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Abstract

Long-term environmental consequences of taxing fossil fuel usage have been extensively studied in the literature. However, these taxes may also impose several short-run macroeconomic policy challenges, the nature of which remains underexplored. This paper investigates the mechanisms through which environmental taxes on fossil fuel usage can affect the main macroeconomic variables in the short-run. We concentrate on a particular mechanism: speculative storage. Formulating and using a dynamic stochastic general equilibrium (DSGE) model, calibrated for the United States, with an explicit storage facility and nominal rigidities, we show that in designing environmental tax policies it is crucial to account for the fact that fossil fuel prices are subject to speculation. The existence of forward-looking speculators in the model improves the effectiveness of tax policies in reducing fossil fuel usage. Improved policy effectiveness, however, is costly: it drives inflation and interest rates up, while impeding output. Based on this tradeoff, we seek an answer to the question how monetary policy should interact with environmental tax policies in our DSGE model of fossil fuel storage. We show that, in an environment with no speculative storers, monetary policy should respond to output along with CPI inflation in order to minimize the welfare losses brought by taxes. However, when storage facility is activated, responding to output in the monetary policy rule becomes less desirable.

JEL codes: E31; E52; H23; O44.
Keywords: Fossil fuel; environmental taxes; speculative storage; DSGE.

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1 Introduction

This paper formulates and solves a dynamic stochastic general equilibrium (DSGE) model with nominal rigidities and an energy market (with exhaustible and renewable resources), where government implements tax policies to discourage fossil fuel usage. One distinctive feature of the model, which should perhaps be emphasized in advance, is the existence of a fossil fuel storage facility that allows for speculation. This facility operates through forward-looking speculators, who maximize profits based on the (rational) expectations they form about the future movements in fossil fuel prices. Actions of these speculators may have important macroeconomic reflections; thus, may need to be taken into account in designing policy measures (e.g., environmental taxes) targeted at reducing fossil fuel usage.

Speculative storage is important to model, because it introduces a dynamic link among fossil fuel inventories, storers' expectations of the price of fossil fuel, and the spot price of fossil fuel. Our modeling approach for the fossil fuel storage builds on the seminal works of Wright and Williams (1982, 1984, 1991) and Deaton and Laroque (1992, 1996). We postulate that storage is a way of transferring fossil fuel from current to future periods. Storage is performed by competitive, risk-neutral storers (speculators), who buy fossil fuel from fossil fuel producers at the after-tax spot price and optimally decide how much to sell or store. In the presence of storage, the market-clearing price becomes a function of availability (given by new production plus change in storage) relative to the total demand. In this paper, we do not explicitly model the commodity futures market. Hamilton (2009), Alquist and Kilian (2010), and Kilian and Murphy (2014) indicate that, in the presence of competitive storage, there is an arbitrage condition linking the commodity futures market and the spot market. As in Kilian and Murphy (2014), this simplification enables us to focus on the speculation in the spot market without loss of generality.

Incorporating the fossil fuel storage facility into a DSGE model is also important for macroeconomic policy because it generates a new transmission channel through which the monetary policy can operate. In fact, in our model, changes in the real interest rate have direct effects on the storage demand. Hence, it is particularly interesting to investigate the effects of speculative fossil fuel storage motives within a short-run general equilibrium model, which is suitable for monetary policy analysis.

There is a vast literature investigating the effects of environmental taxes on the workings of the fossil fuel markets.[1] A particular strand of this literature focuses on assessing the macroeconomic effects of environmental taxes. For example, Ganelli and Tervala (2011) construct a two-country New Keynesian model to examine the effects of country-specific environmental tax policies on the macroeconomic variables. Sinn (2008) develops a simple dynamic model to assess the supply-side responses to the introduction of fossil fuel taxes. de Miguel and Manzano (2011) evaluate the welfare effects of green tax reforms. To the best of our knowledge, there is no work in the literature investigating the role of speculative storage in amplifying and deepening the short-term fluctuations brought by environmental taxes.[2] We attempt to fill this gap.

The financialization of commodity markets has often been blamed for the surges in fossil fuel prices in 2000s. In fact, during the last decade, the amount of speculative oil storage in the US has been on an increasing trend. According to the data provided by Energy Information Agency, ending stocks of crude oil as a percentage of the quarterly total oil usage has increased to 83 percent in 2010 from 62 percent in 2000 in the US.[3] The rise in oil stocks along with the oil prices has attracted the attention of both academics and policymakers and led to an extensive literature on the role of speculative motives in driving the oil prices. See, for example, Alquist and Kilian (2010) and Kilian and Murphy (2014) for the role of crude oil inventories in transmitting the shifts in expectations to the real price of oil *via* the shifts in the speculative demand for oil storage [see also Dvir and Rogoff (2009), Hamilton (2009), and Fattouh, Kilian, and Mahadeva (2013)]. In particular, Unalmis, Unalmis, and Unsal (2012)

[1] See, for example, Golosov, Hassler, Krusell, and Tsyvinski (2014) who calculate the optimal taxes in the global economy to maximize welfare while minimizing carbon emissions in general equilibrium. Sinclair (1990) is an earlier study on optimal fossil fuel taxation. See also de Mooij, Keen, and Parry (2012) for a review of fiscal policy alternatives to mitigate climate change.

[2] There are many papers attempting to calculate the "social cost" of climate change. Papers in this literature include Tol (1995), Nordhaus and Boyer (2000), Maddison (2003), and Rehdanz and Maddison (2005). Tol (2008) surveys a large set of the relevant work. In this paper, we argue that short-term macroeconomic costs can also be large and this implies that they should also be accounted for in pre- and/or post-policy social cost calculations.

[3] We define total oil supply as the sum of US field production and the US net imports of crude oil. The data source is the Energy Information Agency.

(UUU hereafter) study the role of speculative storage in a DSGE framework and show that accounting for oil storage improves the fit of the model to the data. UUU also emphasize that the link between storage demand and macroeconomic impact of fossil fuel fluctuations is a dynamic general equilibrium phenomenon—i.e., the existence of storage can amplify or mitigate the dynamic responses of fossil fuel price depending on the source of the shock.

In this paper, building on UUU, we analyze the effects of environmental taxes on the short-run responses of the main macroeconomic variables in a model with fossil fuel storage. Taking advantage of the dynamic general equilibrium nature of our model, we first analyze the role of speculative storage on the short-run responses of the main macroeconomic variables to environmental tax policies by comparing responses with and without storage. We then discuss the monetary policy alternatives that would increase the effectiveness of environmental tax policies and reduce the associated macroeconomic costs. There are two important differences between this paper and UUU. First, fossil fuel is no more the only source of energy in the model. We introduce "renewable energy" as an alternative energy source, which is both directly consumed by the households and used in the production of goods by the firms. This modification is important, because when taxes are imposed on fossil fuel usage, agents substitute away from fossil fuel towards renewable energy. Such a modification non-trivially changes all the responses obtained from the model. Second, domestic production of both the fossil fuel and renewable energy are endogenously modeled. This feature of the model improves upon most of the DSGE studies assuming fossil fuel supply completely exogenous such as Bodenstein, Guerrieri, and Kilian (2012).

Our main finding is that speculative storage motives play a major role in determining (1) the effectiveness of fossil fuel taxes (either only on consumers, only on producers, or both) and (2) the impact of these taxes on macroeconomic aggregates. Following the introduction of taxes on fossil fuel usage, the storage demand for fossil fuel would surge due to increased expected return to speculation. A higher storage demand reduces the fossil fuel supply available in the market, raises the price, and decreases the overall fossil fuel usage; thus, enhances policy effectiveness since carbon emissions would go down further. When the storage technology is ignored, this mechanism would be idle and, thus, the impact of the fossil fuel taxes on overall fossil fuel consumption would be substantially underestimated. These results highlight the importance of accounting for speculative storage properly in designing environmental policies for storable resources.

As taxing fossil fuels under speculative storage brings unwarranted volatility in several macroeconomic variables including inflation and output, it is of interest to explore how central bank could design monetary policy to limit the impact of the tax policy on main variables of interest. We show that, without storage facility, responding to CPI inflation (rather than to the core inflation) along with output would cause smaller macroeconomic fluctuations following a fossil fuel tax shock—responding to the immediate effects as well as the second-round effects of the environmental taxes on inflation is justified in our framework. However, when speculative storage is considered, reacting to output in the monetary policy rule becomes less desirable. Policymakers could instead further limit the welfare loss associated with environmental taxes by responding solely to the CPI inflation. This is due to the significantly higher volatility in the CPI inflation in response to a tax shock under storage.

The plan of the paper is as follows. Section 2 introduces the model in detail. Section 3 presents the results along with a detailed discussion of the calibration, impulse responses, and policy implications. Section 4 concludes.

2 Model

Our model extends the framework developed by UUU toward several directions. First, fossil fuel supply is partly endogenous in our model. Second, there is an alternative energy source—renewable energy—which is also produced endogenously. Third, we include a more detailed treatment of fiscal policy, where the government taxes consumption and/or production of fossil fuels to promote a substitution toward renewable energy sources from fossil fuels. Finally, we focus on the dynamics following a fossil fuel tax shock.

