2002 to 2008.

To summarize all the empirical results above, we provide synthesis tables of the impulse response functions in the whole sample period and in the time-varying context (Tables 5 and 7 in

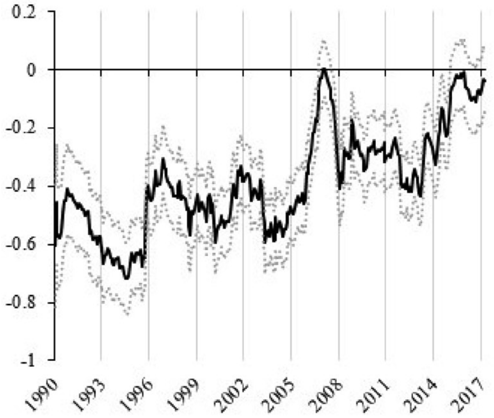
Figure 6C: Time-varying impulse responses of non-renewable energy consumption to one standard-deviation structural oil-specific demand shocks *(SVAR models, point estimates with one-standard-error band)*



A. Coal Consumption

B. Natural Gas Consumption

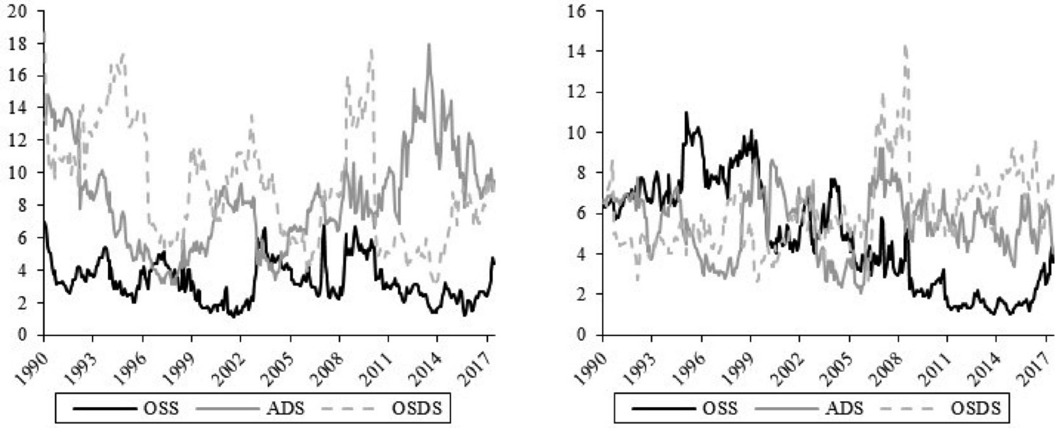
C. Petroleum Consumption



Notes: see notes to Figure 4A.

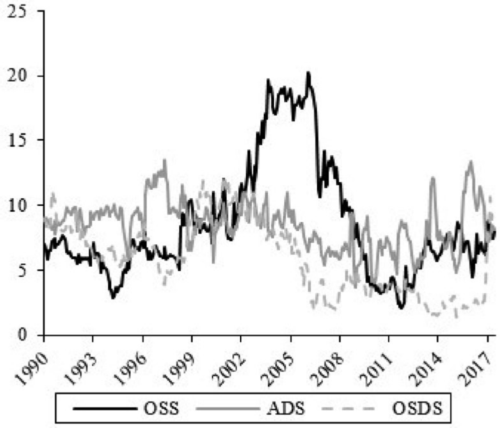
the Appendix), as well as those of the dynamic connectedness measure (Tables 6 and 8 in the Appendix). These synthesis tables allow us to draw the following conclusions. First, wood and waste energy consumption respond the most to all oil shocks while petroleum responds the most to oil specific shocks (supply and demand). Renewable energy consumption responds the most to aggregate demand shocks and oil supply shocks while it is oil specific demand shocks for non-renewable energy consumption. Second, oil shocks spillover the most to hydropower energy consumption while aggregate demand shocks spillover the less. Furthermore, oil shocks spillover the most hydropower, waste, coal and petroleum energy consumption. Third, the time-varying empirical analysis shows that the interaction between oil shocks and energy consumption depends on the period, on the energy source and on the type of oil shocks. In general, we find that energy consumption responds the most to oil shocks over the 1990–2000 and 2008–2018 periods when there were numerous renewable energy policies in the U.S. (1990–2000 as shown in Tables 1–4 in the Appendix) and a global financial crisis (2008–2018). The implications of these results are further analyzed in the next section.

