Comparing Renewable Energy Policies in E.U.15, U.S. and China: A Bayesian DSGE Model

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ABSTRACT

The promotion of renewable energy sources (RES) by governments is one way of helping countries to meet their energy needs while lowering greenhouse gas emissions. In this paper, we examine the role of energy policy in RES promotion, based on a carbon tax and RES price subsidy, at a time of technological and demand shocks in the European Union (E.U.) 15 countries, the United States (U.S.) and China, focusing on the macroeconomic implications. Using a dynamic stochastic general equilibrium model for RES and fossil fuels, our results suggest that, in the presence of a total factor productivity shock in the fossil fuel sector, such an energy policy can also be a driving force for smoothing the reduction of RES in the energy market (and vice versa). Additionally, we show that the E.U.15 grouping has a comparative advantage in terms of reaching grid parity compared with the other countries we considered which are more fossil fuel dependent.

Keywords: renewable energy sources, fossil fuels, productivity shocks, price subsidy, dynamic stochastic general equilibrium model

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1. INTRODUCTION

Environmental and energy problems came to the forefront of political debate in the 1980s, with the emergence of global warming, the instability associated with oil markets and the ongoing requirement for huge investments to fund the productivity of fossil fuels reservoirs (Trombetta, 2008). Renewable energy sources (RES) may represent a viable alternative to fossil fuels (Panwar et al., 2011). Currently, in the global electricity generation fuel mix, RES account for 23.2% in the European Union (E.U.), in the United States (U.S.) for 13.1% (Energy Information Administration, 2016) and in China for 28% (China Energy Group, 2014). The European Commission's future policy target envisages a RES target of at least 27% of energy consumption by 2030 for E.U. member countries, which are given the flexibility to set national targets (European Commission, 2014)[1]. In the U.S., the future target set by the Clean Power Plan (U.S. Environmental Protection Agency, 2016) is 21% by 2030, although an important element of that relies on individual states

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[1] In terms of this E.U. future policy target, by E.U. is meant the E.U.27, excluding the Czech Republic. Elsewhere throughout this paper, the group referred to is the E.U. 15.

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(Moosavian et al., 2013). China has also adopted a challenging long-term RES plan target. Under the country's 12th Five Year Plan, covering 2011–2015, China aims to source 11.4% of its primary energy from RES by 2015, and 15% by 2020 (The Climate Group, 2015).

RES provide benefits that do not have a market value, but which can be translated into generally lower social costs (Ortega-Izquierdo and Del Ro, 2016; Owen, 2004), although, in many cases, they have higher production costs than fossil fuels (Jenner et al., 2012). Indeed, from an economic point of view, the main barrier to RES implementation is the establishment of proper financial support systems (Haas et al., 2011; Garnier and Madlener, 2016).

The aim of this paper is to analyze the role of energy policy in RES deployment, based on a carbon tax and RES price subsidy at a time of technological shocks in the E.U.15—that is, the E.U. member countries prior to May 1, 2004, including: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, United Kingdom—the U.S. and China, focusing on the macroeconomic implications. This enables both partial and general equilibrium short- and long-run effects on the different sectors of the economy to be considered, also taking into account household welfare and company productivity. We model the RES and fossil fuels sectors in a dynamic stochastic general equilibrium (DSGE) model using Bayesian techniques for the three economies we considered. The inferential procedure we adopted is based on Markov Chain Monte Carlo (MCMC) methods, which are able to estimate the model parameters and the dynamics of some relevant variables (i.e., fossil fuels and RES prices). In addition, we evaluate the potential of RES technologies for viable energy generation in the E.U.15, the U.S. and China—that is, when and where grid parity will likely occur first.

The design of subsidy regimes that will guarantee a proper RES deployment is key (Battle et al., 2012; Chen and Tseng, 2011; De la Hoz et al., 2016; Gerlagh and Van der Zwaan, 2006; Traber and Kemfert, 2009). Indeed, RES require forms of government support to accelerate their implementation and governments have adopted a range of policies aimed at increasing RES investment (Stokes, 2013). In general, governments may offer different support mechanisms that fall into three main categories that are either price based or quantity based: feed-in tariffs, bidding processes and tradable green certificate schemes (Amundsen and Bergman, 2012; Fischer, 2010). Results obtained by various countries from the support mechanism they have implemented suggest that feed-in tariffs are better than competitive bidding procedures (Finon et al., 2002; Narbel, 2014). In fact, in terms of installed capacity, much better results have been obtained with price based approaches than with quantity based approaches (European Commission, 2014; Energy Information Administration, 2016; Irena, 2014). Such differences might be because fixed prices, i.e., feed-in tariffs, represent a strong incentive. In our paper we assume that feed-in tariffs are the incentive system used to effect RES implementation.

Fischer and Newell (2008), assessing different policies for promoting the spread of RES, found that an optimal portfolio of policies will include an emissions price and subsidies for RES research and development (R&D) and learning, but the emissions reductions are attributable primarily to the emissions price and the optimal RES learning subsidy is small. Government intervention can support RES through other mechanisms that harness market incentives or correct for market failures. The European emission trading scheme (ETS) is one example (Frondel et al., 2010). An often-cited rule for best design policy mixes was first addressed in policy design studies by Tinbergen (1952). It is assumed that policymakers have many tools to address their policy targets, and the optimal ratio of the number of tools to targets is 1:1, i.e., matching one target with one policy measure could accomplish the target set out for it.

However, Gawel et al. (2014), evaluating the policy mix in European climate and energy policy, stressed that the interaction of both RES subsidies and an emission trading system may be useful to improve energy policy efficiency. Atallah and Blazquez-Lidoy (2015) reestablished that an increase in hydrocarbon prices did not impact economic growth for the following several decades but led to a stagnation in energy productivity over the last 10 years. This opens the door for further implementation of an RES approach based on guaranteed markets and pricing.

Few studies have addressed dynamic economic models focusing on policy instruments, which are closely related to our interest. Golosov et al. (2014), using a stochastic dynamic general equilibrium model of the world, treated as a uniform region, characterized optimal global policy qualitatively and quantitatively, finding that if taxes are set according to their formula, there is no need to subsidize RES technology relative to other kinds of technology, at least not from the perspective of climate change. Annicchiarico and Di Dio (2015) develop a New Keynesian DSGE model to evaluate the effects of environmental policies on business cycle fluctuations, following the seminal papers of Fischer and Sprinborn (2011), Heutel (2012) and Angelopoulos et al. (2013). This strand of literature is mainly focused on the effects of pollution reduction policies on macroeconomic variables at a time of stochastic shocks on total factor productivity.

To the best of our knowledge, this paper is the first to integrate the effects of the policy mix based on RES monetary subsidy and a carbon tax in a dynamic context in three countries (considering the E.U.15 group as a ‘country’). In addition, we measure the effects of such a policy on macroeconomic variables in the presence of total factor productivity shocks and simulate a path for fossil fuels and RES prices with the corresponding grid parity between them.

