Abstract

Over the last years many countries have implemented policies to promote electricity production from renewable energy sources (RES), thus affecting the price of both fossil fuels and RES electricity. However, a large number of crucial regulatory questions are still waiting for a proper response. The aim of this paper is to investigate the effectiveness of complex policy strategies for fossil and RES in a dynamic stochastic general equilibrium 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. This paper provides policy-makers with analysis to foster successful penetration of RES policies. Government effects are measured in monetary terms as the commitment to encourage new technology developments and to influence market decisions. Dynamic simulations show that RES policies have differential effects in the three big economies as a result of a positive technology shock to the final output and to the energy sector output and of a positive demand shock to preferences. Country differences in the timing of occurrence of the price parity between fossil fuels and RES are then shown.

**JEL codes:** D58, H23, O44, Q48.

**Keywords:** RES, fossil fuels, productivity shocks, monetary subsidy
1 Introduction

International debates about climate change, the instability of major oil producing countries, and the continuous need for huge investments to maintain the productivity of fossil fuels reservoirs have spurred the development of renewable energy sources (RES). All these considerations have prompted governments to set policies aimed at improving the technology learning curve associated with the RES diffusion. Although these are, in many cases, immature technologies characterized by high production costs and reliability issues higher than fossil fuels (Jenner et al., 2012), RES provide benefits that are not valued by the market, but that can be translated into a generally lower social cost (Ortega-Izquierdo and Del Río, 2016; Owen, 2004).

More than a decade after the first pioneering efforts involving RES policy, it appears that, while the learning of RES technology has been very important, a large number of crucial regulatory questions are still awaiting a tangible solution. A crucial issue remains on how to improve design subsidy regimes that guarantee a proper RES development (Batlle et al., 2012; Chen and Tseng, 2011; De la Hoz et al., 2016; Gerlagh and Van der Zwaan, 2006; Traber and Kemfert, 2009).

Currently, there are three types of support mechanisms, i.e., price-based mechanisms, quantity-based mechanisms and other instruments. Price-based mechanisms refer to feed-in tariffs (FITs), which guarantee a fixed price per kWh and feed-in premiums (FIPs), and are paid on top of the market price for electricity (Farrell et al., 2017). Quantity-based mechanisms include tradable green certificates (TGC), renewable portfolio standards (RPS) and tendering schemes. The first two require that a percentage of electricity generation comes from RES (Amundsen and Bergman, 2012; Fischer, 2010), while tendering schemes are bidding systems in which developers compete for supply contracts to build RES electricity capacity. Other instruments include investment
supports, such as direct subsidies, capital grants, tax exemptions or financial incentives (Ragwitz et al., 2012).

The aim of this paper is to investigate the effectiveness of a comprehensive strategy for RES development, based on price-based mechanisms, through a dynamic stochastic general equilibrium (DSGE) model estimated for three big economies: the European Union (EU), the United States (US) 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). A burgeoning literature links economic growth to environmental issues (Tahvonen and Kuuluvainen, 1993; Tahvonen and Salo, 2001). Focusing on the relationship between economic growth and RES development, our paper fits in NOT CLEAR the related literature (Sakamoto and Managi, 2016), comparing the relative effectiveness in the three economic systems both for RES quantity goal and 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 EU has traditionally had a leading role regarding a sustainable climate and energy policy at the international level. Total net electricity generation in the EU was 3.10 million GWh in 2013 and it was concentrated in few countries, i.e., Germany, France and the United Kingdom that accounted for 47.9% of net electricity generation. Almost half of the net electricity generated in the EU-28 in 2013 came from power stations using fossil fuels (49.8%), followed by nuclear power plants (26.8%), hydropower plants (12.8%), wind turbines (7.5%) and solar power (2.7%) (Eurostat, 2016a). The current Directive 28/2009/EC on the promotion of RES has set a 20% RES target of energy consumption in 2020 (European Commission, 2009). The recent 2030 climate and energy framework
has endorsed a RES target of at least 27% of energy consumption by 2030, with flexibility for EU member countries to set national targets (European Commission, 2014). Among the main policy instruments used in the RES electricity sector in the EU, FITs and FIPs, applied as the main instrument in 20 member countries, dominate the support schemes, while quota systems with TGC are applied in the remaining countries. Overall, the European Commission has pointed out that some support mechanisms, such as FITs, have been too expensive and not suitable to integrate an increasing volume of RES in electricity markets (Ortega-Izquierdo and Del Río, 2016).

Total US electric power generation amounted to 4.1 million GWh during 2013, of which 38.9% from coal, 27.3% from natural gas, 19.4% from nuclear power and 13.1% from RES (Energy Information Administration, 2016). Currently, the US seems to be going through a golden age of shale gas growth, thus becoming self-sufficient (Wang et al., 2014). However, the use of shale gas has raised environmental concerns, thus helping further RES development, although fossil fuels remain the main source (Ohler, 2015). The RES sector grew from 13.6% in 2013 compared to 2012; solar thermal and photovoltaic energy increased 56.9% and wind power grew 15.3% (Energy Information Administration, 2016). The most popular state-level policy to increase RES electricity generation is represented by RPS (Yin and Powers, 2010; Jenner and Lamadrid, 2013), together with price-based mechanisms such as FITS, direct subsidies (Moosavian et al., 2013), and fiscal incentives (Battle et al., 2012).

China faces international pressure to control its carbon emissions, which has intensified since it overtook the US as the world’s largest carbon polluter (Christoff, 2010). China’s installed electricity capacity was 5,126 TWh in 2013. Coal is the leading source of the country’s electricity generation with a share of 63%, followed by hydropower (22%) and wind (6%) (China Energy Group,
Although coal is deeply integrated into China’s economic development and then in the electricity sector (Wang and Chen, 2015), the Renewable Energy Law, which came into effect on January 2006, has led to RES development, particularly wind and photovoltaic power, in order to attain the sustainable development of the economy and society. The rapidly expanding RES industry has put great pressure on the government to finance its development. China has adopted three policy measures, revolving around RPS, FITs and direct subsidies. RPS were introduced in China in 2007 by the National Development and Reform Commission in the Mid- and Long-Term Development Plan for Renewable Energy, assigning RES targets for grid companies (1% non-hydro RES by 2010, and 3% by 2020), and generators (3% non-hydro RES by 2010, and 8% by 2020). FITs and FIPs were implemented in China as early as 2003 in order to support wind power development (Lo, 2014). China’s support mechanisms have had few problems. For instance, in 2011, premium payments began to be delayed due to the huge numbers of wind projects, thus having a considerable impact on investors and then on the entire supply chain (Irena, 2014).

It appears that different countries at different stages of development have a common global concern for the exploitation of RES for electricity generation. However, they use different tools with potentially different degrees of effectiveness, which motivates a comparative analysis of cost-optimized development scenarios for RES.

The paper proceeds as follows. Section 2 describes the model structure for the three big economies. Section 3 presents the model estimation. Section 4 summarizes the model dynamics. Section 5 concludes.
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 environmental sectors, following Acemoglu et al. (2012). Previous literature has estimated DSGE models (An and Kang, 2011; Millard, 2011; Böhringer and Löchel, 2006; Sakamoto and Managi, 2016), which we extend in this paper by considering one final consumer good and three intermediate goods, i.e., 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 subsidizes the RES production through the fiscal revenues coming from environmental tax.

The model structure is the same for all three countries and therefore we omit the country subscript in all the equations for the sake of clarity.

