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An Agent-based Stock-flow Consistent Model of the Sustainable Transition in the Energy Sector

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ABSTRACT

In this paper, we investigate the effects on the economy of a feed-in tariff policy mechanism aimed to foster investments in renewable energy production capacity. To this purpose, we employ an enriched version of the agent-based Eurace macroeconomic model, where we have included an energy sector with a fossil-fuel power producer as well as a renewable-energy based one. Both power producers take pricing and capacity investment decisions based on the price of imported fossil fuel and the feed-in tariff government policy. Results show that the feed-in tariff policy is effective in fostering the sustainability transition of the energy sector and that it increases the level of investments with a positive impact on the unemployment rates. Moreover, we observe that its financing costs do not impact government finances, which actually improve following the better economic conditions. For high policy intensity, however, we observe an increasing GDP share of the investment sector in the economy, due to the building-up of renewable production capacity, with a resulting crowding out of consumption, higher interest rates and prices. The final outcome on household well-being therefore depends on what extent the chosen value judgment recognizes the importance of an economically and ecologically sustainable growth path.

1. Introduction

Sustainability transitions are long-term, multi-dimensional, and fundamental transformation processes that bring socio-technical systems to shift to more sustainable modes of production and consumption. Sustainability challenges can be observed in several domains, for example, energy supply, water supply, sanitation systems, transportation sector, agriculture and food system (Geels, 2011; Gil and Beckman, 2009; Gleick, 2003).

Focussing to the energy sector, major structural changes to the current fossil-fuel based economic systems are needed in order to address the challenge of climate change and economic recovery (Zysman and Huberty, 2013). In this respect, the European Union, has displayed a series of documents to reach the greenhouse gas (GHG) emission reduction level necessary for staying below the politically agreed limit of 2° temperature increase (European Commission, 2011a). The current EU roadmap is based on the so called “20-20-20” target, i.e., a 20% reduction in GHG emissions, a 20% share of renewable energy in gross final energy consumption and a 20% reduction in total primary energy consumption for EU, by year 2020 compared to year 1990. In 2011, the European Commission defined the long-term GHG emission reduction target for 2050 as 80%–95% below 1990 levels in order to reach the global political goal of staying below a 2° temperature increase (see the “Energy Roadmap 2050”, European Commission (2011a), and the “Roadmap Towards a Competitive Low-carbon Economy Until 2050”, European Commission (2011b)). Moreover, two intermediate goals for 2030 have been defined in 2013: the reduction of 40% GHG emission and 27% share of renewable energy with respect to 1990 levels, see European Commission (2013a,b). Finally, in 2015 the critical role that finance needs to play in enabling the resource efficient and low carbon transition has been discussed in Paris at the 21st Conference of the Parties (COP21) organized by the United Nations Framework Convention on Climate Change (UNFCCC) (McInerney and Johannsdottir, 2016; Johannsdottir and McInerney, 2016).

These challenging goals will only be achieved with an effective Renewable Energy Sources (RES) support policy and with a concrete effort towards the improvement of energy efficiency. Within various re-

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newable energy technologies, Photovoltaic (PV) system has become one of the major actor in the electricity sector in Europe, and different PV support measures have been introduced, for example capital subsidies, VAT reduction, tax credits, quota obligation, net-metering and feed-in tariffs (FiTs) (IEA, 2015). Each support mechanism offers both pros and cons for the producers and the collectivity. The most diffuse PV support policy is the Feed-In Tariff (FiT) system that is considered the most effective policy in order to stimulate the rapid development of RES (Couture and Gagnon, 2010; Menanteau et al., 2003; Stern et al., 2006; Butler and Neuhoff, 2008; Fouquet and Johansson, 2008). In this regard, Mazzucato (2015) points out that the feed-in tariff (FIT) policy adopted in Europe, e.g Italy and Germany, is a good form of public 'patient capital' supporting the long-term growth of renewable energy markets, whereas tax credits employed in the US and the UK are a form of 'impatient capital', due to their frequent uncertainty, and which indeed has not helped industry take-off (Porritt, 2011; Cowell, 2013).

According to the feed-in tariff policy electricity produced by RES can be sold at guaranteed prices for fixed periods of time. These prices are generally guaranteed by the government in a non-discriminatory manner for every kWh of electricity produced, so that a large number of investors can participate, including households, landowners, farmers, municipalities, and small business owners (Klein, 2008; Lipp, 2007).

Integrated Assessment Models (IAMs), based on computable general equilibrium, are the most common models for the analysis of climate policy and physical and socio-economic effects of climate change (Pindyck, 2015). In a general equilibrium framework, where economies are considered as "static, unchanging and perfectly efficient" (The Global Commission on the Economy and Climate, 2014), and the economic agents optimize their individual state and neglect external effects, climate policies are introduced as an additional constraint leading to less optimal (or efficient) outcomes. The overall economic costs (mainly in terms of GDP) of climate and energy policies and how these costs can be shared, e.g. among the member states of EU are the main important points of discussion about sustainability (Wolf et al., 2016).

Therefore, the cost of climate mitigation can lead only to lower economic welfare, with no room for possible long-term economic benefit. The only possibility of not reducing welfare is if the models assume very large damages in the future (in combination with lower discount rates).

Actually, the structural changes required to realize the transition to a low carbon economy are beyond the horizon of standard climate policy analysis models, and thus are the potential benefits from these changes. In fact, the possibility that climate policy offers economic opportunities has been largely neglected in previous macroeconomic modeling. The economic state of the European Union, characterized by low investment rates, low growth and high unemployment, however, suggests that there is an urgent need for new economic opportunities. To explore such opportunities, Burke et al. (2016) outline the need of research progress on climate economics, and in particular on refining the social cost of carbon (SCC), improving understanding of the consequences of particular policies and better understanding of the economic impacts and policy choices in developing economies.

The need of new approaches and tools based on complex system and network analysis has been recently advocated by many authors, see e.g. Battiston et al. (2016), Farmer et al. (2015), Rezai and Stagl (2016). Agent-based modeling (ABM), already employed for the study of complex systems, such as financial markets (Farmer et al., 2005; Ponta et al., 2011b; Pastore et al., 2010; Ponta et al., 2011a, 2012) and economic systems (Raberto et al., 2008; Dosi et al., 2010; Raberto et al., 2012; Caiani et al., 2016; Russo et al., 2016), is an alternative approach able to address shortcomings of IAMs because it provides a way for addressing out-of-equilibrium dynamics in economic systems (Farmer et al., 2015).

In particular, while general equilibrium models are characterized by rational and optimizing representative agents and by equilibrium solutions subject to exogenous shocks, agent-based models are characterized by a large number of heterogeneous and interacting agents, endowed with adaptive expectations, and by the ensuing evolutionary macroeconomic dynamics emerging from those endogenous interactions. In this regard, it is interesting to consider the recent and comprehensive survey by Fagiolo and Roventini (2017), where the theoretical, empirical and political-economy pitfalls of the equilibrium approach to policy analysis, in particualr the DSGE modeling framework adopted in macroeconomics, are discussed and a more fruitful research approach addressing the economy as a complex evolving system has been advocated. In particular, Fagiolo and Roventini (2017) point out the importance of taking into account the far-from-equilibrium interactions that continuously change the structure of the economic system, i.e. what is exactly the methodological core of agent-based computational economics, whose successful applications to different economic domains they present and discuss in details, including the ones on climate change economics.

The ABM framework looks indeed the appropriatemodeling approach to investigate the transition to a sustainable low carbon economy, because ABM allows the study of the sustainability transition not as an equilibrium suboptimal solution but as a possible dynamic path emerging from the appropriate coordination of the endogenous interactions and decisions of different economic agents characterized by limited rationality and information.

A recent detailed review of the literature on complex systems, related to the climate issues, with particular attention to ABM, is provided in Balint et al. (2016), where the authors identify different areas where accounting for heterogeneity, interactions and disequilibrium dynamics provides a complementary and novel perspective to the one of standard equilibrium models. In particular, two early contributions about the application of the ABM methodology to climate issues deserve attention: the ENGAGE model by Gerst et al. (2013) and Lagom regiO by Wolf et al. (2013). ENGAGE is a multi-level, multi-agent, evolutionary economic model, where a diverse set of agents (negotiators, firms, and consumers) engages in purposeful behavior by observing and interacting with their surrounding environment and other agents, and whose purpose is to simulate the two-way dynamic feedback between international agreements and domestic policy outcomes. Lagom regiO is a multi-agent model of several growing economic areas in interaction with the purpose to understand equilibrium selection and identify win-win opportunities for climate policy. Both ENGAGE and Lagom regiO provided insights on the importance of multi-country interaction for climate policy. On the other hand, the study presented in this paper focuses on a singe-country economy and on the fiscal costs and the macroeconomic impact of green investments subsidies.

Among more recent contributions, the papers by Safarzyńska and van den Bergh (2016) and by Rengs et al. (2015)are worth mentioning. In the former study, the authors propose a formal behavioral-evolutionary macroeconomic model populated by heterogeneous consumers, producers, power plants and banks, interacting through interconnected networks, and examine how decisions by all these economic agents affect financial stability, the direction of technological change and energy use. In Rengs et al. (2015), the authors propose a macroeconomic multi-agent model with agents that change the behavior associated with carbon-intensive goods to test the effect of various policies on both environmental and economic performance. Furthermore, besides agent-based modeling, the use of other approaches encompassing out-of-equilibrium dynamics in economic systems to investigate the climate change and relative economic policies is worth mentioning. In this respect, Monasterolo and Raberto (2018) propose the EIRIN flow-fund behavioral model with heterogeneous agents as a tool to simulate green fiscal and targeted monetary policies, displaying their effects on firms' investments, unemployment, wages, credit market and economic growth. Jackson and Victor (2015) develop a system dynamics macro-economic model for describing financial assets and liabilities in a stock-flow consistent Framework (FALSTAFF) and use this model to explore the potential for stationary state outcomes in an economy with balanced trade, credit creation by banks, and private equity. Then, this model has been enriched developing a socio-economic sustainability transition in order to analyze the economic, ecological and financial aspects (Jackson et al., 2015).

In this paper, we address the question on how to foster the rebuilding of the energy system with the aim of reaching a low carbon economy, and whether rebuilding the energy system has the potential to trigger a sustainability transition towards an economically and ecologically sustainable growth path. In this respect, abstracting from the obvious improvements in GHG emissions, we aim to assess the trade-off between the fiscal economic costs of financing a transition to a renewable and fossil-fuels free energy system and the benefits of reducing substantially fossil fuels imports, in particular in the long term. Our goal is to devise the better policy combination that improves the long-term benefits with respect to the short-term costs for the macroeconomy as a whole. Finally, it is worth remarking that the current study ignores the biophysical impact of the sustainability transition on the environment, but focuses only on its financial and economic implications. In order to investigate the macroeconomic effects of the sustainability transition in the energy sector, we employ and enrich the agent-based macroeconomic model and simulator Eurace as it will be outlined in the following section (Cincotti et al., 2010, 2012a,b; Raberto et al., 2012, 2014; Teglio et al., 2012, 2015).

Computational results show that the feed-in tariff mechanism is clearly able to foster accumulation of renewable energy production capacity and then to increase the share of renewable energy production. The impact of the financing costs on the economy, through the higher tax burden, is limited to the highest values of the feed-in tariffs and characterized by reduced consumption levels at the expense of a higher share of the investment sector on GDP, due to the increasing weight of green investments on the economy. The impact on the unemployment rate is generally positive, in particular if compared with the case where no feed-in tariff policy is adopted.

The paper is organized as follows: Section 2 describes the main enrichments made to the Eurace model in order to address the issue of the sustainability transition in the energy sector, Section 3 shows the results of the computational experiments and, finally, Section 4 provides our concluding remarks.

2. Modeling the Sustainability Transition in Eurace

2.1. Overview of the Eurace Model

The model presented in this paper is an enrichment of the macroeconomic agent-based simulator Eurace (Cincotti et al., 2010, 2012a,b; Raberto et al., 2012, 2014; Teglio et al., 2012, 2015). The baseline Eurace originally included the following agents: households (HHs), acting as workers, consumers and financial investors; consumption goods producers (CGPs), which are firms producing a homogenous consumption good; a capital goods producer (KGP), commercial banks (Bs) and two policy makers, namely a government (G) and a central bank (CB), in charge of fiscal and monetary policy, respectively. To address the issue of the sustainability transition in the energy sector, the following agents have been included in the model: a fossil-fuels based electricity company, which imports fossil fuels and produces electricity with decreasing returns to scale, a renewable-source based (e.g. solar or wind power) electricity producer, which invests in renewable technology subject to government sustainability policy, and a fossil-fuels exporting foreign economy. The new agents interact on a monthly basis with the original agents through the (newly introduced) electricity market.

Fig. 1 shows a graphical representation of the present Eurace model in terms of agent classes (ellipses or rectangles) and current account monetary flows (arrows). Rectangles are used when just one instance of the class is considered in the model, whereas ellipses are intended to represent the presence of multiple heterogeneous instances of the agent class. The yellow background refers to newly introduced agents. The arrows represent the current account flows reported in the upper part of the transaction flow matrix, i.e. Table A3 in Appendix A.

Eurace agents interact through different decentralized markets for consumption and capital goods, labor, housing and credit, where disperse prices are set by suppliers and based on costs. Two centralized Walrasian market exist: a financial market for firms/banks' stocks and government bonds and the newly introduced electricity market.

Agents' behavior is myopic and characterized by bounded rationality, backward-looking adaptive expectations, and limited capabilities of computation and information gathering. In particular, agents' behavior follows adaptive rules derived from the management literature about firms and banks, and from experimental economics literature about the behavior of consumers and financial investors. For instance, CGPs (i) make short-term production plans based on past sales and present inventory stocks, along the lines of the inventory management literature (Hillier and Lieberman, 1986) ; (ii) follow mark-up pricing on unit costs, see e.g. Plott and Sunder (1982), Fabiani et al. (2006), where costs are given by wages, debt interests and electricity; (iii) plan investments according to net present value calculations, i.e. discounting expected future revenues at their weighted average cost of capital; (iv) follow the pecking order theory (Myers and Majluf, 1984) for financing decisions.

Households make their consumption/saving decisions with the aim to accumulate a target stock of liquid wealth, determined as a multiple of their income, to be used as a buffer in cases of income downfalls, according to the theory of buffer-stock saving (Carroll, 2001; Deaton, 1992). Savings can be allocated in stocks (i.e. the claims on firms/banks equity and future dividends) and government bonds. Households also buy and sell housing units in an appropriate market, which opens on a monthly basis, and finance entirely[1] house purchases by means of mortgages granted by banks.

Banks provide short-term loans to firms and long-term mortgages to households at interest rates determined by the cost of central bank loans, i.e. the central bank policy rate, plus a markup. According to the *modus operandi* of the banking system in a modern capitalist economy, see e.g. McLeay et al. (2014), banks lending in the Eurace model is not limited by the available liquidity and, whenever a bank grants a loan or a mortgage, a corresponding deposit, entitled to the borrower, is created on the liability side of the bank' balance sheet. If a bank becomes short of liquidity, it canget a loan from the central bank which provide liquidity to the banking system in infinite supply. In line with the post-Keynesian literature, see e.g. Fontana (2003); Godley and Lavoie (2012), we then follow the endogenous moneymodeling approach, where loans create deposits, not the other way around. Bank lending is however limited by a Basel II-like capital requirement rule; in this respect, each bank assesses the credit risk by considering the financial leverage of the prospective borrower before deciding about a credit request.

A detailed description of agents' behavior and interactions in the different markets for the original baseline Eurace model is provided in Teglio et al. (2015) . Details about the Eurace housing market are provided in Ozel et al. (2016).

Finally, a distinctive feature of the Eurace modeling approach is that every agent is modeled through a double-entry balance sheet that includes the details of all assets and liabilities. The dynamical change

[1] This feature has been assumed in order to separate household consumption/saving decisions from housing purchasing decisions. See Ozel et al. (2016) for further details.