Briefly, our contribution analyzes the role of RES subsidy in the fluctuations of the energy market and the effect of such policy in making RES competitive in the energy market.

The paper includes the following: Section 2 describes the model structure for three major economies. Section 3 presents the model analysis. Section 4 summarizes the model dynamics results. Section 5 sets out our conclusions.

2. MODEL STRUCTURE

In this paper, we build a micro founded DSGE model, explicitly focusing on an energy sector composed of fossil fuels and RES. Previous literature (Acemoglu et al., 2012) has dealt with DSGE models with clean and dirty inputs; our approach aims to deepen the existing research by considering one final consumer good and three intermediate goods, i.e., energy, fossil fuels and RES. The Government subsidizes RES production through the fiscal revenues collected from an environmental tax on the fossil fuels sector.

Households, the driving force behind the final demand in the model, own the productive factors, sell them to the firms, receive the corresponding value from marginal productivities and earn the resulting profits.

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, (or final good), $Y_t(fg)$ is produced competitively, with constant returns to scale technology, according to a Cobb-Douglas production function making use of the three inputs of labor, L_t^{fg}, private capital, K_{t-1}^{fg}, and energy services, $(EN)_t$:

$$Y_t = A_t^{fg}(L_t^{fg})^{\alpha}(EN)_t^{\gamma}(K_{t-1}^{fg})^{1-\alpha-\gamma} \tag{1}$$

where A_t^{fg} is total factor productivity (TFP). Both on the supply and demand side, the law of motion of the stochastic shocks is described by an AR(1) process with zero mean and IID normally distributed residuals ε_t^i with $(i = fg, ef, er)$. On the supply side, the law of motion is the following:

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

where $\bar{A}^i$ indicates the steady state value of the sectoral 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, with constant returns to scale technology:

$$(EN)_t = (\eta (ER)_t^{-\varepsilon} + (1-\eta)(EF)_t^{-\varepsilon})^{-\frac{1}{\varepsilon}} \tag{3}$$

where

$$\varepsilon = \frac{1-\sigma}{\sigma} \tag{4}$$

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

The fossil fuel sector, the second intermediate goods sector, produces with constant returns to scale its output competitively and is represented by a hydrocarbons extraction firm employing private capital, K_{t-1}^{ef}, and labor, L_t^{ef}, according to a Cobb-Douglas production function:

$$(EF)_t = A_t^{ef} (L_t^{ef})^{\theta} (S_{t-1})^{\varsigma} (K_{t-1}^{ef})^{1-\theta-\varsigma} \tag{5}$$

where S_{t-1} is the stock of fossil fuel deposit from which the fuel is extracted, the dynamics of which are described by the process in equation (6), with this transversality condition holding:

$$S_t - S_{t-1} = -\delta^s S_{t-1} - (EF)_t \tag{6}$$

$$\lim_{t\to\infty} \rho^t \lambda_t S_t = 0 \tag{7}$$

where λ_t is the dynamic Lagrange multiplier, δ^s represents the depreciation rate of S_t. A_t^{ef} is total factor productivity (TFP) that follows the law of motion described in equation (2). The RES sector, the third intermediate goods sector, is represented by a RES producer in a regime of a perfectly competitive market[2]. We postulate that the RES production function with constant returns to scale technology depends on the inputs of private capital, K_{t-1}^{er}, labor, L_t^{er}:

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[2] Both RES and fossil fuels are subsidized through different mechanisms, meaning that, all externalities considered, RES are competitive with fossil fuels. It is appropriate to assume a perfectly competitive energy market (Pineda and Bock, 2016). Furthermore, in the RES sector there are no excessive concentrations of market power and in many cases the energy inputs are free. Indeed, the levelized costs of energy for RES power generation in OECD countries and China, with the exception of offshore wind and concentrated solar power, lie in the same range as fossils fuels (Irena, 2015). The Chinese government, recognizing insufficiencies and inefficiencies in the energy sector, is exploring specific market oriented reforms to improve energy price formation mechanisms and encourage market competition (Bo et al., 2015).

$$(ER)_t = A_t^{er}(L_t^{er})^{\iota}(K_{t-1}^{er})1-\iota \tag{8}$$

where A_t^{er} is TFP, that follows the law of motion described in equation (2). In this scenario, we assume that the government pays a monetary subsidy μ_t to the RES sector to support RES development that is entirely financed by a tax on the fossil fuel sector.

2.2 Households and Government

The economy's demand side is populated by an infinite number of infinitely living households with defined preferences for the following variables: private consumption C_t; labor services, L_t. These latter are allocated to final output production L_t^{fg}, fossil fuel sector L_t^{ef} and RES sector L_t^{er} on a period by period basis[3].

Agents are infinitely living and maximize their utility under the assumption of rational expectations. Each agent maximizes the expected value of an intertemporal risk adverse utility function:

$$E_0(U_t) = E_0\left[\Sigma_{t=0}^{\infty}\rho^t\left(\left(Y_t\frac{(C_t)^{1-q}}{1-q}\right)-\frac{(L_t^{fg})^{1+\chi}}{1+\chi}-\frac{(L_t^{ef})^{1+\omega}}{1+\omega}-\frac{(L_t^{er})^{1+\psi}}{1+\psi}\right)\right] \tag{9}$$

with ρ^t corresponding to the subjective discount factor and Y_t being a taste shifter (Stockman and Tesar, 1995). The law of motion is described by the usual AR(1) process with zero mean and the IID normally distributed residuals ε_t^Y:

$$\log Y_t = (1-\phi^Y)\log \bar{Y} + \phi^Y \log Y_{t-1} + \varepsilon_t^Y \tag{10}$$

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

The representative household maximizes the utility function subject to a period by period budget constraint, which states that the total flow of consumption and investments, indicated by X_t^{fg}, X_t^{ef} and X_t^{er} cannot exceed disposable income:

$$\begin{aligned} C_t + X_t^{fg} + X_t^{ef} + X_t^{er} \leq W_t^{fg}L_t^{fg} + W_t^{ef}L_t^{ef} + W_t^{er}L_t^{er} + r_t^{fg}K_{t-1}^{fg} + \\ + r_t^{ef}K_{t-1}^{ef} + r_t^{er}K_{t-1}^{er} + F_tS_{t-1} + \Pi_t^{fg} + \Pi_t^{e} + \Pi_t^{ef} + \Pi_t^{er} \end{aligned} \tag{11}$$

where $W_t^i(i = fg,ef,er)$ represents the nominal wages paid for each type of labor, r_t^i are the corresponding returns on capital, F_t is the cost for the exploitation of the stock, S_{t-1}, Π_t^i 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 sectoral net capital formations read as:

$$X_t^i = K_t^i - (1-\delta^i)K_{t-1}^i \tag{12}$$

where δ^i, with $(i = fg,ef,er)$, indicates the corresponding sectoral rates of capital depreciation.

