Renewable energy shocks and the US macroeconomy

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ARTICLE INFO

Keywords:
Renewable energy consumption
Vector autoregressions
Inflation
Output
Wages

ABSTRACT

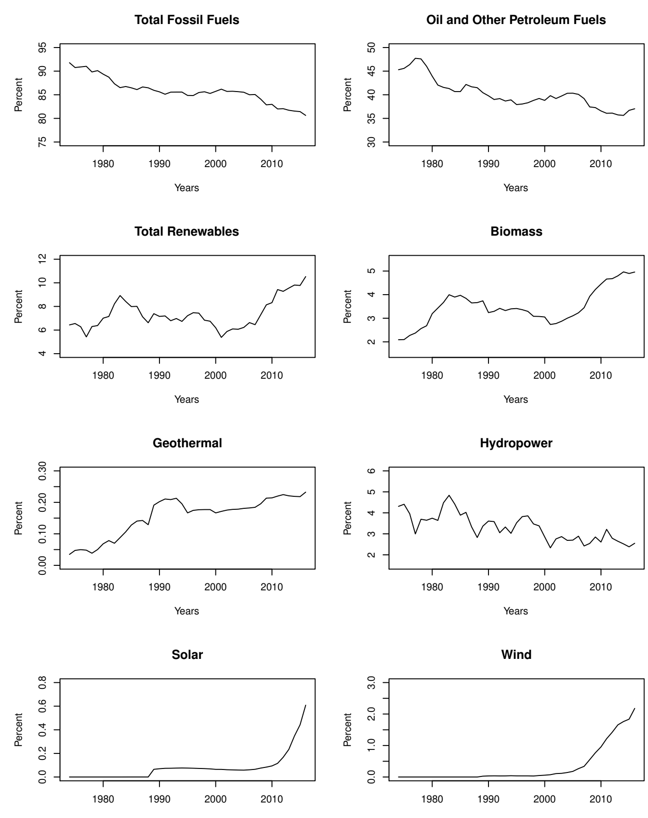
The U.S. is on the precipice of a renewable energy revolution. Concerns about climate change, the U.S. dependence on foreign oil, and changes in the price and volatility of nonrenewable energy sources have led to government incentive programs and policies that have caused an unprecedented growth in U.S. renewable energy consumption. This article provides estimates of the response of various macroeconomic variables to a renewable energy shock. Using a structural VAR model with monthly data from 1976:1 to 2018:12, we find that aggregate output, prices, and wages all rise following a shock to renewable energy consumption, while the unemployment rate falls. Disaggregate analyses show that the macroeconomic response is mostly driven by shocks to biomass consumption.

1. Introduction

The literature on the macroeconomic effects of oil shocks has produced overwhelming evidence that higher energy prices are followed by a reduction in output.[1] While energy shocks are still contractionary, it is now widely accepted (see e.g. Blanchard and Gali (2007); Bachmeier and Cha (2011); Baumeister and Peersman (2013), Blanchard and Riggi (2013), and Sardar and Sharma (2022)) that the response has weakened relative to the 1970s. Blanchard and Gali (2007) argue that one of the factors driving this change has been a smaller share of oil and other petroleum products in production and consumption. Barsky and Kilian (2001), De Gregorio et al. (2007), Edelstein and Kilian (2007, 2009), Herrera and Pesavento (2005, 2009), and Blanchard and Riggi (2013) also make similar arguments and document similar findings.

The decreased importance of oil and other fossil fuel energy sources has coincided with an increase in the share of renewable energy in consumption and production (Zhou and Ang, 2008). Figure 1 shows the breakdown of total U.S. primary energy consumption by source. The share of U.S. energy coming from fossil fuels has steadily declined over time, from over 90% in the 1970s to under 80% in 2018, primarily due to a smaller share of oil and other petroleum products. There has been a corresponding increase in renewable energy's share, from 6% in the 1970s to over 12% in 2018. Electricity generated with renewable energy sources exceeded electricity generated with coal in 2019.[2] Among the different renewable energy sources, the expansion has occurred primarily in biomass (which includes ethanol) and, to a lesser extent, wind.

Figure 1: Percent of total primary energy consumption by various energy sources



Source: Energy Information Administration, U.S. Department of Energy

Several explanations for the increased use of renewables have been proposed, including the increased volatility of oil and other nonrenewable energy prices (Rentschler, 2013); the U.S. dependence on foreign energy (Bowden and Payne, 2010); the environmental consequences of carbon emissions and climate change (Zweibel, Mason and Fthenakis (2008), Wang, Zhou, Zhou and Wang (2011), Zhou, Jin and Fan (2016)); and various government energy incentive programs that provide subsidies, rebates, and tax credits for renewable energy production, the installation of renewable energy

[*] This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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[1] See Bachmeier and Plante (2019) for a review of the literature and references. A small sampling of the literature includes Hamilton (1983, 1996, 2003), Lee and Ni (2002), Balke et al. (2002), Kilian (2008a,b, 2009), Atems et al. (2015), Atems and Melichar (2019).

[2] https://edition.cnn.com/2019/06/11/business/renewable-energy-coal-capacity/index.html

systems, renewable energy portfolio standards, and the creation of markets for renewable certificates (Kaygusuz (2007) Apergis and Payne (2010), Zhou et al. (2022)).[3] Macroeconomic indicators such as output, prices, and the unemployment rate are important barometers of performance. Policymakers monitor them to assess economic health and possible future interventions Mügge (2018). Despite this growth in renewable energy consumption, there has not been much research on the macroeconomic effects of the shift from nonrenewable to renewable energy. One important characteristic of renewable energy is that it is produced domestically.

This paper investigates the behavior of macroeconomic aggregates following a shock to renewable energy consumption.[4] We add measures of renewable energy consumption to a standard structural vector autoregressive (VAR) model that has been used previously to measure the macroeconomic effects of energy price shocks (see e.g. Blanchard and Gali (2007); and Ramey and Vine (2011)). Our main finding is that a shock to renewable energy consumption results in significant increases in aggregate output, consumer prices, commodity prices, and wages, and a decrease in the unemployment rate. The magnitude and persistence of the responses vary depending on the renewable energy source. In particular, the macroeconomic responses following a shock to biomass consumption mimic the responses to total renewable energy consumption, while in some cases, the responses to a shock to geothermal, hydropower, solar, and wind differ noticeably. We find that, on average, over 8.4% of the long run variation in aggregate output can be attributed to changes in the share of renewables in overall energy consumption.

The next section discusses our empirical methodology and the interpretation of impulse responses. Section 3 clarifies the mechanism by which a shock to renewable energy consumption can affect the macroeconomy. Section 4 discusses our findings. Section 5 concludes.

2. Methodology

2.1. VAR Model

We start with a reduced-form VAR model of seven variables:

$$Y_t = A(L)Y_{t-1} + U_t \tag{1}$$

where $Y_t = \left(E_t, P_t, C_t, W_t, X_t, N_t, R_t\right)'$ includes a measure of nonrenewable energy prices, nonenergy consumer prices, nonenergy commodity prices, nominal hourly wages of private nonproduction employees, the industrial production index (output), the unemployment rate, and the measure of renewable energy consumption; $U_t = (U_{Et}, U_{Pt}, U_{Ct}, U_{Wt}, U_{Xt}, U_{Nt}, U_{Rt})'$ is the corresponding vector of reduced-form residuals; L is the lag operator; and $A(\cdot)$ is a polynomial in L. The lag length is determined by minimizing the Akaike Information Criterion (AIC). Our findings are generally unchanged when using other lag selection criteria.