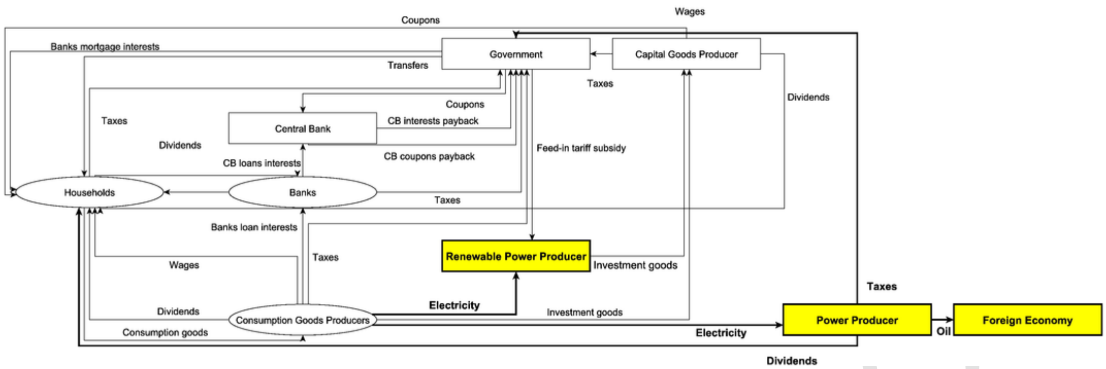

Fig. 1. Graphical representation of the present Eurace model in terms of agent classes (ellipses or rectangles) and current account monetary flows (arrows). Rectangles are used when just one instance of the class is considered in the model, whereas ellipses are intended to represent the presence of multiple heterogeneous instances of the agent class. The yellow background refers to newly introduced agents.

of balance sheet variables depends on agents' plan and on the result of agents' interaction within the different market settings. A complete and compact structural description of all Eurace agents and sectors is provided in Appendix A by Tables A1, A2, A3 and A4, where we have highlighted the stock-flow consistency of the model, according to the methodology described by Godley and Lavoie (2012) and along the lines of post-Keynesian economics, see Caverzasi and Godin (2015) . The tables highlight a set of relevant identities that need to be taken into account to check for the consistency between stocks and flows in the simulated data.

2.2. New Features: The Energy Sector

In order to investigate how to foster the sustainability transition in the energy sector, a feed-in-tariff system is considered. A feed-in tariff mechanism is a policy mechanism designed to accelerate investment in renewable energy technologies (Couture and Gagnon, 2010). The feed-in-tariff system usually has three components:

- A fixed price for a fixed amount of years (long-term contract),
- Grid priority to electricity produced by renewable energy (meaning renewable energy will be bought first),
- Financing costs covered by a mix of a reallocation charge τ_E, paid only by electricity consumers, and general taxation.

The feed-in tariff mechanism is modeled in Eurace in a similar way. In particular, we postulate that the renewable energy producer is entitled to sell electricity at a feed-in tariff p_E^r, assumed constant and guaranteed forever by the government. The value p_E^r is set exogenously and is the parameter characterizing our experiments. The difference between the feed-in-tariff price p_E^r and the market electricity price p_E, paid by electricity consumers, is paid by the government by using its general tax revenues[2].

Two types of electricity producers, i.e. a fossil-fuel based one, henceforth PP, and a renewable-source based one, henceforth RP, have been included, along with a fossil-fuels exporting foreign country, henceforth foreign economy (FE). In particular, the renewable electricity producer uses renewable technology, say solar panels or wind turbines, to produce electricity that will be sold to electricity consumers (firms), whereas the non-renewable electricity producer employs fossil fuel imported from the foreign economy to produce the residual demanded quantity, as we assume that renewable energy has priority in the market.

Both PP and PP are characterized by a balance sheet, described in Table A1, in the same way of the other agents. In particular, both PP and RP are characterized by liquidity M in the assets side and by equity E in the liabilities side. Moreover, the RP is also characterized by a capital endowment, say the number of solar panels (or wind turbines) installed, n_{sp}, in the assets side and by debt D in the liabilities side. As the solar panels (or wind turbines) are identified as capital goods in the model, they are produced domestically by the capital goods producer that employs labor force as production factor.

2.2.1. Electricity Demand

Electricity is demanded by consumption goods producers (CGPs) on a monthly basis. Firms need electricity, as it is a non-substitutable production factor, in addition to labor and capital, that any firm f employs to produce the monthly amount of output q_{C_f}. To this purpose, we consider now a production function characterized by a nested Cobb-Douglas and Leontief technology where the usual Cobb-Douglas production function, characterized by labor N and capital K inputs (see Eq. 8 of Teglio et al., 2015), is coupled with a third non-substitutable input, i.e. the amount of electricity q_{E_f}, as follows:

$$q_{C_f} = \min\left(\gamma N_f^{\alpha} K_f^{\beta}, \eta_E q_{E_f}\right) \ , \tag{1}$$

where η_E is the electricity efficiency parameter (supposed uniform across firms), which gives the amount of output per unit of electricity.

We assume that electricity is immediately delivered to CGPs by one of the two electricity producers and that firms are never rationed in their demand for electricity. Electricity demand (and consumption) q_{E_f} is then given for any firm f by its output q_{C_f} as follows:

$$q_{E_f} = \frac{q_{C_f}}{\eta_E} \ . \tag{2}$$

Aggregate demand (and consumption) of electricity is then given by $\Sigma_f q_{E_f}$.

2.2.2. Renewable Power Producer (RP)

Renewable energy comprises a heterogeneous class of technologies, among which bioenergy, solar energy, hydro-power, geothermal energy, ocean energy and wind energy. We focus in this paper on the technologies for electricity production, remarking that by the end of

[2] In order to investigate the system behavior at high feed-in tariffs (relative to the electricity market price) and then huge financing costs, our experiments have been designed with τ_E set to zero, then considering feed-in tariff costs always fully financed by general taxation, to better distribute the burden on a broader fiscal base and then avoid too high electricity surcharges.

2015 renewable capacity in place was enough to supply an estimated 23.7% of global electricity[3].

The Renewable Producer (RP) described in this section employs physical capital units (say solar panels, wind turbines, hydropower turbines, geothermal power stations) in order to produce electricity from a renewable source. The RP designed in the model is quite generic and could represent a wide range of technologies; however, for the sake of conciseness, we use solar energy as the preferential narrative for the paper. In this perspective, RP employs solar panels, built and sold by the capital goods producer (KGP). The level of production of renewable electricity depends on the number of solar panels installed, n_{sp}, as follows:

$$q_{E_{RP}} = q_{E_{sp}} n_{sp}, \tag{3}$$

where $q_{E_{sp}}$ is the amount of electricity supplied on a monthly basis by any single solar panel. The number of installed solar panels is the cumulative result of monthly investment decision, Δn_{sp}, made by the renewable producer RP. The investment decision is based on a Net Present Value (NPV) calculation, which assesses if the (discounted) expected future cash flows given by the additional electricity sales are larger than the initial investment cost in the solar panel infrastructure, i.e.,

$$NPV(\Delta n_{sp}) = -p_{sp}\Delta n_{sp} + \sum_{m=1}^{\infty} \frac{p_E^r q_{E,sp} \Delta n_{sp}}{(1 + r/12)^m} \tag{4}$$

where p_{sp} is the price of a single solar panel, r is the yearly average cost of capital for the RP and m represents the index of months. Assuming no particular risk for the renewable electricity production, the yearly average cost of capital r is equal to the interest rate set by the central bank. Furthermore, assuming the feed-in tariff p_E^r constant over time, considering that $q_{E,sp}\Delta n_{sp}$ is constant as well (we assume that solar panels are not subject to wear), and using the well-known properties of geometric series, Eq. (4) can be written as:

$$NPV(\Delta n_{sp}) = -p_{sp}\Delta n_{sp} + \frac{p_E^r q_{E_{sp}} \Delta n_{sp}}{r/12} \ . \tag{5}$$

It is worth noting that at the current state of technology, the average life span of a photovoltaic panel is guaranteed by producers to be in the range from 20 to 30 years, see e.g. Bastidas-Rodríguez et al. (2015) and the fact sheets provided by large producers. Therefore, the assumption of no degradation for newly acquired solar panels is consistent with the time span of our simulations, set to 20 years.

Eq. (4) points out that, given the costs of solar panels, the discounted expected revenues from selling the electricity at the feed-in-tariff price p_E^r determine if the NPV is positive or negative, and therefore if an investment to acquire additional solar panels should be made. If NPV is positive, the investment is undertaken and new solar panels are purchased from the capital goods producer. It is worth noting that, as the NPV increases linearly and monotonically with Δn_{sp}, the size of investments should be as large as possible depending on the financing possibilities. To consider the most conservative case regarding the accumulation of renewable production capacity, we postulate that the size of investment Δn_{sp} is limited by the liquidity M_{RP} available to the renewable power producer, i.e. $\Delta n_{sp} = M_{RP}/p_{sp}$, where p_{sp} is the monthly unit price of solar panels. Therefore, we assume that RP is not allowed to take debt to finance investments, which are instead financed by internal financial resources only, i.e. by retained earnings.

Investment in new solar panels and production of electricity occur sequentially, during the same day at the beginning of each month. New solar panels are immediately delivered to the RP agent by the KGP and employed for the production of electricity.

Table A1 presents the balance sheet of the RP agent. All balance-sheet entries are updated on a monthly basis. In particular, physical capital is given by the number n_{sp} of solar panels installed, which takes into account new acquisitions Δn_{sp}; liquidity M_{RP} changes according to RP' cash flows[4], i.e., investment cost $p_{sp}\Delta n_{sp}$ and electricity sales $p_E^r q_{E_{sp}} n_{sp}$ as follows:

$$\Delta M_{RP} = -p_{sp}\Delta n_{sp} + p_E^r q_{E_{sp}} n_{sp} \ ; \tag{6}$$

where revenues $p_E^r q_{E_{sp}} n_{sp}$ shall be considered equal to profits, as no operating costs are assumed for the renewable power producer, but just capital costs. Finally, equity E_{RP} (net worth) is calculated according to the usual accounting rule:

$$E_{RP} = M_{RP} + n_{sp} p_{sp} \ . \tag{7}$$

We assume that the RP equity capital is divided equally among households; however, the agent does not pay out dividends and retains all its profits in order to increase the liquidity available for investments.

2.2.3. Power Producer (PP)

The power producer (PP) agent produces electricity using a non-renewable energy source, say oil, according to a production function characterized by decreasing returns to scale, as follows:

$$q_{E_{PP}} = \gamma_E \, q_O^{\beta_E} \quad \text{with} \quad \beta_E < 1, \tag{8}$$

where q_O is the oil input amount and γ_E and β_E are positive parameters. In particular, β_E is the electricity production elasticity, while γ_E is simply a production scale factor. Table 1reports the values assigned to these parameters in our simulations.

We characterize the non-renewable electricity producer with decreasing returns to scale to replicate the realistic setting of an aggregate electricity supply curve which is the result of aggregating the single supplies of different producers. In particular, the aim is to mimic an electricity wholesale market where the market price is set at the marginal price, i.e. at the intersection of aggregate supply and demand curves (Borenstein, 2000, Somani and Tesfatsion, 2008). In the real market setting, market supply is aggregated over each single producer's supply, each characterized by different technologies/non-renewable sources and then different unit costs. In that setting, the aggregate supply curve is upward sloping in the usual quantity/price plan, with rising unit costs that emerge by construction.

On the other hand, renewable electricity production is characterized by negligible operational costs, compared to the non-renewable case, and by capital costs (e.g. photovoltaic panels and land in the case of solar energy) which can be considered as essentially linear with respect to the amount of electricity produced. These technological and market setting considerations justify the difference between themodeling of the non-renewable and the renewable electricity production sectors.

Clearly, this realistic difference is in principle an advantage for the renewable production technology, in particular for increasing electric-

[3] See for instance the "Renewables 2016 Global Status Report" by REN21, http://www.ren21.net/wp-content/uploads/2016/10/REN21_GSR2016_FullReport_en_11.pdf.

[4] It is worth noting that the RP agent does not bear direct electricity production costs for the very nature of green electricity production technology, whereas negative cash flows are given only by investment costs. Furthermore, the grid priority foreseen by the feed-in tariff policy implies that all the electricity produced by the renewable power producer is sold, because the renewable producer does not compete with the non-renewable one for the sale of energy in the market.

Table 1
Relevant parameters values used in the simulation.

Symbol	Parameter	Value
η_E	Electricity efficiency	1.0 u.c.g./GWh
p_E^r	Feed-in-tariff	[0.09–0.5] E€
$q_{E_{sp}}$	Quantity of electricity produced by a single solar panel	0.2 GWh
k_E	Electricity efficiency coefficient	1.0
β_E	Electricity production elasticity	0.9
γ_E	Electricity production scale factor	1.0
p_O	Oil price	0.0035 E€
μ_E	Markup	10%
τ_E	Reallocation charge	0.0
δ_E	Percentage increase in electricity demand estimation	10%

ity demand. However, it is worth noting that in the range of values of calibration of the model, non-renewable electricity production is usually more convenient, as showed by the very low renewable investments for the lowest feed-in tariff value or even no investments at all in the case of no policy adopted.

The PP buys oil abroad, i.e. from a representative agent of a foreign economy, say Foreign Economy (FE) agent. As we assume that the RP has priority in the power grid, the quantity of electricity $q_{E_{PP}}$ that the PP will sell during the month is set as a residual between the aggregate demand of electricity, $\Sigma_f q_{E_f}$, and the supply provided by the RP, $q_{E_{RP}}$, i.e.,

$$q_{E_{PP}} = \sum_f q_{E_f} - q_{E_{RP}} \ . \tag{9}$$

It is worth noting that the aggregate demand of electricity, $\Sigma_f q_{E_f}$, is unknown at the beginning of the month because electricity is demanded by firms at their activation day, i.e. the day of production planning and execution, which are different across firms, see Teglio et al. (2015) for further details. However, at the beginning of each month the PP agent has to set the electricity price p_E that will be valid for the rest of the month and will be taken into account by firms for their production planning cost assessment. To this purpose, as the price of electricity p_E is set by the PP according to a mark-up on unit costs, the power producer needs to estimate in advance its incoming month production/sales, say $q_{E_{PP}}$, and related unit costs $\hat{c}_E$. The estimate is based on the electricity sold in the previous month increased by percentage amount, say δ_E, to take into account a possible demand increase.

Given the estimate $q_{E_{PP}}$ and the production technology set by Eq. (8), the quantity of oil $\hat{q}_O$ that would be necessary to meet the production plan is given by

$$\hat{q}_O = \left(\frac{\hat{q}_{E_{PP}}}{\gamma_E} \right)^{(1/\beta_E)} \ . \tag{10}$$

Then, the PP, estimates the unit costs $\hat{c}_E$ that are equal to

$$\hat{c}_E = \frac{p_O \hat{q}_O}{\hat{q}_{E_{PP}}} = \frac{p_O \hat{q}_{E_{PP}}^{(1/\beta_E - 1)}}{\gamma_E^{1/\beta_E}}, \tag{11}$$

where p_O is the oil price set by the foreign economy. Accordingly, the PP sets the electricity price p_E as:

$$p_E = (1 + \tau_E)(1 + \mu_E)\hat{c}_E \tag{12}$$

where μ_E is a fixed markup and τ_E is the reallocation charge[5], whose value depends on the policy adopted. It is worth noting that the unit cost, and therefore the price, increases with the estimated electricity production/sales $q_{E_{PP}}$ because $1/\beta_E - 1 > 0$.

The revenues of the PP are evaluated at the end of each month by summing up the effective quantity of electricity sold during the month, i.e. $q_{E_{PP}}$ set by Eq. 11, at the market price p_E. Costs are given by the effective amount of oil imported q_O paid at price p_O, where

$$q_O = \left(\frac{q_{E_{PP}}}{\gamma_E} \right)^{(1/\beta_E)} \ . \tag{13}$$

Profits are then given by $q_{E_{PP}} p_E - q_O p_O$ and, if positive, are paid out to shareholders as dividends.

Table A1 presents the balance sheet of the PP. Liquidity M_{PP} is updated monthly following PP profits. Equity E_{PP} is also updated once a month at the beginning of the month according to the usual accounting rule and then set equal to liquidity M_{PP}, as no debt liability is foreseen for the PP agent in our model.

2.2.4. Feed-in Tariff Policy Costs

Since the renewable power producer is remunerated by the feed-in tariff value p_E^r for each unit of renewable energy sold, whereas firms pay the market price p_E, where $p_E < p_E^r$, the difference is financed by the government through general taxation. The monthly feed-in tariff policy costs can then be quantified by the difference between the two prices, times the monthly amount of electricity $q_{E_{RP}}$ sold by the renewable electricity producer, i.e. $(p_E^r - p_E) q_{E_{RP}}$.

2.2.5. Foreign Economy

The Foreign Economy (FE) is a stylized agent that works as provider of the oil that the PP needs in order to produce electricity. The FE sets the oil price and receives the oil export payments which are accumulated as liquidity. The FE balance sheet is simply characterized by a liquidity entry on the asset side and the corresponding net worth (Equity) on the liabilities side.

2.2.6. Calibration

Ranges of recent costs of energy for commercially available RE technologies are wide, and depend on several factors, including technology characteristics, regional variations in cost and performance, and differing discount rates. Some RE technologies are already competitive with existing market energy prices, while many of the other RE technologies can provide competitive energy services in certain circumstances, for example, in regions with favorable resource conditions. In most regions of the world, policy measures are still required to ensure rapid deployment of many RE sources[6]. In order to fine-tune costs and performance of the energy variables in the model, we referred to the Italian industrial sector, as explained in the next paragraphs.

We consider the Italian economy as reference for calibration because it represents an advanced economy that is highly dependent on imports for its energy needs. This choice is consistent with the design of the energy sector in Eurace, where the non-renewable energy production depends on fossil fuels imported from the foreign sector. We

[5] The reallocation charge is a surcharge on the electricity price aimed to finance the feed-in tariff scheme together with general taxation, as pointed out in Section 2.2. It is worth noting, however, that in this paper we investigate the case where the feed-in tariff policy is financed only by general taxation, therefore the reallocation charge is set to zero, as specified in Table 1 where the values of the energy sector parameters are reported.