The government's budget is assumed balanced every time, i.e., the entirety of the revenues

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[3] We develop the model taking into account the wage rates that vary across the three considered sectors (United States Department of Labor, 2015; Irena, 2013).

from environmental taxation can finance RES monetary subsidy. The government's budget constraint, where tax revenues on fossil fuels (the left side of the equation) are equal to the entire amount of the subsidy (the right hand side of the equation), is:

$$\tau(EF)_t = \mu_t(ER)_t \tag{13}$$

The optimal conditions, which characterize the decentralized equilibrium, are derived in the Online Appendix.

3. MODEL ESTIMATION

3.1 Method and Data

The inferential procedure adopted for the estimation of the parameters, 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[4] 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 four 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 90% highest posterior density (HPD) credible interval for the estimates, ensures the robustness of our results[5].

The sources for our data for the period 1980–2012, on an annual frequency, are the Ameco database for the E.U.15 private consumption and final output (Ameco, 2016), while the U.S. and Chinese private consumption and final output data are sourced from the World Bank database (The World Bank, 2016). Finally, the source of all the energy data is the U.S. Energy Information Administration (EIA, 2016).

All of the model computations were performed using DYNARE software[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 hand side):

$$\begin{bmatrix} \Delta\ln C_t \\ \Delta\ln(EF)_t \\ \Delta\ln(ER)_t \\ \Delta\ln Y_t \end{bmatrix} = \begin{bmatrix} \Gamma^{(A)} \\ \Gamma^{(A)} \\ \Gamma^{(A)} \\ \Gamma^{(A)} \end{bmatrix} + 100 * \begin{bmatrix} c_t - c_{t-1} \\ (ef)_t - (ef)_{t-1} \\ (er)_t - (er)_{t-1} \\ y_t - y_{t-1} \end{bmatrix} \tag{14}$$

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[4] These are a class of sample algorithms that construct a Markow Chain whose steady state distribution corresponds to the one of interest, i.e., the posterior distribution.

[5] In detail, the estimation procedure is based on two steps. In the first, we have estimated 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, we have used the Metropolis-Hastings algorithm in order to draw a complete picture of the posterior distribution and compute the log marginal likelihood of the model. Moreover, following Brooks and Gelman (1998), we carried out the univariate convergence diagnostic based on a comparison between pooled and within MCMC moments.

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

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; $\Delta\ln EF_t$ is gross inland consumption[7], with growth expressed in percentage terms, measured as the sum of solid fuels, total petroleum products, gas and nuclear heat. The RES consumption growth, in percentage terms, is expressed by $\Delta\ln(ER)_t$ and measured by gross inland consumption growth expressed in percentage terms of RES, 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 to consumption, GDP, fossil fuel and RES, expressed in percentage terms ($100*\ln\Gamma$) that is the average potential output growth rate in the three countries. This parameter is assumed normally distributed and calibrated using 1.6 for the E.U.15, (Ameco, 2016), 2.0 for the U.S. (Federal Reserve Economic Data, 2016) and 10.0 for China (International Monetary Fund, 2015). The standard deviations of $\Gamma^{(A)}$ are set equal to 0.1 for each investigated country. Finally, the third vector indicates the corresponding model variables in log differences. Note 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 affect both energy demand and prices, both for RES and fossil fuels.

3.2 Parameter Definitions and Posterior Distributions

The parameters employed in our model, together with their definitions and the posterior values estimated, are shown in Table 1.

A detailed discussion of the calibration procedure and the corresponding prior parametrization is included in the Online Appendix.

The posterior values of the structural parameters are estimated using observable variables (private consumption, RES, fossil fuels and final output) conditionally to the model. The fourth, sixth and eighth columns of Table 1 show the posterior means, while the fifth, seventh and ninth columns indicate the 90% HPD credible interval for the estimated parameters obtained by the Metropolis-Hastings algorithm[8].The posterior estimates for supply side sectors are higher for all the parameters than the prior assumptions (see Tables 3, 4 and 5 in the Online Appendix) . The environmental tax rate, τ and the capital depreciation rates, δ^i ($i = ef, s, er$) are quite similar to the prior assumptions, whereas the elasticity of substitution between RES and fossil fuels, σ, exhibits a positive shift for the E.U.15 and a negative shift for the U.S. and China.

Table 1 shows that important differences exist among these three countries[9]. For the sake of brevity, we focus only on some main parameters. The final output energy elasticity values are consistent with the literature (for example, see Yao et al., 2012 and Giraud et al., 2014 for China and U.S. respectively). U.S. value is greater than those of China and the E.U.15 and this is coherent with the fact that this elasticity is higher in high income countries. In the E.U.15, energy elasticity

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[7] 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.

[8] We have increased the standard deviations of the prior distributions of the parameters by 50% in order to evaluate the sensitivity of the estimation results with the assumptions on prior estimates (Smets and Wouters, 2007). Overall, the estimation results are very similar (results are available upon request).

[9] Although we are aware that the E.U.15, politically speaking, is not a country but a Union of countries, throughout the paper we refer to the geographical dimension of the E.U.15 instead of the current political one.

