Environmental policies in the Big Three: US, EU, China, in a Bayesian DSGE model

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May 13, 2016

Abstract

Environmental policy measures to reduce negative externalities related to climate change are common practice in many developed countries and are based on various types of economic incentives, such as fees and subsidies. However, the effectiveness of such policies continues to need investigation, especially when shortsighted measures lead to suboptimal investments in the absence of a credible, long-lasting governmental commitment. The aim of this paper is to investigate the effectiveness of complex policy strategies for fossil and renewable energy sources (RES)

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in a DSGE model estimated with Bayesian estimation techniques for the Three Big economies: US, Europe, China. We use official data. Environmental policy is financed by a carbon tax and is ultimately born by the household sector. Govermment effects are measured in monetary terms as the committment to encourage new technology developments and to influence market decisions. In the model, policy effects pervade both the production and the household sector, trough price and incomes and taxes. Our primary findings show the relative effectivness of policy strategies in the Three Bog economies. Indeed, our dynamic simulations show RES policies have differential effects as a result of a positive technology shock to the final output and the energy sector output. The same result holds in the presence of a positive demand shock to preferences. Moreover, our simulations show country differences in the timing of occurence of the sol called price parity between fossil fuels and RES.

JEL codes: D58, H23, O44, Q48.

Keywords: RES, fossil fuels, productivity shocks, monetary subsidy

1 Introduction

The reduction of greenhouse gas (GHG) emissions undoubtedly plays a priority role in addressing climate change. It is a commitment that first involves the electrical industry, which contributes approximately 40% of GHG emissions (International Energy Agency, 2014).

Policies supporting the use of renewable energy sources (RES) can make an important contribution to climate change mitigation.

The aim of this paper is to investigate the effectiveness of a comprehensive strategy for RES through a DSGE model estimated on three Big economies: US, EU and China, using Bayesian estimation techniques. The inferential procedure adopted is based on Markov Chain Monte Carlo methods (MCMC), which are able to estimate not only the model parameters but also the dynamics of some relevant variables (i.e., fossil fuels and RES prices). We compare the relative effectiveness in the three economic systems in terms of achievement both of the RES goals announced by policy makers and of price parity between RES and fossil fuels. The RES considered include the most common non-hydro RES, i.e., wind, solar photovoltaic and biomass.

The model captures the proposal by Grimaud et al. (2011), which shows that two instruments—an R&D subsidy and a carbon tax—are necessary to correct for the two market failures, i.e., R&D spillovers and pollution.

Ideally, the most efficient solution to stimulate RES development would be the implementation of an optimum carbon tax (Chen and Tseng, 2011). However, the use of an optimum carbon tax alone can discourage the use of fossil fuels, but it can not also stimulate research and development (R&D) activities in RES can lead to excessive distortions (Acemoglu et al, 2012). Then, governments must rely other instruments to achieve the environmental goals established by international environmental agreements. Countries' primary policy instruments are generally classified as either price-oriented or quantity-oriented; some claim to be more market oriented than others, whereas other schemes are claimed to be more efficient in promoting the development of RES (Meyer, 2003). There is no general agreement on the effectiveness of each scheme; this assessment is made even more difficult by the fact that RES differ among countries: although two countries may offer the same support scheme, the quality of their energy sources will differ. The resulting differences in RES production costs might lead to misleading evaluations of support instruments (Held et al., 2006; Klessmann, 2009). RES subsidies are generally the most expensive policy instrument used to mitigate climate change (e.g., energy savings, carbon dioxide capture and storage technologies are less expensive) (Gerlagh and Van der Zwaan, 2006; Gerlagh et al., 2009; Goswami, 2007; Kalkuhl et al., 2013).

The diversity of current environmental policies suggests that policymakers are attracted by different support mechanisms. Moreover, policymakers must find cost-efficient policy instruments to make RES competitive in the energy market.

Designing successful schemes for RES development is fundamental to reach price parity, i.e., the point at which RES technologies become competitive with fossil-fuel-based technologies, without any further need of public support (Breyer and Gerlach, 2013; Hernández-Moro and Martínez-Duart, 2013; Bazilian et al., 2014; Breyer et al., 2009). In the traditional oil market literature, this concept is referred to as the possibility to implement a backstop technology (Dasgupta and Heal, 1979). This would determine the exact intersection of the (downward sloping) cost curve of supplying the alternative backstop substitute and the fossil fuels' (upward sloping) cost curve, which depends on the Hotelling rule (Strand, 2010). In the electricity market literature, this concept is referred to as grid-parity (Lund, 2011).

Recent literature has explicitly focused on the energy and environment sectors in a DSGE model (Dhawan et al. 2010, Tumen et al. 2015, Annicchiarico et al. 2015) but to the best of our knowledge, there is few literature estimating a long-run DSGE model with fossil and RES inputs using Bayesian techniques.

The paper proceeds as follows. Section 2 describes the structure of the theoretical model. Section 3 presents the Bayesian estimation method, the data used and the results of the estimates. Section 4 addresses the model's dynamic properties. Section 5 concludes the paper.

2 The model structure for the three big economies

In this paper, we build a micro-founded DSGE model, explicitly focusing on the energy and environment sectors DSGE model in the spirit of Acemoglu et al. (2012). In the model, there are one final consumer good and three intermediate goods, represented by energy, fossil fuels and RES. Households own the productive factors, sell them to the firms and receive the corresponding value of marginal productivities. The Government through the fiscal revenues coming from the environmental tax subsidizes the clean energy production.

2.1 The firms

Final output, Y_t, is produced competitively according to a Cobb-Douglas production function making use of the three inputs of labor,N_t^y, private capital, K_t^y, and energy services E_t:

$$Y_t = A_t^y \left(N_t^y\right)^{\alpha} \left(K_t^y\right)^{\beta} \left(E_t\right)^{\gamma} \tag{1}$$

where A_t^y is total factor productivity (TFP), whose law of motion is described by the following AR(1) process with zero mean and uncorrelated residuals ε_t^y:

$$\log A_t^y = (1 - \phi^y) \log \bar{A}^y + \phi^y \log A_{t-1}^y + \varepsilon_t^y \tag{2}$$

where $\bar{A}^y$ indicates the steady state value of the final output TFP.

The first intermediate goods sector is represented by the energy sector, which sells energy competitively and is based on clean and dirty inputs. The former are RES $(ER)_t$, whereas the latter are fossil fuels $(EF)_t$. Following Acemoglu et al. (2012), we assume that these inputs are substitutable according to the following CES production function:

$$E_t = A_t^e \left(\eta \left(ER\right)_t^{-\epsilon} + \zeta \left(EF\right)_t^{-\epsilon} \right)^{-\frac{1}{\epsilon}} \tag{3}$$

where A_t^e is total factor productivity (TFP), whose law of motion is described by the following AR(1) process with zero mean and uncorrelated residuals ε_t^e

$$\log A_t^e = (1 - \phi^e) \log \bar{A}^e + \phi^e \log A_{t-1}^e + \varepsilon_t^e \tag{4}$$

where $\bar{A}^e$ indicates the steady state value of the energy TFP and

$$\epsilon = \frac{1 - \sigma}{\sigma} \tag{5}$$

with σ corresponding to the elasticity of substitution between RES and fossil fuels.

The fossil fuel sector (the second intermediate goods sector) produces its output competitively and is represented by a mining firm employing private capital, K_t^{ef}, and labor, N_t^{ef}, according to a Cobb-Douglas production function:

$$(EF)_t = A_t^{ef} \left(N_t^{ef}\right)^{\theta} \left(K_t^{ef}\right)^{\vartheta} \tag{6}$$

where A_t^{ef} is total factor productivity (TFP), whose law of motion is described by the following AR(1) process with zero mean and uncorrelated residuals ε_t^{ef} :

$$\log A_t^{ef} = \left(1 - \phi^{ef}\right) \log \bar{A}^{ef} + \phi^{ef} \log A_{t-1}^{ef} + \varepsilon_t^{ef} \tag{7}$$

where $\bar{A}^{ef}$ indicates the steady state value of the fossil fuels' TFP.

The RES sector (the third intermediate goods sector) is represented by a RES producer in a regime of a perfectly competitive market[1].