[6] See the 2012 "Special Report on Renewable Energy Sources and Climate Change Mitigation", published for the Intergovernmental Panel on Climate Change (IPCC) for more details on this subject (https://www.ipcc.ch/pdf/special-reports/srren/SRREN_FD_SPM_final.pdf).

address a foreign dependent energy sector not just because it is a common and realisticfeature of most advanced economies but in particular because it allows to take into account the long-term economic benefits of decreasing fossil fuels imports due to domestic investments in renewable energy.

The monthly electricity $q_{E,sp}$ supplied by a single solar panel as well as its unit cost p_{sp} have been calibrated to values consistent with the size of the other Eurace economic variables, considering real solar panel costs and performance. The average cost (including installation) of a solar panel of power 1 kW has been reported[7] to be around 5000 €, whereas, at the present state of the art of technology, its average monthly performance could be approximated to be 100 kWh.

In order to put the above numbers in the context of Eurace, we devised a sort of equivalence between the Euro (€) and the currency unit used in Eurace, let's call it the Eurace Euro (E€). For this purpose, considering that in Italy there are around 30 million of families (households) with a net monthly labor income at around 1500 € per family, and that the computational experiments have been performed with 3000 households with an initial money wage set to be 1.5 E€, the equivalence between the euro and the Eurace euro has been obtained by equating the aggregate labor income of households in Italy and Eurace, that is

$$3\ 10^3 * 1.5E€ = 3\ 10^7 * 1500€ \quad , \tag{14}$$

that gives

$$1E€ = 10^7€ \ . \tag{15}$$

In our model design, solar panels are identified with the capital goods units, whose initial unit cost is set to be 1 E€; therefore, we need to characterize the Eurace solar panel with a monthly performance consistent with its high initial cost, i.e. 10 million Euro, as stated by Eq. (15). As a real solar panel, characterized by 1 kW of power and a monthly performance of 100 kW, is valued at around 5000 €, we assume that the Eurace solar panel is equivalent to 2000 real solar panel and, accordingly, is characterized by a power 2 MW and a monthly performance $q_{sp} = 200$ MWh, i.e. 0.2 GWh. Moreover, it is worth noting that, as we identify solar panels with regular capital goods, the equivalence between the price of an Eurace solar panel unit (p_{sp}) and the price of capital goods p_K, will hold for the entire duration of the simulation.

Furthermore, we have set electricity demand and market prices similar to the one observed in a reference country, say Italy. According to Terna[8], the monthly electricity consumption of the Italian industrial sector is around 10,000 GWh; therefore, considering that, with the parameters used for the production sector, see Teglio et al. (2015) , the monthly aggregate production capacity of 50 CGPs in Eurace is around 10,000 units of consumption goods (u.c.g.), then according to Eq. (2), the electricity efficiency η_E of each CGP has been set to 1.0 u.c.g./GWh.

According to GME[9], the order of magnitude of the electricity market price is tens of €/MWh, i.e. centimes of E€/GWh; therefore, according to Eqs. (7)–(11), we have set the electricity production function parameters, γ_E and β_E, as well as the price of oil, here assumed constant and equal to 0.0035 E€, to values consistent with the monthly electricity production of 10,000 GWh at a unit cost around 0.01 E€/GWh.

Finally, it is worth noting that with the calibration here described, the oil bill of the economy is set to be of the order of 1% of GDP, see Fig. 9c, then consistent with the ratio observed in the reference country considered[10].

3. Computational Results

The methodology of the study is based on Monte Carlo computational experiments, consistingof running simulations with different seeds of the pseudorandom number generator for each scenario. Six feed-in tariff electricity price scenarios along with a no policy scenario, and 50 seeds per scenario, for a total of 350 simulations have been considered. Simulations have been performed *ceteris paribus*, meaning that all the parameters are identical across the different policy scenarios, with the exception of the feed-in tariff, i.e. p_E^r, whose value characterizes the policy rule of a specific scenario. In particular, the feed-in tariff price is taken as an exogenous parameter that assumes six values, i.e. 0.09, 0.1, 0.2, 0.3, 0.4 and 0.5 E€. The value 0.09 has been verified to be close to the threshold under which, given the NPV investment rule and the order of magnitude of the parameters and the variables of the system, there are only negligible investments in new solar panels. On the contrary, in the no policy scenario, the renewable power producer has still grid priority but no subsidized feed-in tariff p_E^r is foreseen, therefore, the RP agent is able to sell electricity only at the endogenous market price p_E.

Table 1 summarizes the parameter values related to the newly introduced energy sector. The parameter values of the original Eurace model can be retrieved in Teglio et al. (2015), whereas in Ozel et al. (2016) one can find the housing market parameters. Simulations cover a fictitious time span of twenty years. The Figures from (2) to (8) present a series of boxplots showing, for the no policy case and for every value of the feed-in tariff considered, the distribution of 28 relevant economic variables over the 50 seeds used to initialize the pseudo-random number generator. In particular, boxplots show the distribution of the time averages over the entire 20 years long time span, related to any of the 50 seeds (simulations). Boxes include all the values from the 25th to the 75th percentile, the red horizontal segments and the blue diamond markers represent the median and the mean of the distribution, respectively. Boxplots also include whiskers extending to the most extreme data points not considered outliers, whereas outliers, if any, are plotted individually. The value of the mean of the distribution, along with the standard error (in round bracket), are reported in the Appendix in Table C1, whereas Table C2 reports for any of the 28 economic variables the average over the 50 seeds of the coefficient of variation. It is worth noting that for each seed, the coefficient of variation is computed as the ratio between the standard deviation and the mean, both over time. Tables 2 and 3 present the two-sided Wilcoxon rank-sum test with the aim to test the null hypothesis that data samples referred to two different feed-in tariffs are drawn from continuous distributions with equal medians, against the alternative that they are not, see e.g. Gibbons and Chakraborti (2011). In particular, in Table 2, the no policy sample is tested against the samples related to each feed-in tariff value considered, whereas Table 3 tests samples referred to two consecutive feed-in tariffs. Both tables report the p-value of the test; therefore, values lower than 0.05 (0.01) signal that the null hypothesis is rejected at the 5% (1%) significance level. Finally, Table 4 reports the results of the test for the unemployment rate variable for all the possible combinations of the no policy case and the feed-in tariff values.

Fig. 2 shows that the feed-in tariff policy adopted is very effective to spur investments in renewable energy production capacity. This result is clearly evident when one observes how the distribution of the number of installed solar panels and, correspondingly, of renewable en-

[7] http://www.ecoage.it/mappa-solare-italia.htm.

[8] http://www.terna.it/default/Home/SISTEMA_ELETTRICO/statistiche/consumi_settore_merceologico.aspx.

[9] https://www.mercatoelettrico.org/it/.

[10] "Foreign trade and import prices", April 2016, ISTAT

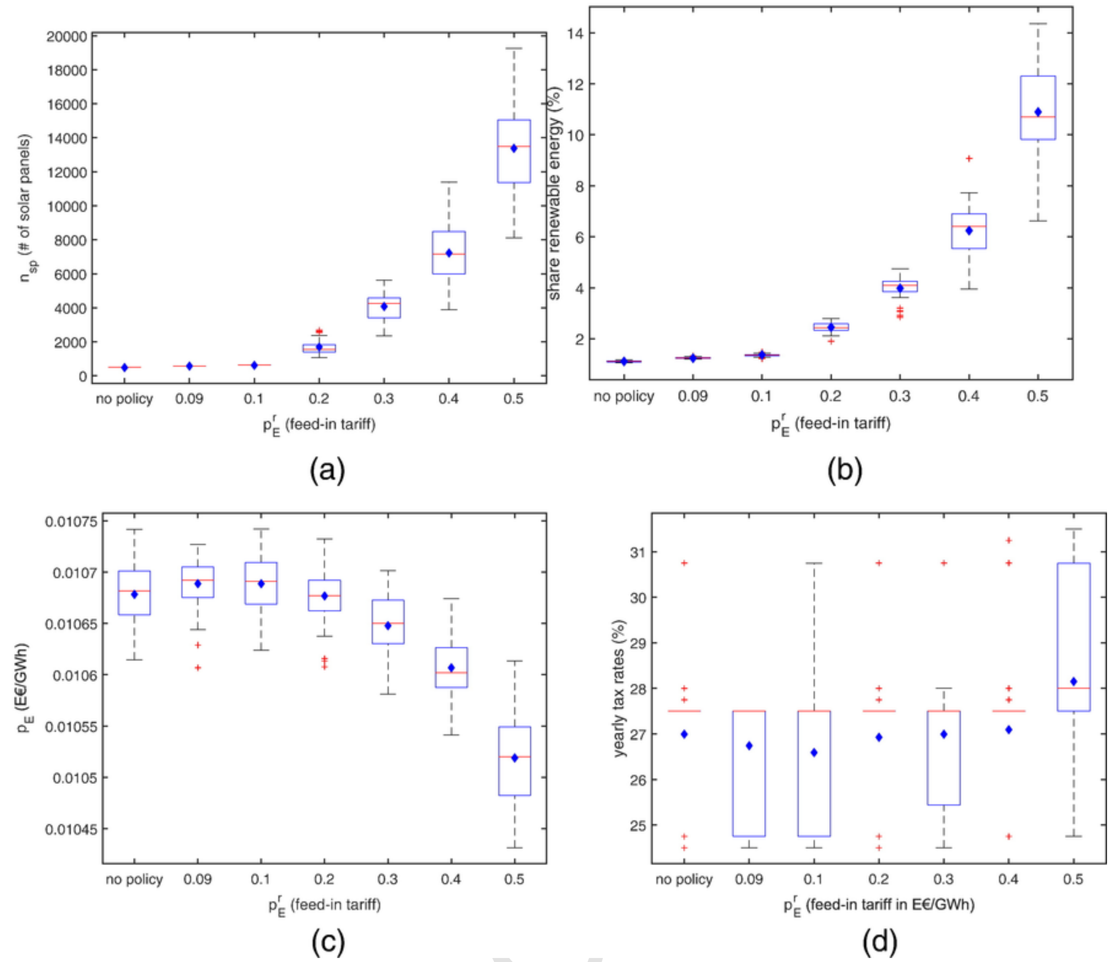

Fig. 2. The Figure presents a series of boxplots showing, for any value of the feed-in tariff, p^r_E, considered and the no policy case, the distribution of the number of solar panels installed, n_{sp} (a), the share of renewable energy (b), the monthly electricity market price, p_E (c) and the general tax rate (d) over the 50 seeds of the simulation. The values in the range represented by the boxplots refer to time averages over 20 years for each one of the 50 seeds.

ergy production capacity (as a percentage of total production) change with respect to the feed-in price value and the no policy case. In particular, we can observe how both the median value (red line) and the mean (blue diamond) of the distribution clearly increase with the feed-in tariff, whereas the relative position of the box edges, which delimitate the 25th and 75th percentiles, indicates a clear difference between the outcomes related to two consecutive feed-in tariff values considered. Both Tables 2 and 3 show that the null hypothesis of samples derived from the same population is rejected at the 1% significance level. Furthermore, in the no policy case, we do not observe any new investments in solar panels and the level of units installed remains at its initial level, i.e. 500, see Table C1.

Panel (c) of Fig. 2 shows how the policy affects the distribution of electricity market prices, whose values decrease for high values of the feed-in tariff p^r_E. This happens because higher feed-in tariffs lead to more renewable capacity and consequently less electricity produced by means of fossil fuels, which in turn implies lower unit costs/market prices for electricity due to the decreasing returns to scale of power production based on fossil fuels. Statistical tests, see Tables 2 and 3, confirm that the difference is statistically significant. Finally, panel d of Fig. 2 reports the distribution of average tax rates. It is worth remembering that the government budget finances the difference between the revenues of the RP agent, which are based on the feed-in tariff p^r_E, and the amount paid by electricity consumers, which is evaluated at the market price p_E, where $p_E < p^r_E$. Therefore, it is important to investigate how fiscal policy (tax rates), which is stick to the usual 3% deficit targeting rule, is affected by the additional feed-in tariff financing costs. Panel d and statistical tables show that there is a significant impact on average tax rates only at the highest considered values of p^r_E, whereas for lower values of the feed-in tariff the impact is limited, in particular if we consider the median value which increases only for the maximum value assumed by p^r_E.

Furthermore, in Fig. 2 (d) we can observe a particular shape of the boxplot distribution, where for most feed-in tariffs the median (the red line) corresponds to the upper edge of the box and, consistently, the mean (the blue point) is significantly lower. Therefore, the evidence of this Figure points out that about half of points are grouped around the median, whereas there is a significant number of "outliers" of much lower value that displaces the mean with respect to the median. To this regard, it is worth remembering that the frequency of tax rate update by the government is yearly, i.e. lower than the usual monthly frequency of other variables; moreover, the tax rate change is most often sluggish as no change at all occurs with respect to the previous year level if the government yearly deficit stays within the (0, -3%) bounds, see Teglio et al. (2015) for further details. Therefore, we argue that the lower update frequency of the tax rate along with its sluggishnessexplains the characteristic data distribution observed in the figure; in particular, what happens is that if the tax rate is lowered during a simulation, then the simulation time span is not sufficient to allow it to return to its say long-term mean value due to its low update frequency and sluggish change dynamics. However, it is worth noting that the number of seeds used to compute our statistics is sufficient to allow us

Table 2
p-Values of the two-sided Wilcoxon rank sum test, under the null hypothesis that the two samples are selected from Populations having the same distribution. The test has been performed between the no policy sample data and the data referred to each feed-in tariff considered. Values lower than 0.05 (0.01) signal that the null hypothesis is rejected at the 5% (1%) significance level.

	p_E^r					
Variables	0.09	0.1	0.2	0.3	0.4	0.5
n_{sp}	0.000	0.000	0.000	0.000	0.000	0.000
Share renewable energy (%)	0.000	0.000	0.000	0.000	0.000	0.000
p_E(E€/GWh)	0.055	0.058	0.789	0.000	0.000	0.000
Yearly tax rates (%)	0.234	0.130	0.823	0.810	0.636	0.000
Employment rate CGP (%)	0.070	0.001	0.011	0.185	0.315	0.000
Employment rate KGP (%)	0.052	0.718	0.438	0.007	0.000	0.000
Unemploymnet rate (%)	0.000	0.000	0.000	0.000	0.000	0.000
Nominal wage (E€)	0.003	0.025	0.150	0.005	0.000	0.000
p_C (E€)	0.004	0.071	0.221	0.004	0.000	0.000
p_K(E€)	0.001	0.008	0.036	0.000	0.000	0.000
$\Delta p_C/p_C$ (%)	0.002	0.015	0.143	0.003	0.000	0.000
$\Delta p_K/p_K$ (%)	0.000	0.004	0.023	0.000	0.000	0.000
Yearly real consumption	0.012	0.006	0.002	0.162	0.392	0.000
Yearly real investments	0.023	0.602	0.284	0.004	0.000	0.000
Real consumption growth rate (%)	0.000	0.000	0.000	0.004	0.363	0.001
Real investments growth rate (%)	0.792	0.857	0.608	0.004	0.000	0.000
K_F	0.028	1.000	0.973	0.915	0.836	0.136
$\Delta K_F/K_F$ (%)	0.022	0.319	0.644	0.763	0.303	0.708
D_F (E€)	0.000	0.000	0.000	0.000	0.000	0.000
$\Delta D_F/D_F$ (%)	0.000	0.000	0.000	0.000	0.000	0.000
CB policy rate (%)	0.014	0.003	0.055	0.000	0.000	0.000
Government bond yield (%)	0.293	0.414	0.668	0.190	0.000	0.000
Government debt/GDP (%)	0.003	0.139	0.061	0.287	0.872	0.931
Government budget/GDP (%)	0.000	0.002	0.000	0.001	0.015	0.056
Feed-in tariff policy cost/GDP (%)	0.000	0.000	0.000	0.000	0.000	0.000
Feed-in tariff policy cost/Tax (%)	0.000	0.000	0.000	0.000	0.000	0.000
Oil import costs/GDP (%)	0.005	0.111	0.024	0.000	0.000	0.000
Electricity cost CGPs/GDP (%)	0.006	0.158	0.218	0.002	0.000	0.000

to neglect these statistical fluctuations since the statistical tests, see Tables 2 and 3, point out that the tax rate is not statistically different over the different feed-in tariffs except for the highest value of the incentivized electricity price p_E^r.