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, $K_{t-1}^y$, and energy services $E_t$:

$$Y_t = A_t^y (N_t^y)^{\alpha} (K_{t-1}^y)^{\beta} (E_t)^{\gamma}$$

(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 $\epsilon_t^y$:

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

(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:

\[
E_t = A^e_t \left( \eta (ER)_t^{-\epsilon} + \zeta (EF)_t^{-\epsilon} \right)^{-\frac{1}{\epsilon}}
\]

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

\[
\log A^e_t = (1 - \phi^e) \log A^e_{t-1} + \phi^e \log A^e_{t-1} + \varepsilon^e_t
\]

where \(A^e\) indicates the steady state value of the energy TFP and

\[
\epsilon = \frac{1 - \sigma}{\sigma}
\]

with \(\sigma\) 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, \(K^{ef}_t\), and labor, \(N^{ef}_t\), according to a Cobb-Douglas production function:

\[
(EF)_t = A^{ef}_t \left( N^{ef}_t \right)^{\theta} \left( K^{ef}_{t-1} \right)^{\theta} \left( S_{t-1} \right)^{\kappa}
\]
where $S_{t-1}$ is the stock of fossil fuel deposit from which the fuel is extracted and $A_{t}^{ef}$ is total factor productivity (TFP), whose law of motion is described by the following AR(1) process with zero mean and uncorrelated residuals $\varepsilon_{t}^{ef}$:

$$\log A_{t}^{ef} = (1 - \phi^{ef}) \log \bar{A}^{ef} + \phi^{ef} \log A_{t-1}^{ef} + \varepsilon_{t}^{ef}$$

(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, $K_{t-1}^{er}$, labor, $N_{t}^{er}$:

$$(ER)_{t} = A_{t}^{er} (N_{t}^{er})^{\gamma} (K_{t-1}^{er})^{\kappa}$$

(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 $\mu_{t}$ to the RES sector that is entirely financed by a tax on the fossil fuel sector.

### 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

\(^1\)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.
consumption $C_t$; pollution level, $Z_t$; labor services, $N_t$. These latter are allocated to final output production $N^y_t$, fossil fuel sector $N^{ef}_t$ and RES sector $N^{er}_t$ on a period-by-period basis.

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

$$E_0 \sum_{i=0}^{\infty} \rho^t U_t \left( C_t, Z_t, N^y_t, N^{ef}_t, N^{er}_t \right)$$

(9)

with $\rho^t$ corresponding to the subjective discount factor.

The period utility function assumes the following constant relative risk aversion form:

$$U_t = \left( \frac{\Upsilon_t (C_t)^{1-q}}{1-q} \right) - Z_t - \left( \frac{(N^y_t)^{1+\chi}}{1+\chi} \right) - \left( \frac{(N^{ef}_t)^{1+\omega}}{1+\omega} \right) - \left( \frac{(N^{er}_t)^{1+\psi}}{1+\psi} \right)$$

(10)

where $\Upsilon_t$ 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 $\varepsilon^\Upsilon_t$:

$$\log \Upsilon_t = (1 - \phi^\Upsilon) \log \bar{\Upsilon} + \phi^\Upsilon \log \Upsilon_{t-1} + \varepsilon^\Upsilon_t$$

(11)

with $\bar{\Upsilon}$ indicating the steady state value of the taste shifter.

The law of motion of the pollution stock is described by the following process:

$$Z_t = (1 - \xi) Z_{t-1} + \varrho (EF)_t$$

(12)

where $\varrho$ indicates the sensitivity of pollution to fossil fuels, whereas $\xi$ is the rate of "environmental regeneration".

The representative household maximizes the utility function subject to an intertemporal budget constraint, which states that the total flow of consump-
tions and investments, indicated by $X^y_t$, $X^{ef}_t$ and $X^{er}_t$ cannot exceed disposable income:

$$C_t + X^y_t + X^{ef}_t + X^{er}_t \leq W^y_tN^y_t + W^{ef}_tN^{ef}_t + W^{er}_tN^{er}_t + r^y_tK^y_{t-1} +$$

$$+ r^{ef}_tK^{ef}_{t-1} + r^{er}_tK^{er}_{t-1} + f_tS_{t-1} +$$

$$+ \Pi^y_t + \Pi^{ef}_t + \Pi^{er}_t$$

where $W^i_t (i = y, ef, er)$ represents the nominal wages paid for each type of labor, $r^i_t (i = y, ef, er)$ are the corresponding returns on capital, $f_t$ is the cost for the exploitation of the stock, $S_{t-1}$, $\Pi^i_t (i = y, ef, er)$ represents the nominal profits received by the households, who are the firms’ owners, in each sector and the price of final consumer goods has been normalized to unity.

The sectorial net capital formations read as:

$$X^y_t = K^y_t - (1 - \delta^y)K^y_{t-1}$$

$$X^{ef}_t = K^{ef}_t - (1 - \delta^{ef})K^{ef}_{t-1}$$

$$X^{er}_t = K^{er}_t - (1 - \delta^{er})K^{er}_{t-1}$$

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:

$$\tau \left( EF \right)_t = \mu \left( ER \right)_t$$
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 \((W^y_t, R^y_t = 1 + r^y_t - \delta^y_t, P^e_t)_{t=0}^\infty\), the final consumer goods firm aims to maximize the following profit function:

\[
\max_{N^y_t, K^y_{t-1}, E_t} \Pi^y_t = A^y_t \left( N^y_t \right)^\alpha \left( K^y_{t-1} \right)^\beta (E_t)^\gamma \left( 1 - \delta^y_t \right) K^y_{t-1} - W^y_t N^y_t - R^y_t K^y_{t-1} - P^e_t E_t
\]

(18)

with \(P^e_t\) representing the price of energy.

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

\[
W^y_t = A^y_t \alpha \left( N^y_t \right)^{\alpha-1} \left( K^y_{t-1} \right)^\beta (E_t)^\gamma
\]

(19)

\[
R^y_t = A^y_t \beta \left( N^y_t \right)^\alpha \left( K^y_{t-1} \right)^{\beta-1} (E_t)^\gamma + \left( 1 - \delta^y_t \right) K^y_{t-1}
\]

(20)

\[
P^e_t = A^y_t \gamma \left( N^y_t \right)^\alpha \left( K^y_{t-1} \right)^\beta (E_t)^{\gamma-1}
\]

(21)

The energy-producing firm, given \(\left( P^f_t, P^{\text{er}}_t \right)_{t=0}^\infty\), where \(P^f_t\) is the price of fossil fuels and \(P^{\text{er}}_t\) is the price of RES, solves the following maximization problem:
\[
\max_{(EF)_t,(ER)_t} \Pi^e_t = P^e_t A^e_t \left( \eta (ER)_t^{-\varepsilon} + \zeta (EF)_t^{-\varepsilon} \right)^{-\frac{1}{\varepsilon} - \left( P^e_t + \tau \right) (EF)_t - P^e_r (ER)_t}
\]

(22)

with the following fossil fuels and RES demands:

\[
P^e_f + \tau = \left[ P^e_t A^e_t \left( -\frac{1}{\varepsilon} \right) \left( \eta (ER)_t^{-\varepsilon} + \zeta (EF)_t^{-\varepsilon} \right)^{-\frac{1}{\varepsilon} - 1} \right]
\]

(23)

\[
P^e_r = \left[ P^e_t A^e_t \left( -\frac{1}{\varepsilon} \right) \left( \eta (ER)_t^{-\varepsilon} + \zeta (EF)_t^{-\varepsilon} \right)^{-\frac{1}{\varepsilon} - 1} \right]
\]