Figure 7: Time-varying spillovers from oil shocks to energy consumption sources



A. Coal Consumption **B.** Natural Gas Consumption

C. Petroleum Consumption



Notes: see notes to Figure 5.

6. CONCLUSION

We have performed a study on the impact of different types of oil shocks on renewable and non-renewable energy consumption produced from hydropower, geothermal, wood, waste, coal, natural gas and petroleum in the U.S. with monthly data from January 1974 to February 2018. The contributions of the paper rely on the disaggregation of both oil shocks and energy sources. Indeed, oil shocks are disaggregated to three levels: oil supply shocks, aggregate demand shocks and oil-specific demand shocks following the Kilian (2009) approach. The disaggregation of energy consumption from various sources was possible thanks to detailed information provided by the US Energy Information Administration (EIA). This double disaggregation is important because oil shocks from the supply or demand sides do not have the same impact on the economy and each energy source requires a different production process. For this reason, we analyze seven different energy consumption components mentioned above. Our empirical methods consist of investigating how each category of energy consumption responds to oil shocks and how oil shocks are spillovered to energy consumption. For that, we rely on the impulse response functions estimated from a SVAR model and the dynamic connectedness measures proposed by Diebold and Yilmaz (2014). Finally, the time-varying estimates of these two measures based on the time-rolling window approach further constitute an important contribution of our study.

Our results show that the three kinds of oil shocks have different impacts on energy consumption. Indeed, wood and waste energy consumption respond the most to oil shocks. This result implies that biomass energy consumption is the most sensitive to oil shocks and energy policies related to biomass should consider this constraint. This strong relationship between biomass energy consumption and oil shocks may be due to the use of oil in the electricity production from biomass (according to the book of National Academy of Sciences 2010). On the other hand, hydropower receives the highest spillover from oil shocks. This result suggests that the potential development of hydropower (see the Hydropower Vision published by the U.S. Department of Energy) should consider the high impact of oil shocks, mostly oil supply and oil demand shocks. We also find that aggregate demand shocks spillovers the less on energy consumption. This result suggests that oil supply and demand shocks have a higher impact on energy consumption than aggregate demand shocks. Thus, policies related to the aggregate demand may not have significant impacts on renewable energy consumption, except for biomass energy consumption which responds significantly to aggregate demand shocks. With non-renewable energy consumption, petroleum consumption behaves differently to oil shocks, compared with coal and natural gas consumption. Indeed, petroleum responds significantly to oil supply shocks while coal and natural gas consumption respond significantly to aggregate demand shocks. This result suggests that policies related to the aggregate demand of the economy has a high impact on natural gas consumption while oil supply and demand shocks have significant impacts on petroleum consumption. Furthermore, oil shocks spillover more on petroleum than on coal and natural gas consumption. Thus, policies related to the oil market would be more efficient in the reduction of petroleum consumption than that of coal and natural gas consumption. Finally, we would suggest using policies related to the aggregate demand of the economy to adjust the consumption of biomass, coal and natural gas consumption while using policies related to oil supply and demand to adjust the consumption of petroleum and hydropower energy consumption. Furthermore, the time-varying analysis shows that the number of energy policies and the existence of economic crises tend to intensify the interaction between oil shocks and energy consumption.

Overall, these findings show that choosing the adequate policy, related to the aggregate demand, oil supply or oil demand, is important regarding its different impacts on each source of energy. The aggregate demand impacts strongly biomass energy consumption while oil supply and demand have a high impact on petroleum and hydropower energy consumption. Thus, mastering the variation of the aggregate demand, oil supply and demand would help accelerate the substitution of fossil fuels by renewable energy given the high potential of this latter in the U.S. According to the REmap-2030 report of the IRENA in 2015,[20] the U.S. can lead the global transition to renewable energy with its rich resources (wind, solar, geothermal, hydro and biomass), its innovation culture, its high financing opportunities and its skilled workforce. The report forecasted that the share of renewable energy would reach 10% by 2030, compared to 7.5% in 2010. The report also indicated that this share can even be at 27% given the potential of renewable energy in the U.S. To attain this objective, the required investment would be $86 billion per year. However, this investment can save about $140 billion annually by 2030 given the improved health and lower CO_2 emissions.