All data are monthly covering the period 1976:1-2018:12, except data on wind energy, and solar energy consumption, which respectively cover the periods 1983:1-2018:12 and 1984:1-2018:12. The dataset includes data on the U.S. industrial production index to measure aggregate output, the U.S. Producer Price Index (PPI) for energy goods to measure nonrenewable energy prices, the PPI less energy to measure nonenergy commodity prices, the various measures of renewable energy consumption, the civilian unemployment rate, the U.S. Consumer Price Index for All Urban Consumers (CPI) less energy, and the average hourly wages of nonsupervisory employees. The data on output, nonrenewable energy prices, commodity prices, the unemployment rate, CPI, and wages, were collected from the Federal Reserve Economic Database (FRED) of the Federal Reserve Bank of Saint Louis.

Data on renewable energy consumption are expressed as a share of total primary energy consumption and come from the U.S. Department of Energy (Energy Information Administration - EIA). This is conventional in this literature (see e.g. Sadorsky (2009), Mishra et al. (2009), Chow et al. (2003)). Disaggregate measures on renewable energy are also available from the EIA. We consider the five most commonly used renewable energy sources, namely biomass (which includes wood and wood waste, municipal solid waste, landfill gas and biogas, ethanol, and biodiesel), hydropower, geothermal, wind, and solar. Figure 1 shows the share of total U.S. primary energy accounted for by various energy sources. From the figure, it is apparent that while the shares of oil and other fossil fuel-based energy sources in total primary energy have generally declined over time, the share of renewable energy sources have typically risen.

To ensure we are working with stationary variables, we take the first difference of the logarithm of all the variables (except the unemployment rate) used in this paper. Expressing the variables in log first differences is supported by several unit root tests.[5]

2.2. Identification

Following the convention in the SVAR literature, we assume the residuals, U_t, from (1) are related to the structural shocks according to $U_t = B_0^{-1}\varepsilon_t$, where ε_t denotes the structural shocks. Equation (1) can then be rewritten in terms of ε_t by premultiplying by B_0:

$$B_0 Y_t = B(L)Y_{t-1} + \varepsilon_t \tag{2}$$

[3] The U.S. shale revolution raised the total domestic energy production. By 2021, the U.S. produced 75% of its crude oil and 90% of its natural gas supply. According to Shepard and Pratson (2022), these figures fueled the common misconception of U.S. energy independence. The Russian invasion and the subsequent oil import ban provided evidence for their argument. The March, 2022 ban exacerbated the already increasing average domestic gasoline prices.

[4] In the context of structural vector autoregressive (VAR) models, a shock represents an exogenous change in one variable of the system. For example, Blanchard and Quah (1989) famously estimated the impact of aggregate supply and aggregate demand shocks on output and unemployment using structural VAR models.

[5] The Augmented Dickey-Fuller (ADF) and the Elliott et al. (1992) Dickey-Fuller generalized least squares (DF-GLS) tests both support taking the log first difference of most of the variables.

where $B(L) = B_0 A(L)$. The ordering of the first six variables in Y_t is similar to Blanchard and Galí (2009) and Ramey and Vine (2011). In the former, Y_t includes, in this order, the nominal price of oil, the CPI, the GDP deflator, wages, GDP, and employment. In the latter, Y_t includes the nominal oil price, the CPI, the GDP deflator, nominal nonfarm compensation, real GDP, and nonfarm business hours.[6] Given the sluggishness of economic activity and aggregate wages and prices, we assume that aggregate quantities and prices do not respond to shocks to renewable energy consumption within the same month, but affect renewable energy consumption on impact. This implies the system (2) has a recursive structure, allowing impulse response functions to be computed using the Cholesky decomposition. Of greatest interest is the response to ε_R, the shock to the equation for renewables consumption. Given its centrality to our analysis, we elaborate on the interpretation of ε_R below.

2.3. What our model identifies

This section clarifies the interpretation we attach to the responses to ε_R. We do not interpret ε_R as an exogenous movement in renewable energy consumption. It would not be reasonable to attempt to identify the effect of shocks to renewables that do not also affect nonrenewables, as the two are substitutes, and one of the goals of policies to increase renewables consumption is to decrease nonrenewables consumption. Even if we were able to reliably identify exogenous variation in renewables, doing so would not answer an interesting question.

Our goal is to identify the effect of a shift from nonrenewable to renewable energy consumption on the macroeconomy. The shock ε_R can be interpreted as a composite of the underlying causes of this shift, including factors such as changes in policy, changing consumer preferences, and so on. Whatever is the underlying reason for the observed ε_R at a point in time, we are able to capture the impact of that change with our impulse response functions, which is a weighted average of the (unidentified) underlying shocks causing the shift. The largest category of renewables is biomass, which includes ethanol production, so the effect of a change in aggregate renewables consumption is driven largely by the effect of increased ethanol production on the U.S. economy. This effect is in turn determined by the effect on agriculture and the process of converting agricultural products into fuel. There is no need to identify the underlying determinants of ε_R.

One potential concern for identification is that ε_R is capturing changes in economic activity. That would be problematic, because an increase in economic activity would cause both renewable and nonrenewable consumption to rise, and the response to ε_R would no longer be a measure of the effect of a shift from nonrenewable to renewable energy. We investigated this possibility further by computing the correlation of our identified renewables shocks with the aggregate demand shock of Kilian (2009). For all categories of renewables, the correlation was both close to zero in magnitude and not significantly different from zero. These results can be found in the attached not-for-publication appendix. Kilian's aggregate demand shock is widely used in the literature, and importantly, it is external to our empirical model. We conclude that ε_R is capturing the shift from nonrenewables to renewables rather than changes in economic activity that affect both variables.

2.4. Causes of the shift to renewable energy

Our goal is to estimate the effect of a shift from nonrenewable to renewable energy consumption on the macroeconomy. This section discusses some of the driving forces behind that shift. While several of the highlighted processes unfold over the long run, their progressive impact on renewable consumption is our focus.

2.4.1. *Costs of greenhouse gas emissions and climate change*

Greenhouse gas emissions from the burning of fossil fuels have played a large role in the unprecedented rise in atmospheric greenhouse gas concentrations. The Universal Ecological Fund reports that the environmental impacts of climate change have cost the U.S. economy approximately $240 billion annually over the last decade. Households and firms might switch to renewable energy sources to mitigate the undesirable environmental and economic effects of greenhouse gas emissions and climate change.