(24)

Moreover, we assume that the price of RES, \( P^e_r \), 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 fossil fuel representative firm, given \( W^e_f, F_t, R^e_f = 1 + \delta^e_f - \delta^e_f \sum_{t=0}^{\infty} \), aims to maximize the profit function subject to the constraint determined by the exhaustibility of the fossil fuel deposit, \( S_t \):

\[
\max_{N^e_f, K^e_f, S_t} \sum_{t=0}^{\infty} \beta^t \left( \Pi^e_t \right) = \left( P^e_f + \tau \right) A^e_t \left( N^e_f \right)^{\theta} \left( K^e_f \right)^{\vartheta} (S_{t-1})^{\infty} + \left( 1 - \delta^e_f \right) K^e_{t-1} +
\]

(25)

\[- W^e_f N^e_f - R^e_f K^e_f - F_t S_{t-1} \]

s.t. \( s.t. [S_t - S_{t-1} = -\delta^e S_{t-1} - (EF)_t] \)

(26)
with the following transversality condition:

$$\lim_{t \to \infty} \rho^t \lambda_t S_t = 0$$  \hspace{1cm} (27)$$

where $\lambda_t$ is the dynamic Lagrange multiplier and $\delta^s$ representing the depreciation rate of $S_t$. The corresponding demand curves for labor, capital and fossil fuel deposits (the analytical derivation is reported in the Appendix) read as follows:

$$W^\text{ef}_t = A^\text{ef}_t \theta \left( N^\text{ef}_t \right)^{\theta - 1} \left( K^\text{ef}_{t-1} \right)^{\theta} \left( S_{t-1} \right)^{\kappa^*}$$  \hspace{1cm} (28)$$

$$R^\text{ef}_t = A^\text{ef}_t \theta \left( N^\text{ef}_t \right)^{\theta} \left( K^\text{ef}_{t-1} \right)^{\theta - 1} \left( S_{t-1} \right)^{\kappa^*}$$  \hspace{1cm} (29)$$

$$\begin{align*}
&\text{MP of labor} \\
&\qquad \times \left[ \left( P^\text{ef}_t + \tau \right) + W^\text{ef}_t - \left( P^\text{ef}_t + \tau \right) A^\text{ef}_t \theta \left( N^\text{ef}_t \right)^{\theta - 1} \left( K^\text{ef}_{t-1} \right)^{\theta} \left( S_{t-1} \right)^{\kappa^*} \right] + (1 - \delta^f) \\
&\text{MP of capital} \\
&\qquad \times \left[ \left( P^\text{ef}_t + \tau \right) + R^\text{ef}_t - \left( P^\text{ef}_t + \tau \right) A^\text{ef}_t \theta \left( N^\text{ef}_t \right)^{\theta} \left( K^\text{ef}_{t-1} \right)^{\theta - 1} \left( S_{t-1} \right)^{\kappa^*} \right]
\end{align*}$$
where the subscript "MP" indicates the marginal productivity.

Note that equation 30 represents the Hotelling rule, which states that the expected discounted price of fossil fuels is an increasing function of the marginal productivity of capital and the net cost of the fossil fuel deposits and a decreasing function of the ratio between the marginal productivity of fossil fuel deposits and the marginal productivity of capital\(^2\).

Finally, the RES sector, given \((W^e_t, R^e_t = 1 + r^e_t - \delta^e_t)_{t=0}^\infty\), faces the following maximization problem:

\[
\max_{N^e_t, K^e_{t-1}} \Pi^e_t = (P^e_t + \mu_t) A^e_t \left( N^e_t \right)^\theta \left( K^e_{t-1} \right)^{\theta-1} (S_{t-1})^\kappa + (1 - \delta^e_t) K^e_{t-1} + W^e_t N^e_t - R^e_t K^e_{t-1}
\]

\(\text{max} \) in Appendix, we show that, given the model’s structure, an alternative formulation of the Hotelling rule can be based on marginal productivity of labor instead of marginal productivity of capital.\(^2\)
with the corresponding first order conditions:

\[ W_t^{er} = (P_t^{er} + \mu_t) A_t^{er} \left( N_t^{erf} \right)^{t-1} \left( K_{t-1}^{er} \right)^{\kappa} \]  \hspace{5cm} (32) 

\[ R_t^{er} = (P_t^{er} + \mu_t) A_t^{er} \kappa \left( N_t^{erf} \right)^{t} \left( K_{t-1}^{er} \right)^{\kappa-1} + (1 - \delta^{er}) \]  \hspace{5cm} (33) 

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

\[
\max_{(C_t, N_t^i, K_t^i)} \sum_{t=0}^{\infty} \rho^t U_t (C_t, N_t^i, Z_t, K_t^i) \\
\text{s.t.} \\
C_t + X_t^y + X_t^{erf} + X_t^{er} - \Pi_t^y - \Pi_t^e - \Pi_t^{er} \leq W_t^y N_t^y + W_t^{erf} N_t^{erf} + W_t^{er} N_t^{er} + \\
+ r_t^y K_{t-1}^y + r_t^{erf} K_{t-1}^{erf} + r_t^{er} K_{t-1}^{er} + f_t S_{t-1}
\]  \hspace{5cm} (34) 

Moreover we assume that:

- the initial values of the capital stocks, \( K_0^i \) with \( i (y, ef, er) \), and fossil fuel deposit, \( S_0 \), are given and positive;

- these inequality constraints hold: \( C_t > 0, N_t^i > 0 \) with \( i (y, ef, er) \), \( Z_t > 0 \);

- this transversality condition holds:

\[
\lim_{t \to \infty} \rho^t \omega_t K_t = 0 
\]  \hspace{5cm} (36)
where \( \varpi_t \) is the dynamic Lagrange multiplier.

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

\[
\begin{align*}
\Upsilon_t (C_t)^{-q} W_t^y &= (N_t^y)^\chi \\
\Upsilon_t (C_t)^{-q} W_t^{ef} &= (N_t^{ef})^\omega \\
\Upsilon_t (C_t)^{-q} W_t^{er} &= (N_t^{er})^{\psi} \\
W_t^y N_t^y + W_t^{ef} N_t^{ef} + W_t^{er} N_t^{er} + r_t^y K_{t-1}^y + r_t^{ef} K_{t-1}^{ef} + r_t^{er} K_{t-1}^{er} + f_t S_{t-1} &= C_t + \\
&+ X_t^y + X_t^{ef} + X_t^{er} + \\
&- \Pi_t^y - \Pi_t^{ef} - \Pi_t^{er} \\
E_t \left[ \rho \left( \frac{\Upsilon_{t+1}}{\Upsilon_t} \right) \left( \frac{C_t}{C_{t+1}} \right)^q R_{t+1}^y \right] &= 1 \\
E_t \left[ \rho \left( \frac{\Upsilon_{t+1}}{\Upsilon_t} \right) \left( \frac{C_t}{C_{t+1}} \right)^q R_{t+1}^{ef} \right] &= 1 \\
E_t \left[ \rho \left( \frac{\Upsilon_{t+1}}{\Upsilon_t} \right) \left( \frac{C_t}{C_{t+1}} \right)^q R_{t+1}^{er} \right] &= 1
\end{align*}
\]

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: $R^p_{t+1} = R^f_{t+1} = R^r_{t+1}$

3 Model estimation

3.1 Method and data

The inferential procedure adopted for the parameters’ estimation, the simulation of the time series for the variables and their dynamic responses in the presence of stochastic shocks are based on the MCMC methods and, in particular, on the Metropolis-Hastings algorithm, which belongs to the family of Bayesian estimation methods (see among others Canova, 2007; Smets and Wouters, 2007). In particular, we have built a multi-chain MCMC procedure based on 4 chains of size 100,000; the algorithm converges within 50,000 iterations to its expected value. Therefore, to remove any dependence from the initial conditions we remove the first 50,000 observations from each chain. This high number of iterations-together with the 95% confidence interval for the estimates-ensures the robustness of our results.