It is however important to note that the withdrawal of the U.S. from the COP21 Paris Agreement on June 1, 2017, has high impacts on the research and development of renewable *Energies* in the U.S. According to Zhang et al. (2017, page 216), in the early 2017, the Environment

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[20] International Renewable Energy Agency. 2015. A renewable energy roadmap—REmap 2030.

Protection Agency (EPA) has had the largest budget cut in 2018 of \$2.6 billion, or 31.4% of the whole budget. The budget for the Department of Energy has been reduced by \$1.7 billion or by 5.6% of the total budget. The budget demand for the NASA was lowered by 0.8% compared to the 2017 implementation level. The research budgets have also been cut for other agencies such as the Web of Science of the US Science Information Research Institution, the US Ministry of Agriculture, the US Geological Investigation Agency, the US National Ocean Atmosphere Management Agency, US Ministry of Energy, US Forestry Agency, and some federal agencies. Face to these difficulties, the near future of renewable energy technologies in the U.S. may be impacted and it is thus important to update the results of this research on a regular basis to adapt to the impact of these budget cuts.

This study has indicated the importance to use the adequate macroeconomic policy related the aggregate demand, oil supply and oil demand to adjust the renewable and non-renewable energy consumption in the U.S. In the future, a study at regional level in the U.S. would be of interest since Rausch and Karplus (2014) found that there is a heterogeneity in the response of different states to regulatory policies regarding the climate policy proposals. Furthermore, the natural resources and the political considerations can be different in other countries. That is why we would suggest the application of this research method on other countries to suggest appropriate policy actions for each country. It is also interesting to investigate how behavioral science can impact the decision of energy consumption at state and country levels, as demonstrated by Hahn and Metcalfe (2016).

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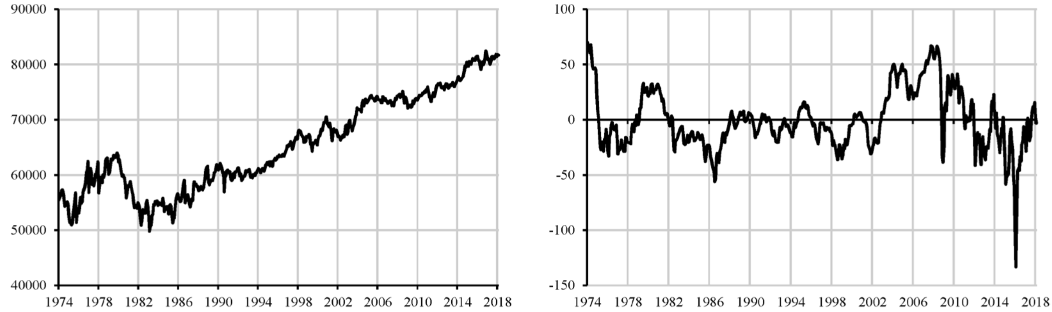
APPENDIX