Figures from (3) to (6) aim to assess the impact of the feed-in tariff policy on the real economy and in particular on the labor, consumption goods and capital goods markets. For this purpose, we employ again the boxplot representation to show how the distribution over 50 seeds of the time averages of relevant economic variables changes with respect to the feed-in tariff. In particular, we consider the employment rates, real consumption and investment levels, and prices. Fig. 3 shows that high feed-in tariffs have a clear impact on the employment rate in the capital goods production sector (panel b), as also confirmed by the statistical tables. In particular, we observe that a larger demand for solar panels, due to higher p_E^r, determines higher employment rates at the solar panel supplier, i.e., the capital goods producer (KGP). *The upward slope that we can observe in*Fig. 3 (b) *for*$p_E^r \geq 0.3$*E€ is statistically relevant with respect to both the no policy case*[11]*and with respect to the scenarios characterized by lower values of the feed-in tariff*[12] This is not a surprising outcome, indeed, but it is worth to point out that the production of more solar panels creates a sort of crowding out effect on thelabor market as it can be observed that, while the employment rate at the KGP agent increases, the employments rate at the CGPs decreases (panel a). *The downwards slope of the CGPs employment rate is statistically relevant only for the two highest value of*p_E^r*, i.e. 0.4 E€ and 0.5 E€, see*Table 3. *This evidence suggests a moderately positive net effect on the total employment rate. This is in fact the graphical evidence we can observe in panel c of*Fig. 3*, where the total unemployment rate is displayed. In particular, a graphical inspection points out a much higher unemployment rate in the no policy case, i.e. in the absence of green investments, and a decreasing trend of the unemployment mean and median for increasing values of the feed-in tariff. It is worth noting that this difference in the distribution of the unemployment rate is statistically significant at the 1% significance level, both when we compare the no policy case with all the feed-in tariff scenarios, see*Table 2*, and when we compare the cases with the highest*p_E^r*values, i.e., 0.4 and 0.5, with the cases with the lowest ones, i.e.*$p_E^r \leq 0.2$*E€, see*Table 4.

On the other hand, this sort of crowding out effect of solar panel production has a fairly negligible negative impact on the capital accumulation of firms, whose capital endowment levels and growth rates look pretty stable across the values of p_E^r, see Fig. 6,panels (a) and (b). Statistical tests confirm that the small differences between the boxplot distributions are not statistically significant, see Tables 2 and 3.

Lower unemployment for high feed-in tariffsleads to an increase of the nominal wage level (panel d) because of the higher pressure[13] on the labor market. Higher wages imply higher general unit production costs and then higher prices both for consumption and capital goods, as observed accordingly in Fig. 4. However, unit costs of CGPs depend also on capital goods prices as well as on interest rates, which increase at high p_E^r, see Fig. 7, then consumption goods prices increase more than nominal wages, as we can figure out by comparing Fig. 3 (d) with

11 As regards, the KGP employment rate distribution, Table 2 reports p-values lower than 1% for $p_E^r \geq 0.3$ E€

12 Table 3*shows p-values lower than 1% for the KGP employment rate when we compare the scenario*$p_E^r = 0.3$*E€ with the one*$p_E^r = 0.4$*E€, and the scenario*$p_E^r = 0.4$*E€ with the one*$p_E^r = 0.5$ E€.

13 If firms have difficulties in increasing the labor force, then they raise their wage offer. A detailed description of the labor market in Eurace is provided in Dawid et al. (2014).

Table 3
p-Values of the two-sided Wilcoxon rank sum test, under the null hypothesis that the two samples are selected from Populations having the same distribution. The test have been performed between samples referred to two consecutive feed-in tariffs, for each of the 28 economic variables examined. Values lower than 0.05 (0.01) signal that the null hypothesis is rejected at the 5% (1%) significance level.

	p_E^r				
Variables	0.09 vs 0.1	0.1 vs 0.2	0.2 vs 0.3	0.3 vs 0.4	0.4 vs 0.5
n_{sp}	0.000	0.000	0.000	0.000	0.000
Share renewable energy (%)	0.000	0.000	0.000	0.000	0.000
p_E(E€/GWh)	0.872	0.027	0.000	0.000	0.000
Yearly tax rates (%)	0.585	0.155	0.965	0.465	0.001
Employment rate CGP (%)	0.025	0.293	0.319	0.020	0.000
Employment rate KGP (%)	0.042	0.664	0.041	0.001	0.000
Unemploymnet rate (%)	0.181	0.226	0.072	0.074	0.236
Nominal wage (E€)	0.309	0.410	0.105	0.018	0.503
p_C (E€)	0.143	0.521	0.082	0.007	0.006
p_K(E€)	0.287	0.516	0.043	0.001	0.000
$\Delta p_C/p_C$ (%)	0.508	0.342	0.108	0.005	0.000
$\Delta p_K/p_K$ (%)	0.579	0.434	0.047	0.001	0.000
Yearly real consumption	0.654	0.738	0.119	0.032	0.000
Yearly real investments	0.018	0.521	0.051	0.001	0.000
Real consumption growth rate (%)	0.668	0.758	0.176	0.029	0.000
Real investments growth rate (%)	0.815	0.299	0.004	0.002	0.000
K_F	0.014	0.830	0.920	0.723	0.078
$\Delta K_F/K_F$ (%)	0.088	0.569	0.941	0.418	0.407
D_F (E€)	0.111	0.373	0.815	0.384	0.678
$\Delta D_F/D_F$ (%)	0.635	0.345	0.995	0.221	0.602
CB policy rate (%)	0.512	0.407	0.108	0.006	0.040
Government bond yield (%)	0.032	0.204	0.037	0.001	0.551
Government debt/GDP (%)	0.100	0.804	0.462	0.087	0.878
Government budget/GDP (%)	0.192	0.883	0.574	0.204	0.810
Feed-in tariff policy cost/GDP (%)	0.000	0.000	0.000	0.000	0.000
Feed-in tariff policy cost/Tax (%)	0.000	0.000	0.000	0.000	0.000
Oil import costs/GDP (%)	0.059	0.418	0.002	0.000	0.000
Electricity cost CGPs/GDP (%)	0.044	0.941	0.051	0.003	0.001

Table 4
p-Values of the two-sided Wilcoxon rank sum test, under the null hypothesis that the two samples are selected from Populations having the same distribution. The test has been performed for the unemployment rate variable for all the possible combinations of the no policy case and the feed-in tariff values. Values lower than 0.05 (0.01) signal that the null hypothesis is rejected at the 5% (1%) significance level.

	p_E^r						
p_E^r	No policy	0.09	0.1	0.2	0.3	0.4	0.5
No policy	1.000	0.000	0.000	0.000	0.000	0.000	0.000
0.09	0.000	1.000	0.181	0.931	0.077	0.000	0.000
0.1	0.000	0.181	1.000	0.226	0.442	0.004	0.000
0.2	0.000	0.931	0.226	1.000	0.072	0.000	0.000
0.3	0.000	0.077	0.442	0.072	1.000	0.074	0.002
0.4	0.000	0.000	0.004	0.000	0.074	1.000	0.236
0.5	0.000	0.000	0.000	0.000	0.002	0.236	1.000

Fig. 4 (a), with the result that real wages decrease when the feed-in tariff increases. Therefore, higher consumption goods prices, lower real wages as well as lower supply capacity by the CGPs (because of lower employment rates) explain lower consumption levels in the economy. Fig. 5 shows the substitution effect between investment and consumption both in terms of average yearly levels (panel a and b) and in terms of average yearly growth rates (panel c and d).

It is worth noting that all the above considerations about wages, prices, consumption and investment, can be based both on the graphical inspection of the boxplot figures and on the statistical tests reported in Tables 2 and 3. In particular, the difference in the distribution of theabove-mentioned variables between the no policy case and the feed-in tariff scenarios is usually statistically significant for $p_E^r \geq 0.3$ E€ with a few exceptions. The exceptions regard the consumption level and its growth rates whose distribution is significantly different (lower) with respect to the no policy case only for the highest feed-in tariff value. This is an interesting outcome because the distribution is also significantly different (but with a higher median) with respect to the no policy case also for relatively low p_E^r, i.e. 0.1 E€ and 0.2 E€, as it is also evident by looking at the bell shaped pattern we can observe in panel (a) and (c) of Fig. 5. This suggests the possibility to attain a maximum value for the consumption level/growth rate for a feed-in tariff value around 0.2 E€.

Fig. 7 shows how high feed-in tariffs impact interest rates and government finances. The central bank average interest rate increases at higher p_E^r due to the Taylor-rule response to higher consumption goods prices, shown in Fig. 4panels(a) and (c). In particular, the rise of the CB rate with respect to the no policy case is clearly statistically relevant (at the 1% significance level) for $p_E^r \geq 0.3$ E€, see Table 2, as also confirmed by Table 3 where the statistics is reported with respect to the consecutively lower values of the feed-in tariff.

Government finances are affected by the feed-in tariff in different ways. In particular, the government budget seems positively affected

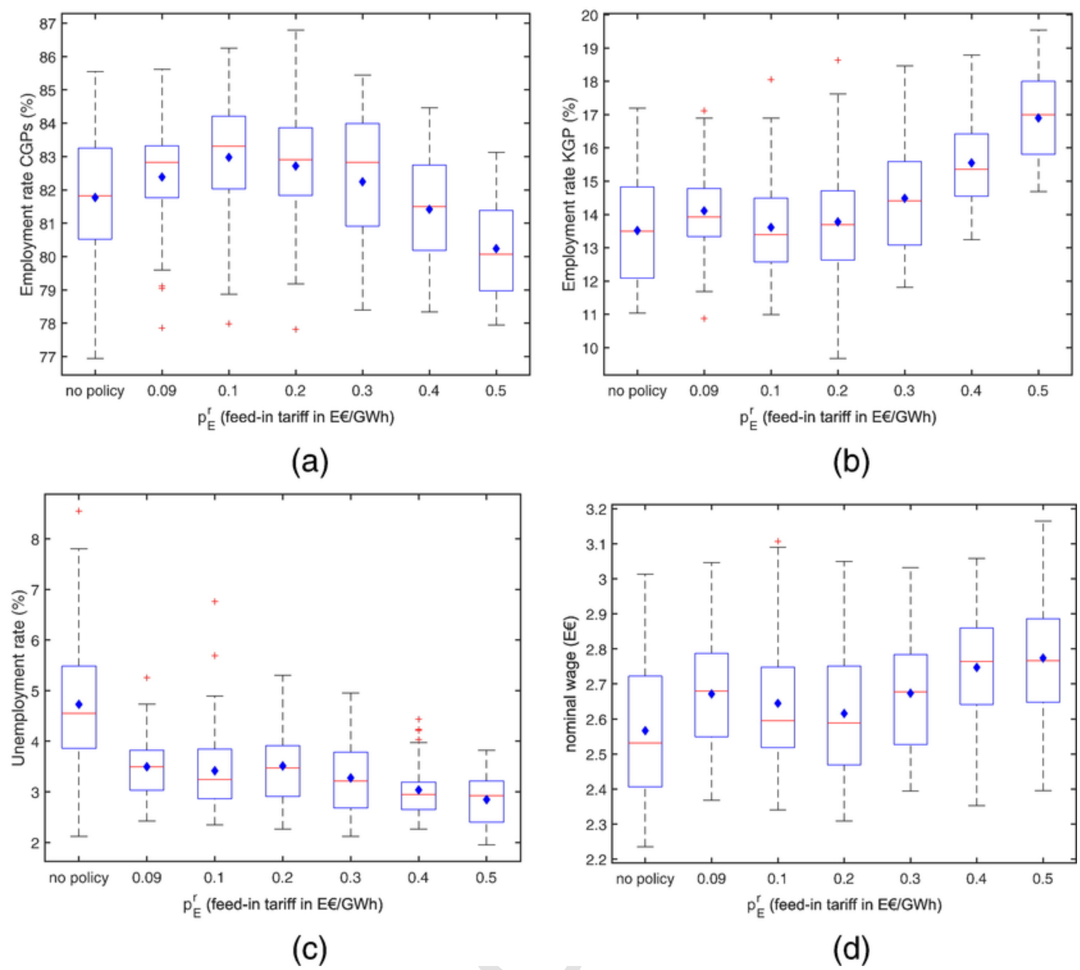

Fig. 3. The Figure presents a series of boxplots showing, for any value of the feed-in tariff p^r_E considered and the no policy case, the distribution of the employment rate in the consumption goods sector (a), the employment rate in the investment good sector (b), the unemployment rate (c) and the nominal wage level (d) over the 50 seeds of the simulation. The values in the range represented by the boxplots refer to time averages over 20 years for each one of the 50 seeds.

by the introduction of the policy, with low or moderate intensity. This statement is grounded on the graphical inspection of Fig. 7, panel (d), where both the means and the medians of the government budget to GDP ratio Monte Carlo distribution assume clearly higher values with respect to the no policy case whenever the feed-in tariff is equal or lower than 0.3 E€. Statistical tests confirm that this result is very significant (at the 1% significance level) for $p^r_E \leq 0.3$ E€, whereas less or no significance can be assessed at higher values of the feed-in tariff, see Table 2. Our interpretation of this result is that the lower government deficit can be explained by the previously discussed positive effects on the economy of the green policy. Better economic conditionsimply that, ceteris paribus, tax revenues rise more than what would be necessary to finance the feed-in tariff mechanism, given the Maastricht-like deficit target, at least up to the point where the policy intensity is so high that its financing costs become a burden for the economy.

If we consider the distribution of the debt-to-GDP ratio, see Fig. 7, panel (c), we can observe that the reduced government deficit at relatively low feed-in tariffs, is also reflected in lower values of the median of the debt-to-GDP ratioMonte Carlo distribution with respect to the no policy case. In particular, according to the statistical tests reported in Table 2, the difference is statistically significant for $p^r_E = 0.09$ E€. This latter result, combined with the bell shaped curve found for the consumption level, see Fig. 5, panel (a) suggests that the application of the green policy adopted can not only speed-up the transition to renewable energy and reduce GHG emissions but also improve both economic performance and the sustainability of government finances, in particular, for relatively low intensity of the policies.

The value of the feed-in tariff seems to have a more important and statistically significant impact on the government bond yields. We argue that the impact on bond yields for high values of the feed-in tariff, depends both on the larger amount of government debt to be financed and on the higher central bank interest rate for high p^r_E; the first factor implies a higher supply of government bonds in the market, whereas the second one implies that the government bond yields need to increase to make debt instruments preferable as much as liquidity.

Fig. 8 reports the boxplots related to the feed-in tariff policy costs with respect to both the nominal GDP (panel a) and the tax revenues (panel b) as well as the oil import costs (panel c) and the overall costs of electricity consumption (panel d), both with respect to nominal GDP. The feed-in tariff policy cost, relative to GDP, clearly increases exponentially with p^r_E in line with the benefits we observe inpanels (a) and (b) of Fig. 2; while the cost to GDP of oil import and electricity decrease at high feed-in tariffs consistently with the evidence observed in Fig. 2 concerning the decrease of the share of non-renewable electricity production (panel b) and of electricity market price (panel c). It is worth noting that, with the present calibration, the order of magnitude of oil import costs (panel c) is much lower than the financing costs of the feed-in tariff policy, being both costs reported with respect to nominal GDP; therefore, the economic benefits (lower imports) of the sustainability transition are lower than its financing costs.

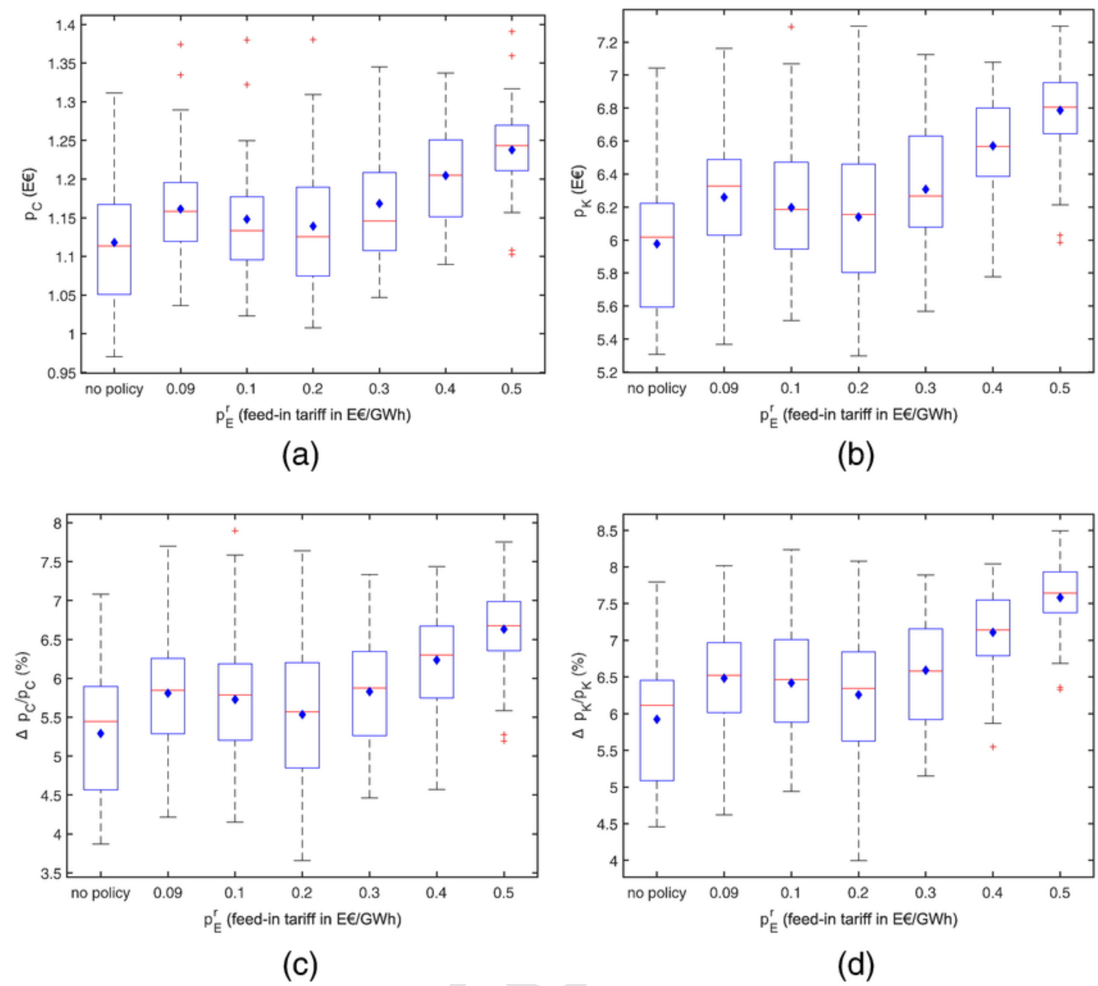

Fig. 4. The Figure presents a series of boxplots showing, for any value of the feed-in tariff p^r_E considered and the no policy case, the distribution of the consumption goods price level, p_C (a), the capital good price level, p_K (b), the yearly growth rate of the consumption goods price (c) and the yearly growth rate of the capital good price (d) over the 50 seeds of the simulation. The values in the range represented by the boxplots refer to time averages over 20 years for each one of the 50 seeds.