The sources of our data for the period 1995-2012 at an annual frequency is the Ameco database for EU private consumption and final output (Ameco, 2016) and the Eurostat database for the EU-15 energy variables (Eurostat, 2016b). The source of all the US and Chinese data is the World Bank database (The World Bank, 2016).

All of the model computations have been performed using DYNARE soft-

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3 MCMC is the acronym of Monte Carlo Markov Chains: these are a class of sample algorithms which construct a Markow Chain whose steady-state distribution corresponds to the one of interest, i.e. the posterior distribution.

4 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.

5 Given the lengths of the time period investigate, we have used the data for the EU-15.
ware\textsuperscript{6}. Below, we summarize the measurement equations considered, i.e. the relationships between the data (first vector on the left side) and the model variables (second and third vectors on the right side):

$$\begin{bmatrix}
\Delta \ln C_t \\
\Delta \ln E_t \\
\Delta \ln (EF)_t \\
\Delta \ln (ER)_t \\
\Delta \ln Y_t
\end{bmatrix} = \begin{bmatrix}
\Gamma^{(A)} \\
\Gamma^{(A)} \\
\Gamma^{(A)} \\
\Gamma^{(A)} \\
\Gamma^{(A)}
\end{bmatrix} + 100 \cdot \begin{bmatrix}
c_t - c_{t-1} \\
\epsilon_t - \epsilon_{t-1} \\
(ef)_t - (ef)_{t-1} \\
(er)_t - (er)_{t-1} \\
y_t - y_{t-1}
\end{bmatrix}$$ \hfill (44)

The data used in the first vector are: $\Delta \ln C_t$ that is measured according to the total final consumption expenditure of households in constant prices for 2010; $\Delta \ln E_t$ is the growth rate of energy services\textsuperscript{7}, $\Delta \ln EF_t$ is fossil fuels’ use growth expressed in percentage terms, measured as the electricity production from solid fuels, total petroleum products, gas and nuclear heat. The RES consumption growth, in percentage terms, is expressed by $\Delta \ln (ER)_t$ and $\Delta \ln Y_t$ is the real gross domestic product (GDP) growth expressed in percentage terms, which is measured by real GDP in 2010 constant prices. In the second vector, $\Gamma^{(A)}$ is the annual trend growth rate common of consumption, GDP, energy, fossil fuel and RES, expressed in percentage terms (100 $\cdot \ln \Gamma$) that is the average potential output growth rate in the three countries. This parameter is assumed normally distributed and calibrated with a value of 1.6 for the EU, (Ameco, 2016), 2.0 for the US (Fred Economic Data, 2016) and 10.0 for China (International Monetary Fund, 2015). The standard deviations of $\Gamma^{(A)}$ are set

\textsuperscript{6}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

\textsuperscript{7}It is expressed in percentage terms, which refers to the use of primary energy before transformation to other end-use fuels.
equal to 0.1 for each investigated country. Finally, the third vector indicates the corresponding model variables in log-differences. Notice that these observable variables are useful in order to construct simulated time series for RES and fossil fuel prices, in the presence of public policies for RES development. Accordingly, real GDP and private consumption data are good measures of economic activity levels, which affects both energy demand and prices both for 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, 3, 4, 5, 6 and 7.

The prior densities of the observable variables are consistent with the domain of the parameters.

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 $\alpha, \beta$ and $\gamma$ 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 GDP, with a standard deviation of 0.05.

Fossil fuel and RES production function elasticities ($\theta, \delta, \iota, \kappa$) 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 fuel deposit depreciation rates ($\delta^y, \delta^{cf}, \delta^{er}, \delta^s$) are distributed according to a beta random variable with means equal to 0.10. This value is consistent with the average private capital rental rates of the three countries. The standard deviations are set to 0.05 for
Table 1: **Parameter definitions**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>final output elasticity of labor</td>
</tr>
<tr>
<td>$\beta$</td>
<td>final output elasticity of capital</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>final output elasticity of energy</td>
</tr>
<tr>
<td>$\delta^y$</td>
<td>depreciation rate of final output capital</td>
</tr>
<tr>
<td>$\delta^f$</td>
<td>depreciation rate of fossil fuels’ capital</td>
</tr>
<tr>
<td>$\delta^{er}$</td>
<td>depreciation rate of RES capital</td>
</tr>
<tr>
<td>$\delta^s$</td>
<td>depreciation rate of fossil deposit</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>elasticity of substitution between RES and fossil fuels</td>
</tr>
<tr>
<td>$\zeta$</td>
<td>fossil fuels’ share in energy production</td>
</tr>
<tr>
<td>$\eta$</td>
<td>RES share in energy production</td>
</tr>
<tr>
<td>$\theta$</td>
<td>fossil fuels’ elasticity of labor</td>
</tr>
<tr>
<td>$\vartheta$</td>
<td>fossil fuels’ elasticity of capital</td>
</tr>
<tr>
<td>$\iota$</td>
<td>RES elasticity of labor</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>RES elasticity of private capital</td>
</tr>
<tr>
<td>$\varphi$</td>
<td>Pollution sensitivity to fossil fuels</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Coefficient of relative risk aversion</td>
</tr>
<tr>
<td>$\phi^p$</td>
<td>Persistence in final output TFP</td>
</tr>
<tr>
<td>$\phi^e$</td>
<td>Persistence in energy TFP</td>
</tr>
<tr>
<td>$\phi^f$</td>
<td>Persistence in fossil fuels’ TFP</td>
</tr>
<tr>
<td>$\phi^{er}$</td>
<td>Persistence in RES TFP</td>
</tr>
<tr>
<td>$\phi^t$</td>
<td>Persistence in taste shifter</td>
</tr>
<tr>
<td>$\psi$</td>
<td>Inverse of RES Frisch elasticity of labor supply</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Inverse of fossil fuels’ Frisch elasticity of labor supply</td>
</tr>
<tr>
<td>$\chi$</td>
<td>Inverse of final output Frisch elasticity of labor supply</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Intertemporal discount factor</td>
</tr>
<tr>
<td>$\xi$</td>
<td>Environmental regeneration rate</td>
</tr>
<tr>
<td>$\tau$</td>
<td>Effective tax rate on fossil fuels’ production (Euro per TOE)</td>
</tr>
</tbody>
</table>

RES = Renewable Energy Sources; TFP = Total Factor Productivity; TOE = Tons of Oil Equivalent

final output capital and 0.1 for the remaining depreciation rates, namely $\delta^f$, $\delta^{er}$ and $\delta^s$.

The shares of fossil fuels and RES in the energy production function— $\zeta$ and $\eta$—follows a beta distribution with means equal to the average shares of RES and fossil fuels in energy production from 2006 to 2011 (The World Bank, 2016). The elasticity of substitution between RES and fossil fuels follows a gamma distribution with a mean of 0.45 for the EU and 0.51 for China and US (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 1.1 for the EU, 1.4 for the US and 2.5 for China\(^8\) (Gandelman and Murillo, 2015) and a standard deviation of 0.5.