Figure A: Time trend of oil supply, global economic activity and real oil prices

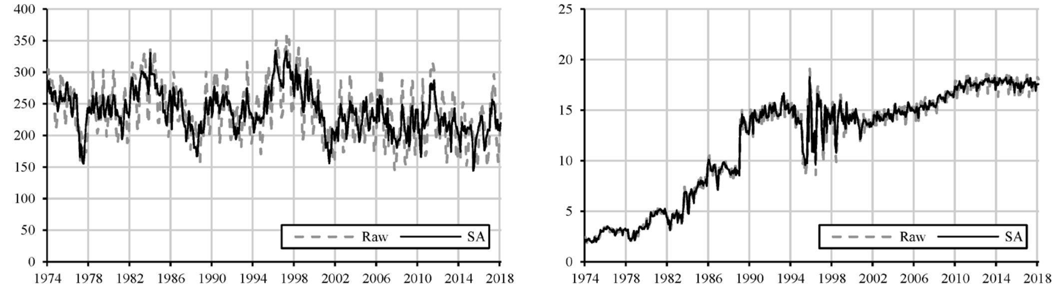


A. World oil supply

B. Global real economic activity

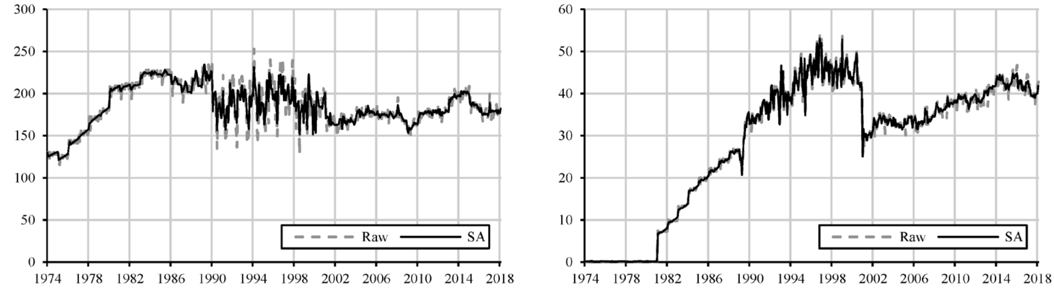
C. Real oil prices (USD / barrel)

Figure B: Time trend of renewable energy consumption and seasonal adjustment



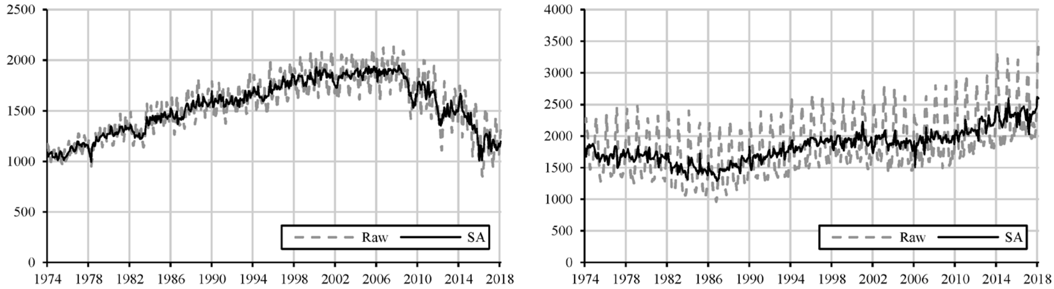
A. HPC (Trillion Btu)

B. GEC (Trillion Btu)



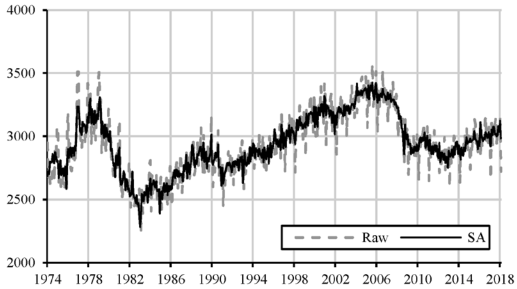
C. WoEC (Trillion Btu)

D. WsEC (Trillion Btu)



E. Coal Consumption

F. Natural Gas Consumption



G. Petroleum Consumption

Notes: "Raw" is for raw series, "SA" is for seasonal adjustment. HPC = Hydropower energy consumption, GEC = Geothermal energy consumption, WoEC = Wood energy consumption, WsEC = Waste energy consumption, "Btu" stands for British thermal unit which is the amount of heat required to raise the temperature of 1 pound of liquid water by 1-degree Fahrenheit at a constant pressure of one atmosphere.

Table 1: Energy policies related to multiple renewable energy sources in the US, 1978–2016