The model economy is populated by households, three types of production firms, a government, a monetary authority, and fossil fuel storers (or speculators). Households receive utility from consumption (of both core and energy goods), provide labor to the firms producing core goods, hold physical capital stocks, and rent capital to firms in a perfectly competitive rental market. The households own all the firms in the economy and, therefore, receive profits from these firms. Energy is consumed directly and also used as an input in the production process. The total energy used in consumption and production are CES aggregates of renewable energy and fossil fuels.

There are three types of production firms. Firms producing a differentiated core consumption good use capital, labor, and energy as inputs. These firms set prices in a staggered fashion and, hence, prices are sticky. Firms producing renewable energy and fossil fuel use only capital. Fossil fuel production is assumed to be partially endogenous. This is similar to Backus and Crucini (2000), in which "OPEC supply" is determined exogenously. The difference is that, in our model, the exogenous part is the "fossil fuel supply outside of the U.S."

In the model, one major difference between renewable energy and fossil fuel is that fossil fuel is storable. The activity of the risk-neutral, profit-maximizing, and competitive fossil fuel storers (speculators) is to carry forward fossil fuel as above-ground inventories from one period to the next. They buy fossil fuel directly from the producers and optimally decide how much to sell or store through an intertemporal arbitrage condition. Conditional on the current information, whenever expected appreciation (depreciation) in the price of fossil fuel exceeds the marginal cost of storage, speculators increase (decrease) their stock holdings until the equilibrium in the fossil fuel market is restored.

In what follows, small letters denote percentage deviations of the respective variables from their steady-state levels. The main elements of the model are sketched in this section, while the details of the log-linearized equations—using which we solve our model through a first-order approximation—are omitted.

2.1 Households

There is a continuum of infinitely-lived households indexed in the unit interval $j \in [0,1]$. The representative household seeks to maximize the expected present discounted value of utility given by

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left(\frac{(C_t(j) - H_t)^{1-\sigma}}{1-\sigma} - \frac{N_t(j)^{1+\varphi}}{1+\varphi} \right), \tag{2.1}$$

where $H_t = hC_{t-1}$ captures external habit formation with $h \in [0,1]$, $0 < \beta < 1$ is a subjective discount factor, $\sigma > 0$ is the inverse of the intertemporal elasticity of substitution of consumption, $\varphi > 0$ is the inverse of the intertemporal elasticity of hours, $C_t(j)$ denotes consumption, and $N_t(j)$ denotes hours of work.[4] Note that the habit stock refers to the aggregate habit consumption rather than the individual habit consumption. The aggregate consumption is

$$C_t = \left(\int_0^1 C_t(j)^{\frac{\varepsilon-1}{\varepsilon}} dj \right)^{\frac{\varepsilon}{\varepsilon-1}}, \tag{2.2}$$

where ε denotes the elasticity of substitution between varieties. $C_t(j)$ is itself a CES aggregate of energy consumption $E_{c,t}(j)$ and core consumption $Z_t(j)$ as follows:

$$C_t(j) = \left[(1-\omega_{ec})^{\frac{1}{\rho_c}} Z_t(j)^{\frac{\rho_c-1}{\rho_c}} + \omega_{ec}^{\frac{1}{\rho_c}} E_{c,t}(j)^{\frac{\rho_c-1}{\rho_c}} \right]^{\rho_c/(\rho_c-1)}, \tag{2.3}$$

where ρ_c is the intratemporal elasticity of substitution between energy and core consumption and $0 < \omega_{ec} < 1$ indicates the expenditure share of the energy in the consumption basket of households. $E_{c,t}(j)$ is also a CES aggregate of renewable-energy consumption $RE_{c,t}(j)$ and fossil fuel consumption $FF_{c,t}(j)$:

$$E_{c,t}(j) = \left[(1-\omega_{ff,c})^{\frac{1}{\rho_e}} RE_{c,t}(j)^{\frac{\rho_e-1}{\rho_e}} + \omega_{ff,c}^{\frac{1}{\rho_e}} FF_{c,t}(j)^{\frac{\rho_e-1}{\rho_e}} \right]^{\rho_e/(\rho_e-1)}, \tag{2.4}$$

[4] For greater realism and a better empirical fit, recent studies on standard medium- and large-scale DSGE models generally include a number of nominal and real frictions in the model. Coupled with an empirically plausible calibration, it has been shown that the impulse responses from such a model can be sufficiently close to those from standard time series estimation methods such as VARs [see Smets and Wouters (2003), among many others]. In particular, many papers, including ours, rely on habit formation to generate persistent, hump-shaped responses of key variables to exogenous shocks.

where ρ_e is the intratemporal elasticity of substitution between renewable energy and fossil fuel consumption and $0 < \omega_{ff,c} < 1$ indicates the expenditure share of the fossil fuel in the energy basket of households.

Let $P_{e,t}$ and $P_{z,t}$ denote the prices of energy and non-energy consumption goods, respectively. The consumer price index (CPI) P_t can be written as

$$P_t = \left[(1-\omega_{ec})P_{z,t}^{1-\rho_c} + \omega_{ec}P_{e,t}^{1-\rho_c}\right]^{1/(1-\rho_c)}. \tag{2.5}$$

Let $P_{re,t}$ and $P_{ff,t}$ denote the prices of renewable energy and fossil fuel, $s_{re,c,t}$ and $\tau_{ff,c,t}$ denote the percentage subsidy on $P_{re,t}$ and percentage tax imposed on $P_{ff,t}$, respectively. Hence, the energy price index $P_{e,t}$ can be written as

$$P_{e,t} = \left[(1-\omega_{ff,c})\left\{(1-s_{re,c,t})P_{re,t}\right\}^{1-\rho_e} + \omega_{ff,c}\left\{(1+\tau_{ff,c,t})P_{ff,t}\right\}^{1-\rho_e}\right]^{1/(1-\rho_e)}. \tag{2.6}$$

Demand functions for renewable energy consumption, fossil fuel consumption, and core consumption are given by

$$RE_{c,t}(j) = (1-\omega_{ff,c})\left[(1-s_{re,c,t})\frac{P_{re,t}}{P_{e,t}}\right]^{-\rho_e} E_{c,t}(j), \tag{2.7}$$

$$FF_{c,t}(j) = \omega_{ff,c}\left[(1+\tau_{ff,c,t})\frac{P_{ff,t}}{P_{e,t}}\right]^{-\rho_e} E_{c,t}(j), \tag{2.8}$$

and

$$Z_t(j) = (1-\omega_{ec})\left[\frac{P_{z,t}}{P_t}\right]^{-\rho_c} C_t(j), \tag{2.9}$$

respectively.

The household enters period t with portfolio $D_t(j)$ that pays out one unit of currency in a particular state, earns wage income from labor effort, earns rental income from capital holdings, and receives profits (e.g., dividends) $\Pi_t(j)$ from monopolistic firms that produce core goods. $K_{1,t}(j)$, $K_{2,t}(j)$, and $K_{3,t}(j)$ are the beginning-of-period-t capital stocks; and $R_t^{K_1}(j)$, $R_t^{K_2}(j)$, and $R_t^{K_3}(j)$ represent rate of return on capital used in core goods production, renewable energy production, and fossil fuel production, respectively. $W_t(j)$ is the nominal wage. In each period, the household purchases consumption goods $C_t(j)$ and investment goods $I_{1,t}(j)$, $I_{2,t}(j)$, and $I_{3,t}(j)$. We assume that investment goods are composed of only non-energy goods. $D_{t+1}(j)$ is the expected nominal payoff in period $t+1$ of the portfolio held at the end of period t, including the shares in firms. Hence, the representative household's budget constraint in period t can be formulated as

$$\begin{aligned} P_t C_t(j) + P_{z,t} I_{1,t}(j) + P_{z,t} I_{2,t}(j) + P_{z,t} I_{3,t}(j) + R_t^{-1} D_{t+1}(j) \\ \leq D_t(j) + W_t N_t(j) + R_t^{K_1} K_{1,t}(j) + R_t^{K_2} K_{2,t}(j) + R_t^{K_3} K_{3,t}(j) + \Pi_t(j) \end{aligned} \tag{2.10}$$

and the law of motions for physical capital accumulation for different types of capital are

$$K_{\iota,t+1}(j) = (1-\delta) K_{\iota,t}(j) + \Phi\left(\frac{I_{\iota,t}(j)}{K_{\iota,t}(j)}\right) K_{\iota,t}(j), \tag{2.11}$$

where $\iota = 1, 2, 3$. In Equation (2.11), $0 < \delta < 1$ is the depreciation rate and the term $\Phi\left(\frac{I_t(j)}{K_t(j)}\right) K_t(j)$ captures capital adjustment costs, where we assume that the steady state values of Φ, its first derivative, and its second derivative are $\Phi_{ss} = \delta$, $\Phi'_{ss} = 1$, $\Phi''_{ss} = \xi < 0$, respectively, with $\delta\xi = -1$. The representative household, therefore, maximizes the utility (2.1) subject to (2.10) and (2.11).