Figures from (9) to (11) present three trajectories over time of relevant variables. This different representation is aimed to provide an understanding of dynamics over time of the Eurace economy. All the three trajectories have been simulated by using the same seed and refer to three different scenarios according to the value of p^r_E, i.e. 0.09 (black-dotted line), 0.3 (blue-dashed line), and 0.5 (green continuous line). We can observe that the dynamics of the share of renewable energy production capacity, reported in panel (b) of Fig. 9, is characterized by both big jumps and a relatively steady growth. In particular, accordingly with the investment decision rule based on the NPV, see Eq. (4), jumps occur whenever interest rates, reported in panel (d) of Fig. 11, are very low or close to zero, see e.g. years 9 and 13 in the blue-dashed line scenario and years 9, 15, 19 in the green continuous-line one. Concerning economic variables, we observe an increasing difference between the three scenarios, in particular in the second half of the simulation time span, i.e. when the difference in the renewable production capacity becomes relevant. The black-dotted line scenario is affected by a severe endogenous crisis around year 11, see the unemployment rate (Fig. 10a) and consumption (Fig. 11d,b), that causes a huge reduction of investments. The crisis in the black-dotted line scenario is so severe that causes a drop even in the productive capital stock of firms, because of a very low investment rate combined with the bankruptcy of many firms that stay out of production for months. This crisis has also the effect of cooling down the dynamics of all relevant prices, i.e. nominal wage (Fig. 10b), consumption and capital goods prices (Fig. 11a and c). On the contrary, in the green continuous line scenario investments are generally maintained at higher rates, certainly also because of solar panel production, that helps to keep the economy in good shape avoiding a prolonged unemployment crisis fromyears 11 to 16, as in the black-dotted line scenario. The absence of this big crisis in the green continuous line scenario is the cause of steeper nominal wage dynamics in the second half of the simulation time span (Fig. 10b) and, being wages the most relevant costs for both capital and consumption goods producers, this in turn is the cause of a higher increase of capital and consumption goods prices in the green scenario (Fig. 11a and c)) in the second half of the simulation. Finally, Fig. 11 shows the long-run trade-off between the production of investment goods (panel b), partly characterized by solar panels, and the one of consumption goods (panel d), already observed in the previous box plots, see Fig. 5. Moreover, Fig. 10c, shows that investments in renewable production capacity occurs to some extent also at the expense of capital accumulation in the economy among consumption goods producers, as the capital endowment of firms in the green continuous line scenario is constantly lower than in the black-dotted line case and very similar to the blue-dashed line scenario.

4. Concluding Remarks

This study presented a set of computational experiments based on the Eurace agent-based macroeconomic model and simulator. The Eu-

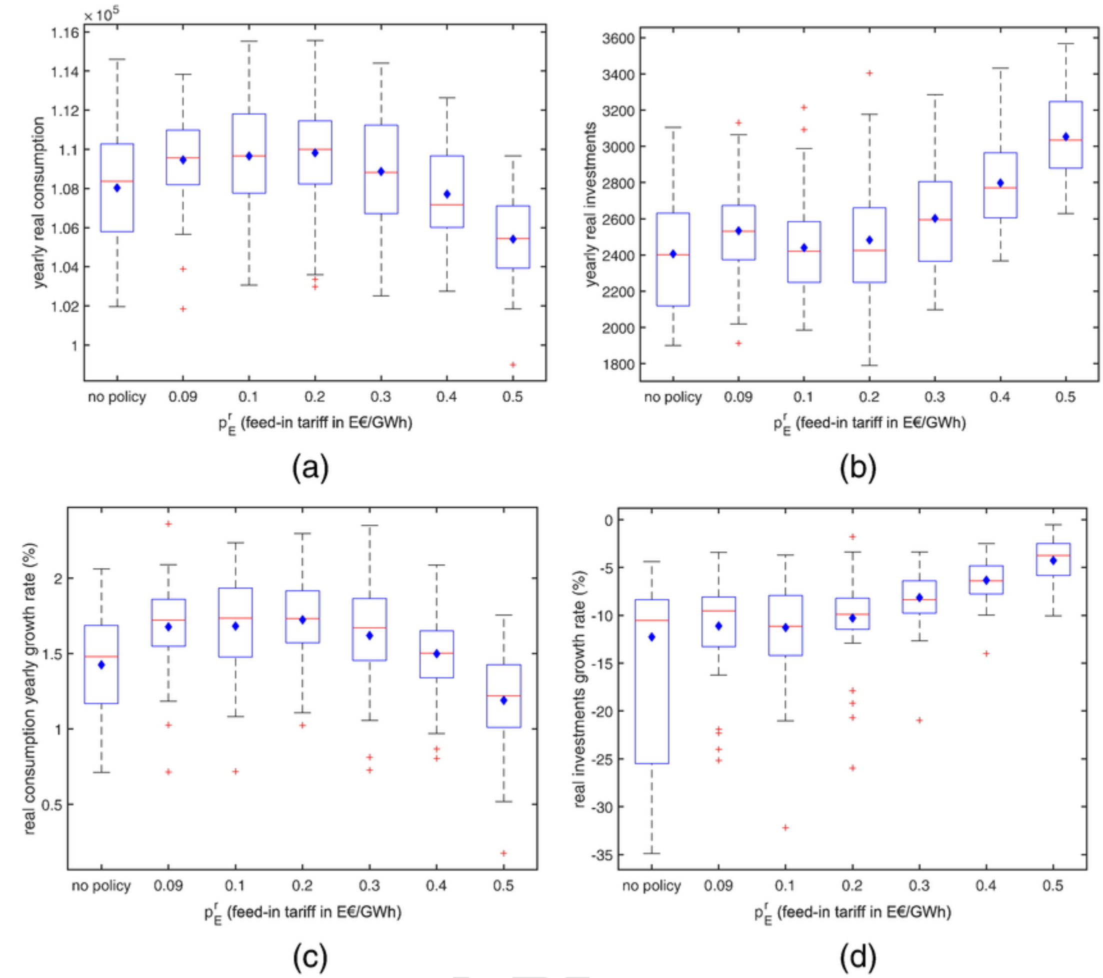

Fig. 5. The Figure presents a series of boxplots showing, for any value of the feed-in tariff p^r_E considered and the no policy case, the distribution of the real consumption level (a), the real investment level (b), the real consumption yearly growth rate (c) and the real investment yearly growth rate (d) over the 50 seeds of the simulation. The values in the range represented by the boxplots refer to time averages over 20 years for each one of the 50 seeds.

race model has been enriched with new features to allow the investigation of the transition towards a sustainable energy production paradigm. The work focuses on a policy proposal aimed to foster the transformation of the present economic system, where energy production is mainly based on fossil-fuels, to an alternative one based on renewable energy. In particular, we study the effectiveness and the impact on the economy of a feed-in tariff policy aimed at incentivizing the production of energy by means of a renewable source, e.g. solar energy. In this perspective, a new energy sector has been designed into the Eurace model, by including an electricity market, power producers (renewable and fossil-fuel based) and a more complete version of the capital goods producer, which employslabor force to produce both investment goods for firms and solar panels for the renewable power producer.

Computational results clearly show a significant impact of the feed-in-tariff mechanism, which successfully incentivizes the production of solar panels and increases the share of renewable energy consumed in the Eurace economy. *As for the impact on the economy, statistical tests generally show a significant difference between the no policy scenario and the scenarios with the policy, irrespective of its intensity, at least for relatively low value of the feed-in tariff. In particular, we can observe a general improvement of economic performance with respect to the no policy case, considering both employment and consumption/investment levels. Furthermore, the costs of financing the transition to renewable energy does not affect government finances, which actually improve for relatively low intensity of the feed-in tariff policy.* This is an important and positive result that depends on the higher tax revenues following improved economic conditions due to green investments. It is also worth noting that this outcome was not obvious a priori, also considering that the fiscal costs of the policy is much higher than the economic benefits of lower fossil fuel import costs for the economy, according to a realistic calibration based on the present fossil fuels import bill of an advanced economy. *On the other hand, for very high intensity of the policy, we observe an increasing weight of the investment sector in the economy, due to the needed production of solar units, which however is realized at the expense of the production of consumption goods. This important outcome implies a reduced purchasing power of consumption goods by households, and then lower living standards, if measured only according to the perspective of a consumerist society. The policy implications of our computational results are twofold: first, subsidizing green investments in renewable energy production capacity has a significant positive effect on the economy; second, there is an indication of a trade-off between incentivizing investments in renewable energy and assuring high living standards, measured in terms of consumption level, at relatively low intensity of the policy. This latter result deserves to be further investigated as a viable policy option in a democratic society, where it could be difficult for the electorate to accept very strong policy measures, in particular at the beginning of the transition, when the awareness about the need of climate change mitigation is still not fully shared and widespread.*

The crowding out of consumption by the investments sector is an important negative result that however deserves further scrutiny, in

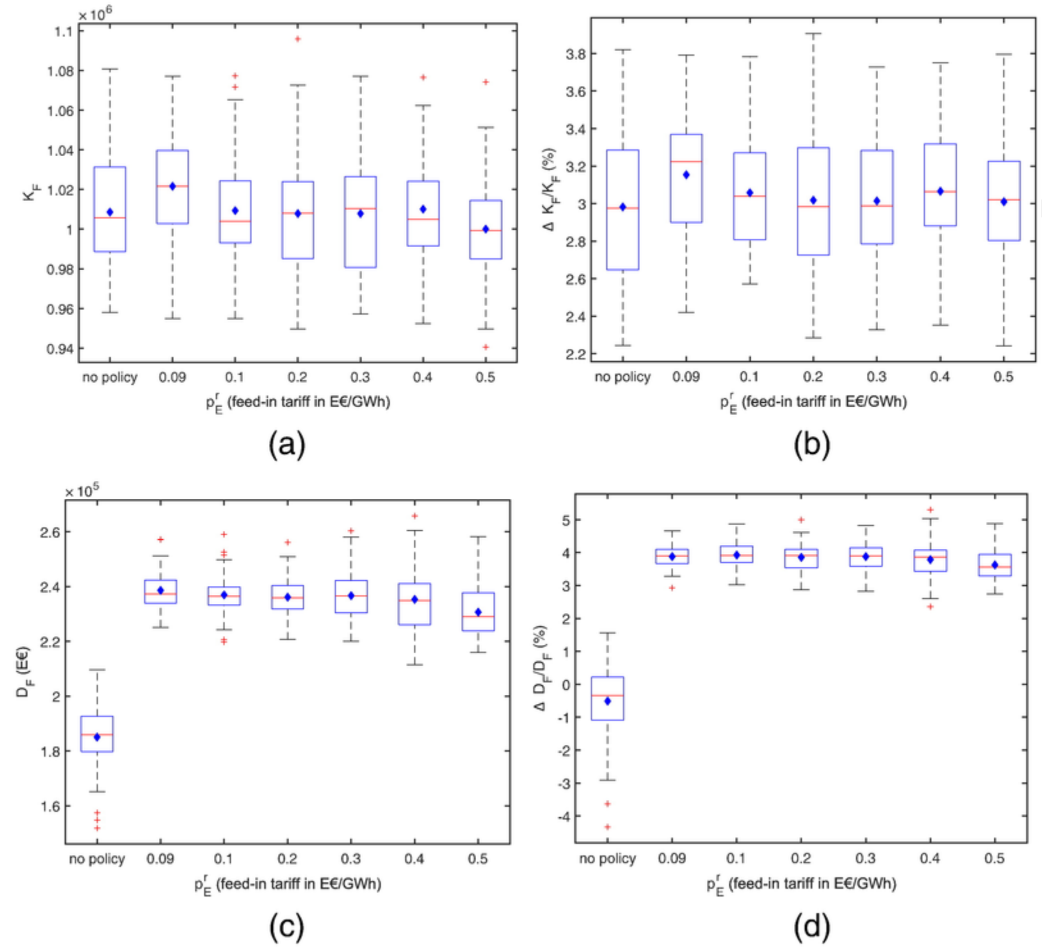

Fig. 6. The Figure presents a series of boxplots showing, for any value of the feed-in tariff p_E^r considered and the no policy case, the distribution of the firms' aggregate capital stock, K_F (a), the firms' aggregate capital stock yearly growth rate (b), the firms' aggregate debt, D_F (c) and the yearly growth rate of the firms' aggregate debt (d) over the 50 seeds of the simulation. The values in the range represented by the boxplots refer to time averages over 20 years for each one of the 50 seeds.

particular considering the relative small weight that that photovoltaic industry is expected to play in the economy. In this regard, it is worth to point out again that the solar panel sector in our model should be considered as a representative of the whole renewable energy production sector; moreover, investments in new solar panels shall be considered as representative of all green investments. As a matter of fact, our design of the renewable energy production technology, which is characterized by huge capital costs and negligible variable costs, is compatible with several renewable energy technologies for producing electricity, like solar, hydropower, wind, and geothermal, to cite some of them. The main point is that the RP agent employs physical capital units (solar panels, wind turbines, hydropower turbines, geothermal power stations) in order to produce electricity from a renewable source which is free. Under this perspective, the RP agent in the model is quite generic and could represent a wide range of technologies.

We also add that, according to the latest Frankfurt School-UNEP Centre/BNEF Report[14] on "Global Trends in Renewable Energy Investment" (2017), global investments in new renewable energy production capacity ranged from 200 from 300 billion US dollars in last few years. However, different studies have pointed out that the size of investment required each year in low carbon sectors to limit the temperature increase to the two degree target should be much higher, i.e. in a range from \$650 billions to \$1 trillion, see e.g. IEA (2012), WEF (2013). It is worth noting that 1 trillion is around 2% of the world final consumption expenditures, estimated at 55 trillion US dollars according to World Bank statistics[15]. On the other hand, from Fig. 5a we can observe that the largest size of crowding out, measured as the difference between the lowest (at $p_E^r = 0.2$ E€) and the highest ($p_E^r = 0.5$ E€) median consumption level is around 5%, which is a number consistent with the previous 2% number provided. The size of crowding out in the model shall then be considered as a realistic figure to fully address the COP21 target.

Furthermore, we would like to emphasize that the trade-off between consumption and investment is not a new result in the climate change adaption and mitigation research domain. In this respect, it worth mentioning that one of the central forecast by Randers (2012) famous book is a substantial increase in the fraction of GDP which will be required for investments to cope with climate change.

In any case, it is worth noting that if factors like better employment rates and the reduced GHG emissions are also taken into account, along with reduced consumption, by an appropriate preference function, the final outcome on well-being should be probably deemed asfavorable.

Future research will investigate and compare different policy options for the financing of the feed-in tariff mechanism, with particular

14 http://fs-unep-centre.org/publications/global-trends-renewable-energy-investment-2017.

15 http://data.worldbank.org/indicator/NE.CON.TOTL.KD?view=chart.