Moreover, we consider the following policy intervention in the RES sector. We postulate that the RES production function depends on the inputs of private capital, K_t^{er}, labor, N_t^{er}:

$$(ER)_t = A_t^{er} \left(N_t^{er}\right)^{\iota} \left(K_t^{er}\right)^{\kappa} \tag{8}$$

where A_t^{er} is TFP, whose law of motion is described by an AR(1) process with zero mean and uncorrelated residuals.

In this scenario, to support RES development we assume that the government pays a monetary subsidy μ_t to the RES sector that is entirely financed by a tax on the fossil-fuel sector, as discussed in the next subsection.

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[1] Although we are aware that the energy sector is characterized by oligopolistic competition, we think that the assumption of a perfectly competitive market is more relevant when adopting a long-term perspective in which barriers to entry are progressively removed.

2.2 The Households and the Government

The economy's demand side is populated by an infinite number of infinitely living households with preferences defined for the following variables: private consumption C_t, with share Θ^c; pollution level, Z_t; government's expenditure for public goods, G_t, with share $1-\Theta^c$; labor services, N_t. These latter are allocated to final output production (N_t^y), fossil fuel sector $\left(N_t^{ef}\right)$ and RES sector (N_t^{er}) on a period-by-period basis.

Each agent maximizes the expected value of an intertemporal utility function, i.e.:

$$E_0 \sum_{t=0}^{\infty} \rho^t U_t \left(C_t, Z_t, G_t, N_t^y, N_t^{ef}, N_t^{er}\right) \tag{9}$$

with ρ^t corresponding to the subjective discount factor.

Let the period utility function assume the following CRRA form:

$$U_t = \Theta^c \left(\Upsilon_t \frac{(C_t)^{1-q}}{1-q}\right) + (1-\Theta^c) G_t - Z_t - \frac{(N_t^y)^{1+\chi}}{1+\chi} - \frac{\left(N_t^{ef}\right)^{1+\omega}}{1+\omega} - \frac{(N_t^{er})^{1+\psi}}{1+\psi} \tag{10}$$

where Υ_t is a taste shifter (Stockman and Tesar, 1995), whose law of motion is described by the following AR(1) process with zero mean and uncorrelated residuals ε_t^{Υ} :

$$\log \Upsilon_t = \left(1-\phi^{\Upsilon}\right) \log \bar{\Upsilon} + \phi^{\Upsilon} \log \Upsilon_{t-1} + \varepsilon_t^{\Upsilon} \tag{11}$$

where $\bar{\Upsilon}$ indicates the steady state value of the taste shifter.

Furthermore, public expenditure for public goods, G_t, is financed by a lump-sum taxation, T_t, i.e.:

$$G_t = T_t \tag{12}$$

There are three resource constraints in our model. The first constraint relates to the allocation of capital services according to the policy intervention regime, i.e.:

$$K_t = K_t^y + K_t^{ef} + K_t^{er} \tag{13}$$

The second constraint is typically an intertemporal budget constraint, which states that the total flow of consumptions and investments, indicated by X_t^y, X_t^{ef} and X_t^{er} cannot exceed disposable income:

$$C_t + X_t^y + X_t^{ef} + X_t^{er} \leq W_t^y N_t^y + W_t^{ef} N_t^{ef} + W_t^{er} N_t^{er} + r_t^y K_{t-1}^y + r_t^{ef} K_{t-1}^{ef} + r_t^{er} K_{t-1}^{er} \tag{14}$$

where $W_t^i \, (i = y, ef, er)$ represents the nominal wages paid for each type of labor, $r_t^i \, (i = y, ef, er)$ represents the corresponding return on capital and the price of final consumer goods has been normalized to unity.

The third constraint relates to the relationship between pollution and fossil fuels, i.e.:

$$Z_t = \frac{\varrho \, (EF)_t}{(1 + \xi)} \tag{15}$$

where ϱ indicates the sensitivity of pollution to fossil fuels, whereas ξ is the rate of "environmental regeneration".

Capital accumulation constraints are:

$$X_t^y = K_t^y - (1 - \delta^y) K_{t-1}^y \tag{16}$$

$$X_t^{ef} = K_t^{ef} - (1 - \delta^{ef}) K_{t-1}^{ef} \tag{17}$$

$$X_t^{er} = K_t^{er} - (1 - \delta^{er}) K_{t-1}^{er} \tag{18}$$

where $\delta^i \, (i = y, ef, er)$ indicates the corresponding rates of capital depreciation.

The government's budget is assumed balanced at each time, i.e. the entirety of the revenues from environmental taxation can finance RES monetary subsidy.

The government's budget constraint is:

$$\tau \left(EF\right)_t = \mu_t ER_t \tag{19}$$

where tax revenues on fossil fuels (the left side of the equation) are equal to the entire amount of the subsidy (the right side of the equation).

2.3 The Competitive Equilibrium

In this subsection, we derive optimal conditions that characterize the decentralized equilibrium of firms and households given a set of parameters whose values will be discussed in the next section.

Each representative firm faces a different profit-maximization problem according to its technological structure and constraints.

Given $(W_t^y, R_t^y = 1 + r_t^y - \delta^y, P_t^e)_{t=0}^{\infty}$, the final consumer goods firm aims to maximize the following profit function:

$$\max_{N_t^y, K_{t-1}^y, E_t^y} \Pi_t^y = A_t^y \left(N_t^y\right)^{\alpha} \left(K_{t-1}^y\right)^{\beta} \left(E_t\right)^{\gamma} + \left(1 - \delta^y\right) K_{t-1}^y - W_t^y N_t^y - R_t^y K_{t-1}^y - P_t^e E_t \tag{20}$$

with P_t^e representing the price of energy.

Thus, the demand curves for the productive factors of this firm read as follows:

$$W_t^y = A_t^y \alpha \left(N_t^y\right)^{\alpha-1} \left(K_{t-1}^y\right)^{\beta} \left(E_t\right)^{\gamma} \tag{21}$$

$$R_t^y = A_t^y \beta \left(N_t^y\right)^{\alpha} \left(K_{t-1}^y\right)^{\beta-1} \left(E_t\right)^{\gamma} + \left(1-\delta^y\right) \tag{22}$$

$$P_t^e = A_t^y \gamma \left(N_t^y\right)^{\alpha} \left(K_{t-1}^y\right)^{\beta} \left(E_t\right)^{\gamma-1} \tag{23}$$

The energy-producing firm, given $\left(P_t^{ef}, P_t^{er}\right)_{t=0}^{\infty}$, where P_t^{ef} is the price of fossil fuels and P_t^{er} is the price of RES, solves the following constrained maximization problem:

$$\max_{(EF)_t,(ER)_t,S_t} E_0 \sum_{t=0}^{\infty} \rho^t \left(\Pi_t^e\right) = P_t^e A_t^e \left(\eta \left(ER\right)_t^{-\epsilon} + \zeta \left(EF\right)_t^{-\epsilon}\right)^{-\frac{1}{\epsilon}} + \tag{24}$$

$$- \left(P_t^{ef} + \tau\right) \left(EF\right)_t - P_t^{er} \left(ER\right)_t \tag{25}$$

$$s.t. \left[S_t - S_{t-1} = -\delta^s S_{t-1} - \left(EF\right)_t\right] \tag{26}$$

with the following transversality condition:

$$\lim_{t \to \infty} \rho^t \lambda_t S_t = 0 \tag{27}$$

where λ_t is the dynamic Lagrange multiplier, S_t is the level of the fossil fuels' deposits, whose exhaustibility determines its dynamic constraint, with δ^s representing the deposit depreciation rate and τ is the environmental tax rate on fossil fuels' production. Moreover, we assume that the price of RES, P_t^{er}, is measured as society's opportunity cost of efficiently deploying RES in the system. For this reason, we consider the LCOE of deploying RES given the best available technologies and the prevailing financial and administrative constraints.