Year	Policy title	Policy type	Policy target
1978	Public Utilities Regulatory Policy Act (PURPA) enacted	In 2017: 29 RPS States plus the District of Colombia (most after 2000)	
1978	*Energy Tax Act provided personal income tax credits and business tax credits for renewables*		
1980	*Federal R&D for renewable energy peaked at 1.3 billion USD (in 1980 USD)*		
1980	*Windfall Profits Tax Act gave tax credits for alternative fuels production and alcohol fuel blending*		
1981	Economic Recovery Act	Economic instruments, fiscal and financial incentives	Multiple RE sources
1986	Tax Reform Act (Superseded)	Economic instruments, fiscal and financial incentives	Solar and Geothermal
1986	Modified Accelerated Cost Recovery System (MACRS) (updated in 2008) (in force)	Economic instruments, fiscal and financial incentives	Wind (Onshore), Geothermal, Solar Thermal, Wind (Offshore)
1992	*California delayed property tax credits for solar thermal power, which caused investment to stop*		
1992	*Energy Policy Act provides tax credits for ethanol fuels for vehicles*		
1992	Energy Efficient Mortgages (in force)	Grants and subsidies	Multiple RE sources
1992	Renewable Energy Production Incentives (REPI)	Fiscal and financial incentives	Multiple RE sources
1992	Federal Business Investment Tax Credit (ITC)	Fiscal and financial incentives	Solar thermal, Geothermal, Solar Photovoltaic
1993	Environmentally Preferable Purchasing (EPP)	Direct investment, procurement rules, information and education, advice and aid	Multiple RE sources
1994	*Federal production tax credit (PTC) takes effect as part of the Energy Policy Act of 1992*		
1994	Federal Utility Partnership Working Group (FUPWG) (in force)	Information and education	Multiple RE sources
1994	Tribal Energy Program (In force)	Fiscal and financial incentives, advice and aid in implementation, information and education, etc.	Wind, Solar photovoltaic
1996	*Net metering laws started to take effect in many states*		
1996	Building Energy Software Tools Directory (Ended)	Information and education	Multiple RE sources
1996	State Energy Program (In force)	Grants and subsidies, information and education, advice and aid in implementation	Multiple RE sources

1997	*States began establishing policies for Renewables Portfolio Standards (RPS) and Public Benefits Funds (PBF) as part of state electricity restructuring*		
1997	Renewable Portfolio Standard - Massachusetts (Amended 2002, 2008, in force)	Codes and standards	Multiple RE sources (power)
1998	Workforce Investment Act of 1998 (Ended)	Grants and subsidies	Multiple RE sources
1999	Tax Relief Extension Act of 1999 (Ended)	Fiscal and financial incentives	Multiple RE sources
1999	Green Parks Plan (Superseded)	Direct investment, infrastructure investment, information and education	Multiple RE sources
2001	*Some states began to mandate that utilities offer green power products to their customers*		
2001	Clean Energy Supply Programs (In force)	Voluntary approaches, negotiated agreements, information and education, advice and aid in implementation, RD&D, technology development	Multiple RE sources
2001	The Economic Security and Recovery Act of 2001 (Ended)	Fiscal and financial incentives	
2001	Green Power Partnership (Superseded)	Unilateral commitments (private sector), information and education, advice and aid in implementation	Multiple RE sources
2002	*Federal production tax credit (PTC) expired and was not renewed until later in the year, causing the wind industry to suffer a major downturn. This happened in 2000 and again in 2004*		
2002	New York State Energy Plan (In force)	Strategic planning and policy support	Multiple sources (power)
2002	Renewable Portfolio Standard - California (In force)	Regulatory instruments, codes and standards, obligation schemes	Multiple RE sources (power)
2003	Self-generation Incentive Program - California (In force)	Grants and subsidies	
2004	Five new states enacted RPS policies in a single year, bringing the total to 18 states plus Washington DC; PBF were operating in 15 states.	Policies and incentive per state	http://www.dsireusa.org/
2004	Hydrogen and Fuel Cells Programs (In force)	RD&D, technology deployment and diffusion, information and education	Multiple RE sources
2004	Renewable Portfolio Standard (In force, amended in 2007 and 2010)	Regulatory instruments, codes and standards, obligation schemes	Multiple RE sources (power)
2005	Interconnection Standards for Small Generators (In force)	Codes and standards	Multiple RE sources (power)