2.4.2. *Avoidance of foreign energy*

While U.S. dependence on foreign energy has decreased over the last decade, net imports of crude oil and petroleum products as a share of total consumption grew substantially in the U.S. over the period 1973-2010, peaking at about 66% in 2005 (Figure 2). This dependence on foreign energy made the U.S. susceptible to events in other parts of the world and the U.S. government has pursued policies aimed at curbing demand for imported energy, while simultaneously encouraging the production and consumption of renewables.[7]

2.4.3. *Changes in the price and volatility of nonrenewable energy sources*

Figure 3 shows the Processed Fuels and Lubricants producer price index (PPI) measure of nonrenewable energy prices for the 1974:1-2018:12 period.[8] As the figure shows,

[6] The exact ordering of the aggregate variables is irrelevant for our purposes. Our interest in this paper is the effect of a shock to renewables consumption on the macroeconomic variables, which requires only that we specify which variables are ordered before and after renewables consumption Christiano et al. (1999).

[7] The 1967 and 1974 Arab oil embargoes and the 1978 Iranian revolution are example of such events. In response, the U.S. has had to adapt its domestic production of energy and in certain cases rely on energy rationing or price controls. The Energy Policy Act of 2005 and the Energy Independence and Security Act of 2007 are two reforms aiming at lowering this dependence on foreign energy (Mette, 2021).

[8] We use this broad measure of energy prices because, as pointed out by Edelstein and Kilian (2007); Kilian (2009), the energy costs incurred by firms are not truly reflected in oil prices, as oil is not a production input of many firms. Rather, most firms tend to rely on gasoline, heating oil, electricity, natural gas and/or other refined petroleum products. Hence, such

Figure 2: Net crude oil and petroleum imports as a percent of domestic consumption

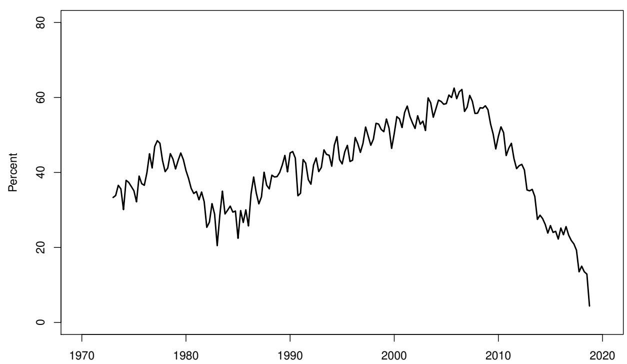
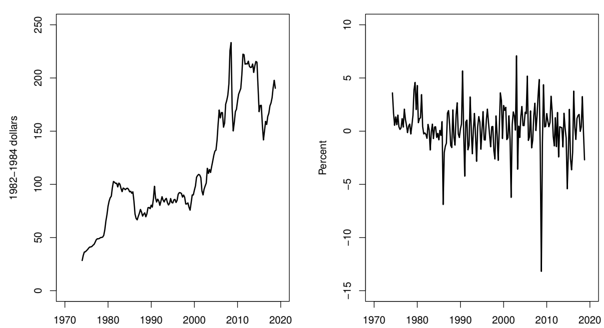


Figure 3: U.S. Nonrenewable energy prices and volatility: 1974:1-2018:12

A. PPI (Level) B. PPI (Percent change)



oil, natural gas, and coal prices have risen considerably since the 1970s (Figure 3A). In addition, they tend to be highly volatile and unpredictable in the short run (Figure 3B). Renewable energy consumption may be driven in part by a desire to avoid the volatility and uncertainty associated with the price and supply of fossil fuels.

2.4.4. Government policies and incentive programs

The U.S. Environmental Protection Agency, and the Database of State Incentives for Renewables and Efficiency, provide comprehensive information on federal, state, and local government and utility requirements and incentives for renewable energy. We briefly summarize here some of the more important of these initiatives.[9]

Government financial incentives: The U.S. federal government provides financial incentives in the form of tax credits, grants, and loan programs for qualifying renewable energy technologies and projects. These incentives and programs include the Renewable Electricity Production Tax Credit, the Investment Tax Credit (ITC), the Residential Energy Credit (REC), and the Modified Accelerated Cost-Recovery System (MACRS).

Renewable portfolio standards (RPS) and state mandates: These consist of state regulations that mandate that some proportion of state electric sales be derived from renewable energy sources (Sun, Zhou and Wen, 2022). Twenty-nine of the fifty U.S. states and the District of Columbia have adopted RPS programs, eight states have voluntary renewable energy goals.[10]

Renewable energy certificates or credits (RECs): RPS requirements apply to investor-owned utilities, municipal utilities, cooperative utilities, and retail suppliers. To verify that utilities meet their targets, utilities are required to obtain Renewable Energy Certificates or Credits (RECs), also known as Green Tags, Renewable Electricity Certificates, or Tradable Renewable Certificates (TRCs), whenever renewable energy is added into the power grid. These policies have increased domestic renewable energy consumption.

Net metering, Feed-in Tariffs (FITs) and green power purchasing: Through net metering, consumers who generate excess electricity from solar are allowed to add this excess back into the main electricity grid. As of December 2018, 38 states and the District of Columbia have net metering regulations. Two states, Idaho and Texas, have no state net metering rules, but utilities allow for net metering.[11] States and electric utilities have also used FITs to incentivize investment in renewable energy technologies. These special rates, referred to as feed-in tariffs, are generally higher than retail electricity rates. In almost every state, green power - defined as electricity from specific sources - is made available to consumers. This provides consumers the option to purchase renewables according to their preferences.

The ethanol (and other renewable) motor fuels program and renewable R&D: Following the passage of the

as broader measure of energy prices is more appropriate. The components of this price index, with their corresponding 2002 weights in parentheses, include electric power (40.32%), natural gas (14.5%), unleaded gasoline (13.98%), diesel fuel (11.36%), jet fuel (9.73%), liquefied petroleum gas (2.4%), residual fuels (2.42%), home heating oil (2.06%), lubricating and similar oils (1.29%), , petroleum and coal products, n.e.c. (1.10%), aviation gasoline (0.57%), kerosene (0.16%), lubricating grease (0.14%).

[9] We add nonetheless that several provisions in the U.S.tax code also incentivize fossil fuel production. There are direct subsidies and other provisions aimed at businesses and individuals. For example, the Environmental and Energy Study Institute (EESI) discusses among others the discounted cost of leasing federal lands for fossil fuel extraction. There is also the intangible drilling costs deduction (26 U.S. Code 263) which allows companies to deduct most of the cost associated with drilling new wells domestically.

[10] Visit the National Conference of State Legislatures for details on RPS policies by state.

[11] More information on net metering by state can be accessed via Solar Energy Industries Association.

Federal Energy Independence and Security Act of 2007, at least 36 billion gallons of biofuels are required to be used annually in the U.S by 2022. Since then, federal government programs have provided financial assistance for ethanol and other biofuels producers. The American Congress also allocates funds for research and development (R&D) of renewable energy technologies. These R&D initiatives have led to the development of cleaner, cheaper, and more efficient renewable energy technologies.

3. The link between renewables and the economy

An increase in renewable energy demand will boost employment and output in the renewable energy sectors, while nonrenewable energy sectors will contract, as the increased investment in renewables crowds out investment in nonrenewable energy. To the extent that this substitution effect is positive, the net macroeconomic effects will be positive. A related empirical literature (Wei et al. (2010), Lehr et al. (2012), Garrett-Peltier (2017)) provides some evidence that the net effect is positive. In the ensuing discussion, we assume that the net effect is positive, so that a shift from nonrenewables to renewables translates into a positive aggregate demand shock.