Table 1: Definition and Posterior Estimation of Parameters

Parameters	Definition	Sector	EU-15		China		US	
			Mean	90% HPD credible int.	Mean	90% HPD credible int.	Mean	90% HPD credible int.
α	Final output elasticity of labor[a]	Final output	0.6347	[0.5880 0.6844]	0.5188	[0.4787 0.5726]	0.601	[0.5869 0.6198]
γ	Final output elasticity of energy[a]	Final output	0.0624	[0.0003 0.1125]	0.0947	[0.0148 0.1653]	0.1216	[0.0476 0.2086]
δ^{fg}	Depreciation rate of final output capital[b]	Final output	0.10	—	0.10	—	0.10	—
ϕ^{fg}	Persistence in final output TFP[a]	Final output	0.8425	[0.7546 0.9178]	0.9747	[0.9449 0.9986]	0.9527	[0.9276 0.9714]
$\Gamma^{(A)}$	Annual common trend growth rate[c]	Final output	1.6274	[1.5719 1.6848]	9.9439	[9.8206 10.0686]	2.0356	[1.9903 2.0867]
o_{ϵ}^{fg}	Standard deviation of final output TFP shock[d]	Final output	0.0573	[0.0498 0.0646]	0.0631	[0.0559 0.0750]	0.0264	[0.0208 0.0330]
δ^{ef}	Depreciation rate of fossil fuel capital[a]	Fossil fuels	0.0838	[0.0034 0.1400]	0.0442	[0.0080 0.0845]	0.0944	[0.0715 0.1242]
δ^{s}	Depreciation rate of fossil fuel deposits[a]	Fossil fuels	0.0116	[0.0000 0.0351]	0.0106	[0.0000 0.0303]	0.0017	[0.0000 0.0043]
θ	Fossil fuel elasticity of labor[a]	Fossil fuels	0.6547	[0.5450 0.7626]	0.5143	[0.4393 0.5739]	0.6144	[0.5656 0.6687]
ζ	Fossil fuels elasticity of deposit[a]	Fossil fuels	0.2816	[0.2174 0.3382]	0.2877	[0.2459 0.3544]	0.2185	[0.1828 0.2653]
ϕ^{ef}	Persistence in fossil fuel TFP[a]	Fossil fuels	0.9628	[0.9287 0.9903]	0.9525	[0.9088 0.9920]	0.9718	[0.9578 0.9963]
τ	Effective tax rate on fossil fuel production[e] (Euro per TOE)	Fossil fuels	575.15	[570.10 590.78]	218.75	[210.36 228.45]	65.78	[63.20 69.12]
o_{ϵ}^{ef}	Standard deviation of fossil fuels TFP shock[d]	Fossil fuels	0.0629	[0.0531 0.0712]	0.0712	[0.0561 0.0909]	0.0804	[0.0671 0.0956]
δ^{er}	Depreciation rate of RES capital[a]	RES	0.1205	[0.0137 0.2177]	0.1282	[0.0072 0.2512]	0.0173	[0.0008 0.0358]
ι	RES elasticity of labor[a]	RES	0.6084	[0.5123 0.6966]	0.5166	[0.5024 0.5175]	0.6408	[0.5810 0.7043]
ϕ^{er}	Persistence in RES TFP[a]	RES	0.5162	[0.4027 0.6280]	0.7789	[0.6618 0.8937]	0.8295	[0.6637 0.7920]
o_{ϵ}^{er}	Standard deviation of RES TFP shock[d]	RES	1.1697	[1.1428 1.1936]	1.177	[1.1502 1.2063]	1.1864	[1.1548 1.2185]
σ	Elasticity of substitution between RES and fossil fuels[e]	Energy	1.2219	[1.1769 1.2471]	0.6646	[0.6133 0.7130]	0.6732	[0.6416 0.7787]
η	RES share in energy production[a]	Energy	0.1315	[0.1291 0.1473]	0.2177	[0.1343 0.2880]	0.08	[0.0001 0.0929]
q	Coefficient of relative risk aversion[c]	Demand	1.0533	[1.0296 1.0699]	2.466	[2.3397 2.4730]	1.32	[1.2783 1.3638]
ψ	Inverse of RES Frisch elasticity of labor supply[e]	Demand	1.9985	[1.8957 2.0722]	1.903	[1.9191 2.1041]	1.9459	[1.9429 2.0236]
ω	Inverse of fossil fuels' Frisch elasticity of labor supply[e]	Demand	2.0965	[2.0192 2.1539]	1.953	[1.7860 1.9851]	1.9545	[1.8715 2.0059]
χ	Inverse of final output Frisch elasticity of labor supply[e]	Demand	1.9031	[1.8573 1.9461]	1.896	[1.8811 2.0963]	1.8999	[1.8519 2.0607]
ρ	Intertemporal discount factor[b]	Demand	0.90	—	0.90	—	0.90	—
ϕ^{Y}	Persistence in taste shifter[a]	Demand	0.985	[0.9682 0.9999]	0.9425	[0.8865 0.9975]	0.8186	[0.7754 0.8709]
o_{ϵ}^{Y}	Standard deviation of taste shifter[d]	Demand	0.0446	[0.0365 0.0513]	0.1857	[0.1528 0.2153]	0.0882	[0.0702 0.1039]

RES = Renewable Energy Sources; TFP = Total Factor Productivity; TOE = Tons of Oil Equivalent;
Types of distribution: [a] Beta; [b] Fixed; [c] Normal; [d] Inv. gamma; [e] Gamma

is lower than in China and the U.S. This could be due to the higher impact of the economic downturn. The posterior estimates of the inverse of Frisch elasticities of labor supply, ψ, ω and χ, confirm the stylized facts related to the annual mean wages in the three sectors considered (final output, fossil fuels and RES). Indeed, according to the U.S. Bureau of Labor Statistics data (2016), the annual mean wage in the U.S. for all occupations amounted to $48,320 in 2015, whereas an industrial engineer in the solar power (RES) sector earned on average $83,620 and an engineer in the fossil fuels sector had an average annual salary of $149,590[10].

The posterior estimated coefficient of the relative risk aversion, q, is lower than the corresponding prior one for all the countries, thus showing a smaller degree of risk aversion than assumed a priori. A closer inspection of the exogenous processes shows that the size of the autoregressive coefficients is substantially confirmed, whereas the standard deviations of TFP and taste shifter shocks show a posterior mean that is always lower than the prior distributions for consumption, final output and fossil fuels. For the RES sector these estimates are always higher. This result sharpens a higher volatility for TFP in the RES markets compared with the results for final output and fossil fuels. Finally, the posterior estimates of the trend growth rates are quite similar to the calibrated ones.

4. MODEL DYNAMICS RESULTS

The dynamic response of the main variables to stochastic shocks to 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 90% credible intervals[11]. We analyze in detail the different impact of TFP shocks on fossil fuels and the RES sectors, thus evaluating the role of energy policies for the E.U.15, China and the U.S., in Figures 1–3 (fossil fuels) and Figures 4–6 (RES).

The impact of TFP shocks on final output and preferences is shown and discussed in the Online Appendix. There are two key results from this paper:

First, the main result is that in the presence of a TFP shock on fossil fuels (or RES), an energy policy involving a carbon tax and a RES subsidy can smooth out the reduction (or increase) of RES in the energy market. In other words, the implementation of such policy represents a sort of automatic stabilizer of the cyclic fluctuations generated by supply shocks. Second, we show that grid parity, as the major milestone for RES diffusion in the energy market, will be realized in the next few years faster in the E.U.15 than in China and the U.S.[12].

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[10] The differences in wage levels between RES engineers and fossil fuels engineers seems most plausibly related to policy uncertainty about RES. Indeed, RES uncertainty, depending on government incentives, affects stable and well-paying jobs in the sector, while this is not the case for fossil fuels (Irena, 2013).

[11] The credible intervals have been computed as the 5 and 95 percentiles of the empirical distributions obtained by the algorithm. Given that the variables are expressed in logs, the measures of the responses can be read as elasticities.

[12] We perform two dynamic exercises in our model. In the first one, we analyze the impulse response functions of the key macroeconomic variables for each shock ceteris paribus (final output TFP, fossil fuels' TFP, RES TFP and taste shifter), the size of which is measured by the corresponding posterior standard deviation, given by the average of the draws of the MCMC algorithm (together with 90% credible intervals). In the second one, for each year, we draw the MCMC realizations of the stochastic shocks simultaneously and then we take the expected value of this sequence as the corresponding value for each year. Finally, the model is solved recursively and is able to generate a time series for each variable (such as RES and fossil fuel prices).