The corresponding first-order conditions are as follows (the analytical derivation is reported in the Appendix):

$$
\begin{aligned}
P_t^{ef} + \tau = {} & \underbrace{\begin{array}{c} \left[P_t^e A_t^e \left(-\frac{1}{\epsilon}\right) \left(\eta \left(ER\right)_t^{-\epsilon} + \zeta \left(EF\right)_t^{-\epsilon}\right)^{-\frac{1}{\epsilon}-1} \right] \\ * \left(-\epsilon\right) \zeta \left(EF\right)_t^{-\epsilon-1} \end{array}}_{MP_t^{ef} \text{(marginal productivity of fossil fuels)}} + \\
& + \rho E_t \underbrace{\left[\left(P_{t+1}^{ef} + \tau \right) - MP_{t+1}^{ef} \right] * \left(1 - \delta^s\right)}_{\text{shadow cost of the deposit}}
\end{aligned}
\tag{28}
$$

$$
P_t^{er} = \underbrace{\begin{array}{c} \left[P_t^e A_t^e \left(-\frac{1}{\epsilon}\right) \left(\eta \left(ER\right)_t^{-\epsilon} + \zeta \left(EF\right)_t^{-\epsilon}\right)^{-\frac{1}{\epsilon}-1} \right] \\ * \left(-\epsilon\right) \eta \left(ER\right)_t^{-\epsilon-1} \end{array}}_{MP_t^{er} \text{(marginal productivity of RES)}}
\tag{29}
$$

Note that equation 28 represents the *Hotelling rule*, which states that the overall price of fossil fuels depends not only on their marginal productivity but also on the future cost of fossil-fuels deposits, which, given the exhaustibility of this source, is expected to increase over time.

The fossil fuel representative firm, given $\left(W_t^{ef}, R_t^{ef} = 1 + r_t^{ef} - \delta^{ef}\right)_{t=0}^{\infty}$, aims to maximize this profit function:

$$
\begin{aligned}
\max_{N_t^{ef}, K_{t-1}^{ef}} \Pi_t^{ef} = {} & \left(P_t^{ef} + \tau\right) A_t^{ef} \left(N_t^{ef}\right)^{\theta} \left(K_t^{ef}\right)^{\vartheta} + \left(1 - \delta^{ef}\right) K_{t-1}^{ef} + \\
& - W_t^{ef} N_t^{ef} - R_t^{ef} K_{t-1}^{ef}
\end{aligned}
\tag{30}
$$

with the following demand curves for labor and capital:

$$W_t^{ef} = \left(P_t^{ef} + \tau\right) A_t^{ef} \theta \left(N_t^{ef}\right)^{\theta - 1} \left(K_{t-1}^{ef}\right)^{\vartheta} \tag{31}$$

$$R_t^{ef} = \left(P_t^{ef} + \tau\right) A_t^{ef} \vartheta \left(N_t^{y}\right)^{\theta} \left(K_{t-1}^{Y}\right)^{\vartheta - 1} + \left(1 - \delta^{ef}\right) \tag{32}$$

Finally, the RES sector, given $\left(W_t^{er}, R_t^{er} = 1 + r_t^{er} - \delta^{er}\right)_{t=0}^{\infty}$, faces the following maximization problem:

$$\max_{N_t^{er}, K_{t-1}^{er}} \Pi_t^{er} = \left(P_t^{er} + \mu_t\right) A_t^{er} \left(N_t^{er}\right)^{\iota} \left(K_t^{er}\right)^{\kappa} + \left(1 - \delta^{er}\right) K_{t-1}^{er} + \tag{33}$$

$$- W_t^{er} N_t^{er} - R_t^{er} K_{t-1}^{er}$$

with the corresponding first order conditions:

$$W_t^{er} = \left(P_t^{er} + \mu_t\right) A_t^{er} \iota \left(N_t^{ef}\right)^{\iota - 1} \left(K_{t-1}^{er}\right)^{\kappa} \tag{34}$$

$$R_t^{er} = \left(P_t^{er} + \mu_t\right) A_t^{er} \kappa \left(N_t^{ef}\right)^{\iota} \left(K_{t-1}^{er}\right)^{\kappa - 1} + \left(1 - \delta^{er}\right) \tag{35}$$

The representative agent aims to maximize the utility function subject to the resource constraints:

$$\max_{\left(C_t, Z_t, N_t^i, K_t^i, S_t\right)_{t=0}^{\infty}} E_0 \sum_{t=0}^{\infty} \rho^t U_t \left(C_t, N_t^i, Z_t, K_t^i, S_t, G_t\right) \tag{36}$$

$$i\left(y, ef, er\right),\ s.t.$$

$$\begin{aligned} C_t + X_t^y + X_t^{ef} + X_t^{er} &\leq W_t^y N_t^y + W_t^{ef} N_t^{ef} + W_t^{er} N_t^{er} + \\ &+ r_t^y K_{t-1}^y + r_t^{ef} K_{t-1}^{ef} + r_t^{er} K_{t-1}^{er} \end{aligned} \tag{37}$$

$$S_t - S_{t-1} = -\delta^s S_{t-1} - \left(EF\right)_t \tag{38}$$

$$Z_t = \frac{\varrho \left(EF\right)_t}{\left(1+\xi\right)} \tag{39}$$

The last two constraints can be combined into one, i.e.:

$$Z_t = \frac{\varrho \left(S_{t-1} - S_t - \delta^s S_{t-1}\right)}{\left(1+\xi\right)} \tag{40}$$

which relates pollution to a net decrase in fossil deposit.

Moreover we assume the following:

- the initial capital stocks, K_0^i with $i\left(y, ef, er\right)$, and fossil deposit, S_0, are given and positive;
- these inequality constraints hold: $C_t > 0, N_t^i > 0$ with $i\left(y, ef, er\right), Z_t > 0, G_t > 0$;

- these transversality conditions hold:

$$\lim_{t\to\infty} \rho^t \lambda_t S_t = 0 \tag{41}$$

$$\lim_{t\to\infty} \rho^t \varpi_t K_t = 0 \tag{42}$$

where λ_t and ϖ_t are the dynamic Lagrange multipliers.

The corresponding optimality conditions are summarized in the following block (the analytical derivation is reported in Appendix):

$$\Theta^c \Upsilon_t (C_t)^{-q} W_t^y = (N_t^y)^\chi \tag{43}$$

$$\Theta^c \Upsilon_t (C_t)^{-q} W_t^{ef} = \left(N_t^{ef}\right)^\omega \tag{44}$$

$$\Theta^c \Upsilon_t (C_t)^{-q} W_t^{er} = (N_t^{er})^\psi \tag{45}$$

$$\rho E_t \left[(Z_{t+1}) (1+\delta^s) \right] = Z_t \tag{46}$$

$$\frac{\varrho (S_{t-1} - S_t - \delta^s S_{t-1})}{(1+\xi)} = Z_t \tag{47}$$

$$W_t^y N_t^y + W_t^{ef} N_t^{ef} + W_t^{er} N_t^{er} + r_t^y K_{t-1}^y + r_t^{ef} K_{t-1}^{ef} + r_t^{er} K_{t-1}^{er} = C_t + \tag{48}$$
$$+ X_t^y + X_t^{ef} + X_t^{er}$$

$$E_t \left[\rho \left(\frac{\Upsilon_{t+1}}{\Upsilon_t} \right) \left(\frac{C_t}{C_{t+1}} \right)^q R_{t+1}^y \right] = 1 \tag{49}$$

$$E_t \left[\rho \left(\frac{\Upsilon_{t+1}}{\Upsilon_t} \right) \left(\frac{C_t}{C_{t+1}} \right)^q R_{t+1}^{ef} \right] = 1 \tag{50}$$

$$E_t \left[\rho \left(\frac{\Upsilon_{t+1}}{\Upsilon_t} \right) \left(\frac{C_t}{C_{t+1}} \right)^q R_{t+1}^{er} \right] = 1 \tag{51}$$

The final three relationships are the *Euler Equations*, which are very commonly explored in these models; in this case, those equations state a *non-arbitrage condition* among private capital rates, i.e.:$R^{y}_{t+1} = R^{ef}_{t+1} = R^{er}_{t+1}$

3 Model estimation (preliminary: EU ONLY – US and China to be added)

3.1 Methodology and data

The inferential procedure we adopt to estimate the parameters, to simulate the time series for the key variables of the model and to analyze their dynamics is based on MCMC methods and, in particular, on the Metropolis-Hastings algorithm. This methodology belongs to the family of Bayesian estimation methods that are very common in the empirical macroeconomic literature (see among others Canova, 2007; Smets and Wouters, 2007). Moreover, because the model is non-linear in some equations, we have preliminarily linearized and solved it using the Blanchard and Khan (1980) algorithm. Next, we have built a multi-chain MCMC procedure based on 4 chains of size 200,000; the algorithm converges within 65,000 iterations to its expected value. Therefore, to remove any dependence from the initial conditions we remove the first 65,000 observations from each chain. This high number of iterations—together with the 95 percent confidence interval for the estimates—ensures the robustness of our results[2].