2005	State Climate and Energy Program (In force)	Strategic planning, information and education, advice and aid in implementation, institutional creation	Multiple RE sources
2005	Energy Policy Act of 2005 (Energy Bill) (In force)	Codes and standards, fiscal and financial incentives, grants and subsidies, RD&D, regulatory instruments	Multiple RE sources, bioenergy co-firing with fuels
2005	Clean Energy - Environment State Partnership Program (Superseded)	Strategic planning, information and education, advice and aid in implementation, institutional creation	Multiple RE sources
2005	Renewable Portfolio Standard - Nevada (In force)	Regulatory instruments, codes and standards, obligation schemes	Multiple RE sources (power, wind, bioenergy, hydropower, solar))
2005	State Utility Commission Assistance (Superseded)	Negotiated agreements (public and private sector), information and education, advice and aid in implementation,	Multiple RE sources (power, CHP)
2006	Section 1703/1705 Loan Guarantee Program (In force)	Fiscal and financial incentives, loans and economic instruments	Multiple RE sources
2006	Maryland Clean Energy Production Tax Credit (Ended)	Fiscal and financial incentives, tax relief	Multiple RE sources (power)
2006	Credit for holders of Clean Renewable Energy Bonds (CREBs) (In force)	Fiscal and financial incentives, taxes	Multiple RE sources
2006	Residential Energy Efficient Property Credit (In force, amended in 2008 and 2009)	Fiscal and financial incentives, tax relief	Wind, Geothermal, Solar (thermal and photovoltaic)
2007	Renewable and Energy Efficiency Portfolio Standard - Illinois (In force)	Codes and standards, obligation schemes	Wind, Bioenergy, Hydropower, Solar
2007	Community Renewable Energy Deployment Grants (Ended)	Direct investment, funds to sub-national governments, fiscal and financial incentives, grants and subsidies	Solar, Geothermal, Wind, Bioenergy, Ocean
2008	Energy Provisions - National Defense Authorization Act for fiscal year 2009 (Ended)	Monitoring economic instruments, direct investment, procurement rules, RD&D, technology deployment and diffusion, mandatory requirements	Wind, bioenergy (biofuels for transports, solar (photovoltaic)
2008	Energy Improvement and Extension Act 2008 - Tax incentives (Superseded)	Fiscal and financial incentives, tax relief	Wind, bioenergy (biofuels for transports), biomass for heat, biomass for power, geothermal for heat, geothermal for power, ocean (tidal and wave), solar
2008	Federal Fleet Fueling Centers (Ended)	Codes and standards, direct investment, infrastructure investments, mandatory requirements	Multiple RE sources
2008	Food, Conservation, and Energy Act of 2008 (Superseded)	RD&D, fiscal and financial incentives, tax relief, grants and subsidies	Wind, bioenergy, geothermal, hydropower, solar

2008	Energy Independence and Security Act of 2007 (In force)	Policy support, strategic planning	Multiple RE sources
2008	Western Renewable Energy Zones (WREZ) Project (Ended)	Strategic planning	Multiple RE sources
2008	Rural Energy for America Program (REAP) (In force)	Fiscal and financial incentives, loans, grants and subsidies	Multiple RE sources
2008	Technology Commercialization Fund (Ended)	RD&D, technology deployment and diffusion	Multiple RE sources
2009	Bureau of Land Management Renewable Energy Resources (In force)	Fiscal and financial incentives, grants and subsidies, strategic planning, information and education	Multiple RE sources
2009	Executive Order 13514: Federal Leadership in Environmental, Energy, and Economic Performance (In force)	Direct investment, procurement rules, policy support, institutional creation	Multiple RE sources
2009	Partnership for Sustainable Communities (In force)	Fiscal and financial incentives, grants and subsidies, information and education, advice and aid in implementation	Multiple RE sources
2009	American Recovery and Reinvestment Act: Appropriations for Clean Energy (Ended)	RD&D, technology deployment and diffusion, fiscal and financial incentives, grants and subsidies, direct investment, procurement rules,	Multiple RE sources
2009	Climate Showcase Communities Grant Program (In force)	Fiscal and financial incentives, grants and subsidies, advice and aid in implementation, funds to sub-national governments	Multiple RE sources
2009	American Recovery and Reinvestment Act of 2009: Tax-based provisions (Ended)	Fiscal and financial incentives, grants and subsidies, funds to sub-national governments, tax relief	Multiple RE sources
2012	US Africa Clean Energy Finance (US-ACEF) Initiative (In force)	Fiscal and financial initiative, grants and subsidies	Multiple RE sources (power)
2013	US Climate Action Plan (In force)	Strategic planning, policy support	Multiple RE sources
Multiple years	State-level Renewable Portfolio Standards (RPS) (In force)	Codes and standards, obligation schemes	Multiple RE sources

Notes: Sources from Martinot et al. (2005) in *italic*, from the IEA and IRENA in normal form. IEA denotes International Energy Agency and IRENA denotes International Renewable Energy Agency.