According to Smets and Wouters (2003; 2007) and Dai et al. (2015), the inverse of the Frisch elasticities of labor supply, $\psi, \omega$ and $\chi$, follow a gamma distribution with means equal to 2 and a standard deviation of 0.75 for all the countries.

Following the real business cycle literature (Blanchard and Quah, 1989; King and Rebelo, 1999), the persistence coefficients for the stochastic processes related to the TFPs and taste shifter are beta distributed with means equal to 0.85 (following the real business cycle literature (Blanchard and Quah, 1989; King and Rebelo, 1999; Smets and Wouters, 2003) and standard deviations equal to 0.10.

The pollution sensitivity to fossil fuels, $\rho$, follows a gamma distribution with a mean of 3, which is the average ratio of tons of CO2 generated to TOE of fossil fuels produced in all the countries from 1995 to 2012, and a standard deviation of 0.1. According to Acemoglu et al. (2012) we assume a target of increase in temperature of $2^\circ C$, meaning that the environmental regeneration rate, $\xi$, follows a beta distribution a mean of 0.37 and a standard deviation of 1.5.

The intertemporal discount factor $\rho$ follows a beta distribution with a mean of 0.90 for all the countries, which is consistent with the steady state values for private capital rentals for all the countries, according to Euler Equations, and a standard deviation of 0.05.

The standard deviations of TFP (for final output, energy, fossil fuels and RES) and taste shifter shocks follow an inverse gamma distribution with means

\(^8\)For China, we use the value estimated for Taiwan.
equal respectively to 0.4 and 0.2 for the EU (Smets and Wouters, 2003), 0.10 and 0.10 for the US (Smets and Wouters, 2007), 0.40 and 0.70 for China (Dai et al. 2015). The corresponding standard deviations are always equal to 2.

The mean of the respective effective tax rates on gasoline and diesel for road use are assumed as proxies of the environmental tax rate, $\tau$ (OECD, 2015). This variable follows a gamma distribution with a standard deviation of 0.1.

### 3.3 Posterior distributions

The posterior values of the structural parameters are estimated using observable variables (private consumption, energy, RES, fossil fuels and final output) conditionally to the model. The fifth and sixth columns of the tables 2, 3, 4, 5, 6 and 7 show the posterior means and a 95% confidence interval for the estimated parameters obtained by the Metropolis-Hastings algorithm compared to their prior distributions.\(^9\) (tables 2 and 3).

The log-marginal value of the likelihood of the model is -349.33 for the EU-15, -326.37 for China and -316.82 for the US.

The posterior estimated values for supply-side sectors are higher for all the parameters than the prior estimated values. This result generates increasing returns to scale for all the sectors in the three countries.

The values of the environmental tax rate, the intertemporal discount factor and the capital depreciation rates are quite similar to the prior values, whereas the elasticity of substitution between RES and fossil fuels exhibits always a positive shift.

---

\(^9\)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 for the EU

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Prior distrib.</th>
<th>Post. distrib.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Distr.</td>
<td>Mean</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>beta</td>
<td>0.60</td>
</tr>
<tr>
<td>$\beta$</td>
<td>beta</td>
<td>0.30</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>beta</td>
<td>0.02</td>
</tr>
<tr>
<td>$\delta^w$</td>
<td>beta</td>
<td>0.10</td>
</tr>
<tr>
<td>$\delta^{cf}$</td>
<td>beta</td>
<td>0.10</td>
</tr>
<tr>
<td>$\delta^{cr}$</td>
<td>beta</td>
<td>0.10</td>
</tr>
<tr>
<td>$\delta^s$</td>
<td>beta</td>
<td>0.10</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>gamma</td>
<td>0.45</td>
</tr>
<tr>
<td>$\zeta$</td>
<td>beta</td>
<td>0.88</td>
</tr>
<tr>
<td>$\eta$</td>
<td>beta</td>
<td>0.12</td>
</tr>
<tr>
<td>$\theta$</td>
<td>beta</td>
<td>0.60</td>
</tr>
<tr>
<td>$\vartheta$</td>
<td>beta</td>
<td>0.30</td>
</tr>
<tr>
<td>$\iota$</td>
<td>beta</td>
<td>0.60</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>beta</td>
<td>0.30</td>
</tr>
<tr>
<td>$\varrho$</td>
<td>gamma</td>
<td>3.00</td>
</tr>
<tr>
<td>$q$</td>
<td>normal</td>
<td>1.10</td>
</tr>
<tr>
<td>$\psi$</td>
<td>gamma</td>
<td>2.00</td>
</tr>
<tr>
<td>$\omega$</td>
<td>gamma</td>
<td>2.00</td>
</tr>
<tr>
<td>$\chi$</td>
<td>gamma</td>
<td>2.00</td>
</tr>
<tr>
<td>$\rho$</td>
<td>beta</td>
<td>0.90</td>
</tr>
<tr>
<td>$\xi$</td>
<td>beta</td>
<td>0.37</td>
</tr>
<tr>
<td>$\tau$</td>
<td>gamma</td>
<td>712.74</td>
</tr>
</tbody>
</table>

The environmental regeneration rate is slightly lower than the prior distributions for China and the US and it is substantially unchanged for the EU-15.

Looking at the households’ sector parameters, the inverse of Frisch elasticities of labor supply are always higher than the prior values, with remarkable differences for the fossil fuels and final output sectors with respect to RES. In detail, there is greater labor market flexibility in the final output and fossil fuels’ sectors with respect to the RES. The posterior estimated coefficient of the relative risk aversion is lower than the prior value for all the countries, thus showing a smaller degree of risk aversion than assumed a priori.

A closer inspection to the exogenous processes shows that the size of the autoregressive coefficients is confirmed, and the energy sector TFP is always
Table 3: Prior and Posterior Distribution of Structural Parameters for the EU cont.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Prior distrib.</th>
<th>Post. distrib.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Distr.</td>
<td>Mean</td>
</tr>
<tr>
<td>$\phi^y$</td>
<td>beta</td>
<td>0.85</td>
</tr>
<tr>
<td>$\phi^c$</td>
<td>beta</td>
<td>0.85</td>
</tr>
<tr>
<td>$\phi^{ef}$</td>
<td>beta</td>
<td>0.85</td>
</tr>
<tr>
<td>$\phi^{er}$</td>
<td>beta</td>
<td>0.85</td>
</tr>
<tr>
<td>$\phi^r$</td>
<td>beta</td>
<td>0.85</td>
</tr>
<tr>
<td>$\sigma_{\epsilon y}$</td>
<td>inv.gamma</td>
<td>0.40</td>
</tr>
<tr>
<td>$\sigma_{\epsilon e}$</td>
<td>inv.gamma</td>
<td>0.40</td>
</tr>
<tr>
<td>$\sigma_{\epsilon f}$</td>
<td>inv.gamma</td>
<td>0.40</td>
</tr>
<tr>
<td>$\sigma_{\epsilon r}$</td>
<td>inv.gamma</td>
<td>0.40</td>
</tr>
<tr>
<td>$\sigma_{\epsilon r}$</td>
<td>inv.gamma</td>
<td>0.20</td>
</tr>
<tr>
<td>$\Gamma^{(A)}$</td>
<td>normal</td>
<td>1.6</td>
</tr>
</tbody>
</table>

more persistent than in the prior estimates.