All of the model computations have been performed using DYNARE software[3]. Below, we summarize the measurement equations considered, i.e. the

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[2] In detail, our estimation procedure is based on two steps. In the first step, we estimate the mode of the posterior distribution by maximizing the log posterior density function, which is a combination of the prior information on the structural parameters with the likelihood of the data. In the second step, we use the Metropolis-Hastings algorithm in order to draw a complete picture of the posterior distribution and compute the log marginal likelihood of the model. The convergence diagnostic is based on Brooks and Gelman (1998) method.

[3] Dynare is a software that is freely available from the website http://www.dynare.org and has the ability to simulate and estimate economic models

relationships between the model variables (on the right side) and the data (on the left side):

$$\begin{bmatrix} \Delta \ln C_t \\ \Delta \ln E_t \\ \Delta \ln (EF)_t \\ \Delta \ln (ER)_t \\ \Delta \ln Y_t \end{bmatrix} = \begin{bmatrix} \Gamma^{(A)} \\ \Gamma_E^{(A)} \\ \Gamma_{EF}^{(A)} \\ \Gamma_{ER}^{(A)} \\ \Gamma^{(A)} \end{bmatrix} + 100 * \begin{bmatrix} c_t - c_{t-1} \\ e_t - e_{t-1} \\ (ef)_t - (ef)_{t-1} \\ (er)_t - (er)_{t-1} \\ y_t - y_{t-1} \end{bmatrix} \tag{52}$$

$\Delta \ln C_t$ is private consumption growth expressed in percentage terms, $\Delta \ln E_t$ is gross inland energy consumption[4] growth expressed in percentage terms, $\Delta \ln (EF)_t$ is fossil fuels' gross inland consumption growth expressed in percentage terms, $\Delta \ln (ER)_t$ is RES inland consumption growth expressed in percentage terms and $\Delta \ln Y_t$ is real GDP growth expressed in percentage terms. Moreover, because the data reveal different annual trend growth rates among the variables, we consider a common annual trend growth rate between consumption and GDP, whereas for the other measured variables we consider specific trend growth rates. $\Gamma^{(A)}$ is the annual trend growth rate common to private consumption and GDP expressed in percentage terms ($100 * \ln \Gamma$), whereas $\Gamma_E^{(A)}, \Gamma_{EF}^{(A)}$ and $\Gamma_{ER}^{(A)}$ are energy, fossil fuel and RES annual trend growth rates, respectively, expressed in percentage terms ($100 * \ln \Gamma_i, i = E, EF, ER$). Finally, the third vector indicates the corresponding model variables in log-differences. The sources of our data for the period 1995-2012 at an annual frequency are the Ameco database (December 2014) for private consumption and final output

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[4] Gross inland consumption is calculated as follows: primary production + recovered products + total imports + variations of stocks - total exports - bunkers. It corresponds to the sum of final consumption, distribution losses, transformation losses and statistical differences (Eurostat).

and the Eurostat database (December 2014) for energy variables.

More specifically, private consumption C_t is measured according to the total final consumption expenditure of households for EU-15 countries in constant prices for 2010. Energy services, E_t, are measured according to the EU-15's gross inland energy consumption (thousand tons of oil equivalent, TOE). Fossil fuels, $(EF)_t$, are measured according to the sum of gross inland consumption of solid fuels, total petroleum products, gas and nuclear heat for the EU-15 countries (TOE). RES, $(ER)_t$, are measured according to the EU-15's energy gross inland consumption for RES (TOE), including wind, solar photovoltaic and biomass. Final output, Y_t, is measured according the EU-15's real GDP in constant prices for 2010.

The choice of these observable variables is motivated by this paper's main purpose, namely, the construction of simulated time series for RES and fossil fuel prices, in the presence of public policies for RES development. In this regard, the use of gross inland consumption data (inclusive of imported energy) instead of primary production appears to be more realistic and consistent with European energy markets, which import a large share of fossil fuels, RES and energy. Furthermore, real GDP and private consumption data are good measures of economic activity levels, which affects both energy demand and price for both RES and fossil fuels.

3.2 Calibration and prior distributions

The parameters employed in our model together with their definitions are shown in table 1, whereas our prior parametrization is summarized in tables **??**, **??**, 2 and 3.

The prior densities are consistent with the domain of the parameters. We use, unless otherwise specified, EU-15 annual data from 1995 to 2012 to com-

Table 1: **Parameter definitions**

Parameter	Definition
α	final output elasticity of labor
β	final output elasticity of capital
γ	final output elasticity of energy
δ^y	depreciation rate of final output capital
δ^{ef}	depreciation rate of fossil fuels' capital
δ^{er}	depreciation rate of RES capital
δ^s	depreciation rate of fossil deposit
σ	elasticity of substitution between RES and fossil fuels
ζ	fossil fuels' share in energy production
η	RES share in energy production
θ	fossil fuels' elasticity of labor
ϑ	fossil fuels' elasticity of capital
ι	RES elasticity of labor
κ	RES elasticity of private capital
ϱ	Pollution sensitivity to fossil fuels
q	Coefficient of relative risk aversion
ϕ^y	Persistence in final output TFP
ϕ^e	Persistence in energy TFP
ϕ^{ef}	Persistence in fossil fuels' TFP
ϕ^{er}	Persistence in RES TFP
ϕ^{Υ}	Persistence in taste shifter
ψ	Inverse of RES Frisch elasticity of labor supply
ω	Inverse of fossil fuels' Frisch elasticity of labor supply
χ	Inverse of final output Frisch elasticity of labor supply
ρ	Intertemporal discount factor
ξ	Environmental regeneration rate
Θ^c	Preference for private consumption
τ	Environmental tax rate on fossil fuels' production

pute the prior means of the parameters and the standard deviations of the stochastic shocks (Eurostat and Ameco databases, December 2014). In the next subsection, instead, we use the same data on the observable variables (private consumption, energy, RES, fossil fuels and final output) conditionally to the model to estimate the posterior values of the structural parameters.

Moreover in the prior estimation phase, we assume that energy sectors' production function elasticities have the same prior means as the corresponding means of final output.

The final output production function elasticities α, β and γ are distributed according to a beta random variable with means equal to the average shares of wages, capital rents and the overall value of energy on the EU-15 GDP, with a standard deviation of 0.05. Moreover, fossil fuel and RES production function elasticities $(\theta, \vartheta, \iota, \kappa)$ follow a beta distribution with means equal to those of the final output, but with a slightly higher standard deviation of 0.1. Capital and fossil deposits' depreciation rates $\left(\delta^{y}, \delta^{ef}, \delta^{er}, \delta^{s}\right)$ are distributed according to a beta random variable with means equal to 0.05, a value consistent with the average private capital rental rate of 9%, that is the net rate of the EU-15 from 1995 to 2012, and standard deviations of 0.05 for final output capital and 0.1 for the others.

The shares of fossil fuels and RES in the energy production function— ζ and η—follow a beta distribution with means equal to 0.93 and 0.07, respectively, which are the average shares of fossil fuels and RES in energy production for the EU-15 from 1995 to 2012, whereas the elasticity of substitution between RES and fossil fuels follows a gamma distribution with a mean of 0.66, which is the value of the estimated elasticity of substitution between clean and dirty energies in the EU (Pelli, 2012).

The coefficient of relative risk aversion, q, which is the inverse of the intertemporal elasticity of substitution of consumption, is normally distributed with a mean of 1.5, a value consistent with the macroeconomic literature on DSGE applied to the EU (Smets and Wouters, 2007), and a standard deviation of 0.5, whereas the inverse of the Frisch elasticities of labor supply, ψ, ω and χ, follow a gamma distribution with means equal to 3.55, which is consistent with a discrete Frisch elasticity of labor supply of 0.28 in the EU-15 and a standard deviation of 0.75.

The persistence coefficients for the stochastic processes related to the TFPs and taste shifter are beta distributed with means equal to 0.9 and 0.5, respectively, (following the real business cycle literature (Blanchard and Quah, 1989; King and Rebelo, 1999)), with standard deviations equal to 0.20.