Under the assumption of complete asset markets, households are subject to perfect risk-sharing and consumption is equal across households. Therefore, there is no need for index j. R_t is the risk-free nominal interest rate. The equilibrium conditions for households are given by

$$\beta \mathbb{E}_t \left[\left(\frac{C_{t+1} - H_{t+1}}{C_t - H_t} \right)^{-\sigma} \frac{P_t}{P_{t+1}} \right] = \frac{1}{R_t}, \tag{2.12}$$

$$(C_t - H_t)^{\sigma} N_t^{\varphi} = \frac{W_t}{P_t}, \tag{2.13}$$

and

$$P_{z,t}\Lambda_t = \beta \mathbb{E}_t \left\{ \left(\frac{C_{t+1} - H_{t+1}}{C_t - H_t} \right)^{-\sigma} \frac{P_t}{P_{t+1}} \left(R^{K_\iota}_{\iota,t+1} + P_{z,t+1}\Lambda_{\iota,t+1}\widetilde{\Phi}_\iota \right) \right\}, \tag{2.14}$$

where $\widetilde{\Phi}_\iota = (1-\delta) + \Phi_\iota \left(\frac{I_{\iota,t+1}}{K_{\iota,t+1}}\right) - \Phi'_\iota \left(\frac{I_{\iota,t+1}}{K_{\iota,t+1}}\right) \frac{I_{\iota,t+1}}{K_{\iota,t+1}}$ and $\Lambda_{\iota,t} = 1/\Phi'_\iota \left(\frac{I_{\iota,t+1}}{K_{\iota,t+1}}\right)$ are the shadow prices of capitals.

2.2 Firms Producing Core Goods

There is a continuum of monopolistically competitive firms which produce a differentiated core (non-energy) good indexed by $i \in [0,1]$ with identical production functions:

$$Y_{z,t}(i) = A_{1t} \left[(1-\omega_{ey})^{\frac{1}{\rho_y}} V_t(i)^{(\rho_y-1)/\rho_y} + \omega_{ey}^{\frac{1}{\rho_y}} E_{y,t}(i)^{(\rho_y-1)/\rho_y} \right]^{\rho_y/(\rho_y-1)}, \tag{2.15}$$

where $E_{y,t}(i)$ is the amount of fossil fuel used in production by firm i, ρ_y is the elasticity of substitution between fossil fuel and value added inputs, $0 < \omega_{ey} < 1$ indicates the share of energy in production, and A_{1t} represents a stationary total factor productivity shock in the goods sector that is common to all firms. Each producer utilizes labor and capital to produce a value added input $V_t(i)$, which is characterized in the following CES form:

$$V_t(i) = \left[(1-\omega_{ny})^{\frac{1}{\rho_v}} K_{1,t}(i)^{(\rho_v-1)/\rho_v} + \omega_{ny}^{\frac{1}{\rho_v}} (N_t(i))^{(\rho_v-1)/\rho_v} \right]^{\rho_v/(\rho_v-1)}, \tag{2.16}$$

where ρ_v is the elasticity of substitution between capital and labor inputs, $0 < \omega_{ny} < 1$ indicates the share of labor in production. The energy input $E_{y,t}(i)$ is produced by using renewable energy ($RE_{y,t}$) and fossil fuel ($FF_{y,t}$), which is characterized in another CES form:

$$E_{y,t}(i) = \left[(1-\omega_{ff,y})^{\frac{1}{\rho_e}} (A_{2t} RE_{y,t}(i))^{(\rho_e-1)/\rho_e} + \omega_{ff,y}^{\frac{1}{\rho_e}} (A_{3t} FF_{y,t}(i))^{(\rho_e-1)/\rho_e} \right]^{\rho_e/(\rho_e-1)}, \tag{2.17}$$

where ρ_e is the elasticity of substitution between renewable energy and fossil fuel, $0 < \omega_{ff,y} < 1$ indicates the share of fossil fuel in production.

Assuming that firms take the price of each input as given, the cost minimization problem of firms implies:

$$\frac{W_t N_t(i)^{1/\rho_v}}{\omega_{ny}^{1/\rho_v}} = \frac{R_t^{K_1} K_{1,t}(i)^{1/\rho_v}}{(1-\omega_{ny})^{1/\rho_v}} \tag{2.18}$$

and

$$\frac{(1+\tau_{ff,y,t}) P_{ff,t} FF_{y,t}(i)^{1/\rho_e}}{\omega_{ff,y}^{1/\rho_e} A_{2t}^{(\rho_e-1)/\rho_e}} = \frac{(1-s_{re,y,t}) P_{re,t} RE_{y,t}(i)^{1/\rho_e}}{(1-\omega_{ff,y})^{1/\rho_e} A_{3t}^{(\rho_e-1)/\rho_e}}, \tag{2.19}$$

which hold for each firm i. The prices of renewable energy and fossil fuel, $P_{re,t}$ and $P_{ff,t}$, are in fact determined endogenously in our model, as will be explored later. The nominal marginal cost of production is constant and the same across all firms, given by:

$$MC_t^n = \frac{1}{A_{1t}} \left[(1-\omega_{ey}) C_{v,t}^{1-\rho_y} + \omega_{ey} C_{e,t}^{1-\rho_y} \right]^{1/(1-\rho_y)}, \tag{2.20}$$

where

$$C_{v,t} = \left((1-\omega_{ny}) \left(R_t^{K_1} \right)^{1-\rho_v} + \omega_{ny} \left(W_t \right)^{1-\rho_v} \right)^{\frac{1}{1-\rho_v}} \tag{2.21}$$

and

$$C_{e,t} = \left((1-\omega_{ff,y}) \left(\frac{(1-s_{re,y,t}) P_{re,t}}{A_{2t}} \right)^{1-\rho_e} + \omega_{ff,y} \left(\frac{(1+\tau_{ff,y,t}) P_{ff,t}}{A_{3t}} \right)^{1-\rho_e} \right)^{\frac{1}{1-\rho_e}}. \tag{2.22}$$

We assume that core goods producing firms set prices according to the Calvo (1983) framework, in which only a randomly selected fraction $(1-\theta)$ of the firms can adjust their prices optimally in each period. We also assume a partial indexation scheme where ς captures the degree of inflation indexation in the economy. Hence, firm's optimal price setting strategy implies the following marginal cost-based (log-linearized) Phillips curve:

$$\pi_{z,t} = \frac{\beta}{1+\beta\varsigma} \mathbb{E}_t \left\{ \pi_{z,t+1} \right\} + \frac{\varsigma}{1+\beta\varsigma} \pi_{z,t-1} + \frac{(1-\theta)(1-\beta\theta)}{\theta(1+\beta\varsigma)} mc_t, \tag{2.23}$$

where $\pi_{z,t} = p_{z,t} - p_{z,t-1}$ is the non-energy CPI inflation between periods $t-1$ and t. The CPI inflation ($\pi_t = p_t - p_{t-1}$) is given by:

$$\pi_t = (1 - \omega_{ec})\pi_{z,t} + \omega_{ec}\pi_{e,t}, \tag{2.24}$$

where $\pi_{e,t} = p_{e,t} - p_{e,t-1}$ is the energy price inflation.

2.3 Firms Producing Renewable Energy and Fossil Fuel

There are two types of competitive firms in the energy market, which produce either renewable energy or fossil fuel, with identical production functions. Fossil fuel is in part endogenously produced and the endogenous fossil fuel production utilizes capital in a linear production function:

$$FF_{s,t}^{endo} = A_{4t}K_{2,t}, \tag{2.25}$$

where A_{4t} represents a stationary capital efficiency shock. The renewable energy is produced using a similar production function:

$$RE_{s,t} = A_{5t}K_{3,t}, \tag{2.26}$$

where A_{5t} represents a stationary capital efficiency shock in renewable energy production. The energy price inflation is given by

$$\pi_t = (1 - \omega_{ff,c})\left\{\pi_{re,t} - \frac{\overline{s}_{re,c}}{1 - \overline{s}_{re,c}}\Delta s_{re,c,t}\right\} + \omega_{ff,c}\left\{\pi_{ff,t} + \frac{\overline{\tau}_{ff,c}}{1 + \overline{\tau}_{ff,c}}\Delta\tau_{ff,c,t}\right\}, \tag{2.27}$$

where $\pi_{re,t} = p_{re,t} - p_{re,t-1}$ is the renewable energy inflation and $\pi_{ff,t} = p_{ff,t} - p_{ff,t-1}$ is the fossil fuel price inflation.

2.4 Monetary Policy

In the baseline scenario, the monetary policy reaction is assumed to follow a simple Taylor rule as follows:

$$r_t = \phi_r r_{t-1} + (1-\phi_r)\phi_\pi \pi_t + (1-\phi_r)\phi_y y_{z,t}, \tag{2.28}$$

where $\phi_r \in [0,1]$ is the interest rate smoothing parameter, and ϕ_π and ϕ_y denote the monetary policy responses to consumer price inflation and output, respectively.