Table 2: Energy policies related to water renewable energy in the US, 2016

Policy title	Year	Policy status	Policy type	Policy target
Hydroelectric Production Incentive Program	2016 (July 29)	In force	Economic instruments	Hydropower
Water Power Technologies Office (WPTO)	2016 (Nov 1st)	In force	RD&D, demonstration project, information and education	Water (power)

Notes: Sources from the IEA and IRENA. IEA denotes International Energy Agency and IRENA denotes International Renewable Energy Agency.

Table 3: Energy policies related to geothermal renewable energy in the US, 1977–2008

Title	Year	Policy status	Policy type	Policy target
Geothermal Energy Research, Development and Demonstration Act	1974	Superseded	RD&D	Geothermal
Geothermal Technologies Office (GTO)	1977	In force	RD&D, Technology deployment and diffusion, Information and education, Advice and aid in implementation, etc.	Geothermal
Geothermal Resource Leasing and Geothermal Resources Unit Agreements	2007	Superseded	Direct investment, funds to sub-national governments, infrastructure investments	Geothermal power and heat
Center for Geothermal Technology Transfer	2008	Ended	Information and education	Geothermal

Notes: Sources from the IEA and IRENA.

Table 4: Energy policies related to biomass renewable energy in the US, 1980–2008

Policy title	Year	Policy status	Policy type	Policy target
Biomass Energy and Alcohol Fuels Act of 1980	1980	Superseded		Bioenergy-Biofuels for transport
Biomass Research and Development Act	2000	Ended	Regulatory instruments, codes and standards, fiscal and financial incentives, grants and subsidies, policy support, RD&D, regulatory instruments	Bioenergy
Biomass Research and Development Initiative (BRDI)	2002	In force	RD&D, technology deployment and diffusion, demonstration project	Bioenergy
Woody Biomass Utilization Initiative	2003	In force	Grants and subsidies	Co-firing with fossil fuels

Notes: Sources from the IEA and IRENA.

Table 5: A synthesis of the results on impulse response functions

Energy consumption	The significance and sign of the impulse response to oil shocks
Oil supply shocks (OSS)	
Hydropower	Not significant in the first months and negative then
Geothermal	Not significant
Wood	Significant and negative
Waste	Significant and negative
Coal	Not significant
Natural gas	Not significant
Petroleum	Significant and positive
Aggregate demand shocks (ADS)	
Hydropower	Not significant
Geothermal	Not significant
Wood	Significant and positive
Waste	Significant and positive in the first months only
Coal	Significant and positive
Natural gas	Significant and positive
Petroleum	Insignificant
Oil specific demand shocks (OSDS)	
Hydropower	Significant and negative most of the time
Geothermal	Not significant
Wood	Significant and positive
Waste	Significant and negative
Coal	Significant and positive
Natural gas	Significant and positive
Petroleum	Significant and negative

Notes: This table shows a synthesis of the results of the impulse response function of energy consumption to the three oil shocks over the whole sample period (1974–2018). This table is a synthesis of Figures 2A, 2B, 2C, 3A, 3B and 3C in the main text.

Table 6: A synthesis of the results on the spillover from oil shocks to energy consumption

Energy consumption	The order of the spillover from oil shocks
Hydropower	OSDS, OSS, ADS (11.14%)
Geothermal	OSS, OSDS, ADS (9.23%)
Wood	OSDS, ADS, OSS (9.68%)
Waste	OSS, ADS, OSDS (11.02%)
Coal	OSDS, ADS, OSS (11.36%)
Natural gas	OSS, OSDS, ADS (9.57%)
Petroleum	OSS, OSDS, ADS (11.18%)

Notes: OSS denotes oil supply shocks. ADS denotes aggregate demand shocks. OSDS denotes oil specific demand shocks. The figure in the parentheses indicates the degree of the total connectedness between the three oil shocks and each energy consumption. The higher the figure, the higher the share of the variation of energy consumption coming from the three oil shocks. The order of the oil shocks indicates the order of the strength of the spillover from oil shocks to energy consumption. For example, to hydropower energy consumption, OSDS spillovers the most, followed by OSS and finally by ADS. The figure "11.14%" means the share of the variation of energy consumption coming from the three oil shocks. This table is a synthesis of Tables 3A and 3B in the main text.