The preference for private consumption follows a beta distribution with a mean equal to 0.6, which is the average propensity to private consumption in the EU-15 from 1995 to 2012, with a standard deviation of 0.05, whereas the pollution sensitivity to fossil fuels, ϱ, follows a gamma distribution with a mean of 3.01, which is the ratio of tons of CO2 generated to TOE of fossil fuels produced in the EU-15, and a standard deviation of 0.1.

The environmental regeneration rate, ξ, follows a gamma distribution with a standard deviation of 0.1 and a mean of 1.03, which has been estimated for EU-15 data according to the following equation:

$$Z_t = \frac{\varrho\,(EF)_t}{(1+\xi)} + \epsilon_t^z \tag{53}$$

given $\varrho = 3.01$ and $\epsilon_t^z \sim N\,(0,1)$

The intertemporal discount factor ρ follows a beta distribution with a mean of 0.92, implying a steady state value of 9% for the private capital rental rate, according to *Euler Equations*, and a standard deviation of 0.05.

The standard errors of TFP and taste shifter shocks follow an inverse gamma distribution with means equal to 0.92 for TFP, which corresponds to a standard deviation of 2.9 calculated on EU-15 TFP data, and 0.6 for taste shifter. This last value has been estimated as the standard deviation of the shock ϵ_t^c of the following AR(1) process:

$$C_t = \phi^{\Upsilon} C_{t-1} + \epsilon_t^c \tag{54}$$

The prior standard deviations for these parameters have been set to 2.

The environmental tax rate, τ, follows a beta distribution with a standard deviation of 0.1 and a mean of 0.02, which is the average effective environmental tax rate calculated on EU-15 data on revenue from taxes on pollution.

Finally the annual trend growth rates, $\Gamma, \Gamma^{E}, \Gamma^{EF}, \Gamma^{ER}$, are Gaussian with means equal to $1.6, 0.13, -0.03, 4.71$, respectively, which match the annual EU-15 growth rates for GDP in the period considered and standard deviations equal to 0.1.

3.3 Posterior distributions

The fifth and sixth columns of the tables 2 and 3 show the posterior means and a 95 percent confidence interval for the estimated parameters obtained by the Metropolis-Hastings algorithm compared to their prior distributions (tables 2 and 3), i.e. the presence of a monetary subsidy[5].

The log-marginal value of the likelihood of the model is -349.33. As a further robustness check, we also estimate a version of the model without any policy intervention in the RES sector and we obtain a log-marginal value of the likelihood of -362.51, that is worse than the previous one. Hence, a correct specification of a DSGE model incorporating RES sector needs a form of public policy intervention.

The posterior estimated values for supply-side sectors are higher than the prior labor elasticities and lower than the prior capital elasticities in the cases of final output, fossil fuels and RES production. This result indicates a labor-intensive feature of these sectors.

The values of the elasticity of substitution between RES and fossil fuels and the capital depreciation rates are quite similar to the prior values, whereas the

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[5] Following Smets and Wouters (2007), to evaluate the sensitivity of the estimation results to our assumptions on prior estimates, we have increased the standard errors of the prior distributions of the parameters by 50 percent. Overall, the estimation results are very similar. These results are available upon request.

Table 2: **Prior and Posterior Distribution of Structural Parameters**

Parameter	Prior distrib.			Post. distrib.	
	Distr.	Mean	St. Dev.	Mean	Conf. Interval 95%
α	beta	0.45	0.05	0.5712	[0.5311 0.6129]
β	beta	0.27	0.05	0.1597	[0.1257 0.1934]
γ	beta	0.12	0.05	0.0367	[0.0321 0.0413]
δ^y	beta	0.05	0.05	0.0450	[0.0438 0.0464]
δ^{ef}	beta	0.05	0.1	0.0510	[0.0501 0.0518]
δ^{er}	beta	0.05	0.1	0.0520	[0.0515 0.0525]
δ^g	beta	0.05	0.1	0.0475	[0.0473 0.0477]
δ^s	beta	0.05	0.1	0.0511	[0.0510 0.0512]
σ	gamma	0.66	0.05	0.6911	[0.6900 0.6922]
ζ	beta	0.93	0.05	0.9893	[0.9649 1.0000]
η	beta	0.07	0.05	0.0107	[0.0100 0.0114]
θ	beta	0.45	0.1	0.4539	[0.3718 0.5563]
ϑ	beta	0.27	0.1	0.1852	[0.1356 0.2346]
ι	beta	0.45	0.1	0.4917	[0.4405 0.5429]
κ	beta	0.27	0.1	0.2128	[0.1908 0.2452]
ϱ	gamma	3.01	0.1	3.0558	[2.9801 3.1104]
q	normal	1.50	0.5	0.9399	[0.8912 0.9850]
ψ	gamma	3.55	0.75	3.6231	[3.6030 3.6432]
ω	gamma	3.55	0.75	3.6123	[3.6062 3.6184]
χ	gamma	3.55	0.75	3.2236	[3.2135 3.2337]
ρ	beta	0.92	0.05	0.9585	[0.9584 0.9586]
ξ	gamma	1.03	0.1	1.0446	[1.0352 1.0540]
Θ^c	beta	0.6	0.05	0.6584	[0.6142 0.7018]
τ	beta	0.02	0.1	0.0359	[0.0265 0.0453]

environmental tax rate and the intertemporal discount factor exhibit a positive shift.

Pollution sensitivity to fossil fuels and the environmental regeneration rate are slightly higher than the prior distributions.

Looking at the households' sector parameters, the inverse of Frisch elasticities of labor supply are substantially in line with the prior values, with higher values for the fossil fuels and RES sectors and slightly lower values for the final output sector, from 3.55 to 3.22. These last results show that there is greater labor market flexibility in the final output sector with respect to the energy sectors. The posterior estimated coefficient of the relative risk aversion

Table 3: **Prior and Posterior Distribution of Structural Parameters**

Parameter	Prior distrib.			Post. distrib.	
	Distr.	Mean	St. Dev.	Mean	Conf. Interval 95%
ϕ^y	beta	0.90	0.2	0.9727	[0.9295 1.0000]
ϕ^e	beta	0.90	0.2	0.9965	[0.9913 1.0000]
ϕ^{ef}	beta	0.90	0.2	0.7507	[0.6921 0.8118]
ϕ^{er}	beta	0.90	0.2	0.7392	[0.6290 0.8500]
ϕ^{Υ}	beta	0.50	0.2	0.4755	[0.4034 0.5524]
σ_{ε^y}	inv.gamma	0.92	2.0	0.9277	[0.9250 0.9304]
σ_{ε^e}	inv.gamma	0.92	2.0	0.8950	[0.8835 0.9065]
$\sigma_{\varepsilon^{ef}}$	inv.gamma	0.92	2.0	0.9041	[0.8925 0.9157]
$\sigma_{\varepsilon^{er}}$	inv.gamma	0.92	2.0	0.8825	[0.8811 0.8839]
$\sigma_{\varepsilon^{\Upsilon}}$	inv.gamma	0.60	2.0	0.6431	[0.6217 0.6645]
Γ	normal	1.6	0.1	1.5510	[1.5500 1.5520]
Γ^E	normal	0.13	0.1	0.1725	[0.1699 0.1751]
Γ^{EF}	normal	-0.03	0.1	-0.0547	[-0.0511 -0.0583]
Γ^{ER}	normal	4.71	0.1	4.6815	[4.6612 4.7018]

is lower than the prior value (from 1.5 to 0.94), thus showing a smaller degree of risk aversion than assumed a priori. The preference of private consumption, is slightly higher than prior estimates.

A closer inspection to the exogenous processes shows that the size of the autoregressive coefficients is confirmed, and the energy sector TFP is more persistent than in the prior estimates.

Regarding final output, it is interesting to note that the final output TFP persistence exhibits a positive shift that is always greater than the persistence of the taste shifters. This evidence confirms the economic features of TFP and taste shocks. The former are typically more persistent, dealing with the supply-side of the economy, whereas the latter, that are demand shocks, deplete their effects in the short-term (Blanchard and Quah, 1989).

The standard errors of TFP and taste shifter shocks show a posterior mean that is substantially consistent with the prior distributions for consumption and final output, whereas for energy sectors these values are lower. This result sharpens a lower volatility for TFP in the energy markets compared with the results for final output.

Finally, the posterior estimates of the trend growth rates are lower than their prior values with the exception of energy sector, whose values exhibit a positive shift.