Figure 1: E.U.15 IRF for a Positive TFP Shock in Fossil Fuels Sector

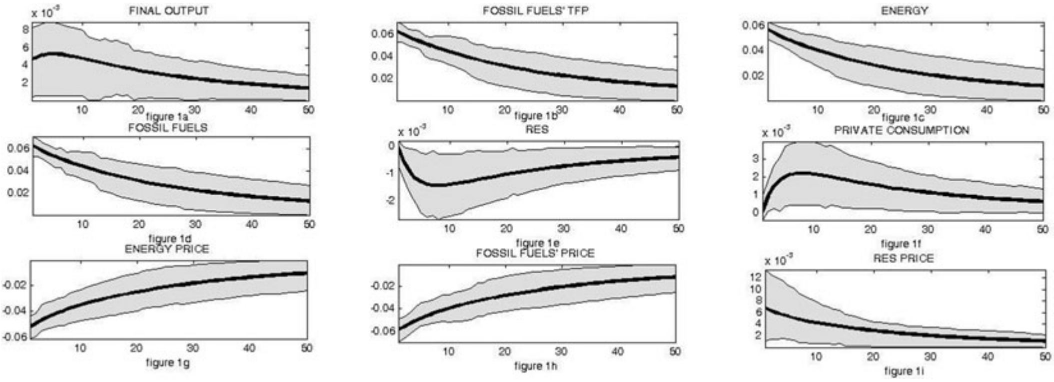

figure 1a figure 1b figure 1c
figure 1d figure 1e figure 1f
figure 1g figure 1h figure 1i

Figure 2: China IRF for a Positive TFP Shock in Fossil Fuels Sector

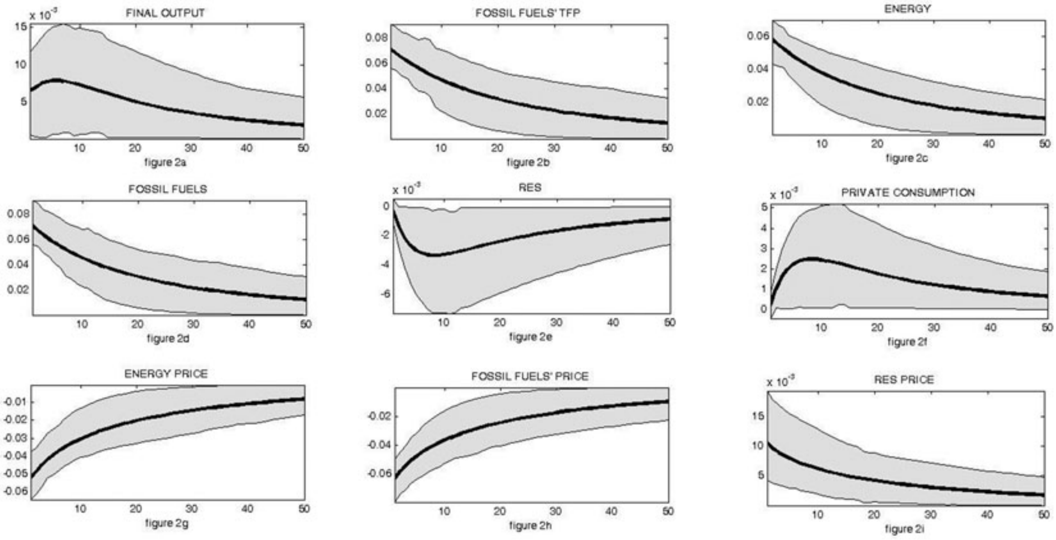

figure 2a figure 2b figure 2c
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figure 2g figure 2h figure 2i

Figure 3: U.S. IRF for a Positive TFP Shock in Fossil Fuels Sector

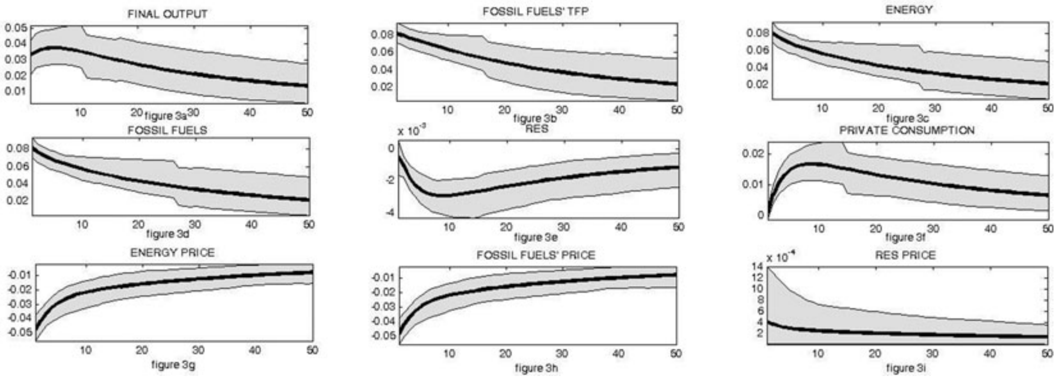


figure 3a figure 3b figure 3c
figure 3d figure 3e figure 3f
figure 3g figure 3h figure 3i