Table 7: A synthesis of the results on the time-rolling window impulse response functions

Energy consumption	**Significance, sign and period of the impulse response to oil shocks**
Oil supply shocks (OSS)	
Hydropower	Significant and positive (1990–2003), insignificant (2004–2013), significant and negative (2014–2018)
Geothermal	Significant and positive (1990–1999), insignificant (2000–2018)
Wood	Significant and positive (1990–1992), significant and negative (1993–2011), insignificant (2012–2018)
Waste	Insignificant (1990–1993), significant and negative (1994–2015), insignificant (2016–2018)
Coal	Insignificant (1990–2015), significant and negative (2016–2018)
Natural gas	Insignificant (1990–2002), significant and positive (2003–2018)
Petroleum	Significant and positive (whole period)
Aggregate demand shocks (ADS)	
Hydropower	Significant and positive (1990–1990), insignificant (1994–1998), significant and positive (1999–2010), significant and negative (2011–2018)
Geothermal	Significant and positive (1990–1994), significant and negative (1995–1997), insignificant (1998–2008), significant and negative (1999–2015), significant and positive (2016–2018)
Wood	Significant and positive (1990–1996), insignificant (1997–1997), significant and negative (2000–2006), significant and positive (2007–2018)
Waste	Significant and positive (1990–1997), insignificant (1998–2000), significant and positive (2001–2003), insignificant (2004–2008), significant and negative (2009–2012), insignificant (2013–2015), significant and positive (2016–2018)
Coal	Significant and positive (1990–1999), insignificant (2000–2001), significant and positive (2002–2003), insignificant (2004–2012), significant and positive (2013–2018)
Natural gas	Insignificant (1990–1995), significant and positive (1996–2005), insignificant (2006–2018)
Petroleum	Insignificant (1990–2003), significant and positive (2004–2009), significant and negative (2010–2018)
Oil specific demand shocks (OSDS)	
Hydropower	Significant and negative (1990–1998), significant and positive (1999–2005), insignificant (2006–2010), significant and positive (2011–2018)
Geothermal	Significant and positive (1990–2003), significant and negative (2004–2018)
Wood	Significant and positive (1990–1995), insignificant (1996–2006), significant and positive (2007–2018)
Waste	Significant and positive (1990–2000), insignificant (2001–2003), significant and negative (2004–2018)
Coal	Insignificant (1990–1996), significant and positive (1997–2003), insignificant (2004–2008), significant and positive (2009–2018)
Natural gas	Significant and positive (1990–2003), significant and negative (2005–2011), insignificant (2012–2014), significant and positive (2015–2018)
Petroleum	Significant and negative (1990–2014), insignificant (2015–2018)

Notes: This table shows the impulse response of energy consumption to oil shocks in a time-varying context. The indicated significance and sign correspond to the period between parentheses. This table is a synthesis of Figures 41, 4B, 4C, 6A, 6B and 6C in the main text.

Table 8: A synthesis of the results on the time-rolling window impulse response functions

Energy consumption	**The oil shock with the strongest spillover**
Hydropower	OSS the highest (1990–2003)
Geothermal	OSS the highest (2006–2014)
Wood	ADS the highest (1995–2011)
Waste	OSDS the highest (1997–2003)
Coal	OSDS the highest (1990–2010)
Natural gas	OSDS the highest (2005–2018)
Petroleum	OSS the highest (2002–2006)

Notes: This table shows the oil shock that spillovers the most to each energy consumption. OSS denotes oil supply shocks. ADS denotes aggregate demand shocks. OSDS denotes oil specific demand shocks. The period inside the parentheses indicates the period in which the spillover is the highest. This table is a synthesis of Figures 5 and 7 in the main text.