4. The macroeconomic effects of renewable energy shocks

This section presents the responses of U.S. macroeconomic aggregates to ε_R equal to 1% of renewable energy consumption.[12] We first look at the responses for total renewable energy consumption, and then for each of the five disaggregate measures of renewable energy consumption. In all graphs, the solid lines are the point estimates of the cumulative impulse response functions, and the broken lines are the 90% confidence bands constructed using the wild bootstrap with 1000 repetitions. In addition to the impulse response functions, we present variance decompositions for aggregate output, the unemployment rate, prices, and wages.

4.1. Effects of a shock to aggregate renewable energy consumption

4.1.1. Impulse response functions

The responses to a shock to renewable energy consumption are shown in Figure 4. Greater renewable energy consumption is followed by a rise in output for the first 24 months (significantly different from zero for the first ten months). The peak output response occurs after seven months, with an estimated cumulative impact of about 0.4, suggesting that a shock equal to 1% of total renewable energy consumption leads to a cumulative output increase of approximately 0.4% over seven months. While few, if any, studies exist on the output effects of renewable energy consumption, a positive growth effect of renewable energy consumption has been documented by, among others, Sadorsky (2009), Apergis and Payne (2010), and Menegaki (2011).

The labor market responses are consistent with the behavior of output. The unemployment rate steadily decreases for two years. This negative response is exactly what one would expect, as the job gains from renewables tend to exceed the job losses in nonrenewable energy sectors, as documented by Wei et al. (2010), Lehr et al. (2012), Garrett-Peltier (2017). In addition, using data on a panel of 80 countries for the period 1990-2013 and non-linear cointegration and causality analysis, Apergis and Salim (2015) find some evidence of an unemployment-reducing impact of renewable energy consumption.

Nominal wages rise steadily for two years following the shock to renewables. The muted initial response may be due to wage stickiness. This is consistent with the simple AD-AS model described in Section 3. That is, the rise in aggregate demand following the shock to renewable energy consumption leads to a fall in unemployment. As firms compete for workers (due to low unemployment), and workers seek higher wages as a consequence of the higher aggregate prices, nominal wages rise.[13] Another potential explanation for the rise in wages is that renewable energy projects are highly capital-intensive during their manufacturing, construction, and installation phases, and since these projects tend to be more heavily weighted during these phases than in the operation and maintenance phases (which tend to be labor-intensive), the jobs created are generally high-paying jobs (Konrad, 2009).[14] Furthermore, workers in the renewable energy sector generally tend to be highly educated and highly skilled (Hamilton and Liming, 2010). These workers, therefore, have high human capital and productivity. Assuming a competitive model of the labor market where the wage rate is equal to marginal productivity of the market-clearing worker, the rise in wages following a shock to renewable energy consumption in Figure 4 is exactly what one would expect.

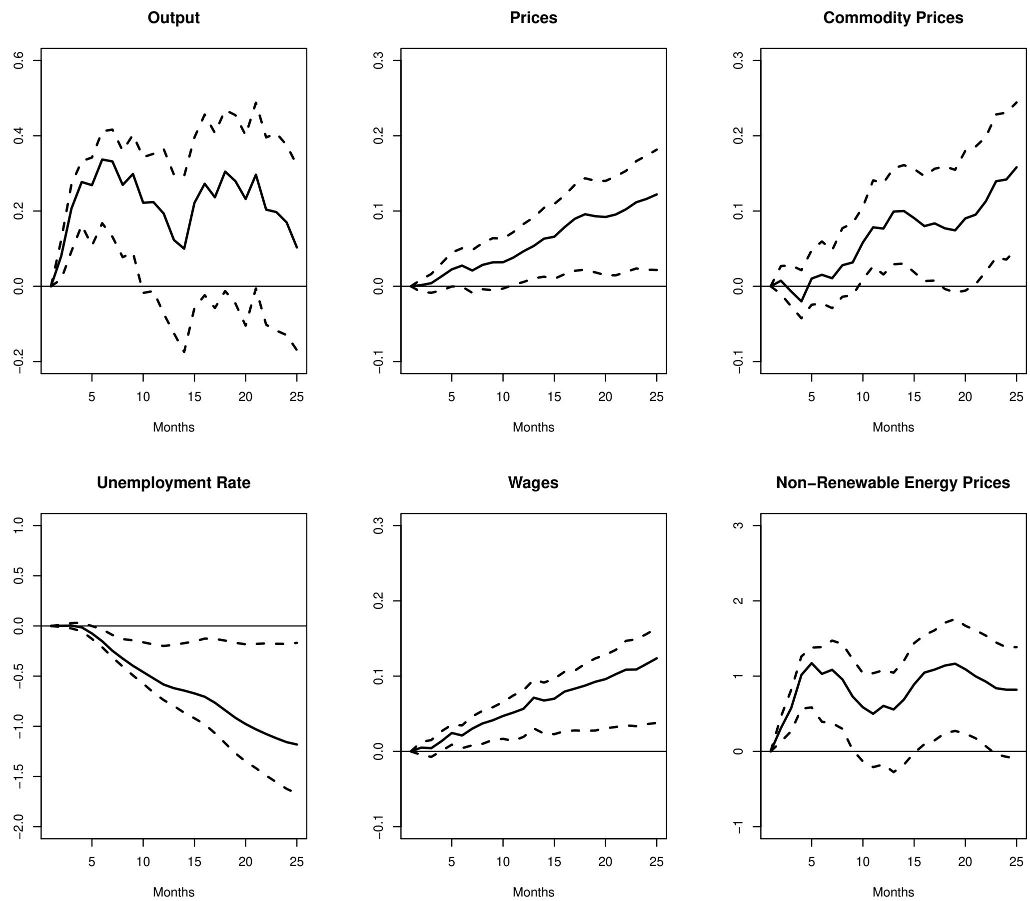
Aggregate consumer prices, commodity prices, and nonrenewable energy prices all rise for a protracted period. For consumer and commodity prices, the positive responses turn significant after a delay of about eleven months, and generally remain significant from then on. The finding that nonenergy consumer and commodity prices rise following a shock to renewables is not surprising. Over the 1976-2018 period, biomass accounted for more than 50% of total renewable energy use. This high demand for biomass, which includes wood and wood waste, municipal solid waste, landfill gas and biogas, ethanol, and biodiesel, is expected to increase the demand for, and therefore prices of related

[12] See section 2.3 for a discussion of the interpretation of this shock.

[13] Bernanke et al. (1997) use aggregate demand shifters to identify the corresponding aggregate supply relationships. The study employs data from 22 countries around the time of the Great Depression. Results show that nominal wages tend to adjust quite slowly to changing prices.

[14] According to the Clean Jobs, Better Jobs report, jobs in grid modernization and storage, energy efficiency and renewable energy sectors earned a median hourly wage of $23.89 in 2019 compared to the $19.14 hourly national average.

Figure 4: Responses of macroeconomic aggregates to a renewable energy shock



Notes: Dotted lines are the 90% confidence bands based on Monte Carlo simulation with 1000 replications.