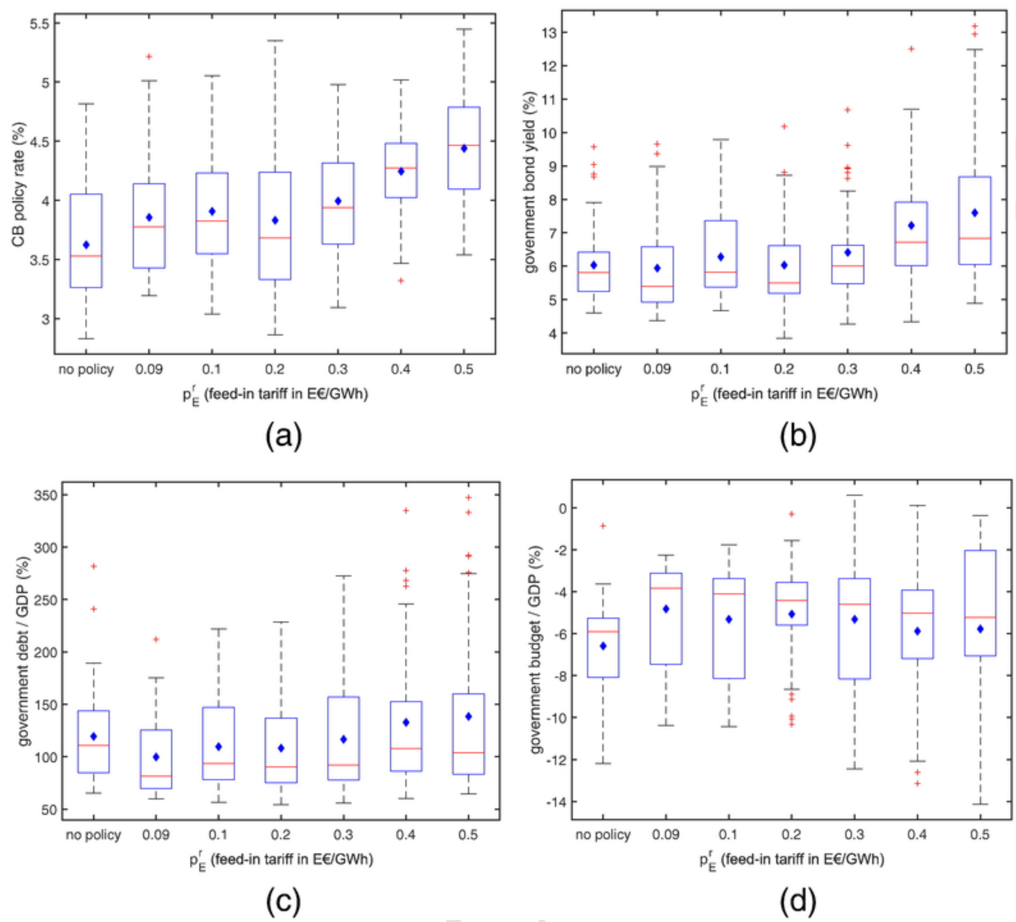

Fig. 7. The Figure presents a series of boxplots showing, for any value of the feed-in tariff p^r_E considered and the no policy case, the distribution of the CB policy rate (a), the government bond yield (b), both on a yearly basis, the government debt to GDP (c) and the government budget to GDP (d) over the 50 seeds of the simulation. The values in the range represented by the boxplots refer to time averages over 20 years for each one of the 50 seeds.

attention to the issuing of green bonds and the adoption of targeted unconventional monetary policies, such as the green quantitative easing.

Acknowledgment

The authors acknowledge EU-FP7 collaborative project SYMPHONY[16] under grant no. 611875. Moreover, the authors thank Franziska Schuetze from Global Climate Forum for the useful discussions.

Appendix A. Model Description

This appendix provides a compact model description that emphasizes the adopted stock-flow-consistentmodeling approach along the lines introduced by Godley and Lavoie (2012) and common also within post-Keynesian economics, see also Caverzasi and Godin (2015). The following tables outline the stocks (balance sheet entries) and flows (income statement entries) characterizing Eurace agents. A detailed description of agents' behavioural rules in the production and consumption sectors is reported in Teglio et al. (2015), whereas Ozel et al. (2016) describes the structural and behavioural features of the housing market. Finally, it is worth noting that the stock-flow-consistentmodeling approach provides a set of relevant theoretical identities at the agent, sector, and aggregate level, whose subsistence need to be numerically verified during the simulation, thus providing a very important diagnostic and validation tool for the model and its implementation.

In the following, four tables (matrices) are presented showing:

- The agent class balance sheet (Table A1), i.e., the asset and liability entries of each particular agent type;
- The sectorial balance sheet (Table A2), i.e., the assets and liabilities aggregated over a sector (all agents belonging to the same class), which sum to zero with their counterparts in other sectors;
- The cash flow matrix (Table A3), i.e. the monetary flows among sectors, both in the current and capital account;
- The revaluation matrix (Table A4), which provides the information about sectors' net worth (equity) changes between periods.

Table A1
Balance sheets of any agent class characterizing the Eurace economy. Balance sheet entries in the table have a subscript character, that is the index of an agent in the class to which the variable refers. In some cases, we can find two subscript characters, where the second one refers to the index of an agent in another class where there is the balance-sheet counterpart. For instance, D_f refers to the total debt of firm f, i.e. a liability, and $\mathscr{L}_b$ refers to the aggregate loans of bank b, i.e. an asset. $\ell_{f,b}$ (or $\ell_{b,f}$) refer to the loans granted by banks b to firms f. Of course, $\sum_b \mathscr{L}_b = \Sigma_f \ell_{b,f}$ represents an aggregate balance sheet identity, that is verified along the entire simulation. $n_{E_{h,x}}$ represent the number of outstanding equity shares of agents x held by households h. The market price of the equity shares is given by p_{E_x}. The stock portfolio's value of household h is then computed as: $\Sigma_x n_{E_{h,x}} p_{E_x}$. Government bonds' number and market price are given by n_G and p_G, respectively.

[16] www.projectsymphony.eu

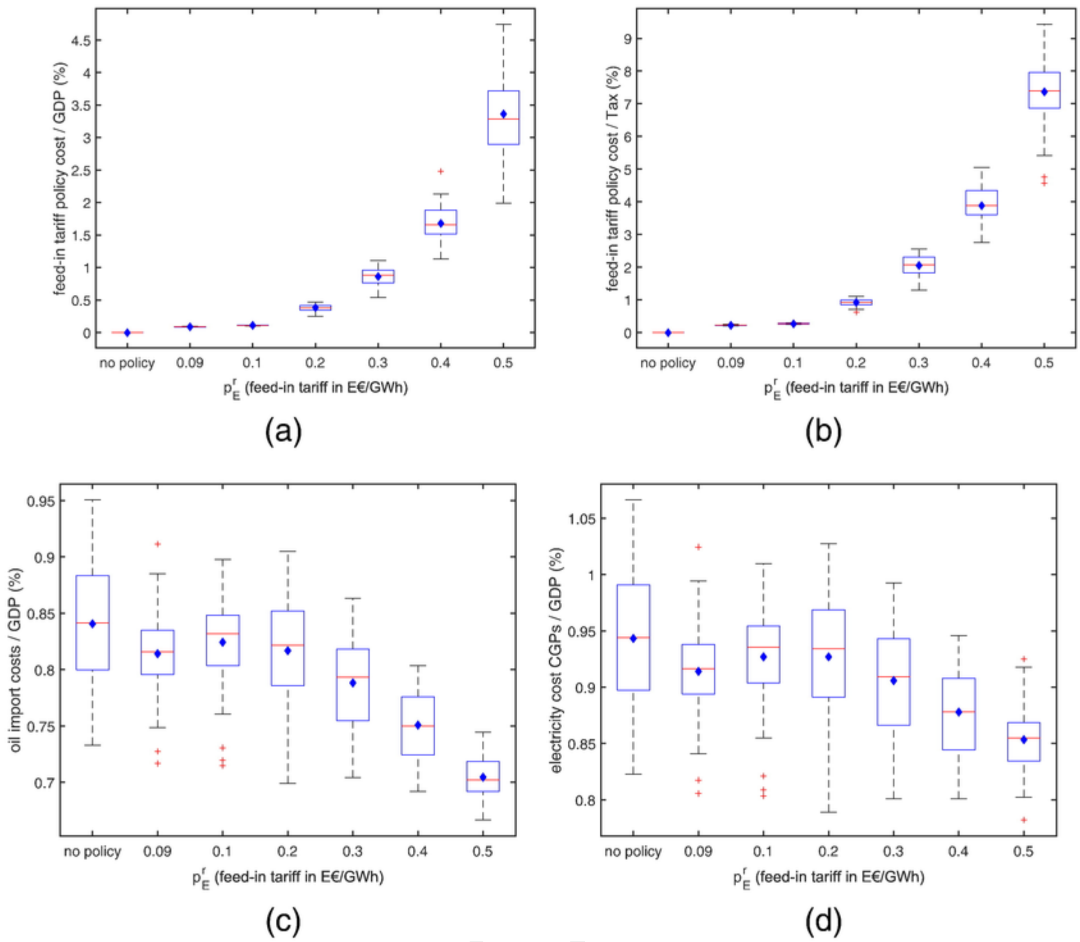

Fig. 8. The figure presents a series of boxplots showing, for any value of the feed-in tariff p^r_E considered and the no policy case, the distribution of the cost of the feed-in-tariff mechanism to GDP (a), to tax revenues (b), oil import costs to GDP (c) and electricity cost of firm to GDP (d) over the 50 seeds of the simulation.The values in the range represented by the boxplots refer to time averages over 20 years for each one of the 50 seeds.

Agent class	Assets	Liabilities
Household *abbrev.*: HH *index*: $h = 1,\ldots,N_{Hous}$	Liquidity: M_h Stock portfolio: $\Sigma_b n_{E_{h,b}} p_{E_b}+$ $\Sigma_f n_{E_{h,f}} p_{E_f}+$ $n_{E_{h,K}} p_{E_K}$ + $n_{E_{h,PP}} p_{E_{PP}}$ + $n_{E_{h,RP}} p_{E_{RP}}$ Gov Bonds: $n_{h,G} p_G$ Housing units: X_h	Mortgages: U_h Equity: E_h
Consumption Goods Producer *abbrev.*: CGP *index*: $f = 1,\ldots,N_{Firm}$	Liquidity: M_f Capital goods: K_f Inventories: I_f	Debt: $D_f = \Sigma_b \ell_{f,b}$ Equity: E_f
Capital Goods Producer *abbrev.*: KGP	Liquidity: M_K Inventories: I_K	Equity: E_K
Power Producer *abbrev.*: PP	Liquidity: M_{PP}	Equity: E_{PP}
Power Producer Renewable *abbrev.*: RP	Liquidity, M_{RP} Solar panels, n_{sp}	Equity, E_{RP}
Bank *abbrev.*: B *index*: $b = 1,\ldots,N_{Bank}$	Liquidity: M_b Loans: $\mathscr{L}_b = \sum_f \ell_{b,f}$ Mortgages: $U_b = \Sigma_h U_{b,h}$	Deposits: $\mathscr{D}_b = \sum_h M_{b,h} + \sum_f M_{b,f} + M_{b,K}$ CB standing facility: $D_b = \ell_{b,CB}$ Equity: E_b
Government *abbrev.*: G	Liquidity: M_G	Outstanding government bonds value: $D_G = n_G p_G$ Equity: E_G
Central Bank *abbrev.*: CB	Liquidity: M_{CB} Loans to banks: $\mathscr{L}_{CB} = \sum_b \ell_{CB,b}$ Gov Bonds: $n_{CB,G} p_G$	Outstanding fiat money: Fiat$_{CB}$ Deposits: $\mathscr{D}_{CB} = \sum_b M_b + M_G$ Equity: E_{CB}
Foreign Economy *abbrev.*: FE	Liquidity, M_{FE}	Equity, E_{FE}

It is worth noting that in the sectorial balance sheet (Table A2), columns report the aggregated balance sheet of each sector, whereas along the rows we can identify the relations among sectors by spotting

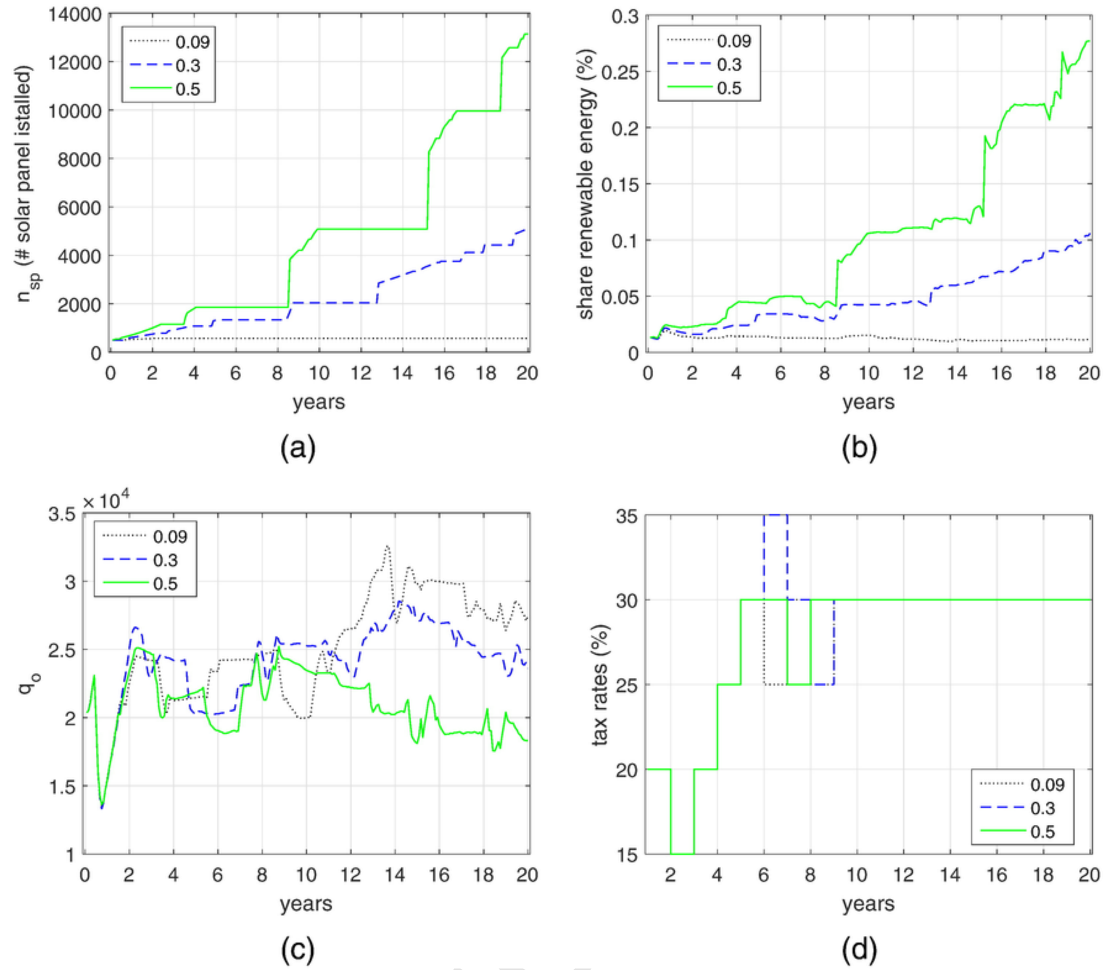

Fig. 9. The Figure shows the number of solar panels installed (a), the share of the renewable energy (b), the oil amount consumed monthly by the PP (c) and the tax rate (d) during the entire 20 years long simulation. The 3 different colors correspond to the 3 values of the guaranteed electricity price p_E^r. In particular the black, blue, green lines represent $p_E^r = 0.09, 0.3, 0.5$, respectively.

the liabilities (with minus sign) in one sector and the corresponding claims, i.e. assets (with plus sign), in another sector, thus generally summing up to zero. Exceptions are: the capital goods accumulated by firms and by the renewable power producer; inventories; housing units and equity shares[17] owned by households.

Table A2
Sectorial balance sheet matrix. Subscripts represent the index of the agent or of the sector (i.e. the set of all agents of the same class) to which the stock refers. Uppercase indexes are used when the stock refers to the whole sector, e.g. F refers to the sector of all CGPs and to the aggregate value of a particular stock in the sector, whereas lowercase subscripts are used when it refers to the single agent (for instance in the case of sums). Finally, superscript characters are introduced in the case of government bonds units n_G, i.e. n_G^H and n_G^{CB}, and $Loans_B$, i.e. $Loans_B^F$ and $Loans_B^{RP}$, because the balance sheet counterpart (in the asset side) is hold by two sectors, i.e. households and central bank in the case of government bonds units and consumption good producers and renewable power producer in the case of loans.

	Sectors			
	Non-Financial Private Agents (NFPAs)			
	HHs	CGPs	KGP	PP
Tangible Capital	$+X_H p_X$	$+K_F p_K$		
Inventories		$+I_F p_C$	$+I_K p_K$	
Debt(−) / Credit(+)	$-U_H$	$-D_F$		
Liquidity:				
NFPA	$+M_H$	$+M_F$	$+M_K$	$+M_{PP}$
Banks/Gov				
Central Bank				
Gov Bonds	$+n_G^H\, p_G$			
Equity Shares (+) / Net worth (−)	$+\Sigma_f n_{E_f} p_{E_f}$	$-E_F$		
	$+n_{E_k} p_{E_k}$		$-E_K$	
	$+n_{E_{PP}} p_{E_{PP}}$		$-E_{PP}$	
	$+n_{E_{RP}} p_{E_{RP}}$			

[17] We assume that equity shares in households' portfolio do not sum up to zero with the corresponding equity counterpart in the issuer balance sheet because of the usual difference between market price and book value.