2.5 Fiscal Policy

The government has a balanced budget. We consider two cases. In the benchmark case, we assume that the amount of receipts from the fossil fuel taxation is transferred to households as lump-sum transfers. In the second case, the tax receipts are utilized as subsidies to the renewable energy sector, where the government budget takes the following form:

$$\begin{aligned}\tau_{ff,y,t} P_{ff,t} FF_{y,t} + \tau_{ff,c,t} P_{ff,t} FF_{c,t} = \\ G_t + s_{re,y,t} P_{re,t} RE_{y,t} + s_{re,c,t} P_{re,t} RE_{c,t},\end{aligned} \tag{2.29}$$

where $\tau_{ff,y,t}$ is the tax on fossil fuel used by producers, $\tau_{ff,c,t}$ is the tax on fossil fuel consumption of consumers, $s_{re,y,t}$ and $s_{re,c,t}$ are subsidies for each unit of renewable energy consumption paid by the government to producers and consumers respectively. G_t denotes government spending. We assume that $\tau_{ff,y,t}$, $\tau_{ff,c,t}$, $s_{re,y,t}$ and $s_{re,c,t}$ follow AR(1) processes

$$\tau_{ff,y,t} = \rho_{ff,y} \tau_{ff,y,t-1} + \varepsilon_{ff,y,t}, \tag{2.30}$$

$$\tau_{ff,c,t} = \rho_{ff,c} \tau_{ff,c,t-1} + \varepsilon_{ff,c,t}, \tag{2.31}$$

$$s_{re,y,t} = \rho_{re,y} s_{re,y,t-1} + \varepsilon_{re,y,t}, \tag{2.32}$$

and

$$s_{re,c,t} = \rho_{re,c} s_{re,c,t-1} + \varepsilon_{re,c,t}, \tag{2.33}$$

where $\varepsilon_{ff,y,t}$, $\varepsilon_{ff,c,t}$, $\varepsilon_{re,y,t}$, $\varepsilon_{re,c,t}$ are i.i.d. tax shocks with variances $\sigma^2_{\varepsilon_{ff,y,t}}$, $\sigma^2_{\varepsilon_{ff,c,t}}$, $\sigma^2_{\varepsilon_{re,y,t}}$, $\sigma^2_{\varepsilon_{re,c,t}}$, respectively.

2.6 Goods Market Equilibrium

The equilibrium condition in the goods market requires that the production of core goods satisfies the following condition:

$$Y_{z,t}(i) = G_t(i) + I_{1,t}(i) + I_{2,t}(i) + I_{3,t}(i) + Z_t(i). \tag{2.34}$$

2.7 Storage and Energy Market Equilibrium

2.7.1 Fossil Fuel Storage

Fossil fuel storage takes the form of holding above-ground fossil fuel inventories. There is a continuum of competitive fossil fuel storers, *competitive speculators*, indexed by $l \in [0,1]$ who are able to buy and sell in the spot market and are able to store fossil fuel. In line with the literature, we assume that there are no barriers to entry into the storage sector and storers are risk neutral. They form rational expectations about the returns to their activities.

The profits earned by a representative "storer," l, from storing $S_t(l)$ is the difference between revenue in period $t+1$ and the cost of purchasing $S_t(l)$ in the spot market in period t, while covering the storage costs. Fossil fuel storers seek to maximize their expected profit, which is

$$\frac{a\mathbb{E}_t(P_{ff,t+1})S_t(l)}{R_t} - P_{ff,t}S_t(l)(1+\Upsilon(S_t(l))), \tag{2.35}$$

where $\Upsilon(S_t(l)) = \kappa + \frac{\Psi}{2}S_t(l)$ is the (physical) cost of storing one unit of fossil fuel with $\kappa < 0$ (reflecting convenience yield) and $\Psi > 0$ (where the cost is increasing with the amount of fossil fuel).[5] We denote $(1-a)$ as the "waste", where $a \in [0,1]$.

[5] The existence of convenience yield is a common assumption in commodity storage literature. A non-exhaustive list of relevant

As each storer shares the same rational expectations with other storers, there is no need for the storer-specific index l. In line with the existing literature on commodity storage, there is a non-negativity constraint on aggregate storage; $S_t \geq 0$—it is impossible to borrow stocks from the future.[6] For this price-taker storer, the FOC with respect to S_t, given the constraint, yields

$$a\mathbb{E}_t[P_{ff,t+1}] = R_t P_{ff,t}(1 + \kappa + \Psi S_t). \tag{2.36}$$

Equation (2.36) is the decision rule for competitive storers: profit maximizing competitive storage, if positive, will set the expected marginal revenue from storage equal to the marginal cost. The log-linearized version of the storage demand equation is, therefore,

$$s_t = \Theta(\mathbb{E}_t \{\widehat{p}_{ff,t+1}\} - \widehat{p}_{ff,t} - (r_t - \pi_{t+1})) + sd_t, \tag{2.37}$$

where $\Theta = \frac{a\beta}{\Psi \bar{S}} > 0$, and $\widehat{p}_{ff,t} = p_{ff,t} - p_t$ is the real price of fossil fuel. On the right hand side of Equation (2.37), we add an exogenous storage demand (sd_t), in order to capture the exogenous disturbances to fossil fuel stocks. The storage demand shock is assumed to follow a stationary stochastic process. According to Equation (2.37), storage demand is driven by the expected real price of fossil fuel, the current real price of fossil fuel, the real interest rate and an exogenous storage demand.

2.7.2 Equilibrium in the Energy Market

We assume that fossil fuel supply is partially exogenous—*aka* the OPEC supply—($FF^{exo}_{s,t}$), which is subject to shocks defined by a stationary AR(1) process.[7] Given storage, the total quantity demanded by households and firms is equal to the sum of exogenous and endogenous

papers includes Brennan (1991), Fama and French (1988), and Gibson and Schwartz (1990). More recently, Alquist and Kilian (2010) also adopt this modeling device.

[6]The level of storage is always positive in our framework as the steady state level is positive, sufficiently high, and *deviations* of storage from its steady state are sufficiently small (within the neighborhood of the steady state). Incorporating non-linearities associated with storage technology is beyond the scope of this paper. Although conceptually appealing, this would make the solution considerably more complicated without providing any additional insight for the issues we focus here.

[7]For the sake of simplicity, we assume that the profits from selling and storing fossil fuel are distributed evenly among the consumers and are included in the lump-sum transfers in the budget constraints of households.

production, plus old inventories net of depreciation, minus new inventories:

$$FF_{c,t} + FF_{y,t} = FF_{s,t}^{exo} + FF_{s,t}^{endo} + aS_{t-1} - S_t. \tag{2.38}$$

For the renewable energy, the total quantity demanded by households and firms is equal to the production:

$$RE_{c,t} + RE_{y,t} = RE_{s,t}. \tag{2.39}$$

3 Results and Discussion

In this section, we perform several quantitative experiments in order to investigate the channels through which fossil fuel tax shocks are transmitted within the economy and how the presence of fossil fuel storage affects the impulse responses. We focus on a positive fossil fuel tax shock separately on consumers, on producers, and on both. We start this section with the calibration. Then we discuss the impulse responses followed by relevant policy implications.

3.1 Calibration

We calibrate the model for the United States with reasonable values mostly as they are set in the literature [see Table (1)]. Time is measured in quarters. We set $\beta = 0.99$, implying a riskless annual return of approximately 4 percent at the steady state. This numbers are consistent with Nordhaus's critique [Nordhaus and Boyer (2000), Nordhaus (2007)] of the Stern (2007) report. The inverse of the elasticity of intertemporal substitution is taken as $\sigma = 1$, which corresponds to log utility. Our selection of $h = 0.7$ is within the range of values used in the literature. For example, Smets and Wouters (2007), Sahuc and Smets (2008), and Edge, Kiley, and Laforte (2008) estimate the habit persistency to be 0.71, 0.629, and 0.76 for the U.S., respectively. The inverse of the elasticity of labor supply φ is set to 3 since it is assumed that 1/3 of the time is spent on working. The share of labor in the production (ω_{ny}) is taken as 0.66. The depreciation rate (δ) is set to be 0.025. The Calvo probability (θ) is assumed to be 0.75, which implies an average period of one year between price adjustments.

The inflation indexation parameter ς is set to 0.5. We use the original Taylor estimates and set $\phi_\pi = 1.5$ and $\phi_y = 0.5$. The persistency parameter of the interest rate in the monetary policy reaction function is set to be $\phi_r = 0.5$. The persistency of the tax shocks are set 0.9. Following Gali, Lopez-Salido, and Valles (2007), we set the share of government purchases in GDP as 0.18.