Table 1
Contribution of total renewables to variability of macroeconomic aggregates

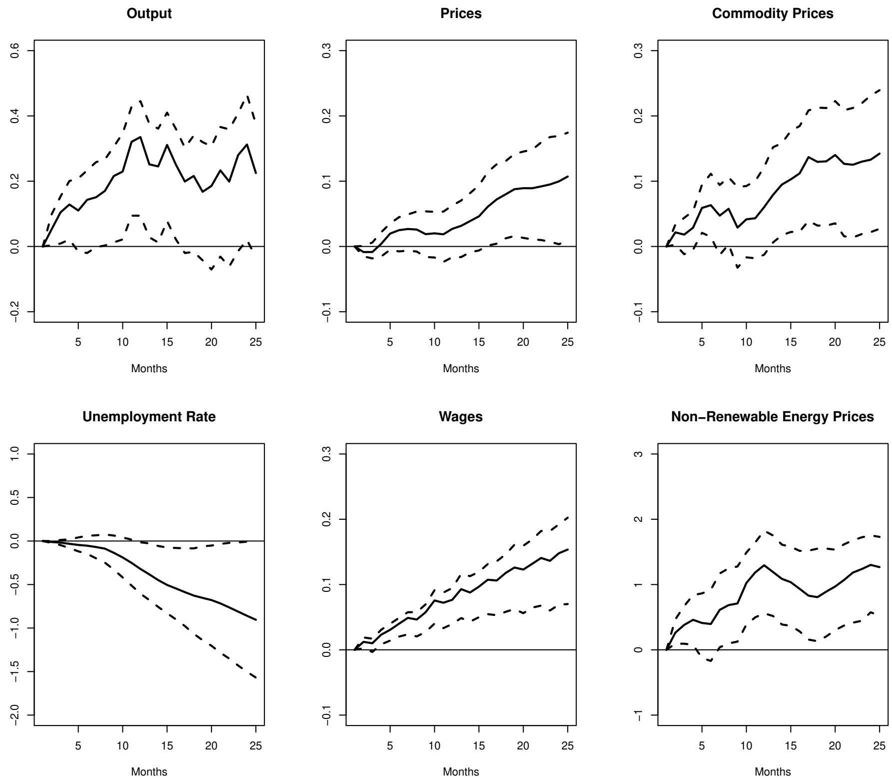
Horizon	Output	CPI	Commodity prices	Unemployment rate	Wages	Nonrenewable energy prices	Renewable
1	2.994	0.063	0.039	0.510	0.462	0.077	95.855
3	3.258	0.599	0.391	0.996	0.713	0.087	93.956
6	3.788	0.884	0.676	1.261	1.996	0.357	91.037
12	4.803	1.352	1.189	6.053	3.263	1.392	81.949
24	6.986	1.588	1.780	7.585	3.365	1.588	77.108
36	8.416	1.813	2.163	8.602	3.452	1.684	73.870

Notes: Based on variance decomposition of the structural VAR models.

commodities (including food), explaining the positive responses of consumer and commodity prices. Baier et al. (2009) document a sizable impact of biofuels on food and commodity prices, reporting that corn and soybean prices respectively increased by more than 14% and 10% percent. They further find that global food prices increased by over 7% between June 2006 and June 2008, as a result of the increase in U.S. biofuels production.

Figure 4 also shows a positive response of nonrenewable energy prices, which is significant for the first nine months following the shock. This impulse response function does not have an obvious interpretation due to the nature of our analysis. The ε_R are capturing factors not included in the SVAR model that cause a shift from nonrenewable to renewable energy. It cannot be attributed to exogenous oil price changes, because the real price of oil is included in the SVAR model. A potential explanation is that policies causing a shift to renewables do so by increasing the cost of nonrenewable energy.

Figure 5: Effects of a shock to biomass energy



4.1.2. Variance decompositions

Table 1 presents the contribution of the shock to renewable energy for each of the variables in the SVAR model (2). In line with expectations, moving from nonrewable to renewable energy is only responsible for a small proportion of the variance of macroeconomic variables. More surprising, perhaps, is that these shocks explain so little of the variation in nonrenewable energy prices in spite of the large increase in renewable's share of total energy consumption. Our conclusion from these results is that moving to renewable energy does have a noticeable impact on the economy (largely through ethanol), based on the impulse response function analysis, but the overall variation in renewables has not been great enough to be a major driver of the economy or bring down nonrenewable energy prices.

4.2. Effects of shocks to disaggregate measures of renewable energy consumption

In addition to total renewable energy, we also have data on the five most commonly used renewable energy sources: biomass (including wood and wood waste, municipal solid waste, landfill gas and biogas, ethanol, and biodiesel), hydropower, geothermal, wind, and solar. This section exploits the disaggregate energy data to better understand the impulse response functions of the previous section. In each case, we replace total renewable energy with the individual energy series.

4.2.1. Biomass

Domestic demand for biomass has required a substantial increase in U.S. biomass production. Much of it is converted to biofuels, primarily ethanol and biodiesel for transportation, feedstock, and other uses. Data from the U.S. Energy Information Administration (EIA) shows that corn and soybeans accounted for more than 85% of U.S. biofuels production in 2018.[15] The USDA's National Agricultural Statistics Service annual Crop Production Report shows that in 2001, 9.5 billion bushels of corn were produced in the U.S., 705 million (7%) of which was used for the production of ethanol. By 2018, U.S. corn production had risen to 14.42 billion bushels, with almost the entire increase in corn production being used to increase ethanol production.

Similarly, the use of soybeans for biodiesel production has risen sharply over the past two decades.[16] Between 2001 and 2018, U.S. soybean production increased by 1.6 billion bushels, from 2.9 billion bushels to 4.5 billion bushels, coinciding with its use in biodiesel production going from close to zero to nearly 2 billion bushels.[17] The responses of the macroeconomic variables to increased biomass consumption in Figure 5 are similar to those for total renewable energy consumption. That is, higher biomass consumption increases aggregate output, prices and wages, and decreases the unemployment rate.

[15] See "Inputs to biodiesel production" on the EIA website.
[16] https://www.nass.usda.gov/Publications/Todays_Reports/reports/croptr19.pdf
[17] https://www.unitedsoybean.org/media-center/issue-briefs/biodiesel/