4 Model dynamics (preliminary: EU ONLY – US and China to be added)

In this section, we discuss the dynamic response of the relevant variables when the economy is hit by stochastic shocks on TFPs and taste shifter, namely impulse response functions (IRFs).

Note that for all of the IRFs, the size of the standard deviations of the stochastic shocks and the variables' responses relate to the posterior-average of the IRFs for each draw of the MCMC algorithm, together with 95 percent confidence intervals[6].Moreover, because the variables are expressed in logs, the measures of the responses can be read as elasticities.

Next, we analyze (through the MCMC algorithm) the dynamic behavior of the prices of fossil fuels and RES for the policy intervention based on monetary subsidies.

We compare the Bayesian IRFs for a TFP shock on final output, as shown in figure (1).

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[6] The confidence intervals have been computed as the 2.5 and 97.5 percentiles of the empirical distributions obtained by the algorithm.

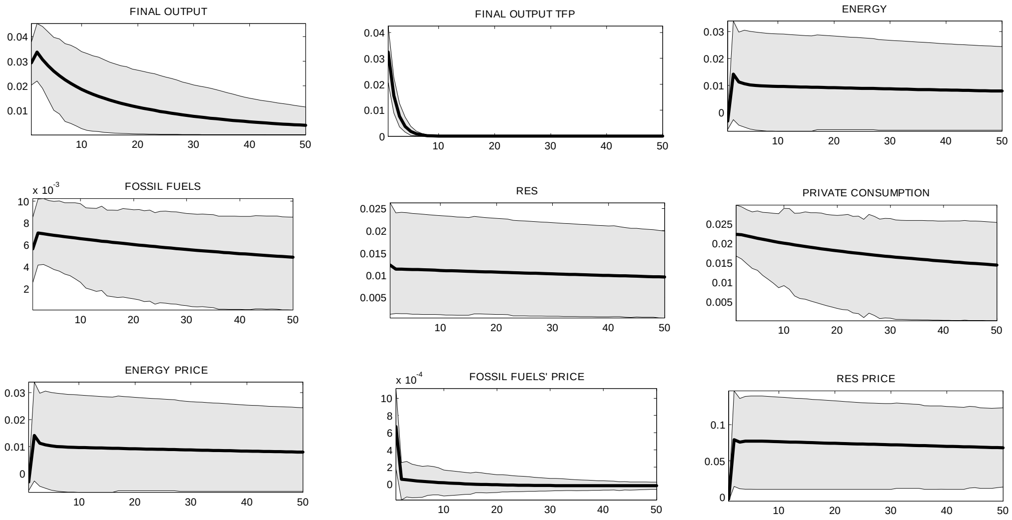

Figure 1: Impulse response functions for a positive TFP shock on final output

A positive technology shock to final output generates an increase in production and consumption through a positive shift of final goods' supply curves and productive factors' demand curves. More specifically, the increased TFP generates a positive growth of energy demand and price, along with increases in both fossil fuels and RES prices, thus inducing a growth in their quantities.

Furthermore, the increase in the RES quantity and the effects on energy price and quantity are different. The increase involves only labor and private capital, with a smaller effect on RES because of the decreasing returns to scale.

We then analyze the IRFs when a positive shock hits the energy sector (figure 2).

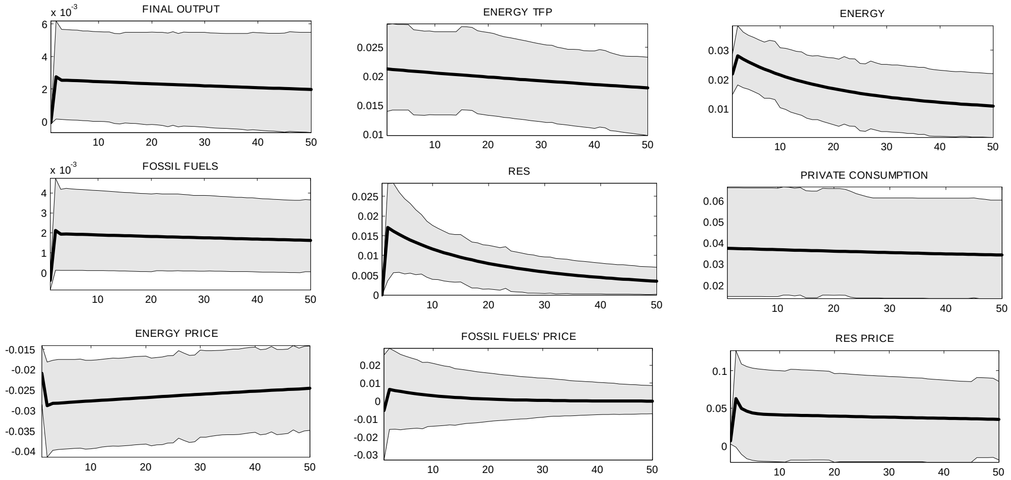

Figure 2: Impulse response functions for a positive TFP shock on energy sector

If energy is more productive, both fossil fuels and RES experience increased prices and quantities.

The positive growth of fossil fuels and RES demand determines an increase in energy production, which has the ability to decrease energy price. We show IRFs in the presence of a TFP shock in the fossil-fuel sector in figure (3).

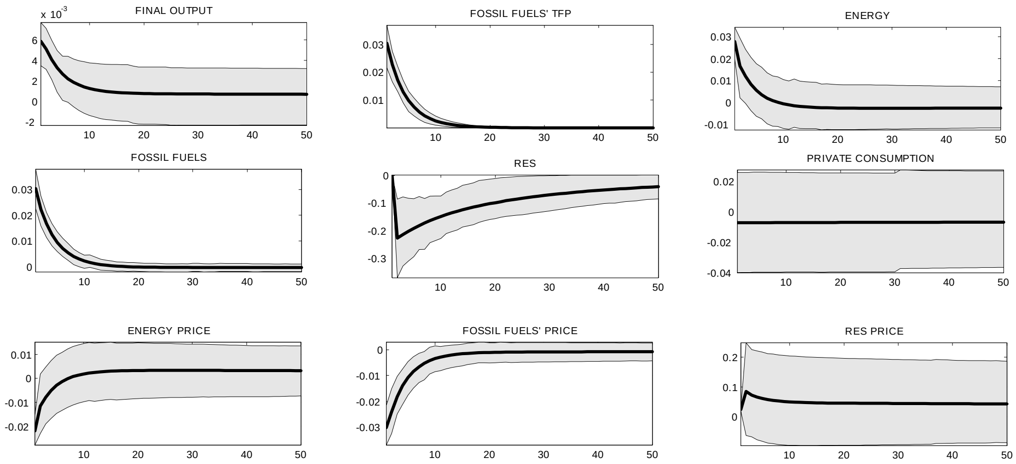

Figure 3: Impulse response functions for a TFP shock on fossil fuels' sector

In this case, a positive shift in fossil fuels' TFP generates a positive growth in fossil fuels' supply curve, thus determining a decrease in fossil fuels' price. Nevertheless, RES production falls, due to the reallocation of private capital and labor toward the fossil-fuel sector, which is more productive. The decrease of RES production determines a positive growth of RES price. The only effect of the increase in the monetary subsidy related to the growth of environmental taxation is to slow down the reduction in profits. The overall effect on energy production is positive and therefore its price decreases.

We analyze the IRFs describing a TFP shock in the RES sector in figure (4).

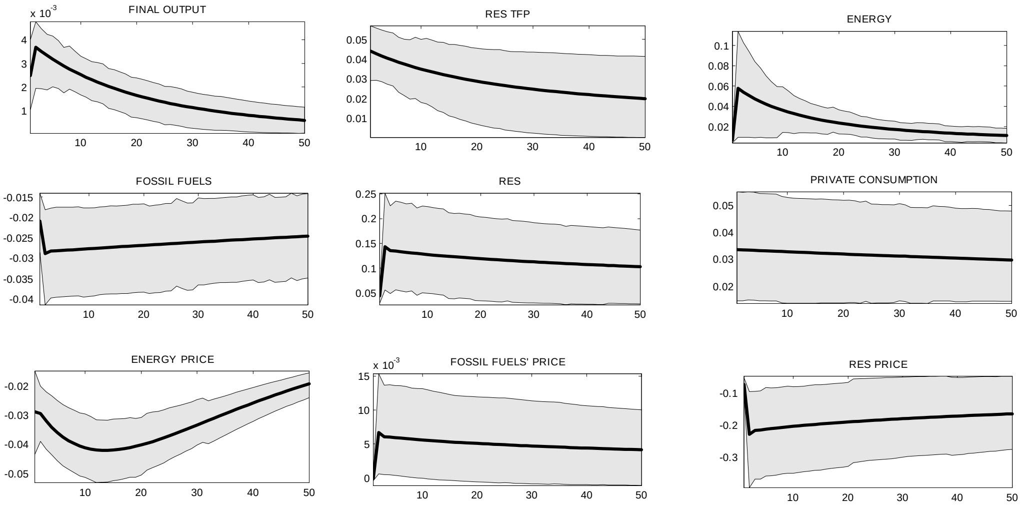

Figure 4: Impulse response functions for a TFP shock on RES sector

A positive growth in RES TFP has the ability to increase RES production. Notice that all of the RES's productive factors (private capital and labor) increase, thus determining a greater growth of RES. In addition, RES and energy prices decrease, whereas energy production increases despite the small relative share of RES in the energy production function.