The standard deviations 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 always higher. This result sharpens an higher volatility for TFP in the energy markets compared with the results for final output. Finally, the posterior estimates of the trend growth rates are quite similar to the prior values.

4 Model dynamics results

The dynamic response of the main variables to stochastic shocks on TFPs and taste shifter are represented by impulse response functions (IRFs) for each country. 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% confidence intervals\(^{10}\). Moreover, because the variables are expressed in logs, the measures

\(^{10}\) The confidence intervals have been computed as the 2.5 and 97.5 percentiles of the empirical distributions obtained by the algorithm.
Table 4: Prior and Posterior Distribution of Structural Parameters for China

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Prior distrib.</th>
<th>Post. distrib.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Distr.</td>
<td>Mean</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>betta</td>
<td>0.50</td>
</tr>
<tr>
<td>$\beta$</td>
<td>betta</td>
<td>0.50</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>beta</td>
<td>0.02</td>
</tr>
<tr>
<td>$\delta^y$</td>
<td>beta</td>
<td>0.10</td>
</tr>
<tr>
<td>$\delta^{ef}$</td>
<td>beta</td>
<td>0.10</td>
</tr>
<tr>
<td>$\delta^{cr}$</td>
<td>beta</td>
<td>0.10</td>
</tr>
<tr>
<td>$\delta^a$</td>
<td>beta</td>
<td>0.10</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>gamma</td>
<td>0.51</td>
</tr>
<tr>
<td>$\zeta$</td>
<td>beta</td>
<td>0.82</td>
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<tr>
<td>$\eta$</td>
<td>beta</td>
<td>0.18</td>
</tr>
<tr>
<td>$\theta$</td>
<td>beta</td>
<td>0.50</td>
</tr>
<tr>
<td>$\vartheta$</td>
<td>beta</td>
<td>0.50</td>
</tr>
<tr>
<td>$\iota$</td>
<td>beta</td>
<td>0.50</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>beta</td>
<td>0.50</td>
</tr>
<tr>
<td>$\varphi$</td>
<td>gamma</td>
<td>3.00</td>
</tr>
<tr>
<td>$q$</td>
<td>normal</td>
<td>2.50</td>
</tr>
<tr>
<td>$\psi$</td>
<td>gamma</td>
<td>2.00</td>
</tr>
<tr>
<td>$\omega$</td>
<td>gamma</td>
<td>2.00</td>
</tr>
<tr>
<td>$\chi$</td>
<td>gamma</td>
<td>2.00</td>
</tr>
<tr>
<td>$\rho$</td>
<td>beta</td>
<td>0.90</td>
</tr>
<tr>
<td>$\xi$</td>
<td>beta</td>
<td>0.37</td>
</tr>
<tr>
<td>$\tau$</td>
<td>gamma</td>
<td>136.50</td>
</tr>
</tbody>
</table>

of the responses can be read as elasticities.

We analyze the impact of TFP shock on final output for each country, namely, for the EU, US and China, in Figures 1-3, on total energy in Figures 4-6, fossil energy in Figures 7-9, RES in Figures 10-12, preferences in Figures 13-15.
Table 5: Prior and Posterior Distribution of Structural Parameters  

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Prior distrib.</th>
<th>Post. distrib.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi^y$</td>
<td>beta 0.85 0.10</td>
<td>0.8990 [0.8977 0.9110]</td>
</tr>
<tr>
<td>$\phi^e$</td>
<td>beta 0.85 0.10</td>
<td>0.8873 [0.8636 1.0000]</td>
</tr>
<tr>
<td>$\phi^{ef}$</td>
<td>beta 0.85 0.10</td>
<td>0.8542 [0.8092 1.0000]</td>
</tr>
<tr>
<td>$\phi^{er}$</td>
<td>beta 0.85 0.10</td>
<td>0.8546 [0.8222 0.8874]</td>
</tr>
<tr>
<td>$\phi^Y$</td>
<td>beta 0.85 0.10</td>
<td>0.8941 [0.8103 0.8988]</td>
</tr>
<tr>
<td>$\sigma_{\epsilon^y}$</td>
<td>inv.gamma 0.40 2.00</td>
<td>0.4300 [0.4199 0.4403]</td>
</tr>
<tr>
<td>$\sigma_{\epsilon^e}$</td>
<td>inv.gamma 0.40 2.00</td>
<td>0.4276 [0.4196 0.4361]</td>
</tr>
<tr>
<td>$\sigma_{\epsilon^{ef}}$</td>
<td>inv.gamma 0.40 2.00</td>
<td>0.4591 [0.4408 0.4787]</td>
</tr>
<tr>
<td>$\sigma_{\epsilon^{er}}$</td>
<td>inv.gamma 0.40 2.00</td>
<td>0.4911 [0.4628 0.5201]</td>
</tr>
<tr>
<td>$\sigma_{\epsilon^Y}$</td>
<td>inv.gamma 0.70 2.00</td>
<td>0.7178 [0.6603 0.7226]</td>
</tr>
<tr>
<td>$\Gamma^{(A)}$</td>
<td>normal 10.0 0.10</td>
<td>10.2345 [9.9563 10.8925]</td>
</tr>
</tbody>
</table>

Figure 1. EU Impulse response functions for a positive TFP shocks on final output sector
Table 6: Prior and Posterior Distribution of Structural Parameters for the US

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Prior distrib.</th>
<th>Post. distrib.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Distr.</td>
<td>Mean</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>beta</td>
<td>0.60</td>
</tr>
<tr>
<td>(\beta)</td>
<td>beta</td>
<td>0.40</td>
</tr>
<tr>
<td>(\gamma)</td>
<td>beta</td>
<td>0.02</td>
</tr>
<tr>
<td>(\delta^e)</td>
<td>beta</td>
<td>0.10</td>
</tr>
<tr>
<td>(\delta^r)</td>
<td>beta</td>
<td>0.10</td>
</tr>
<tr>
<td>(\delta^a)</td>
<td>beta</td>
<td>0.10</td>
</tr>
<tr>
<td>(\sigma)</td>
<td>gamma</td>
<td>0.51</td>
</tr>
<tr>
<td>(\zeta)</td>
<td>beta</td>
<td>0.92</td>
</tr>
<tr>
<td>(\eta)</td>
<td>beta</td>
<td>0.08</td>
</tr>
<tr>
<td>(\theta)</td>
<td>beta</td>
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</tr>
<tr>
<td>(\vartheta)</td>
<td>beta</td>
<td>0.40</td>
</tr>
<tr>
<td>(\iota)</td>
<td>beta</td>
<td>0.60</td>
</tr>
<tr>
<td>(\kappa)</td>
<td>beta</td>
<td>0.40</td>
</tr>
<tr>
<td>(\varrho)</td>
<td>gamma</td>
<td>3.00</td>
</tr>
<tr>
<td>(q)</td>
<td>normal</td>
<td>1.40</td>
</tr>
<tr>
<td>(\psi)</td>
<td>gamma</td>
<td>2.00</td>
</tr>
<tr>
<td>(\omega)</td>
<td>gamma</td>
<td>2.00</td>
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<tr>
<td>(\chi)</td>
<td>gamma</td>
<td>2.00</td>
</tr>
<tr>
<td>(\rho)</td>
<td>beta</td>
<td>0.90</td>
</tr>
<tr>
<td>(\xi)</td>
<td>beta</td>
<td>0.37</td>
</tr>
<tr>
<td>(\tau)</td>
<td>gamma</td>
<td>52.50</td>
</tr>
</tbody>
</table>