Following the Energy Information Agency's (EIA) 2009 Annual Energy Report [EIA (2009)], we calculate the expenditure share of fossil fuel in the energy basket of firms and households as 0.85 and 0.75, respectively. Since we do not have adequate storage data for fossil fuels other than oil, we use the EIA's oil data to calculate the steady state ratio of fossil fuel storage to quarterly fossil fuel supply. The convenience yield (k) is set to be -0.03, as in UUU. Substitution between consumption and energy is set to be 0.4 as in Harrison, Thomas, and de Weymarn (2011). van der Werf (2008) estimates the elasticity of substitution between the fossil fuel and value added input, and the elasticity of substitution between capital and labor as 0.5465 and 0.3194 for the United States, respectively. In line with Gerlagh and van der Zwaan (2003), we assume that renewable energy and fossil fuel are substitutes; accordingly, we set the elasticity of substitution between renewable energy and fossil fuel (ρ_e) to be equal to 0.5. The expenditure share of energy in the production of firms (ω_{ey}) and consumption basket of households (ω_{ec}) are set to be 0.1 and 0.13, respectively, as in Huntington (1991). We take the steady-state tax rate on fossil fuel as 0.1.[8]

3.2 Impulse Responses

Taxing households. Figure (1) documents the impact of a tax shock only on the household-level consumption of fossil fuels with and without storage technology. In such a scenario, a percentage point increase in the taxes on fossil fuel consumption of households increases the real price of fossil fuel faced by the consumers and reduces the households' consumption of fossil fuel. However, due to a decline in fossil fuel usage, the real price of fossil fuel faced

[8] Our selection of 10 percent steady state tax rate for both consumers and producers is reasonable according to data provided by OECD [http://www.oecd-ilibrary.org/deliver/fulltext/9713051ec019.pdf]. We also carry out several sensitivity analyses with higher and different steady state tax rates for consumers and producers. The results do not alter the qualitative nature of the impulse responses, hence our conclusions.

$\beta = 0.99$	Subjective discount factor.
$\sigma = 1$	Inverse of the intertemporal elasticity of substitution.
$h = 0.7$	Level of habit persistence.
$\varphi = 3$	Frisch elasticity of labor supply.
$\delta = 0.025$	Depreciation rate.
$\varsigma = 0.5$	Inflation indexation parameter.
$\omega_{ny} = 0.66$	Share of labor in production.
$\theta = 0.75$	Calvo parameter.
$\phi_\pi = 1.5$	Coefficient of inflation in the policy rule.
$\phi_y = 0.5$	Coefficient of output gap in the policy rule.
$\phi_r = 0.5$	Coefficient of lagged interest rate in the policy rule.
$\omega_{ff,y} = 0.85$	Expenditure share of fossil fuel in the energy basket of firms.
$\omega_{ff,c} = 0.75$	Expenditure share of fossil fuel in the energy basket of households.
$G_y = 0.18$	Share of government spending.
$\omega_{ey} = 0.1$	Expenditure share of energy in the production basket of firms.
$\omega_{ec} = 0.13$	Expenditure share of energy in the consumption basket of households.
$\rho_c = 0.4$	Elasticity of substitution between consumption and energy.
$\rho_y = 0.5465$	Elasticity of substitution between fossil fuel and value added input.
$\rho_w = 0.3194$	Elasticity of substitution between capital and labor.
$\rho_e = 0.5$	Elasticity of substitution between renewable energy and fossil fuel.
$S/FF^s = 0.61$	The steady state ratio of fossil fuel storage in quarterly fossil fuel supply.
$k = -0.03$	Convenience yield in fossil fuel storage.
$\tau_{ff,y} = \tau_{ff,c} = 0.1$	Steady state tax rates on fossil fuel.
$I_{1y} = 0.21$	Steady state share of investment spending in core goods production.
$I_{2y} = 0.05$	Steady state share of investment spending in fossil fuel production.
$I_{3y} = 0.05$	Steady state share of investment spending in renewable energy production.

Table 1: Parameter values and definitions.

by the producers (which is exempt from the tax) declines and fossil fuel used in production increases due to the cost advantage. As a result, total fossil fuel usage does not decline significantly. Since renewable energy is relatively cheaper following the shock, households substitute renewable energy with fossil fuel, hence, households' consumption of renewable energy increases. Rising renewable energy demand stimulates its investment demand, while investment in fossil fuel sector declines. GDP falls initially due to lower capital investments and consumption, but rebounds quickly with the help of reviving capital investments. Marginal cost of firms declines as the real price of fossil fuel faced by producers goes down. The taxes and rising renewable energy prices increase the real cost of energy basket. Therefore, CPI increases to which the central bank responds with a rise in the policy interest rate.

Responses of variables when there are fossil fuel storers in the model are shown in solid lines. Since the fossil fuel price faced by storers goes down, storers increase their fossil fuel holdings in response to a rise in taxes on households' fossil fuel consumption. As this creates additional demand for fossil fuel, the fall in fossil fuel prices is relatively limited in this case. However, total fossil fuel usage drops more, because income declines further in the presence of the storage facility. As a result, fossil fuel usage decreases considerably more when the storage facility is turned on. In other words, speculative fossil fuel storers improve the effectiveness of fossil fuel taxation policies on the fossil fuel consumption.

Taxing firms. Impulse responses of key macroeconomic variables following a tax shock on firms' use of fossil fuel are reported in Figure (2). When there are no speculative fossil fuel storers, a percentage point increase in the fossil fuel taxes reduces the fossil fuel usage in production and increases the fossil fuel usage in consumption. The real price of fossil fuel declines in almost the same amount as the decline in the first case. However, contrary to the first case, GDP increases initially, then declines and stays below the steady-state level for a prolonged time period. Household consumption increases above the steady state level due to falling interest rates and real energy prices. Including speculative storers to the model leads to a lower decline in real price of fossil fuel faced by the consumers and storers as in the first case. Fossil fuel usage of consumers increases less but fossil fuel usage of producers declines more creating much higher contraction in GDP. At the end, the fall in total fossil fuel consumption is almost 50 percent higher compared to the first case. To put it differently, taxing producers is more effective in terms of its effect on the fossil fuel usage.

Taxing both households and firms. Figure (3) documents macroeconomic dynamics after a tax shock on both households' and firms' usage of fossil fuel. Without fossil fuel storage, a percentage point increase in the fossil fuel taxes reduces the real price of fossil fuel faced by storers by almost 1 percent. However, the real price of fossil fuel faced by consumers and producers reports a minimal increase and the increase in renewable energy prices is also quite small; hence, the real cost of the energy basket rises only marginally. Therefore, the effects of the tax increase on the general price level and on the interest rate are both very limited. Responses of fossil fuel usage in consumption and production do not change significantly either. In other words, the effect of the tax increase on overall fossil fuel usage is very small. Existence of speculative fossil fuel storers amplifies the effects of the tax increase on the real

	No Storage	Storage
GDP	-0.055	-0.107
Real Price of FF	0.299	4.441
Real Price of RE	0.220	2.677
Total FF Usage	-0.128	-0.673
Total RE Usage	0.024	0.020

Table 2: Cumulative responses. 5-year cumulative responses to tax shocks on both production and consumption.

price of energy basket. Although the real price of renewable energy declines, the real price of fossil fuel faced by the consumers and produces rises so much that the cost of energy basket goes up. In this case, fossil fuel consumption of households and firms falls by almost the same amount. Not surprisingly, the decline in the fossil fuel usage is the highest among the three scenarios. Having speculative storers leads to higher marginal cost for firms, hence the CPI rises which calls for a tightening of the monetary policy through a higher policy interest rate. Higher interest rates bring lower consumption and investment, hence GDP declines contrary to the no storage case.[9] To provide a better visualization of these results, Table (2) summarizes the 5-year cumulative responses of the key variables to shocks on both production and consumption. Clearly, the decline in output is amplified under storage technology, when fundamental shocks drive the real price of energy up.

Our analysis is related to other recent studies exploring the macroeconomic effects of environmental policies in a general equilibrium setting. Golosov, Hassler, Krusell, and Tsyvinski (2014) calculate the optimal taxes in an economy with an externality through climate change. In their paper, the optimal tax, which decreases the fossil fuel use by about 5 percent would bring a decline in output by about 1 percent in the short run. In our framework with storage, a tax that would bring down the overall fossil fuel consumption by the same amount would result in slightly lower, but comparable, output losses (about 0.6). Our quantitative results are also in line with de Miguel and Manzano (2011). They find that about a 30 percent rise in a fossil fuel tax on households' consumption (firms' use) would bring about 8 percent (11 percent) decline in fossil fuel consumption (used by firms). In our simulations, the same type of shock in the same magnitude would bring a comparable decline in fossil fuel use of about

[9] We carried out several sensitivity analyses for elasticity parameters and found that different parameter values do not alter the qualitative nature of the impulse responses, hence our conclusions. The results are available upon request.

9 percent (10 percent).

In a closer framework to ours, but using a two-country setup, Ganelli and Tervala (2011) analyze international transmission of an environmental regulation shock in a general equilibrium model with nominal rigidities, but without speculative storage. Consistent with our findings, one percent tax shock brings an immediate decline in output and in consumption by about 0.03 – 0.04 percent and 0.005 – 0.015 percent, respectively, depending on the parameter values on the spillovers of the shock between countries. However, reflecting the permanent nature of the shock in their paper, output and consumption do not rebound back.