Figure 4: E.U.15 IRF for a Positive TFP Shock in RES Sector

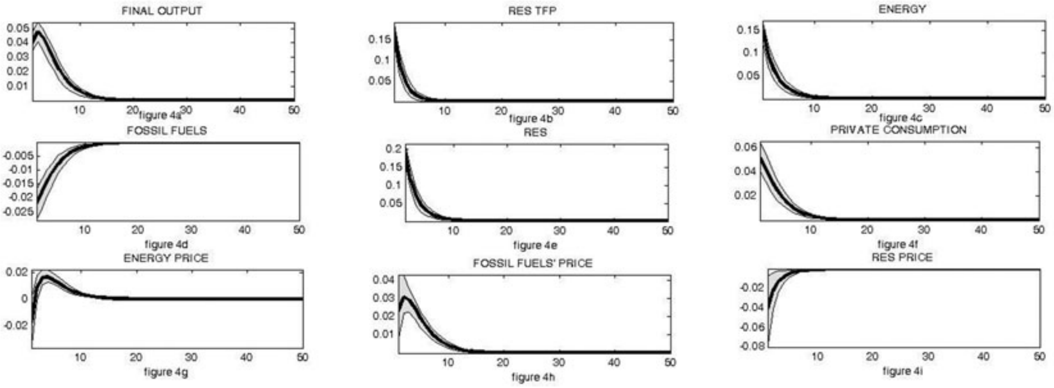
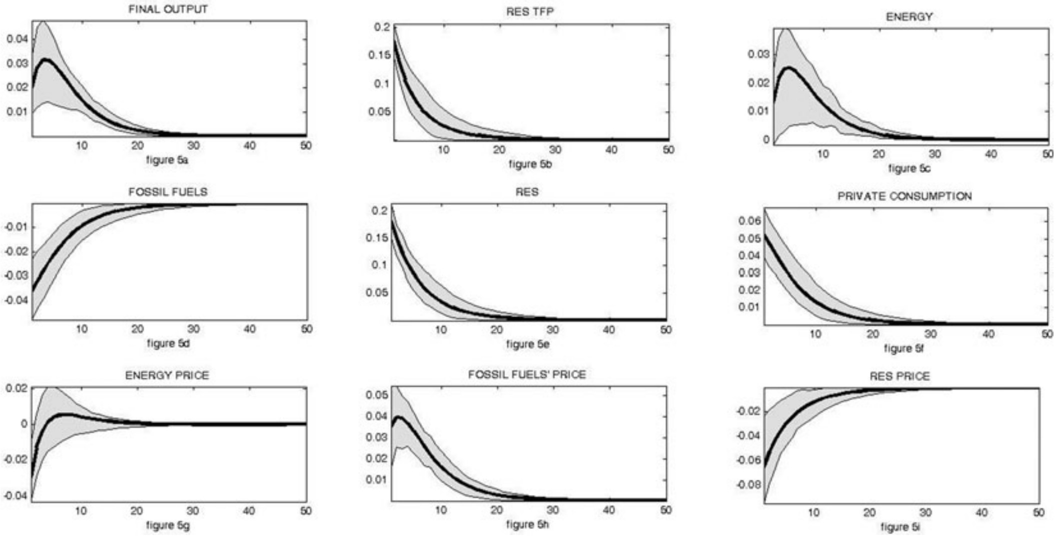
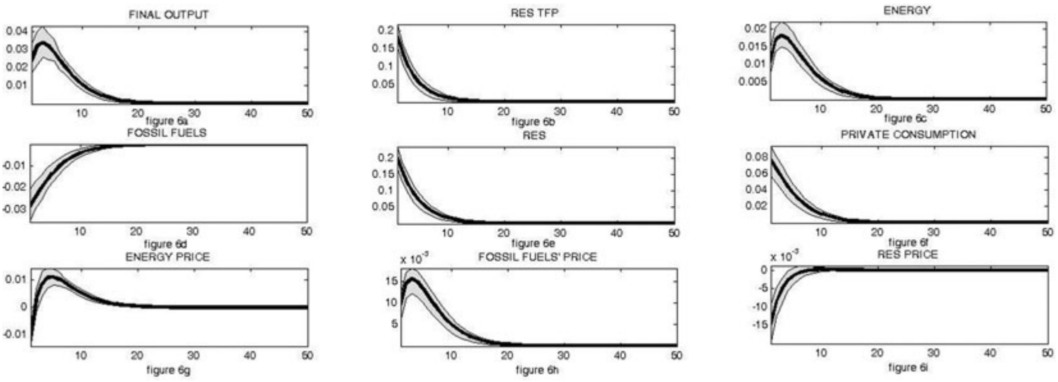


Figure 5: China IRF for a Positive TFP Shock in RES Sector



In the aftermath of TFP shocks hitting both the fossil fuels and RES sectors, the role of energy policies considered in our model is crucial in the transmission of the disturbances. In the case of a fossil fuel TFP shock (Figures 1, 2 and 3), a positive shift in fossil fuel TFP (Figures 1b, 2b and 3b) generates an increase in fossil fuel production (Figures 1d, 2d and 3d), thus producing a decrease in fossil fuel prices (Figures 1h, 2h and 3h). Nevertheless, RES production falls (Figures 1e, 2e and 3e), due to the reallocation of private capital and labor toward the fossil fuel sector, which is more productive. The decrease in RES production has a very similar response in the three economies, although in the E.U.15 the elasticity of substitution between RES and fossil fuels is higher than in China and the U.S. Indeed, the growth in fossil fuel supply leads to an increase in environmental taxation, thus increasing the RES subsidy. This policy mix, based on a fossil fuel taxation and a RES subsidy, can smooth the reduction of RES due to the growth of fossil fuels. The overall effect on energy production is positive and thus its price decreases. Moreover, in the

Figure 6: U.S. IRF for a Positive TFP Shock in RES Sector



E.U.15 the tax rate on fossil fuels is higher than in China and the U.S.; hence, our policy mix after a TFP shock in fossil fuels is able to smooth the strong reduction in RES due to the greater elasticity of substitution between RES and fossil fuels.

In addition, in all the countries the effect of this shock on private consumption is negligible (Figures 1f, 2f and 3f).

In the case of a TFP shock in the RES sector, the growth in RES TFP has the ability to increase RES production (Figures 4e, 5e and 6e). The magnitude of RES growth related to the RES TFP shock is quite similar for the U.S., China and the E.U.15. In addition, RES and energy prices decrease (Figures 4g–4i, 5g–5i and 6g–6i), while energy production increases (Figures 4c, 5c and 6c), although with different intensities. In the U.S. and China the increase in the amount of energy is about ten times lower than the size of the RES TFP shock, whereas in the E.U.15 the energy increase is comparable to the size of the shock. This quicker reallocation in the E.U.15 of the productive factors between fossil fuels and RES is due to the higher elasticity of substitution between RES and fossil fuels in the energy production function there. In this case, the decrease in fossil fuel production in favor of RES also generates a fall in environmental tax revenues and RES subsidy, which compensates for the increase of RES.

Therefore, the energy policy mix based on an environmental tax and RES subsidy acts as an automatic stabilizer on energy market fluctuations.

In addition, we analyze the price dynamics of RES and fossil fuels, with a 95% confidence interval, in order to estimate the point in time by which grid parity is likely to occur in the E.U.15, China and the U.S., in Figures 7, 8 and 9, respectively. Also, each figure represents an operation of 'zooming in' to better see the trajectories of the prices.

The time series of RES and fossil fuel prices are generated for all the countries through the MCMC method over the period 1987–2044[13].