We analyze the IRFs in the presence of a demand shock on the preferences in figure (5).

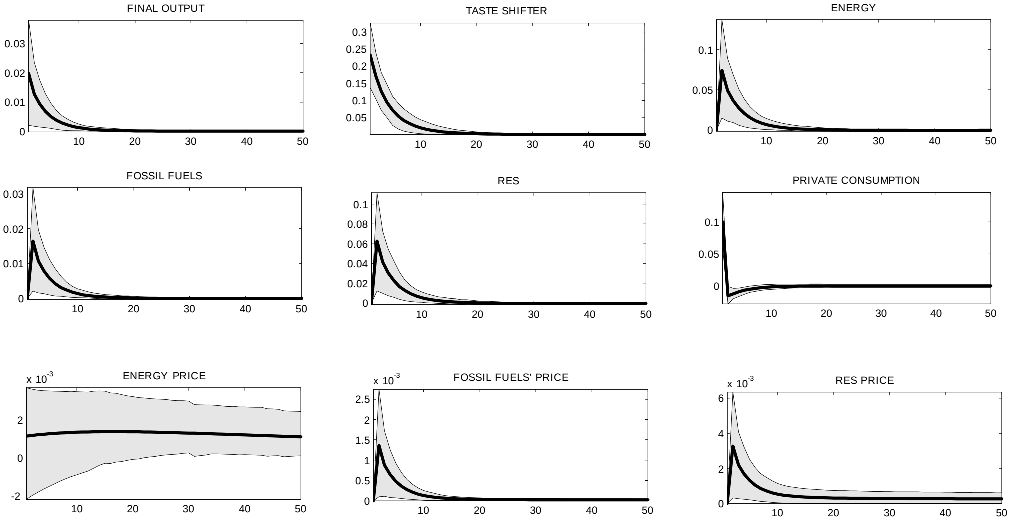

Figure 5: Impulse response functions for a positive demand shock on the preferences

The dynamics of the variables in this context is similar to the case of the final output TFP shock. Now, however, the positive growth of the productive factors' demand curves is determined by tastes, whose rise generates a positive shift of private consumption and hence an higher production through an increaed use of the inputs.

Finally, we analyze the price parity points with a 95 percent confidence interval (figures 5).

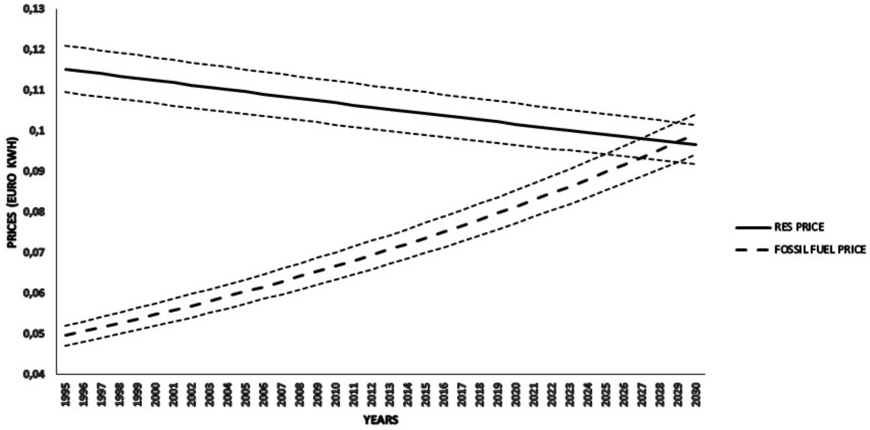

Figure 5: EU-Price Parity

The time series of RES and fossil-fuel prices are generated for the EU-15 through the MCMC method over the 36 years represented in the sample for 1995-2030. For each year, we draw 200,000 realizations of the stochastic shocks described and identified in Section 3.2. Next, we take the expected value of this sequence as the corresponding value for each year . These prices are expressed in Euro/Kwh.

Notice that the rate of decrease of the RES price is linked to positive exogenous shifts of TFP in the RES sector. Notice that according to our model, the achievement of price parity is endogenously determined, whereas in most of the current literature, this achievement is determined by implementing an exogenous experience curve approach (Breyer and Gerlach, 2013; Lund, 2011; Mathews, 2013).

5 Conclusions and policy implications

This paper contributes to the literature by showing the effects of incentive mechanism for RES deployment in Three Big Economies: US, EU and China.

We have assessed the effectiveness of such incentive mechanism compared to most of the literature, which uses a carbon tax and a monetary subsidy to RES producers.

To this aim, we have constructed three data set for the threee economies, where the RES production function depends on private capital and labor and the RES support is provided by a monetary subsidy.

We have estimated our DSGE model using Bayesian techniques; the inferential procedure is based on the MCMC methods to estimate both the model parameters and the dynamics of some relevant variables, such as fossil fuels price and RES price. The estimation results over the period 1995-2012 reveal that assuming an understanding that a carbon tax is required, monetary subsidy to RES producers have different effects for RES long-run development.

Our results show that in the presence of a positive technology shock on the final output sector and with a positive demand shock on preferences, RES production experiences more growth in counties where the policy commitment is more credible.

Moreover, the energy sector is more productive the RES production function generates a greater positive spillover from the monetary subsidy.

Finally, we have investigated the issue of price parity between RES and fossil fuels, which is an important milestone for RES deployment.

Comparing the different countries RES support mechanisms a very encouraging picture emerges for RES performance. Indeed, there is a noticeable anticipation of achieving price parity in more flexible economies

Moreover, the strength of our results is that price parity is endogenously determined by the model, contrary to most of the literature, which deploys price parity calculation based on exogenous assumptions about LCOE and RES learning rates.

This study explores issues related to three big economies taken in isolation: US, E, China. It would be interesting to apply this model to a full world model, where trade and finanicla interactions among countries are modeled, including developing countries.

This would require a deep analysis of the RES support mechanisms implemented in such countries, which is left for future research.

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6 Appendix

The representative energy producer aims to maximize the expected value of the following intertemporal profit function:

$$\begin{aligned}
\max_{(EF)_t,(ER)_t,S_t} E_0 \sum_{t=0}^{\infty} \rho^t \left(\Pi_t^e\right) &= P_t^e A_t^e \left(\eta \left(ER\right)_t^{-\epsilon} + \zeta \left(EF\right)_t^{-\epsilon}\right)^{-\frac{1}{\epsilon}} + \\
&\quad - \left(P_t^{ef} + \tau\right) \left(EF\right)_t - P_t^{er} \left(ER\right)_t \\
&\quad s.t. \left[S_t - S_{t-1} = -\delta^s S_{t-1} - \left(EF\right)_t\right]
\end{aligned}$$