Figure 6: Effect of a shock to wind energy

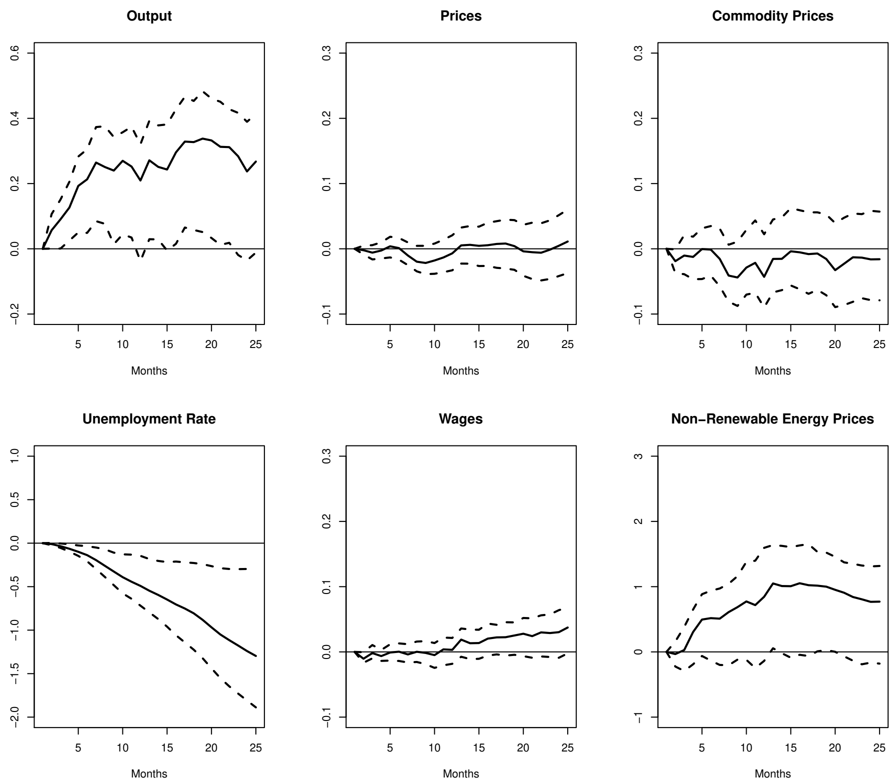


Figure 7: Effects of a shock to solar energy

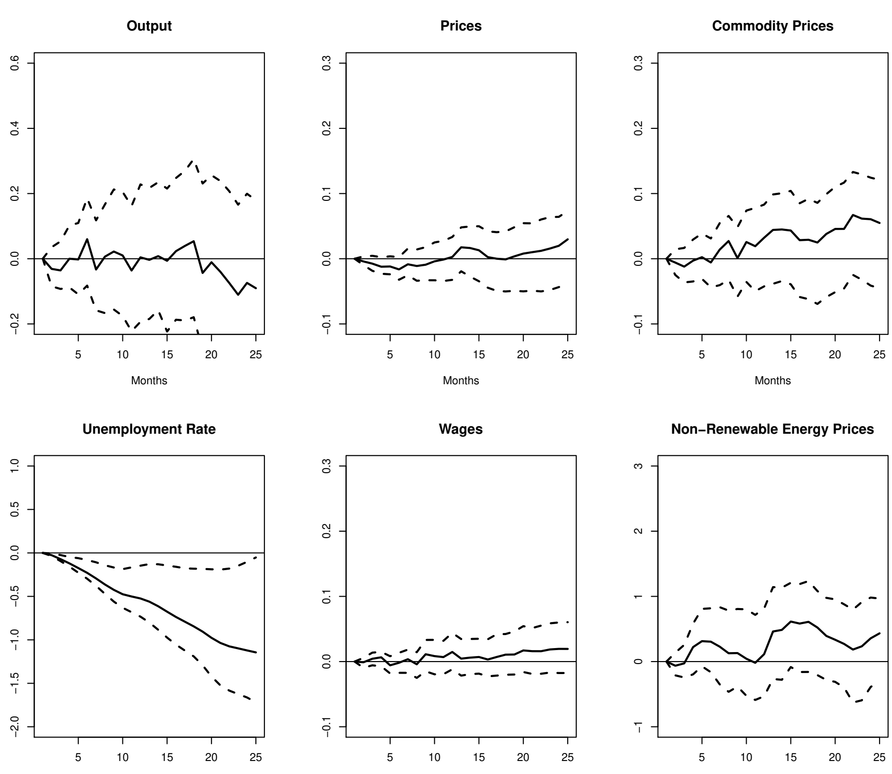


Figure 8: Effects of a shock to hydropower energy

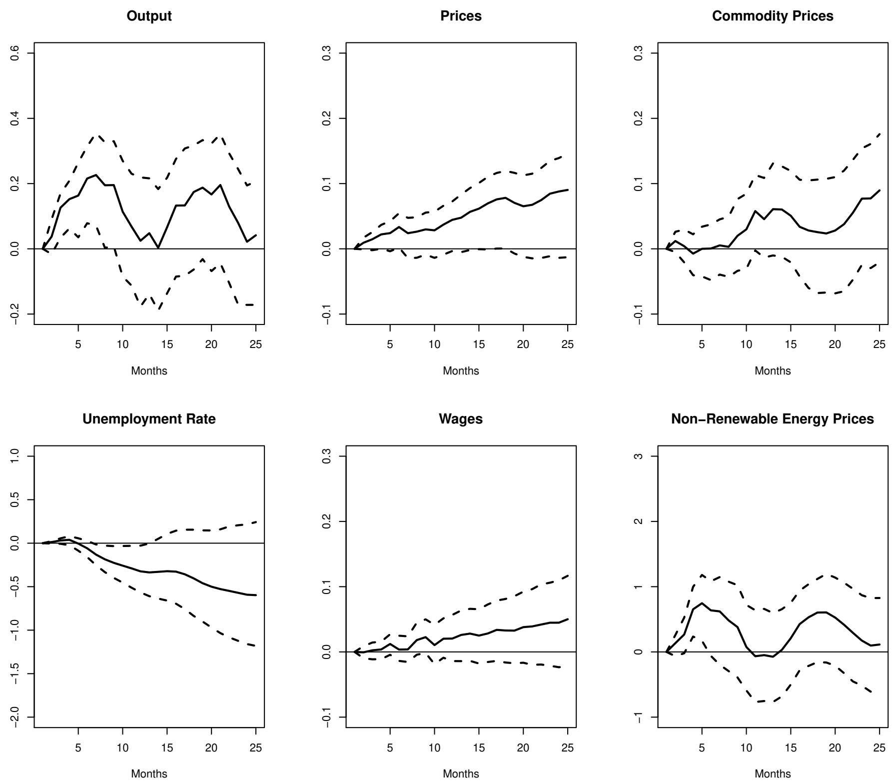
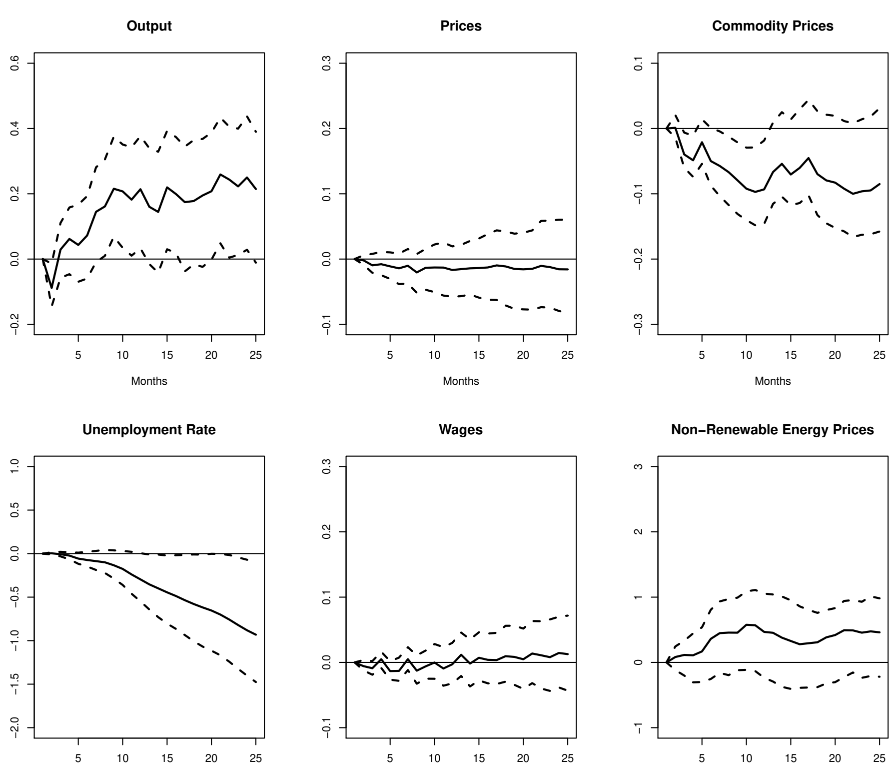