Note that the huge variability of the RES price is linked to the high standard deviation of the exogenous shifts of TFP in the RES sector. It should be emphasized that the achievement of grid parity is endogenously determined, whereas in most of the current literature this achievement

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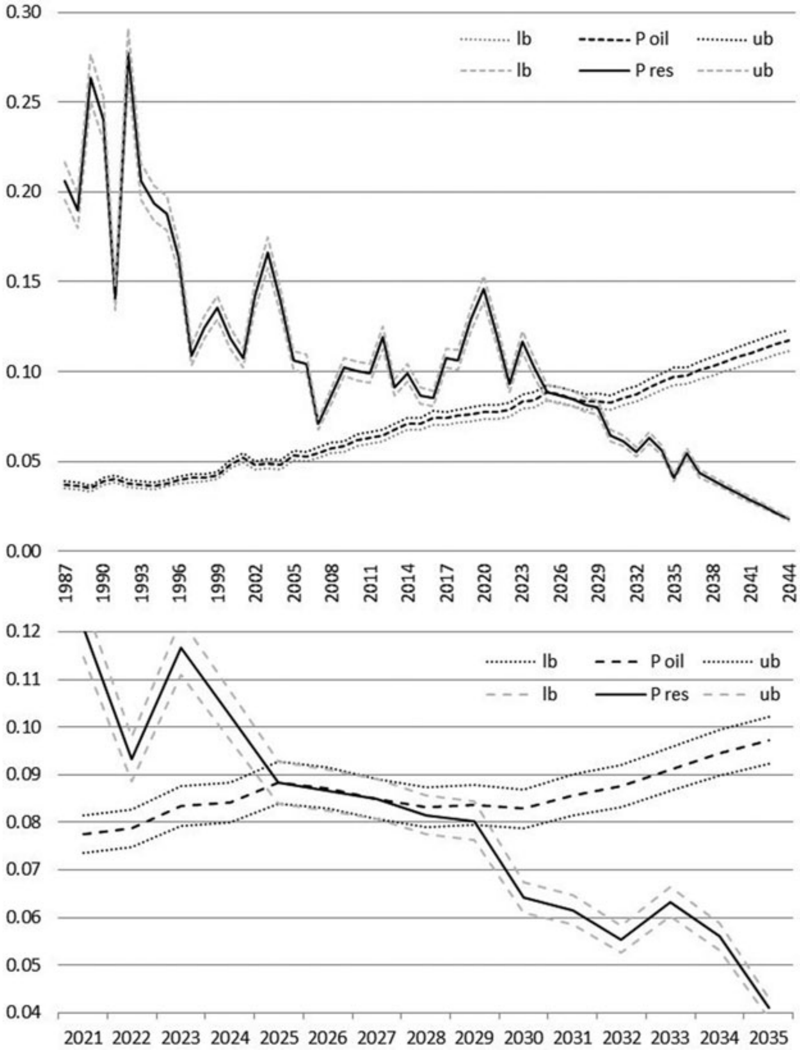
[13] For each year, we drew 200,000 realizations of the stochastic shocks and then took the expected value of this sequence as the corresponding value for each year. Prices are expressed in Euro/kWh.

Figure 7: E.U.15 Grid Parity Trends

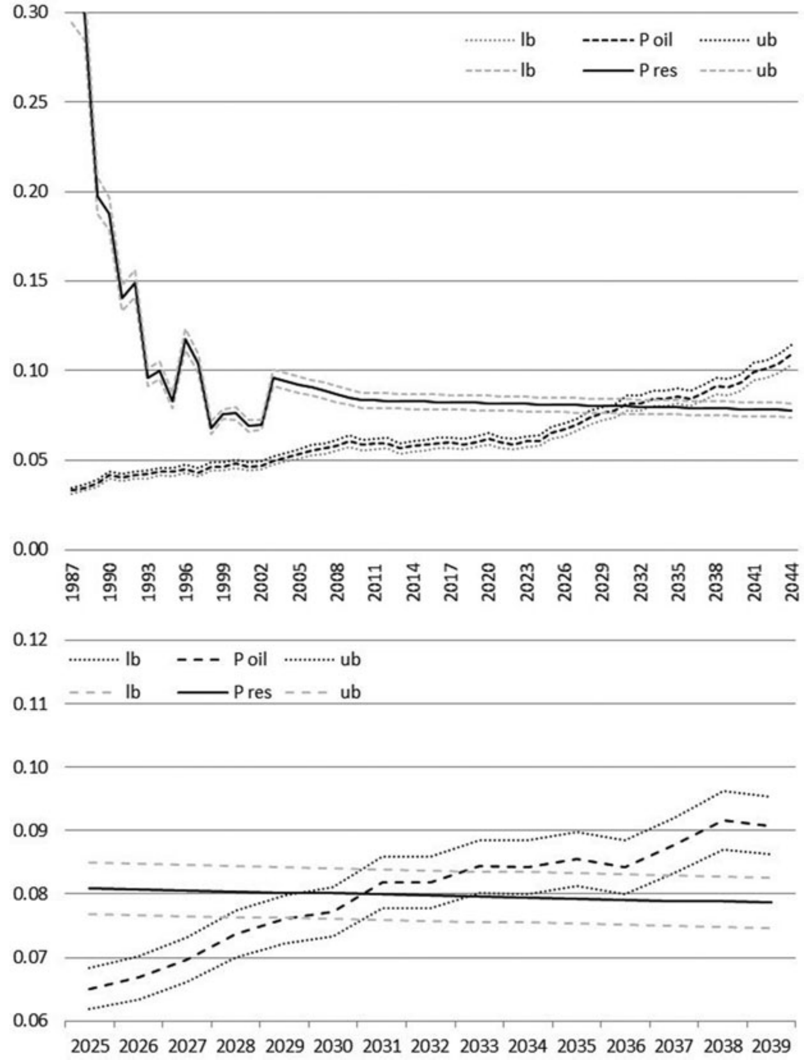


is determined by implementing an exogenous experience curve approach (Breyer and Gerlach, 2013; Lund, 2011; Mathews, 2013; Sun et al., 2014).

Results show that grid parity is achieved earlier in the E.U.15 than in China and, lastly, in the U.S. Indeed, looking at the parameters, the fossil fuel tax rate, and the RES subsidy are both higher in the E.U.15 compared with the other countries considered, thus enabling grid parity to be reached first. Furthermore, the estimated elasticity of substitution between fossil fuels and RES is higher in the E.U.15, thus generating a quicker reallocation of the productive factors within the energy sector and further strengthening the RES sector when it is subsidized. In other words, the impact of RES subsidy, as a smoother of cyclical fluctuations and an instrument to make RES more competitive, is most marked in the E.U.15.

As a further sensitivity analysis, to evaluate the differences among these three economies, we increase (decrease) the tax rate on fossil fuels by 2%, 5% and 10% for all the countries and

Figure 8: China Grid Parity Trends



measure the resulting effects on the grid parity achievement with respect to the baseline case (Table 2).

As shown in Table 2, the results obtained in Figures 7, 8 and 9 are robust for China and the U.S. and quite robust for the E.U.15. Indeed, in the E.U.15 the higher elasticity of substitution between RES and fossil fuels generates stronger effects toward achievement of grid parity than in China or the U.S. For these latter countries, where the initial level of taxation is also lower than in the E.U.15, it is necessary to have an increase (decrease) of at least 10% in order to reach grid parity before (later), whereas for the E.U.15 the higher tax rate, coupled with a greater elasticity of substitution, makes these changes already possible with smaller increases (decreases) in taxation.