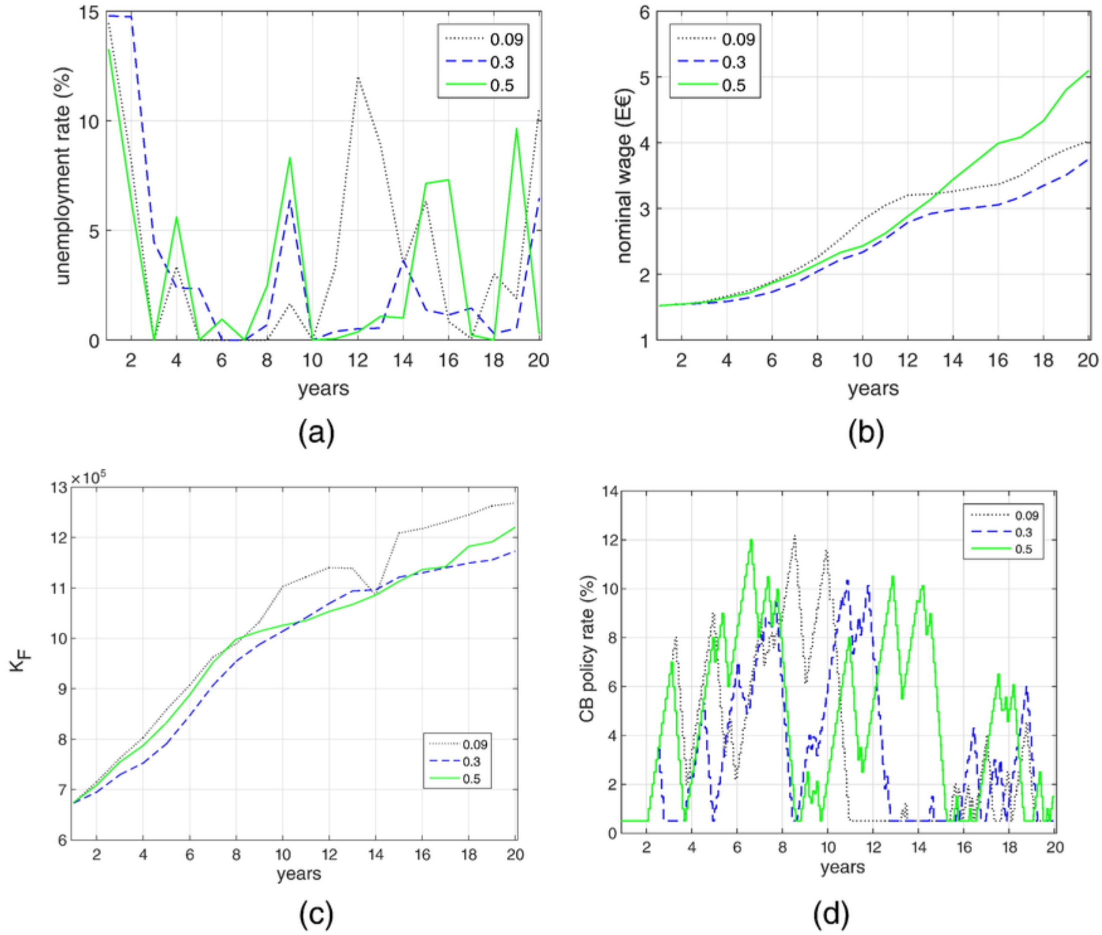

Fig. 10. The Figure shows the unemployment rate (%) (a), the average nominal wage level (b), the firms' aggregate capital stock (c) and the CB policy rate (%) (d) during the entire 20 years long simulation. The 3 different colours correspond to the 3 values of the guaranteed electricity price p_E^r. In particular the black, blue, green lines represent $p_E^r = 0.09, 0.3, 0.5$, respectively.

	$+\Sigma_b n_{E_b} p_{E_b}$			
	$-E_H$			
Σ	0	0	0	0

Furthermore, in the last column of the sectorial balance sheet (Table A2), the difference between central bank liquidity (an asset) and central bank fiat money (a liability) is named $M_{CB,0}$, to emphasize that this difference is equal to the initial central bank liquidity and then is constant over the simulation. Fiat money is the money created by the central bank to provide loans to commercial banks, when they are in liquidity shortage, or to buy government bonds in the secondary market, through quantitative easing operations. Households, that sell government bonds to the central bank, deposit the sale proceeds at their own banks, while the money lend to banks by the central bank is lent to households or firms, then in turn deposited again in the banking sector. Therefore, in both cases, the liquidity of the banking sector is increased by an amount equal to the new Fiat money created. Banks deposit their liquidity at the central bank, then increasing its liquidity by an amount always equal to the Fiat money originally created. It is worth noting however that the money supply in the economy can variate independently from the fiat money created by the central bank, because it endogenously raises every time a bank grants a new loan or mortgage and it decreases when the loan or mortgage is paid back.

Furthermore, the monetary flows among sectors are presented in the cash flow matrix (Table A3), where the current account reports aggregate revenues (plus sign) and payments (minus sign) among sectors, therefore summing to zero along the rows. The capital account reports the endogenous money creation/destruction operations by means of borrowing/debt repayment by private agents with banks as well as fiat money creation/destruction by the central bank by means of the standing facility with banks or government bonds purchase (quantitative easing). These operations, along with the current account net cash flows, determines the liquidity change of a sector.

Finally, the revaluation matrix (Table A4) provides the information about changes in sectors' net worth (equity) between periods. In particular, agents' net worth dynamics depends on net cash flows in the current account, physical capital depreciation and price changes in financial (stocks and bonds) and real (housing units, capital goods and inventories of consumption goods) assets.

Table A3
Sectorial transaction flow matrix of agents populating the EURACE economy. Note that HH stands fo Households, CGP stands for Consumption Goods Producer, KGP stands for Capital Goods Producer, PP stands for Power Producer, Gov stands for Government and CB stands for Central Bank.

		HHs	CGPs	K
Current Account	Consumption goods	–	+	
	Investment goods		–	
	Electricity		–	

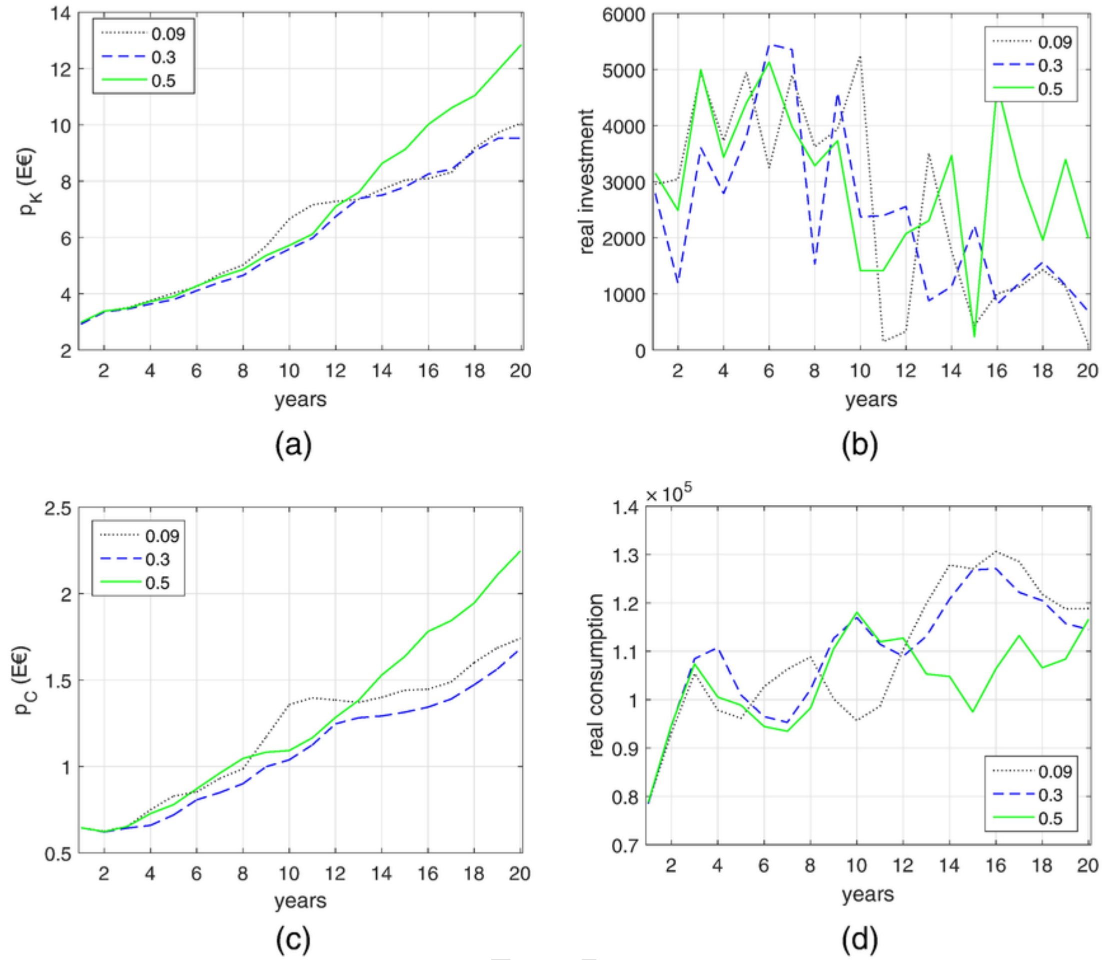

Fig. 11. The Figure shows the capital good price (a), the real investment (b), the consumption goods price (c) and the real consumption (d) during the entire 20 years long simulation. The 3 different colours correspond to the 3 values of the guaranteed electricity price p_E^r. In particular the black, blue, green lines represent $p_E^r = 0.09, 0.3, 0.5$, respectively.

	Oil			
	Wages	+	–	–
	Transfers	+		
	Taxes	–	–	–
	Dividends	+	–	–
	Coupons	+		
	CB coupons payback			
	Banks loan interests		–	
	Banks mortgage interests	–		
	CB loans interests			
	CB interests payback			
		=	=	=
	Net cash flow	Savings	Profits	Pı
Capital Account	Net cash flow	+ Savings	+ Profits	+
	Δ Loans		$+\Delta D_F$	

Δ Mortgages	$+U_H$		
Δ Issue of new shares / bonds	$--\Sigma_f p_{E_f}\Delta n_{E_f}$ $--p_G\Delta n_G$	$+\Sigma_f p_{E_f}\Delta n_{E_f}$	
Δ Quantitative easing	$+p_G\Delta n_G^{QE}$		
Δ Private Liquidity & Δ Banks' deposits	$-\Delta M_H$	$-\Delta M_F$	–ᵢ
Δ Banks/Public Liquidity & Δ Central bank deposits			
Δ CB Liquidity / Δ Fiat Money			
Σ	0	0	0

Table A4
Sectorial revaluation matrix. The matrix provides information about changes in sectors' net worth (equity) between periods. Net worth changes depend on net cash flows in the current account, physical capital depreciation (at rate ξ_K) and price changes in real and financial assets. It is worth noting that net worth of the issuers of financial assets (firms and the government) are not subject to asset price changes.

		HHs	CGPs	F
Equity$_{t-1}$		$E_{H,t-1}$	$E_{F,t-1}$	E
Net cash flow		+Savings	+Profits	-
Revaluations/Devaluations				
	Housing units	$+\Sigma_h X_h \Delta p_X$		
	Capital		$+\Sigma_f K_f \Delta p_K$ $-\Sigma_f \xi_K K_f p_K$	
	Inventories		$+\Sigma_f I_f \Delta p_c$	-
	Equity shares	$+\Sigma_f n_{E_f} \Delta p_{E_f}$ $+\Sigma_b n_{E_b} \Delta p_{E_b}$ $+n_{E_K} \Delta p_{E_K}$ $+n_{E_{PP}} \Delta p_{E_{PP}}$ $+n_{E_{RP}} \Delta p_{E_{RP}}$		
	Bonds	$+n_G^H \Delta p_G$		
		=	=	=
Equity		$E_{H,t}$	$E_{F,t}$	E

Appendix B. Stylized Facts and Robustness Check

This appendix is composed of three sections. In section Appendix B.1 we present some basic stylized facts that are matched by the model. Then we test the robustness of our analysis with respect to some key parameters. In particular, in section Appendix B.2 we show how oil price variations impact some of the key variables in the model. In section Appendix B.3 we show how monetary policy can affect the results obtained in the previous sections.

B.1. Stylized Facts

We present in this section a brief analysis of some main stylized facts that can be found for instance in Uribe and Schmitt-Grohe (2017) and Napoletano et al. (2006).

Making reference to Table C2, showing the coefficient of variation of the main economic indicators of the model, we remark here that the volatility of investments is higher than volatility of consumption, as expected.

Moreover, Table B1 presents the correlation structure of the real GDP. We observe that GDP is positively correlated with investments and consumption, while it is anti-correlated with the unemployment rate. GDP also shows a positive correlation with mortgages to households and loans to firms, which lead the business cycle expansion. Also monetary indicators, such as firms liquidity, are correlated to GDP and tend to lead the business cycle expansion. Prices are countercyclical. This results are in line with stylized facts on the credit cycle (see for instance Cappiello et al., 2010).

Finally, panel (a) of Fig. B1 shows the relationship generated by the model between unemployment rate and GDP yearly variations (Okun law), whereas panel (b) shows the relationship between yearly unemployment and inflation rates (Phillips curve). Both curves are in line with the empirical evidence (see Ball et al., 2013; Fitzgerald et al., 2013 for more details).

Table B1
Cross-correlation with real GDP of the main financial variables in the case $p_E^r = 0.01$. Standard errors of Monte Carlo simulations in parentheses. The significative values out of the confidence bounds are indicated by an *.)

Filtered series	t-4	t-3	t-2
Real GDP	0.0617	0.2825*	0.5226*
	(0.0065)	(0.0064)	(0.0058)
Real consumption	0.0779	0.2373*	0.4239*
	(0.0075)	(0.0071)	(0.0064)
Real investment	0.0093	0.2066*	0.4009*
	(0.0088)	(0.0103)	(0.0107)
Firms liquidity	−0.2889*	−0.2267*	−0.1538*
	(0.0108)	(0.0110)	(0.0111)
Mortgages	−0.1399*	−0.1151	−0.0685
	(0.0122)	(0.0127)	(0.0129)
Loans	−0.5333*	−0.4792*	−0.3606*
	(0.0112)	(0.0111)	(0.0110)
Unemployment	0.0830	−0.0004	−0.0974
	(0.0097)	(0.0101)	(0.0099)
Price level p_C	−0.0769	−0.0684	−0.0789
	(0.0132)	(0.0131)	(0.0143)

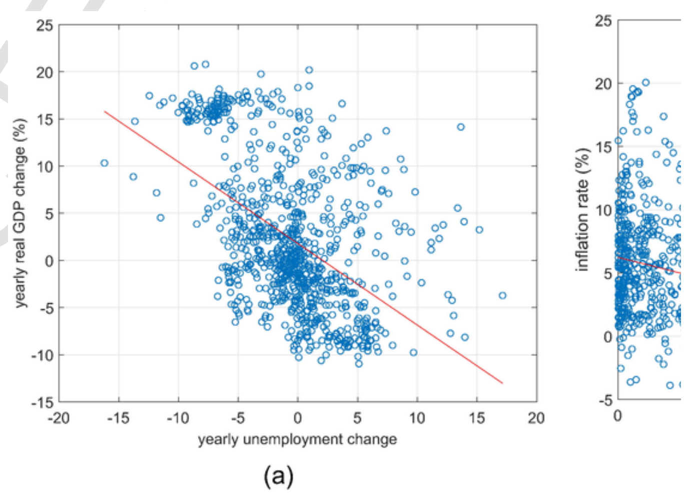

Fig. B1. The Figure presents the Okun law (a) and the Phillips curve (b). Fit: -0.86 (a), Fit:-0.38 (b).

B.2. The Oil Price

Fig. B2 shows the impact of the oil price on electricity prices, consumption, investments and unemployment rate. We study two additional cases with respect to the original one, where oil price is $p_0 = 0.0035$. The first case corresponds to an increase of 40% in the oil price ($p_0 = 0.0049$), whereas the second one corresponds to a decrease in the price of 40% ($p_0 = 0.0021$).

Looking at Fig. B2, we can make some remark. First, the electricity is obviously more expensive in the case of an higher oil price. Second, the trends of the main variables of the model are similar for the different values of the oil price. In particular the trade-off between consumption and investments, observed for the original values of the oil price of $p_0 = 0.0035$, is still valid for higher and lower oil prices. Third, a higher oil price affects negatively the economic performance, triggering a lower level of consumption and a higher unemployment rate.