Figure 9: Effects of a Shock to Geothermal



Biomass accounts for more than 50% of total renewable energy use, suggesting that much of the estimated macroeconomic response to a shock to renewable energy is reflecting biomass consumption, and in particular the production of ethanol. This is consistent with the findings of Baier et al. (2009), which documented a sizeable impact of biofuels on food and commodity prices, reporting that corn and soybean prices increased by more than 14% and 10% percent, respectively, due to biofuels production. They further found that global food prices increased by over 7% between June 2006 and June 2008 as a result of the increase in U.S. biofuels production, and since food is a major component of the CPI, it's plausible that prices may rise as a result.

4.2.2. Wind

There has been a dramatic rise in U.S. wind energy consumption, from almost no wind energy being consumed in 2000, to supplying nearly 3% of total U.S. energy consumption by 2018. A shock to wind energy is expected to create jobs and increase output during the production and installation of turbines. According to the 2011 Wind Technologies Market Report, there was a single utility-scale turbine manufacturer assembling nacelles in the U.S. in 2004, but by 2011 eight out of ten largest wind turbine manufacturers had at least one manufacturing facility in the U.S. Estimates from the American Wind Energy Association (AWEA) imply the wind energy sector employed more than 120,000 workers in the U.S. in 2018. Figure 6 shows an increase in output and a decrease in the unemployment rate following a shock to wind energy consumption.

4.2.3. Solar

Solar energy has followed a similar pattern to wind energy, with a sharp increase in recent years, but solar's share of total energy consumption remains well under 1%. In addition to solar energy's small share, the macroeconomic impact of a shock to solar is less clear than for other renewable energy sources. Hydropower, wind, and geothermal energy typically require substantial investment for the construction, installation, operation, and maintenance of large physical plants such as dams, windmills, and other infrastructure to distribute power. Solar photovoltaic modules require little additional investment and infrastructure beyond the initial upfront financial investment needed to build the plants since solar energy consumption generally takes the form of solar panels owned and operated by individuals. The primary macroeconomic impact of solar power adoption comes through the installation on existing residential and commercial properties. In Figure 7 are the responses to a shock to solar energy. The unemployment rate decreases noticeably, but the effect on the other variables is minimal.

4.2.4. Hydropower

Hydropower is different from the other renewable energy sources. Although its share is still greater than wind, solar, and geothermal, it has faced a steady decline since peaking in the early 1980s. Hydropower has not been subjected to major technological innovations and policy changes the way other renewable energy sources have. The macroeconomic responses to a shock to hydropower consumption, displayed in Figure 8, tell a story of limited effects on the macroeconomy, with the only exceptions being output and the unemployment rate at short horizons. Similar findings have been documented by, among others, Duflo and Pande (2007), Kline and Moretti (2014), Newell and Raimi (2015) De Faria et al. (2017).

4.2.5. Geothermal

Geothermal energy is such a small part of total energy consumption that one might question whether it is even useful to estimate the effect of a shock to geothermal on the macroeconomy. Figure 9 does not present any evidence to the contrary. The only interesting result in that table is the response of commodity prices. A shock to geothermal energy causes commodity prices to decrease in the first year. This is perhaps explained by the fact that geothermal energy provides electricity efficiently, reliably, and at a relatively low and stable cost.

4.3. Heterogeneity across states

An important dimension of the macroeconomic effects of the transition to renewable energy is the distribution of the benefits. This section presents estimates of the effect of a shock to biomass energy on state- level jobs. We focus on biomass because (a) it is by far the dominant source of renewable energy in the U.S., and (b) there is considerable attention given to ethanol in the political process at all levels of government. One question is whether the employment benefits of biomass are concentrated in corn-producing and ethanol-producing states, or if they are spread out equally across the states.

We add the unemployment rate for each state plus Washington DC to our earlier VAR model.[18] Because it is hard to interpret a change in the unemployment rate across states, we convert the response into the number of jobs gained or lost when the unemployment rate in that state changes. Our earlier results tell us that on average there should be job growth, but nothing about the distribution across states. The results can be found in Table 2. The numbers reported are the cumulative change in jobs after one, six, twelve, and twenty four months.

The results in Table 2 show some evidence of heterogeneity in the state responses to a shock to biomass. None of the states have significant job gains within a month. On the other hand, thirteen states experience small but statistically significant job losses. That is consistent with an inability of ethanol producers to increase their workforce quickly following an increase in demand, but small job losses in the fossil fuels sector due to the shock. Meaningful job gains begin to appear in some states after six months. One and two years following a shock to biomass energy, all states experience job gains, with the gains being statistically significant for 27 states. Although the top corn-producing

[18] This is done separately for each state. We estimate a total of 51 VAR models.

Table 2
State job gains and losses from a shock to biomass energy

State	After 1 Month	After 6 Months	After 1 Year	After 2 Years	State	After 1 Month	After 6 Months	After 1 Year	After 2 Years
Alabama	-206	2916	**12810**	**28586**	Montana	-8	**1066**	**2073**	**4442**
Alaska	**-84**	140	280	696	Nebraska	**-144**	**1260**	**3894**	**7491**
Arizona	**-522**	**-6211**	4881	**32446**	Nevada	22	**2393**	4846	9303
Arkansas	-35	**3546**	**6947**	**12824**	New Hampshire	-73	**1328**	**2800**	4284
California	-1098	**33586**	**77370**	168915	New Jersey	-687	**8151**	**27087**	**57955**
Colorado	-105	**7097**	**16468**	**33282**	New Mexico	-69	150	**3324**	**7505**
Connecticut	**-356**	2155	**7890**	17629	New York	162	**25636**	**46718**	**95522**
Delaware	-54	183	638	1103	North Carolina	228	**19242**	**44602**	**85912**
District of Columbia	26	-172	366	1528	North Dakota	11	**823**	**1495**	**2762**
Florida	564	-5065	7962	49646	Ohio	-1031	10579	18553	46991
Georgia	-260	117	16501	**44771**	Oklahoma	**-260**	1924	6109	**18148**
Hawaii	35	377	**2233**	**5148**	Oregon	105	**7526**	**12025**	18877
Idaho	6	**2145**	**3807**	**6778**	Pennsylvania	-823	**11575**	**27507**	49115
Illinois	-886	**15822**	**44463**	**89016**	Rhode Island	-70	**1842**	2729	2671
Indiana	-361	**8414**	**18014**	34573	South Carolina	-68	2342	4289	12472
Iowa	130	**3966**	**5896**	10145	South Dakota	2	**874**	**1093**	1804
Kansas	**-264**	1274	**6172**	**11399**	Tennessee	-97	**7492**	**17422**	**32290**
Kentucky	**-423**	**4786**	**9131**	17268	Texas	-1055	589	**52965**	**134109**
Louisiana	115	1576	**17660**	**37687**	Utah	**-160**	**2452**	**7923**	**13511**
Maine	**-131**	**1302**	2047	3503	Vermont	**-77**	403	783	1408
Maryland	**-424**	2833	7714	13510	Virginia	-300	**5907**	**16477**	29486
Massachusetts	82	**9680**	**27657**	**58466**	Washington	261	**10549**	**20288**	**37250**
Michigan	-834	**19042**	**48527**	**86071**	West Virginia	-142	**2959**	**5233**	8151
Minnesota	245	**10812**	**17141**	**30361**	Wisconsin	-57	**7847**	**16507**	**31320**
Mississippi	**-352**	-619	**6117**	**14818**	Wyoming	**-49**	**487**	940	2454
Missouri	-342	**5732**	**15179**	27758					