3.2.1 Impulse Responses with Subsidy Policy

What if the government implements a more intensive environmental policy by intervening directly into the renewable energy market as well? In this section, we analyze the case where government utilizes the receipts of additional fossil fuel taxation as a subsidy to renewable energy users instead of a lump-sum transfer to households. In this case, a rise in fossil fuel taxation would increase the cost of using fossil fuel while decreasing the cost of using renewable energy. Results are shown in Figure (4). This policy leads to a rise in renewable energy investments and a decline in fossil fuel investments. With storage, the usage of renewable energy both in production and consumption increases when the government subsidizes the renewable energy usage. Indeed, our results show that unless the government subsidizes the renewable energy, it is difficult to increase its usage (both in production and consumption) by the fossil fuel taxation policies only. Therefore, in order to increase the renewable energy consumption, governments may need to support renewable energy consumption through subsidies.

3.2.2 Policy Analysis

When implementing environmental policies, policymakers face the risk of causing unwarranted macroeconomic volatility, which may in turn call for further policy responses, in particular through monetary policy. In this section, we perform some policy experiments for the purpose of seeing how a central bank can reduce the fluctuations in macroeconomic variables of interest

	Taylor Rule with Core Inflation		Taylor Rule with CPI Inflation	
	Storage	No Storage	Storage	No Storage
Standard Errors				
Consumption	0.0205	0.0457	0.0235	0.0528
Output	0.0357	0.0247	0.0320	0.0240
Investment	0.0445	0.0385	0.0458	0.0572
Hours	0.0059	0.0070	0.0058	0.0090
CPI	0.0377	0.0635	0.0309	0.0471
Welfare Losses (Ω)				
$\varpi_\pi = \varpi_y = 0.5$	0.1349	0.2322	0.0989	0.1398
$\varpi_\pi = 1$, $\varpi_y = 0.5$	0.2058	0.4339	0.1466	0.2508

Table 3: POLICY EXPERIMENTS I. The first five rows report the standard deviations calculated from the impulse response series of consumption, output, investment, labor hours worked, and CPI inflation in response to a tax shock on households' and firms' use of fossil fuel. The last three columns report welfare losses. The main policy scenario is a standard Taylor rule, using which the authority targets both output and inflation. In the first two columns, standard deviations are calculated under the assumption that the central bank targets core (i.e., non-energy) inflation. In the last two, they are calculated under the assumption that the CPI inflation is targeted.

following the tax shock. In Table (3), we first compare the volatilities under a Taylor rule targeting core or CPI inflation following a percentage point increase in taxes on fossil fuel use of consumers and producers. The results show that when storage facility is not considered, targeting core inflation reduces the volatility in consumption, investment, and labor hours, but not that of output and inflation [compare the standard errors in columns 2 and 4 in Table (3)]. With speculative fossil fuel storers, however, volatilities of consumption and investment improve when the central bank targets CPI [compare the standard errors in columns 1 and 3 in Table (3)].

We next consider a simpler version of the monetary policy rule, which prompts a reaction only to the changes in inflation (rather than changes in both inflation and output) in Table (4). The results indicate that macroeconomic stabilization from consumption and inflation points of view is better served when central bank solely focuses on inflation (core inflation or CPI), regardless of whether speculative storage is accounted for. Similar to the first scenario, without storage, responding to core inflation brings a lower volatility in consumption, investment, and labor hours than responding to the CPI inflation.

We now present the ranking of the alternative monetary policy rules based on a welfare criterion whereby the policymaker cares about minimizing the variance of CPI inflation and

	Core Inflation		CPI Inflation	
	Storage	No Storage	Storage	No Storage
Standard Errors				
Consumption	0.0188	0.0405	0.0187	0.0497
Output	0.0477	0.0318	0.0404	0.0270
Investment	0.0603	0.0444	0.0531	0.0575
Hours	0.0074	0.0064	0.0066	0.0086
CPI	0.0266	0.0623	0.0174	0.0471
Welfare Losses (Ω)				
$\varpi_\pi = \varpi_y = 0.5$	0.1492	0.2448	0.0967	0.1475
$\varpi_\pi = 1$, $\varpi_y = 0.5$	0.1847	0.4389	0.1118	0.2585

Table 4: POLICY EXPERIMENTS II. The first five rows report the standard deviations calculated from the impulse response series of consumption, output, investment, labor hours worked, and CPI inflation in response to a tax shock on households' and firms' use of fossil fuel. The last three columns report welfare losses. The main policy scenario is a simple rule, using which the central bank targets only inflation rather than both output and inflation. In the first two columns, standard deviations are calculated under the assumption that the central bank targets core (i.e., non-energy) inflation. In the last two, they are calculated under the assumption that the CPI inflation is targeted.

the output gap. The loss function is given as

$$\Omega = \varpi_\pi \text{Var}(\pi_t) + \varpi_y \text{Var}(y_{z,t}), \tag{3.1}$$

where the notation ϖ_x denotes the weight assigned to the variable x. A lower Ω would mean lower welfare loss associated with the tax shock, which would imply a better stabilization performance of the policy. In Tables (3) and (4), the last two rows, we show the calculated welfare losses under alternative assumptions about the relative weights: (i) $\varpi_\pi = \varpi_y = 0.5$, and (ii) $\varpi_\pi = 1$ and $\varpi_y = 0.5$.

Our analysis points out the importance of taking storage technology into account when assessing the appropriate monetary policy response to fossil fuel taxes. If the storage is not considered, responding to CPI inflation along with output would result in the lower welfare losses following the environmental tax policy. This result does not depend on whether the central bank cares more about inflation or output stabilization. With storage, however, responding to output could bring higher welfare losses depending on the relative importance of inflation and output in the welfare function, and hence it could be undesirable.[10]

[10]This is in line with much of the theoretical literature on optimal simple policies within the New Keynesian class of models. Micro-founded versions of Equation (3.1) that come from a second-order approximation to the utility function of a representative household tend to assign a low value on ϖ_y, because in a model with nominal rigidities CPI inflation should be assigned a higher weight (see, for example, Schmitt-Grohe and Uribe (2007) and Woodford (2003)).

4 Concluding Remarks

There is an extensive literature on the design and implementation of environmental tax policies. We contribute to this literature by performing a quantitative assessment of short-term macroeconomic effects of environmental taxes on the market for fossil fuels. In particular, we highlight the role that speculators would play in the diffusion of tax policy into macroeconomic aggregates. Incorporating speculative storage into a New Keynesian general equilibrium model, our framework captures the nexus among financialization of fossil fuel futures and the associated changes in the fossil fuel prices, environmental policies, and their macroeconomic implications.

We show that, in designing environmental tax policies, the fact that fossil fuels are storable (i.e., they are subject to speculative profit making motives) has to be accounted for. In a canonical model without storage, short-term impacts of environmental tax policies are less pronounced. The existence of forward-looking speculators in the model, however, improves the effectiveness of environmental taxes as it decreases overall fossil fuel consumption further through amplified responses of fossil fuel prices. When subsidies to renewable energy usage are in effect, however, total fossil fuel consumption declines in almost the same amount regardless of whether the speculative storage is incorporated or not.

Fossil fuel taxes have also general equilibrium implications for other macroeconomic variables of policymakers' interest such as inflation and output. Our simulations indicate that introducing taxes on fossil fuel usage tends to, among other effects, decrease output and increase core as well as CPI inflation. These adverse consequences call for a monetary policy response within the objective of macroeconomic stabilization. In fact, monetary policy could be designed in a way to reduce volatility implications of environmental taxes on macroeconomic variables. Our results indicate that responding to output impact of the tax shock becomes less desirable when speculative storage is taken into consideration.

This paper could be extended in several directions. For example, we do not take any position on whether the environmental taxes could be justified in economic terms, but rather assume that it is policymakers' choice to implement them. Relatedly, we do not consider fiscal implications or longer-term effects of environmental policies. There are also other long-term issues related to the storage of below-ground inventories, which is neglected in this paper. When below-ground inventories are introduced, the choice of whether to extract them now or later will also be accounted for in the theoretical model. Such an extension will not add much value to the current analysis, since we deal with short-run issues. However, it might yield interesting results in a model designed to address longer-term questions. We leave these issues for future research.