The problem is solved using a dynamic programming technique that maximizes the Lagrangian function, L, i.e.:

$$L = \max_{(EF)_t,(ER)_t,S_t} E \left[\begin{array}{c} \sum\limits_{t=0}^{\infty} \rho^t \left(\begin{array}{c} P_t^e A_t^e \left(\eta \left(ER\right)_t^{-\epsilon} + \zeta \left(EF\right)_t^{-\epsilon}\right)^{-\frac{1}{\epsilon}} + \\ - \left(P_t^{ef} + \tau\right) \left(EF\right)_t - P_t^{er} \left(ER\right)_t \end{array}\right) + \\ + \lambda_t \left(S_{t-1} - \delta^s S_{t-1} - \left(EF\right)_t - S_t\right) \end{array}\right]$$

with the following necessary conditions:

$$\begin{aligned}
\frac{\partial L}{\partial \left(EF\right)_t} &: P_t^{ef} + \tau = \left[P_t^e A_t^e \left(-\frac{1}{\epsilon}\right) \left(\eta \left(ER\right)_t^{-\epsilon} + \zeta \left(EF\right)_t^{-\epsilon}\right)^{-\frac{1}{\epsilon}-1}\right] * \left(-\epsilon\right) \zeta \left(EF\right)_t^{-\epsilon-1} - \lambda_t \\
\frac{\partial L}{\partial \left(ER\right)_t} &: P_t^{er} = \left[P_t^e A_t^e \left(-\frac{1}{\epsilon}\right) \left(\eta \left(ER\right)_t^{-\epsilon} + \zeta \left(EF\right)_t^{-\epsilon}\right)^{-\frac{1}{\epsilon}-1}\right] * \left(-\epsilon\right) \eta \left(ER\right)_t^{-\epsilon-1} \\
\frac{\partial L}{\partial S_t} &: \lambda_t = \rho E_t \lambda_{t+1} * \left(1 - \delta^s\right)
\end{aligned}$$

The third condition states that the present shadow cost of the deposit is related to its expected future value according to the "preference for the future" that here is measured by the parameter ρ. If we substitute the third condition into the first, we obtain the price dynamics of fossil fuels according to the *Hotelling rule*:

$$P_t^{ef} + \tau = \underbrace{\left[P_t^e A_t^e \left(-\frac{1}{\epsilon}\right) \left(\eta \left(ER\right)_t^{-\epsilon} + \zeta \left(EF\right)_t^{-\epsilon}\right)^{-\frac{1}{\epsilon}-1}\right] * \left(-\epsilon\right) \zeta \left(EF\right)_t^{-\epsilon-1} +}_{MP_t^{ef}\,\text{(marginal productivity of fossil fuels)}}$$

$$+ \rho E_t \underbrace{\left[\left(P_{t+1}^{ef} + \tau\right) - MP_{t+1}^{ef}\right] * \left(1 - \delta^s\right)}_{\text{shadow cost of the deposit}}$$

The representative household's problem is solved by maximizing the following dynamic Lagrangian function:

$$L = \max_{\left(C_t, Z_t, N_t^i, K_t^i, S_t\right)_{t=0}^{\infty}} E \sum_{t=0}^{\infty} \rho^t \left[\begin{array}{c} \left(\begin{array}{c} \Theta^c \left(\Upsilon_t \frac{(C_t)^{1-q}}{1-q}\right) + \left(1 - \Theta^c\right) \left(G_t\right) - Z_t + \\ -\frac{\left(N_t^y\right)^{1+\chi}}{1+\chi} - \frac{\left(N_t^{ef}\right)^{1+\omega}}{1+\omega} - \frac{\left(N_t^{er}\right)^{1+\psi}}{1+\psi} \end{array}\right) + \\ +\lambda_t \left(\frac{\varrho\left(S_{t-1} - S_t - \delta^s S_{t-1}\right)}{(1+\xi)} - Z_t\right) + \\ +\varpi_t \left[\begin{array}{c} W_t^y N_t^y + W_t^{ef} N_t^{ef} + W_t^{er} N_t^{er} + r_t^y K_{t-1}^y + r_t^{ef} K_{t-1}^{ef} + r_t^{er} K_{t-1}^{er} + \\ -C_t - X_t^y - X_t^{ef} - X_t^{er} \end{array}\right] \end{array}\right]$$

The corresponding first-order conditions are summarized below:

$$\frac{\partial L}{\partial C_t}:\Theta^c\Upsilon_t\left(C_t\right)^{-q}=\varpi_t \tag{55}$$

$$\frac{\partial L}{\partial Z_t}:\left(Z_t\right)=\lambda_t \tag{56}$$

$$\frac{\partial L}{\partial N_t^y}:\left(N_t^y\right)^{\chi}=\varpi_t W_t^y \tag{57}$$

$$\frac{\partial L}{\partial N_t^{ef}}:\left(N_t^y\right)^{\omega}=\varpi_t W_t^{\omega} \tag{58}$$

$$\frac{\partial L}{\partial N_t^{er}}:\left(N_t^y\right)^{\psi}=\varpi_t W_t^{\psi} \tag{59}$$

$$\frac{\partial L}{\partial K_t^y}:\rho E_t\left(\varpi_{t+1}R_{t+1}^y\right)=\varpi_t \tag{60}$$

$$\frac{\partial L}{\partial K_t^{ef}}:\rho E_t\left(\varpi_{t+1}R_{t+1}^{ef}\right)=\varpi_t \tag{61}$$

$$\frac{\partial L}{\partial K_t^{er}}:\rho E_t\left(\varpi_{t+1}R_{t+1}^{er}\right)=\varpi_t \tag{62}$$

$$\frac{\partial L}{\partial S_t}:\lambda_t=\rho E_t\left[\lambda_{t+1}\left(1+\delta^s\right)\right] \tag{63}$$

$$\frac{\partial L}{\partial \lambda_t}:Z_t=\frac{\varrho\left(S_{t-1}-S_t-\delta^s S_{t-1}\right)}{(1+\xi)} \tag{64}$$

$$\frac{\partial L}{\partial \varpi_t}:W_t^y N_t^y+W_t^{ef}N_t^{ef}+W_t^{er}N_t^{er}+r_t^y K_{t-1}^y+ \tag{65}$$

$$+r_t^{ef}K_{t-1}^{ef}+r_t^{er}K_{t-1}^{er}=C_t+X_t^y+X_t^{ef}+X_t^{er}$$

We are able to eliminate Lagrange multipliers, substituting in each espression their values, i.e.:

$$\frac{\partial L}{\partial C_t} : \Theta^c \Upsilon_t \left(C_t\right)^{-q} = \varpi_t \tag{66}$$

$$\frac{\partial L}{\partial Z_t} : \left(Z_t\right) = \lambda_t \tag{67}$$

$$\frac{\partial L}{\partial N_t^y} : \left(N_t^y\right)^{\chi} = \Theta^c \Upsilon_t \left(C_t\right)^{-q} W_t^y \tag{68}$$

$$\frac{\partial L}{\partial N_t^{ef}} : \left(N_t^{ef}\right)^{\omega} = \Theta^c \Upsilon_t \left(C_t\right)^{-q} W_t^{ef} \tag{69}$$

$$\frac{\partial L}{\partial N_t^{er}} : \left(N_t^{er}\right)^{\psi} = \Theta^c \Upsilon_t \left(C_t\right)^{-q} W_t^{er} \tag{70}$$

$$\frac{\partial L}{\partial K_t^y} : \rho E_t \left[\Upsilon_{t+1} \left(C_{t+1}\right)^{-q} R_{t+1}^y\right] = \Upsilon_t \left(C_t\right)^{-q} \tag{71}$$

$$\frac{\partial L}{\partial K_t^{ef}} : \rho E_t \left[\Upsilon_{t+1} \left(C_{t+1}\right)^{-q} R_{t+1}^{ef}\right] = \Upsilon_t \left(C_t\right)^{-q} \tag{72}$$

$$\frac{\partial L}{\partial K_t^{er}} : \rho E_t \left[\Upsilon_{t+1} \left(C_{t+1}\right)^{-q} R_{t+1}^{er}\right] = \Upsilon_t \left(C_t\right)^{-q} \tag{73}$$

$$\frac{\partial L}{\partial S_t} : \left(Z_t\right) = \rho E_t \left[\left(Z_{t+1}\right)\left(1 + \delta^s\right)\right] \tag{74}$$

$$\frac{\partial L}{\partial \lambda_t} : Z_t = \frac{\varrho \left(S_{t-1} - S_t - \delta^s S_{t-1}\right)}{\left(1 + \xi\right)} \tag{75}$$

$$\frac{\partial L}{\partial \varpi_t} : W_t^y N_t^y + W_t^{ef} N_t^{ef} + W_t^{er} N_t^{er} + r_t^y K_{t-1}^y + \tag{76}$$

$$+ r_t^{ef} K_{t-1}^{ef} + r_t^{er} K_{t-1}^{er} = C_t + X_t^y + X_t^{ef} + X_t^{er}$$