Notes: Numbers in bold indicate that the job gains are significantly different from zero at the 10% significance level.

and ethanol-producing states (Iowa, Nebraska, Illinois, Minnesota, Indiana, and South Dakota, which represent more than 72% of U.S. fuel ethanol production)[19] experience job gains, the benefits are spread out across many states.

5. Conclusions and policy implications

Using a structural VAR model, we found that a shock to consumption of renewable energy increases output, consumer prices, commodity prices, wages, and nonrenewable energy prices, and decreases the unemployment rate. We then looked at the five most important renewable energy sources, biomass, hydropower, geothermal, wind, and solar. A shock to biomass energy consumption - by far the most important component of total renewable energy consumption - has similar effects to a shock in total renewable energy consumption. That is, output, prices, and wages all rise, while unemployment decreases. Finally, using state-level data, we find that a shock to biomass has positive employment effects for a broad set of states throughout the U.S., rather than being concentrated in just the largest corn-producing and ethanol-producing states.

These findings have important policy implications. Renewable energy advances have here been associated with macroeconomic performance beyond the well-documented environmental benefits (Resch et al. (2008), Zhou and Ang (2015), Saint Akadiri et al. (2019)). The growing adoption of renewable energy will thus contribute to meeting sustainable energy efficiency goals but also positively impact aggregate economic outcomes. Policymakers may thus benefit from accounting for this finding noting that this beneficial effect of renewable energy consumption shocks is heterogeneous across states as well as dependent on timing. In the majority of US states the largest job gains are recorded two years following a renewable shock. It is in this light that energy policymakers may have to define a beneficial framework for environmental innovations with the simultaneous achievement of higher output, wages, and employment.

[19] https://www.eia.gov/todayinenergy/detail.php?id=36892

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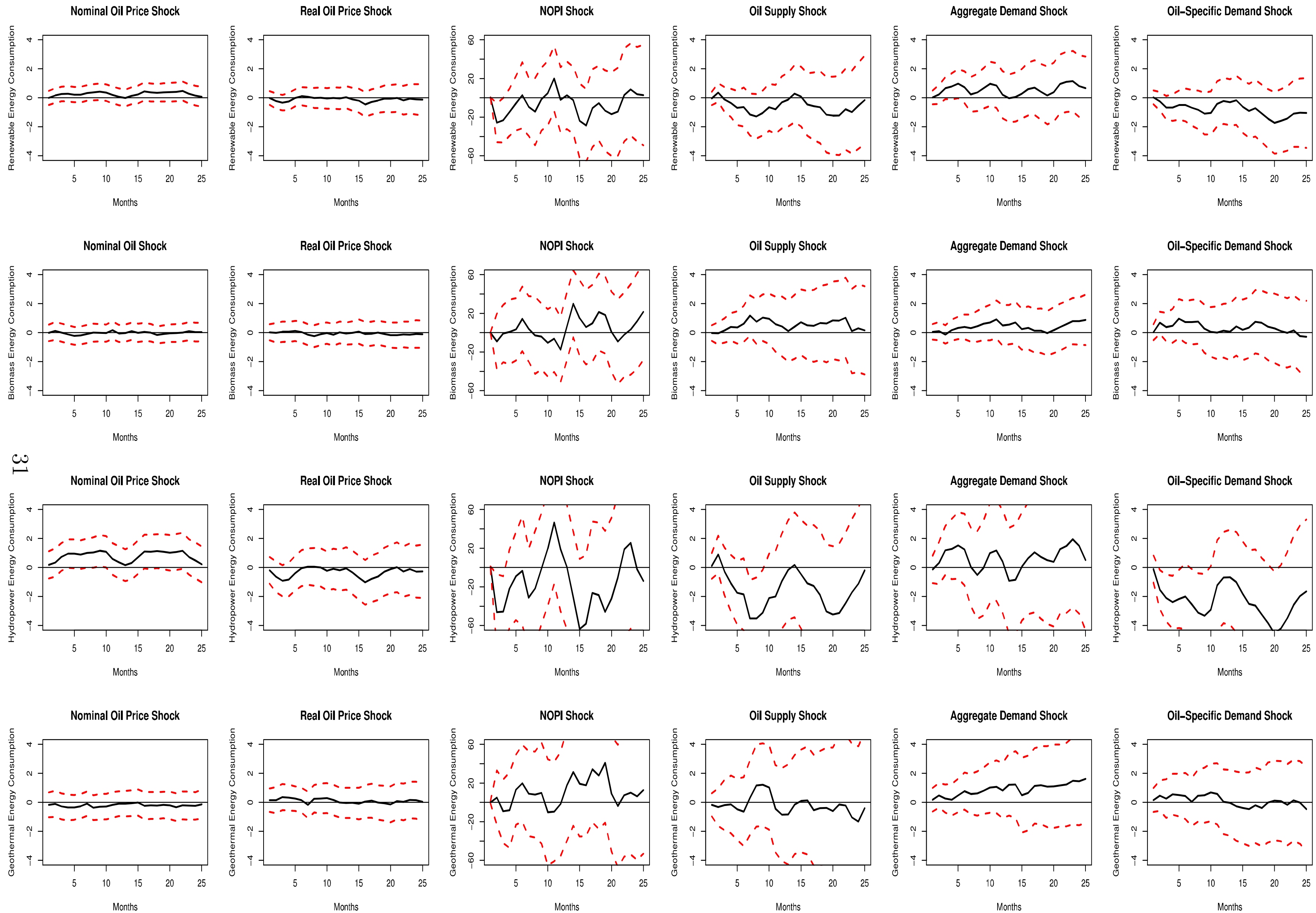
Appendix Figure 1: Renewable Energy Responses to Various Measures of Oil Shocks



Notes: Dotted lines are the 90% confidence bands constructed using the wild bootstrap with 1000 replications. We omit responses of aggregate and coal prices to save space, and because in no instance are they significantly different from zero.