Interestingly, the unemployment gap between a higher and a lower oil price, is larger when there is no feed-in tariff but it becomes smaller for growing feed-in tariffs. This result suggests that the feed-in tariff policy is particularly efficient when the oil price is high enough to generate an important supply driven contraction of the economic activity.

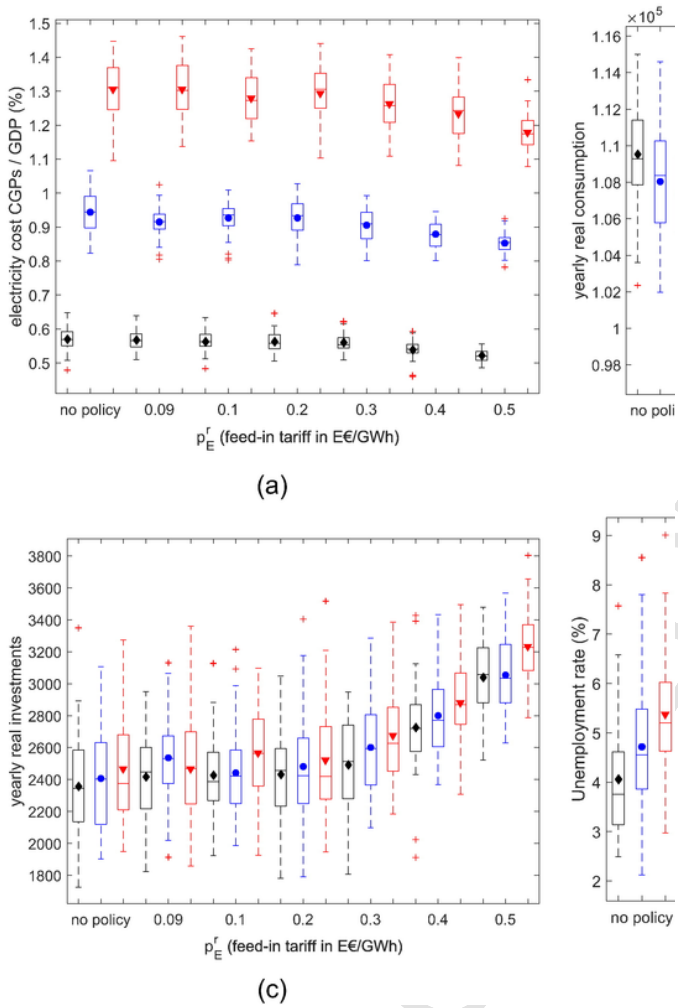

Fig. B2. The Figure shows the electricity cost of firm to GDP (a), the real consumption level (b), the real investment level (c) and the unemployment rate (%) (d) over the 50 seeds of the simulation. The values in the range represented by the boxplots refer to time averages over 20 years for each one of the 50 seeds. The 3 different colors correspond to the 3 values of the imported oil price p_O. In particular the black, blue, red lines represent $p_O = 0.0021, 0.0035, 0.0049$, respectively. $p_O = 0.0035$ is the value used for the main results of the paper.

B.3. The Parameters of the Taylor Rule

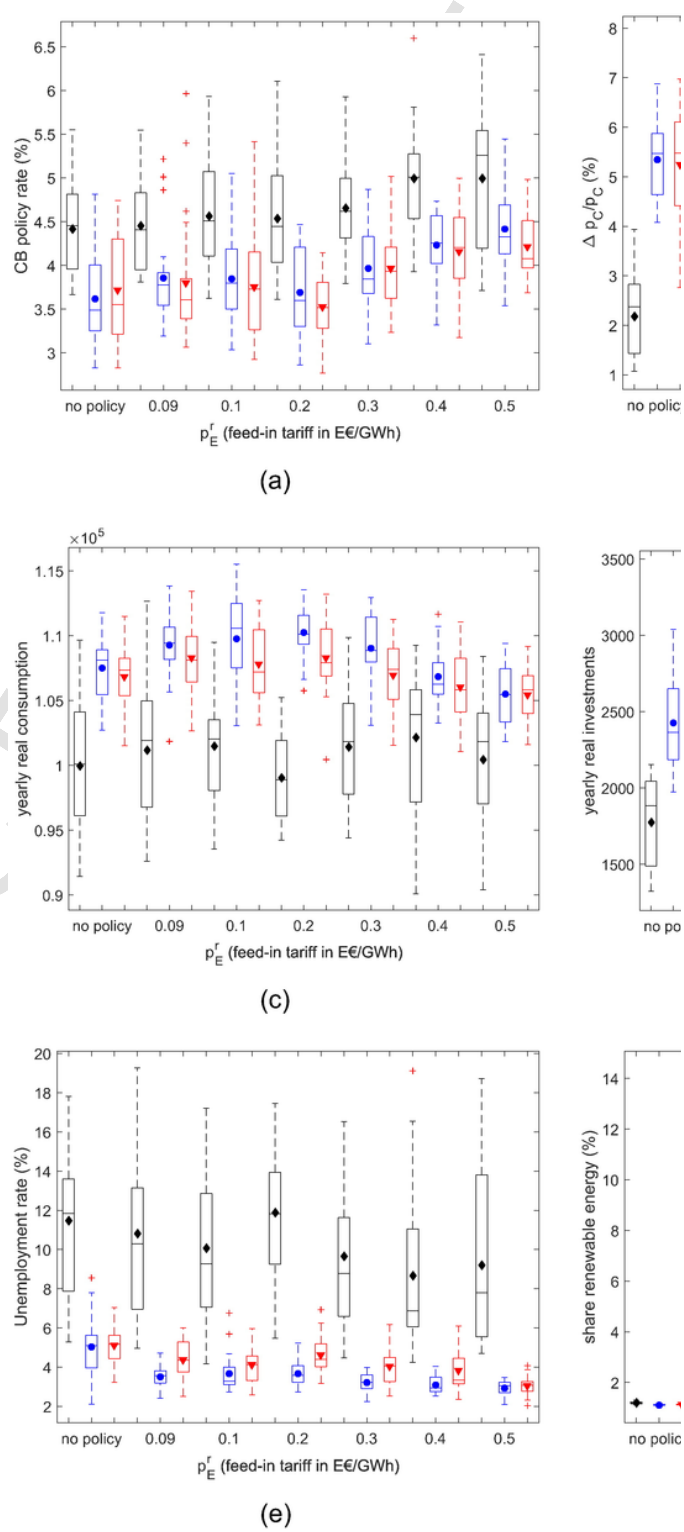

Fig. B3. The Figure shows CB policy rate (%) (a), inflation (b), real consumption level (c), real investment level (d), unemployment rate (%) (e) and the share of renewable energy (f) over the 50 seeds of the simulation. The values in the range represented by the boxplots refer to time averages over 20 years for each one of the 50 seeds. A different weight a_u of the unemployment targeting in the Taylor rule (

$i_t = \pi_t + r^*_t + a_\pi(\pi_t - \pi^*_t) + a_u(u_t - \bar{u}_t)$). The considered a_u values are 0 (black), 0.2 (blue) and 0.4 (red). $a_u = 0.2$ is the value used for the main results of the paper.

We remind here that the central bank agent in the model uses an dual mandate Taylor rule, targeting inflation and unemployment rate, in order to set the interest rate

$$i_t = \pi_t + r^*_t + a_\pi(\pi_t - \pi^*_t) + a_u(u_t - \bar{u}_t).$$

In this section, we try to analyze the impact of different policy settings on the results presented in the main part of the paper. In particular, we want to understand how much the crowding-out effect depends on the parameters governing the central bank policy rule. Therefore, we run two additional set of experiments where we change the value of the unemployment targeting parameter a_u. With respect to the baseline value of this parameter in the paper ($a_u = 0.2$), we increase it to 0.4 and we decrease it to 0. This means that, when $a_u = 0$, the central bank does not operate any more with dual mandate rule and only targets inflation, while in the other case (of $a_u = 0.4$), the weight of the unemployment rate in the Taylor rule is even higher. Results are shown in Fig. B3.

When the purely inflation targeting policy is active (the black boxes in the plots), the central banks sets a higher interest rate, which is between four and five percent. In this case, the central bank does certainly a better job in achieving its target inflation objective of 2% ($pi_t = 2$ in the model). When the monetary policy of the central bank considers the unemployment rate, the interest rate is higher and the 2% inflation target is not reached. On the other hand, the policy is very effective in reducing the unemployment level from an average above 10%, in the case of $a_u = 0$, to an average below 4%, in the case of not purely inflation targeting rules. It is also worth noting the high volatility in the case of $a_u = 0$, which indicates the presence of more extreme cases across the different seeds, where the average unemployment level can reach very high values, clearly indicating more instability and a higher probability of incurring in economic crises.

It is also interesting to notice that the crowding out effect between consumption and investments, for growing values of the feed-in tariff, is softened in the case of $a_u = 0$. Therefore, the feed-in tariff policy seems to be less effective in the case of economies in recession, as shown also be the lower share of renewable energy in panel (f).

Appendix C. Averages and Standard Errors of the Monte Carlo Distributions

This appendix reports the averages and standard errors of the Montecarlo distributions along with the related coefficients of variation of the 28 main economic variables considered in the paper.

Table C1
Monte Carlo averages (standard errors in round brackets) over 50 seeds. For each seed (simulation), the time average over the entire twenty-years time span is considered.

	p^r_E		
Variables	No policy	0.09	0.1
n_{sp}	500.0 (0.0)	572.16 (1.88)	629.67 (3.50)
Share renewable energy (%)	1.1 (0.0)	1.250 (0.004)	1.35 (0.01)
p_E(E€/GWh)	0.010678 (0.000004)	0.010688 (0.000003)	0.010689 (0.000004)
Yearly tax rates (%)	27.00 (0.20)	26.74 (0.18)	26.58 (0.21)
Employment rate CGP (%)	81.76 (0.26)	82.39 (0.21)	82.96 (0.26)
Employment rate KGP (%)	13.52 (0.23)	14.12 (0.19)	13.61 (0.21)
Unemployment rate (%)	4.72 (0.17)	3.49 (0.08)	3.42 (0.11)
Nominal wage (E€)	2.57 (0.03)	2.67 (0.02)	2.64 (0.02)
p_C (E€)	1.12 (0.01)	1.16 (0.01)	1.15 (0.01)
p_K(E€)	5.98 (0.06)	6.26 (0.05)	6.20 (0.05)
$\Delta p_C/p_C$ (%)	5.29 (0.12)	5.80 (0.10)	5.73 (0.11)
$\Delta p_K/p_K$ (%)	5.92 (0.11)	6.48 (0.10)	6.41 (0.11)
Yearly real consumption	108016 (403)	109448 (323)	109663 (409)
Yearly real investments	2405 (43)	2536 (35)	2443 (38)
Real consumption growth rate (%)	1.43 (0.05)	1.68 (0.04)	1.68 (0.05)
Real investments growth rate (%)	−12.31 (1.01)	−11.15 (0.71)	−11.26 (0.73)
K_F	1008724 (4277)	1021660 (3678)	1009206 (3734)
$\Delta K_F/K_F$ (%)	2.98 (0.05)	3.16 (0.04)	3.06 (0.04)
D_F (E€)	185033 (1595)	238543 (941)	237050 (1017)
$\Delta D_F/D_F$ (%)	−0.51 (0.17)	3.89 (0.05)	3.92 (0.06)
CB policy rate (%)	3.63 (0.07)	3.86 (0.07)	3.90 (0.07)
Government bond yield (%)	6.04 (0.16)	5.93 (0.18)	6.28 (0.17)
Government debt/GDP (%)	120 (6)	100 (5)	109 (6)
Government budget/GDP (%)	−6.58 (0.31)	−4.84 (0.32)	−5.33 (0.35)
Feed-in tariff policy cost/GDP (%)	0.0 (0.0)	0.0871 (0.0005)	0.107 (0.001)
Feed-in tariff policy cost/Tax (%)	0.0 (0.0)	0.223 (0.001)	0.271 (0.002)
Oil import costs/GDP (%)	0.84 (0.01)	0.814 (0.006)	0.82 (0.01)
Electricity cost CGPs/GDP (%)	0.94 (0.01)	0.914 (0.006)	0.93 (0.01)

In particular, Table C1 reports the value of the mean of the distribution, along with the standard error (in round bracket). This table provides a more compact information with respect to the one provided by boxplots, see Figures from 2 to 8, and discussed in details in the results section along with the related statistical tests. Table C2 reports the average over the 50 seeds of the coefficient of variation, for each 28 economic variables examined and all the policies considered. For each seed the coefficient of variation is computed as the ratio between the standard deviation and the mean, both over time. From the table we can observe a clear decrease, for increasing values of the feed-in tariff, of the relative variability of the investment level and of the employment rate in the capital goods sector. This outcome is consistent with the bias toward an increasing level of investments in renewable energy production capacity determined by the rising feed-in tariff. On the other hand, in most of the other cases, the direction of change of the coefficient of variation with respect to the feed-in tariff does not exhibit a clearly interpretable pattern. In particular, for most of the variables, the value seems independent from the policy, while for others, like the unemployment rate and the central bank interest rate we can observe an increasing relative variability with the strengthening of the policy.

Table C2
Coefficients of variation averaged over the 50 seeds. For each seed the coefficient of variation is computed as the ratio between the standard deviation and the mean, both over time. The letters “n.a.” stand for “not available” due to a zero by zero division because there are no policy costs in the no policy case.

Variables	p_E^r			
	No policy	0.09	0.1	0
n_{sp}	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	0 (
Share renewable energy (%)	122.8e-05 (2.3e-05)	112.9e-05 (2.0e-05)	104.2e-05 (2.0e-05)	2 (
p_E(E€/GWh)	167.9e-04 (2.2e-04)	176.5e-04 (1.9e-04)	177.8e-04 (2.1e-04)	1 (
Yearly tax rates (%)	0.158 (0.002)	0.155 (0.002)	0.154 (0.002)	0 (
Employment rate CGP (%)	0.102 (0.002)	0.109 (0.002)	0.112 (0.002)	0 (
Employment rate KGP (%)	0.703 (0.019)	0.653 (0.017)	0.683 (0.016)	0 (
Unemployment rate (%)	1.109 (0.021)	1.263 (0.019)	1.283 (0.024)	1 (
Nominal wage (E€)	0.312 (0.007)	0.343 (0.006)	0.341 (0.007)	0 (
p_C (E€)	0.302 (0.007)	0.331 (0.006)	0.327 (0.006)	0 (
p_K(E€)	0.336 (0.006)	0.369 (0.006)	0.366 (0.007)	0 (
$\Delta p_C/p_C$ (%)	0.002 (0.000)	0.002 (0.000)	0.002 (0.000)	0 (
$\Delta p_K/p_K$ (%)	145.8e-05 (6.6e-05)	122.2e-05 (4.8e-05)	124.3e-05 (5.2e-05)	1 (
Yearly real consumption	0.110 (0.002)	0.120 (0.002)	0.122 (0.002)	0 (
Yearly real investments	0.735 (0.021)	0.673 (0.018)	0.709 (0.017)	0 (
Real consumption growth rate (%)	0.010 (0.000)	0.008 (0.000)	0.008 (0.000)	0 (
Real investments growth rate (%)	129.9e-04 (7.8e-04)	134.8e-04 (6.1e-04)	151.9e-04 (8.3e-04)	1 (
K_F	0.175 (0.003)	0.182 (0.002)	0.177 (0.002)	0 (
$\Delta K_F/K_F$ (%)	35.41e-04 (1.5e-04)	309.2e-05 (9.5e-05)	317.4e-05 (9.1e-05)	3 (
D_F (E€)	0.187 (0.006)	0.228 (0.002)	0.230 (0.003)	0 (
$\Delta D_F/D_F$ (%)	18.19e-02 (5.0e-02)	43.32e-04 (1.2e-04)	41.52e-04 (1.4e-04)	4 (
CB policy rate (%)	0.971 (0.018)	0.867 (0.017)	0.850 (0.017)	0 (
Government bond yield (%)	0.415 (0.009)	0.414 (0.008)	0.420 (0.010)	0 (
Government debt/GDP (%)	54.31e-04 (3.5e-04)	38.90e-04 (3.9e-04)	43.10e-04 (4.0e-04)	4 (
Government budget/GDP (%)	2.303 (0.266)	2.772 (0.128)	2.674 (0.175)	3 (
Feed-in tariff policy cost/GDP (%)	n.a.(n.a.)	407.1e-05 (4.9e-05)	368.7e-05 (6.1e-05)	1 (
Feed-in tariff policy cost/Tax (%)	n.a. (n.a.)	623.3e-05 (5.5e-05)	566.4e-05 (6.7e-05)	2 (
Oil import costs/GDP (%)	274.5e-05 (7.3e-05)	300.7e-05 (6.3e-05)	297.8e-05 (6.7e-05)	2 (
Electricity cost CGPs/GDP (%)	272.6e-05 (7.3e-05)	298.7e-05 (6.3e-05)	295.4e-05 (6.5e-05)	2 (

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