We assume that the fossil fuel production in the US is endogenous, but the non-US supply is exogenous [in a similar fashion to the model of non-OPEC and OPEC oil supply in Backus and Crucini (2000)]. We choose such a modeling option for three main reasons. *First*, we deal with short-run responses in our model and it is natural to think that fossil fuel supply could give endogenous responses to changing demand conditions in longer horizons. In fact, as Kilian (2009) states, oil-producing countries do not tend to alter supply in response to demand shocks in the short run. This is mainly because of the existence of adjustment costs and uncertainty about future demand conditions. From this respect, we believe that our assumption is not too restrictive.[11] The idea of the existence of adjustment costs also has more scientific foundations. In a recent paper, Anderson, Kellogg, and Salant (2014) show that "oil production from drilled wells declines asymptotically toward zero and is not affected by shocks to spot or expected future oil prices." The pressure in the underground oil reservoir is high when an oil-well is first drilled. Extraction has to be rapid at the initial stage due to this high pressure. Over time, reserves decline, which means that the pressure declines, and the speed of extraction also declines. Once the amount of production goes down, responding to shocks by reducing the production further becomes undesirable due to capacity constraints. In other words, supply response in the intensive margin is not sensitive to shocks. This mechanical explanation supports our assumption that at least part of the oil production can be taken as exogenous in the short-term. The decision to drill new wells (i.e., the extensive margin), on the other

[11] Exogenous supply assumption is generally adopted in the DSGE models to understand the short-run responses to fundamental shocks in oil markets [see, e.g., Bodenstein, Erceg, and Guerrieri (2011) and Bodenstein, Guerrieri, and Kilian (2012)].

hand, is a long-term phenomenon and might be more sensitive to shocks. Since our model aims to investigate short-term dynamics, we believe that our assumption is sensible. *Second*, oil-producing countries outside the US are mostly located in South America and Middle East, where, in general, the severity of political disorder and frequency of political shocks makes impossible to reasonably model the supply behaviors. *Finally*, assuming exogenous non-US supply component increases the analytical tractability of the model. There are some other modeling options regarding the nature of oil supply. For example, in the model developed by Nakov and Pescatori (2010), OPEC's market power is modeled endogenously and the supply behavior changes in response to shocks. In their model, they consider both the OPEC and non-OPEC components of fossil fuel supply as endogenous variables. Specifically, OPEC is modeled as a cartel (or dominant firm) and small non-OPEC producers are aligned on the competitive fringe. Individual firms on the fringe do not have any market power, but they are able to change the behavior of the dominant firm when they act collectively. In such a setup, it is necessary to solve for a Nash equilibrium, since the optimal behavior of one party is designed as a best response to the other party's actions. Although this is out of the scope of the current paper, we believe that it would be an interesting extension for future research.

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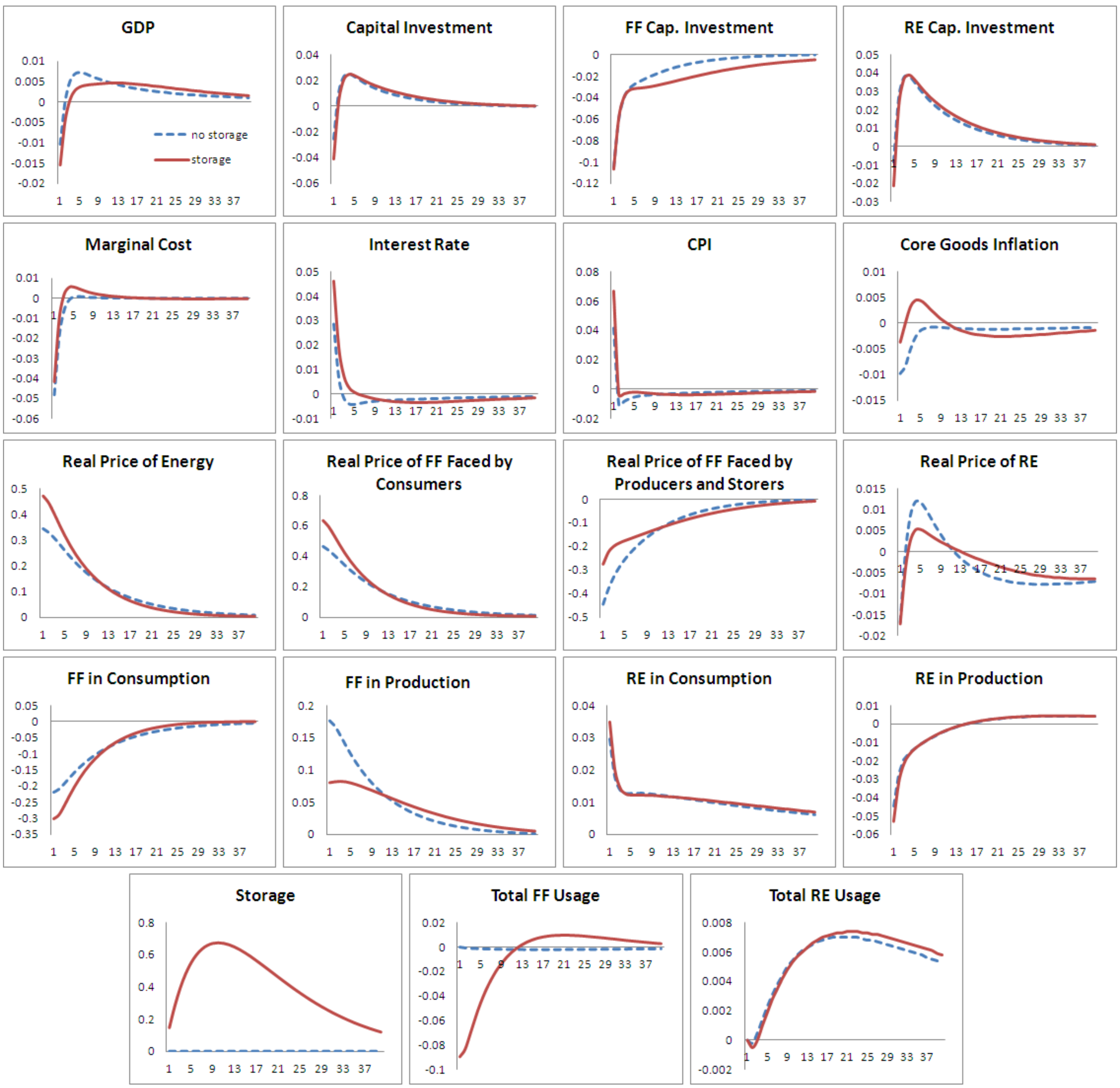

Figure 1: Impulse responses to tax shocks on consumption. FF and RE refer to fossil fuel and renewable energy, respectively.

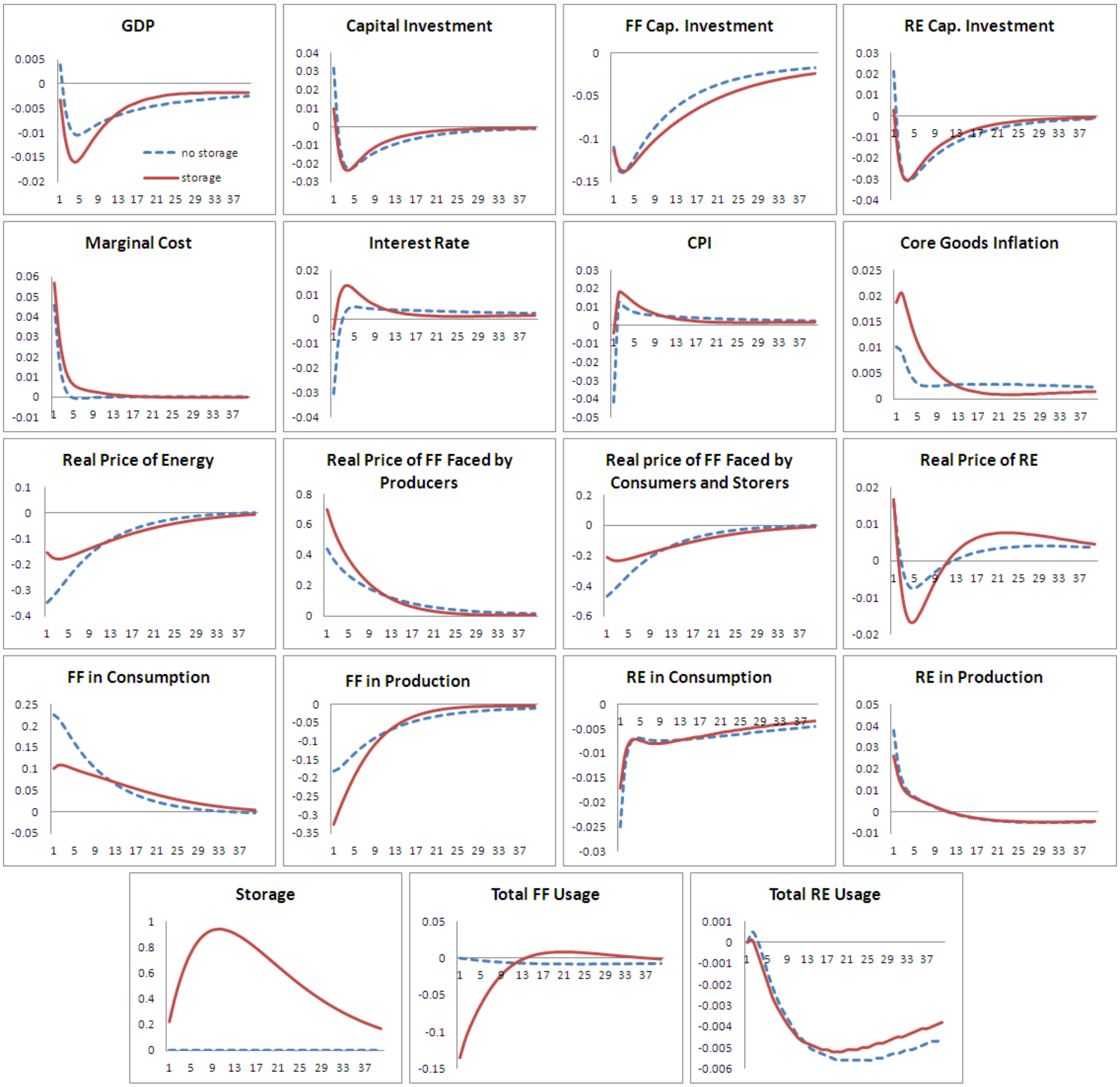

Figure 2: Impulse responses to tax shocks on production. FF and RE refer to fossil fuel and renewable energy, respectively.