Figure 2. US Impulse response functions for a positive TFP shocks on final output sector
Table 7: Prior and Posterior Distribution of Structural Parameters for the US cont.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Prior distrib.</th>
<th>Post. distrib.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi^y$</td>
<td>beta 0.85 0.10</td>
<td>0.8990 0.8977 0.9100</td>
</tr>
<tr>
<td>$\phi^e$</td>
<td>beta 0.85 0.10</td>
<td>0.8873 0.8636 1.0000</td>
</tr>
<tr>
<td>$\phi^{eF}$</td>
<td>beta 0.85 0.10</td>
<td>0.8546 0.8222 0.8874</td>
</tr>
<tr>
<td>$\phi^{eR}$</td>
<td>beta 0.85 0.10</td>
<td>0.8542 0.8292 1.0000</td>
</tr>
<tr>
<td>$\phi^T$</td>
<td>beta 0.85 0.10</td>
<td>0.8941 0.8503 0.8988</td>
</tr>
<tr>
<td>$\sigma_{e^y}$</td>
<td>inv.gamma 0.10 2.00</td>
<td>0.1030 0.0999 0.1403</td>
</tr>
<tr>
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Figure 3. China Impulse response functions for a positive TFP shocks on final output sector

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 in all three economies (Figures 1, 6 and
More specifically, in all countries, an increased in TFP generates different growth paths of energy demand and of both fossil fuel and RES prices. This induces different quantities responses as shown in figures 1, 6 and 11. In the EU, the response of final output and private consumption has almost the same shock size, whereas in the US, final output and private consumption increase ten times more than final output TFP. In China private consumption raises ten times more than final output TFP and final output.

Moreover, a common feature to all countries is that the energy demand increase is mainly determined by the growth of RES rather than the fossil fuels.

We then analyze the IRFs when a positive shock hits the energy sector in the EU, US and China, in Figures 4, 5 and 6, respectively.

Figure 4. EU Impulse response functions for a positive TFP shocks 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. Notice that the energy price decrease is higher in the EU and US than in China. In all the countries, the increase in energy quantity is driven by the RES growth and the effects on final output are smaller than the ones on private consumption.

We show IRFs in the presence of a TFP shock in the fossil fuel sector in Figures 7, 8 and 9.

Figure 7. EU Impulse response functions for a positive TFP shocks 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 is stronger in the US and EU than in China. Furthermore, only in China this shock is able to push up private consumption, whereas in the EU and US this effect is negligible. 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 in the RES sector. 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 Figures 10, 11 and 12.

Figure 10. EU Impulse response functions for a positive TFP shocks 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. The magnitude of the RES growth with respect to the RES TFP shock is quite similar for the US and China, whereas in the EU the increase is about three times higher. In addition, RES and energy prices decrease, whereas energy production increases, although with different intensities: in the US and China the energy quantities increase is about ten times lower than the size of the RES TFP shock, whereas in the EU the energy increase is comparable the size of the shock.

We analyze the IRFs in the presence of a demand shock on the preferences in Figures 13, 14 and 15.

Figure 13. EU Impulse response functions for a positive TFP shocks on preferences
The dynamics of the variables in this context is similar to the case of the
final output TFP shock for all three countries. However, the growth of the productive factors’ demand curves is determined by tastes, whose rise generates a positive shift of private consumption and hence a higher production through an increased input demand. Also in this case, there is an increase in RES quantity in all countries. However, there is a difference in the response of final output to the taste shifter (that is a demand shock): very small for the US and China and about ten times smaller for the EU.

Finally, we analyze the price dynamics of RES and fossil fuels in order to estimate the point in time in which the price parity is likely to occur, with a 95% confidence interval in Figures 16, 17 and 18.

![Figure 16. EU price parity trends](image.png)
Figure 17. US price parity trends
The time series of RES and fossil fuel prices are generated for all the countries through the MCMC method over the 54 years represented in the sample for 1995-2048. 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. 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).

The price parity is achieved earlier in the EU, then in China and lastly in the US. This is an indirect indication that the RES support policies are more
effectively designed in the EU.

5 Conclusions

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 incentive mechanisms that incorporate a carbon tax and a monetary subsidy to RES producers.

To this aim, we have constructed data set for the three 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 being 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.

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. NOT CLEAR

Furthermore, a TFP shock generates a much stronger effect on private consumption in the US and China than in the EU. A common feature is the prominent role of the growth of RES. These latter increase more than fossil fuels not only, as expected, in the presence of the RES TFP shock (where fossil fuels decrease), but also when an energy TFP shock hits the economy. A shock in RES
produces a higher RES growth in the EU than in the US and China, confirming the validity of the favorable policy attitude towards RES in the EU.

Our results have an interesting policy implication. A shock analysis that yields a sluggish response to the economic growth of a country can signal the need for subsidies. These can have the form of price decrease but also tax relief, interest-free loans or relaxation of regulatory burdens. Subsidies in this case can act as a positive externality playing a transitional role in further revitalizing a weak or decaying economic environment by providing actors with tools to increase their productivity. However, in the context of a growing and expanding economy, subsidies can play a negative role in creating inefficiencies by distorting the system and leading to artificial pricing. It may lead to chronic wastage of money and goods while creating the potential for a harmful long-term dependency among consumers. A free market allows prices to act as a signaling tool for agents helping them balance supply and demand as needed and further increasing economic efficiency.

Finally, we have investigated the issue of price parity between RES and fossil fuels, which is an important milestone for RES deployment. The comparison of different countries’ RES support mechanisms reflects an encouraging picture on 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 the levelized cost of energy and RES learning rates.

Further applications of the model could include its implementation on a full world model, where trade and financial interactions among countries are better 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.
References


6 Appendix

The representative fossil fuels’ producer aims to maximize the expected value of the following intertemporal profit function:

$$
\max_{N_t^{ef}, K_{t-1}^{ef}, S_t} E_0 \sum_{t=0}^{\infty} \rho^t \left( P_t^{ef} + \tau \right) A_t^{ef} \left( N_t^{ef} \right)^{\theta} \left( K_t^{ef} \right)^{\delta} (S_{t-1})^X + \left( 1 - \delta^{ef} \right) K_{t-1}^{ef} +$$

$$- W_t^{ef} N_t^{ef} - R_t^{ef} K_{t-1}^{ef} - F_t S_{t-1}$$

s.t. \[ S_t - S_{t-1} = -\delta^s S_{t-1} - (EF)_t \]  \hspace{1cm} (A1)

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

$$
L = \max_{N_t^{ef}, K_{t-1}^{ef}, S_t} \left[ \sum_{t=0}^{\infty} \rho^t \left( P_t^{ef} + \tau \right) A_t^{ef} \left( N_t^{ef} \right)^{\theta} \left( K_t^{ef} \right)^{\delta} (S_{t-1})^X + \right]
$$

$$+ \lambda_t \left( S_t - \delta^s S_{t-1} - (EF)_t - S_t \right)$$

$$\quad + \lambda_t \left( S_{t-1} - \delta^s S_{t-1} - (EF)_t - S_t \right)$$

(A2)

with the following necessary conditions:

$$
\frac{\partial L}{\partial N_t^{ef}} : \left[ A_t^{ef} \theta \left( N_t^{ef} \right)^{\theta - 1} \left( K_{t-1}^{ef} \right)^{\delta} (S_{t-1})^X \right] \left[ \left( P_t^{ef} + \tau \right) - \lambda_t \right] - W_t^{ef} = 0
$$