Finally, to check whether our model fits the real world we performed several tests using main moments and the full distributions, the discussion and results of which are shown in the Online Appendix.

Figure 9: U.S. Grid Parity Trends

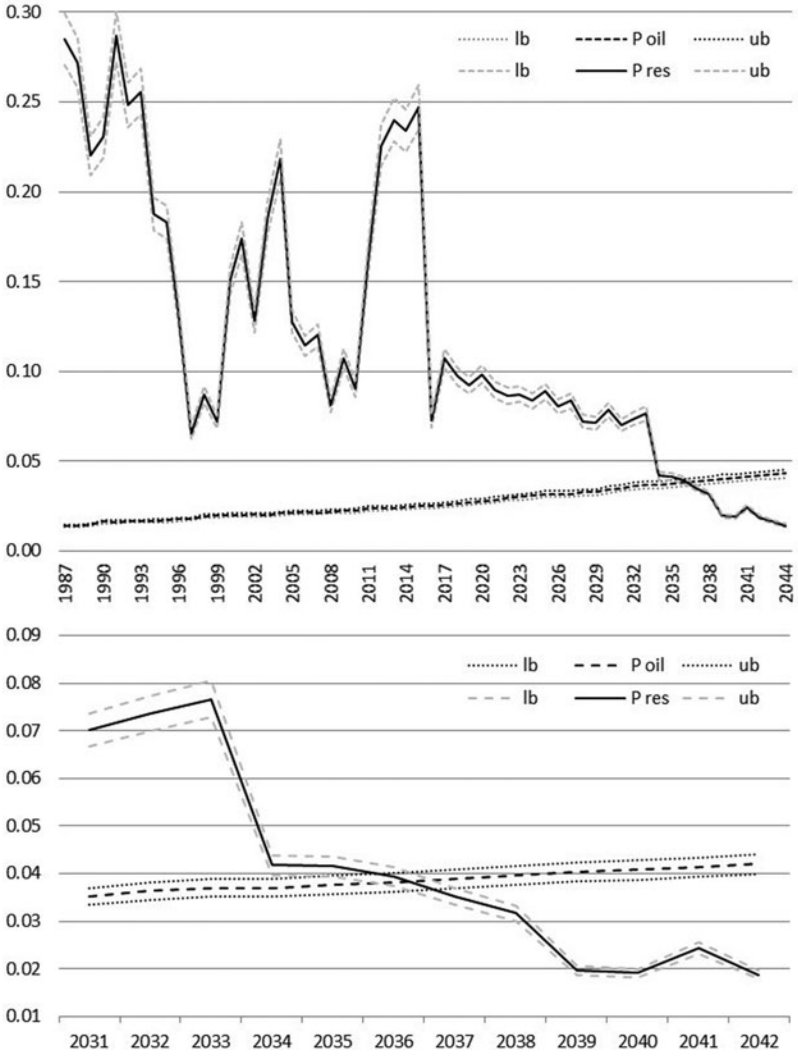


Table 2: Years of the Grid Parity Achievement with a Variation of Fossil Fuels' Tax Rate

		Increase/Decrease in fossil fuel tax rate τ		
Countries	Baseline case	+ 2%; − 2%	+ 5%; − 5%	+ 10%; − 10%
E.U.15	2027	2027; 2027	2025; 2029	2023; 2031
CHINA	2031	2031; 2031	2031; 2031	2027; 2032
U.S.	2037	2037; 2037	2037; 2037	2035; 2040

5. CONCLUSIONS

In this paper, we analyze the role of energy policy in RES deployment based on a carbon tax and RES price subsidy at a time of technological shocks in the E.U.15 countries, the United

States (U.S.) and China, focusing on the macroeconomic implications. We take into account both partial and general equilibrium short and long run effects on the different sectors of the economy, with particular reference to household welfare and company productivity. Using Bayesian techniques for the three economies considered, we model both RES and fossil fuels sectors in a DSGE model.

We find that, in the presence of a TFP shock in the fossil fuel sector (RES), an energy policy involving a carbon tax and a RES subsidy can smooth the reduction (or increase) of RES penetration in the energy market. The implementation of the proposed policy mix represents a kind of automatic stabilizer for the cyclic fluctuations generated by the supply shocks. A shock in RES, instead, produces a higher RES growth in the E.U.15 than in the U.S. and China, confirming the validity of the favorable policy attitude towards RES in the E.U.15.

We also investigate the issue of grid parity between RES and fossil fuels, which is an important milestone for RES deployment. The simulation results over the period 1987–2044 reveal that, assuming a carbon tax is required, monetary subsidies to RES producers have different effects for RES long-run development. In fact, the outcome of grid parity analysis for the countries investigated is a faster reduction in RES costs in the E.U.15 compared with in China and the U.S., so that grid parity is achieved earlier in the E.U.15 than in China and, lastly, in the US.

There are several possible explanations for our findings. First, the E.U.15 group has invested heavily in alternative energy sources ever since the oil crisis of the early 1970s, building global leadership in RES with its ambitious policies. This has not occurred in China or the U.S. The Chinese government has supported the RES sector since the 1980s, but only from the late 1990s has there been a shift to industrialization and the development of RES. The U.S. has experienced a ‘stagnation era’ that lasted until around 1997, caused by several factors such as the reduction of federal and state incentives and lower natural gas prices. The situation changed after 1997 with the implementation of new energy policies. Second, the E.U.15 has a complex set of support regimes for RES: each member country has different RES potential and operates different support schemes at domestic level, and the E.U.15 coordinates national efforts to reach the overall E.U. RES target. In China and the U.S., RES policies have suffered from inconsistency as incentives have been repeatedly enacted for short periods of time and then suspended. Third, as a region, the E.U.15 accounted for the largest proportion of aggregate capital raised by RES infrastructure funds in 2014. The E.U.15 is adapting grid capacity to the growth of electricity production capacity, so attracting RES investments. Our model differs from the existing literature, which deploys a grid parity calculation based on exogenous assumptions about the levelized cost of energy and RES learning rates, in that it endogenously determines grid parity. Future applications of our model could include its implementation on a full world scale, where trade and financial interactions among countries are modeled in more detail, including developing countries. This would require a deep analysis of the RES support mechanisms implemented in such countries, which is left for forthcoming research.

In conclusion, our results have an interesting policy implication. A shock analysis suggests a sluggish response to the economic growth of a country can signal the need for subsidies. These can take the form of a price decrease, but tax relief, interest-free loans or relaxation of regulatory burdens are also possible. 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. A policy suggestion would be to subsidize actors up to a level that enables them to recoup sunk costs, but not enough to completely distort the system because artificial pricing can lead to chronic waste of money and goods.

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