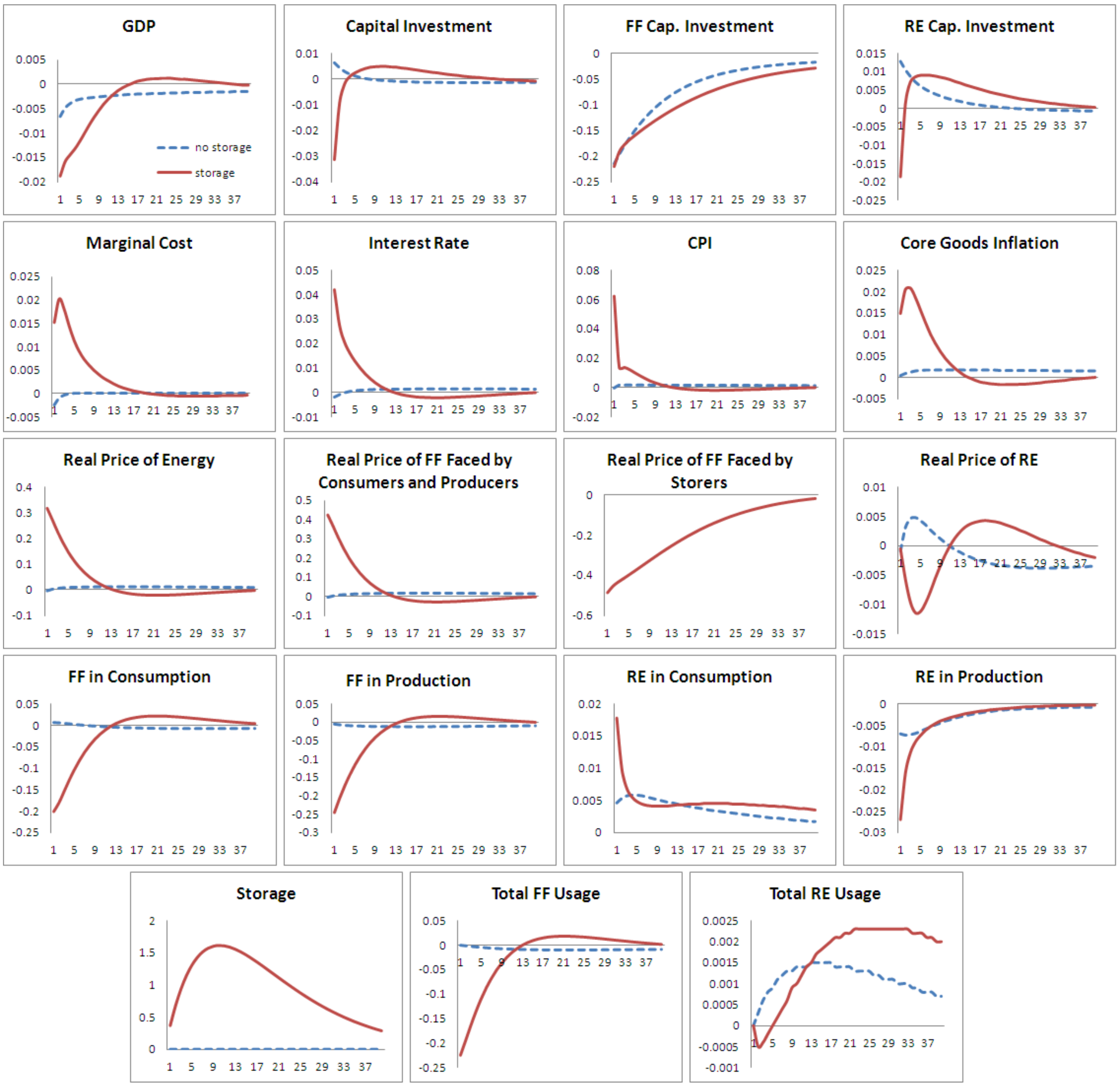

Figure 3: Impulse responses to tax shocks on both production and consumption. FF and RE refer to fossil fuel and renewable energy, respectively.

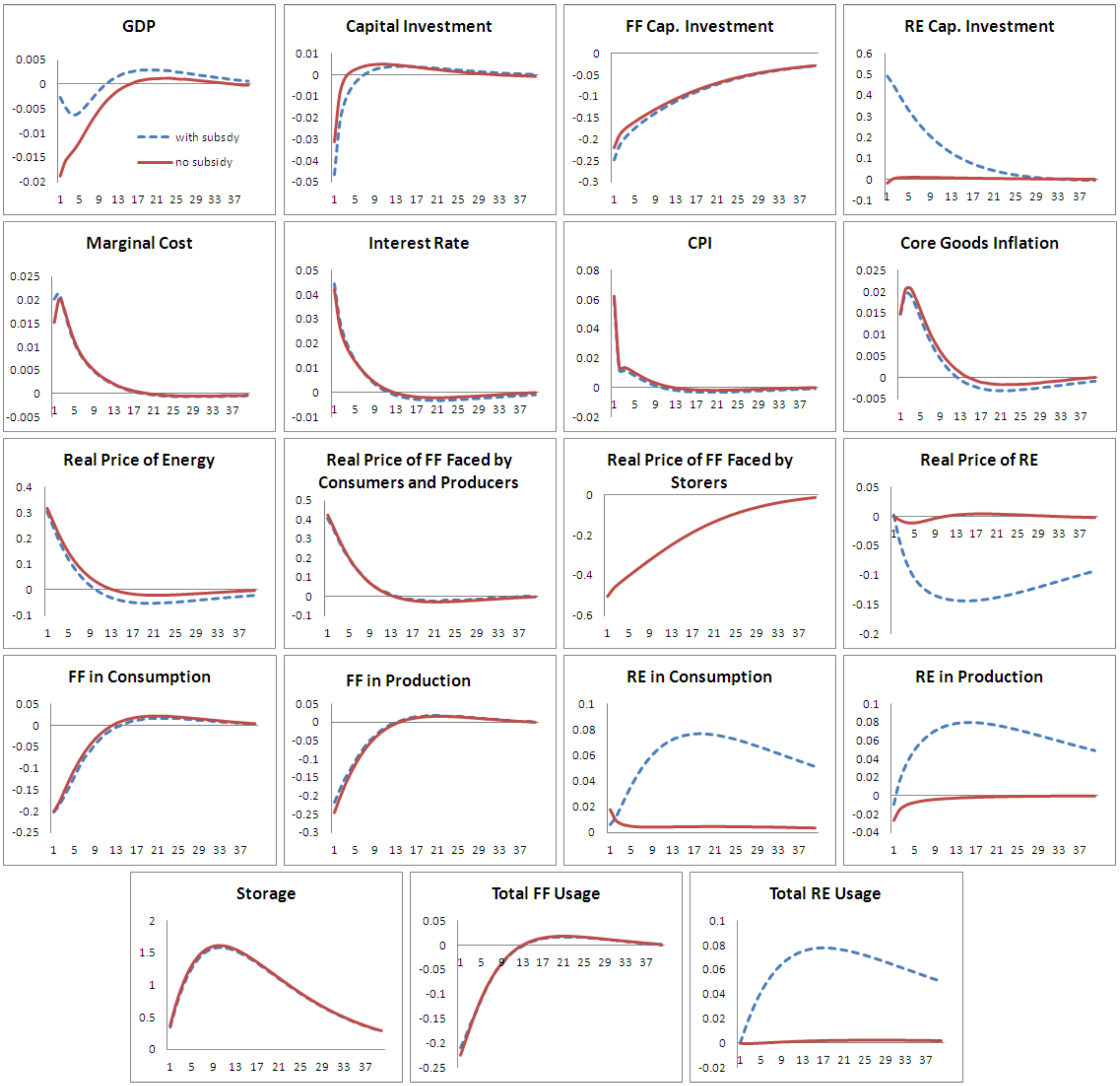

Figure 4: Impulse responses to tax shocks on both production and consumption under subsidies to renewable energy usage. FF and RE refer to fossil fuel and renewable energy, respectively.

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