(A3)

$$
\frac{\partial L}{\partial K_{t-1}^{ef}} : \left[ A_t^{ef} \theta \left( N_t^{ef} \right)^{\theta} \left( K_{t-1}^{ef} \right)^{\theta - 1} (S_{t-1})^X \right] \left[ \left( P_t^{ef} + \tau \right) - \lambda_t \right] - R_t^{ef} + \left( 1 - \delta^{ef} \right) = 0
$$

(A4)

$$
\frac{\partial L}{\partial S_t} : \left[ \delta A_t^{ef} \left( N_t^{ef} \right)^{\theta} \left( K_{t-1}^{ef} \right)^{\delta} (S_{t-1})^X \right] \left[ \left( P_t^{ef} + \tau \right) - \lambda_t \right] - F_t + \lambda_t \rho (1 - \delta^s) = 0
$$

(A5)

(A6)
The substitution of the condition A5 into the A6 leads to the relationship between the expected price of fossil fuels and the cost of fossil deposits, according to the Hotelling rule:

$$E_0 \rho \left( P_{t+1}^f + \tau \right) = E_0 \left( \frac{R_{t+1}^f - (1 - \delta^f)}{A_t^c \theta \left( N_t^c \right)^\theta \left( K_{t-1}^c \right)^{\theta-1} (S_{t-1})^x} \right) + \frac{F_t}{(1 - \delta^s)} +$$

(A7)

The substitution of the condition A4 into the A6 also generates a relationship between the expected price of fossil fuels and the cost of fossil deposits, i.e. the Hotelling rule, but instead of marginal productivity of capital there is the
marginal productivity of labor:

\[
E_0 \rho \left( R_{t+1}^f + \tau \right) = E_0 \rho \left( \frac{R_{t+1}^f - (1 - \delta^f)}{A_t^f \theta \left( N_t^f \right)^{\theta - 1} \left( K_{t-1}^f \right)^\theta (S_{t-1})^\infty} \right) + \frac{F_t}{(1 - \delta^f)} +
\]

(A8)

\[
\left( xA_t^f \left( N_t^f \right)^{\theta - 1} \left( K_t^f \right)^\theta (S_{t-1})^{\infty - 1} \right) - \left( \frac{W_t^f}{(1 - \delta^f)} \right)
\]

The conditions A4 and A5 can be solved for the co-state variable, \( \lambda_t \), in order to obtain the first order conditions for capital, \( K_t^f \), and labor, \( N_t^f \):

\[
W_t^f = A_t^f \theta \left( N_t^f \right)^{\theta - 1} \left( K_t^f \right)^\theta (S_{t-1})^\infty
\]

(A9)

\[
R_t^f = A_t^f \theta \left( N_t^f \right)^{\theta - 1} \left( K_t^f \right)^\theta (S_{t-1})^\infty
\]

(A10)

The representative household’s problem is solved by maximizing the follow-
ing dynamic Lagrangian function:

\[
L = \max_{(C_t, N^e_t, K^r_t)} \sum_{t=0}^{\infty} \rho_t \left[ \left( \frac{Y_t}{C_t^{1-q}} - Z_t + \frac{(N^e_t)^{1+\psi}}{1+\psi} - \frac{(N^{ref}_t)^{1+\psi}}{1+\psi} \right) + W^y_t N^y_t + W^{ref}_t N^{ref}_t + \right.
\]

\[
\left. + \Pi^y_t + \Pi^e_t + \Pi^{ref}_t + r^y_t K^y_{t-1} + r^{ref}_t K^{ref}_{t-1} + f_t S_{t-1} - C_t - X^y_t - X^{ref}_t - X^{er}_t \right]
\]

The corresponding first-order conditions are summarized below:

\[
\frac{\partial L}{\partial C_t} : Y_t (C_t)^{-q} = \varpi_t \tag{A12}
\]

\[
\frac{\partial L}{\partial N^y_t} : (N^y_t)^{\chi} = \varpi_t W^y_t \tag{A13}
\]

\[
\frac{\partial L}{\partial N^{ref}_t} : (N^{ref}_t)^{\omega} = \varpi_t W^{ref}_t \tag{A14}
\]

\[
\frac{\partial L}{\partial N^{er}_t} : (N^{er}_t)^{\psi} = \varpi_t W^{er}_t \tag{A15}
\]

\[
\frac{\partial L}{\partial K^y_t} : \rho \varpi_t (S_{t+1} R^y_t) = \varpi_t \tag{A16}
\]

\[
\frac{\partial L}{\partial K^{ref}_t} : \rho \varpi_t (S_{t+1} R^{ref}_t) = \varpi_t \tag{A17}
\]

\[
\frac{\partial L}{\partial K^{er}_t} : \rho \varpi_t (S_{t+1} R^{er}_t) = \varpi_t \tag{A18}
\]

\[
\frac{\partial L}{\partial \varpi_t} : W^y_t N^y_t + W^{ref}_t N^{ref}_t + W^{er}_t N^{er}_t + r^y_t K^y_{t-1} +
\]

\[
+f_t S_{t-1} + r^{ref}_t K^{ref}_{t-1} + r^{er}_t K^{er}_{t-1} = C_t + X^y_t + X^{ref}_t + X^{er}_t - \Pi^y_t - \Pi^{ref}_t - \Pi^e_t - \Pi^{er}_t
\]

We are able to eliminate Lagrange multipliers, substituting in each expression their values, i.e.:
\[
\frac{\partial L}{\partial C_t} : \Upsilon_t (C_t)^{-q} = \omega_t \\
\frac{\partial L}{\partial Z_t} : (Z_t) = \lambda_t \\
\frac{\partial L}{\partial N_t^y} : (N_t^y)^X = \Upsilon_t (C_t)^{-q} W_t^y \\
\frac{\partial L}{\partial N_t^{\epsilon f}} : \left(N_t^{\epsilon f}\right)^\omega = \Upsilon_t (C_t)^{-q} W_t^{\epsilon f} \\
\frac{\partial L}{\partial N_t^{\epsilon r}} : (N_t^{\epsilon r})^\psi = \Upsilon_t (C_t)^{-q} W_t^{\epsilon r} \\
\frac{\partial L}{\partial K_t^y} : \rho E_t \left[ \Upsilon_{t+1} (C_{t+1})^{-q} R_{t+1}^y \right] = \Upsilon_t (C_t)^{-q} \\
\frac{\partial L}{\partial K_t^{\epsilon f}} : \rho E_t \left[ \Upsilon_{t+1} (C_{t+1})^{-q} R_{t+1}^{\epsilon f} \right] = \Upsilon_t (C_t)^{-q} \\
\frac{\partial L}{\partial K_t^{\epsilon r}} : \rho E_t \left[ \Upsilon_{t+1} (C_{t+1})^{-q} R_{t+1}^{\epsilon r} \right] = \Upsilon_t (C_t)^{-q} \\
\frac{\partial L}{\partial \omega_t} : W_t^y N_t^y + W_t^{\epsilon f} N_t^{\epsilon f} + W_t^{\epsilon r} N_t^{\epsilon r} + r_t^{\epsilon f} K_{t-1}^{\epsilon f} + r_t^{\epsilon r} K_{t-1}^{\epsilon r} + f_t S_{t-1} = C_t + X_t^y + X_t^{\epsilon f} + X_t^{\epsilon r} - \Pi_t^y - \Pi_t^{\epsilon f} - \Pi_t^{\epsilon r}
\]