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Financial stability at risk due to investing rapidly in renewable energy

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ABSTRACT

We present novel insights about effective energy policies using an agent-based model. The model describes relevant feedback mechanisms between technological evolution, the interbank market and the electricity sector. Analysis with it shows that energy policies affect interbank connectivity and hence the likelihood of cascades of bank failures. This effect has not been studied before in the literature. In particular, we find that investments in renewable energy reduce interbank connectivity, increasing the probability of bank failures, while raising taxes on energy has an opposite effect. Increasing the share of renewable energy in electricity production initially increases the price of electricity, and thus improves profits and the ability to re-pay debts of incumbent power plants. However, when the share of renewable energy increases too quickly, financial stability may be at stake as the burden of financing investments in renewable energy offsets the improved profitability of existing power stations. All in all, this study provides a unique and novel perspective on the relationship between renewable energy investments and financial stability.

1. Introduction

Policymakers concerned with sustainability transitions need models capturing feedback mechanisms between different sub-systems of the economy, so that they can simultaneously assess economic, social and environmental performance of anticipated public policies and strategies. But current studies tend to examine climate change, financial instability or inequality without considering their complicated interrelationships. As a result, they are incapable of identifying indirect effects of sustainability policies in social, financial and economic realms. Hence they may overestimate the effectiveness of various policies, particularly by overlooking potential effects of policies directed at one sub-systems on other sub-systems. The proposed new approach avoids this deficiency by accounting for interactions between financial, energy and social subsystems. In particular, in this paper, we employ an agent-based model, capturing interactions between these interrelated systems.

The paper contributes to the literature on transitions to a low carbon economy, by assessing macro-economic impacts of associated policies. Most other studies adopt a more limited perspective, and as a result provide partial insights (Safarzynska et al., 2012). In order to understand the full implications of a transition, it is essential to adopt a macroeconomic perspective as we propose in the paper. A low-carbon transition requires changes that will have non-trivial impacts not only on energy systems but also on financial systems and even income distribution. Recent evidence shows that both inequality and energy prices affect financial stability (Russo et al., 2013; Cardaci and Saraceno, 2015; ESRB, 2016). This illustrates that the three sub-systems are intricately connected. Yet, so far, they have been studied separately. With our model we aimed to fill in this gap, and try to assess important secondary effects of a range of transition policies.

It is increasingly argued that to guide a transition to a low-carbon world, new models are needed that integrate knowledge of social processes with that of technical aspects of climate and energy systems (Nature Energy, 2016; Stern, 2016). Integrated assessment models are widely used tools in studies of macroeconomic impacts of climate policies. These models rely on very simplified assumptions of consumers' and producers' behavior, and ignore bounded rationality and social interactions. Agent-based modeling (ABM) offers realistic representations of socio-economic processes, which allows simulating the economy through interactions between large numbers of distinct agents. Over the last two decades, macro ABMs have been successfully applied to study financial contagion (Cincotti et al., 2010; Gaffeo et al., 2008; Delli Gatti et al., 2009; Neveu, 2013), technological evolution (Windrum and Birchenhall, 1998, 2005), and the relation between inequality, structural change and financial fragility (Russo et al., 2013; Cardaci and Saraceno, 2015). So far, very few macro ABMs include

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energy as an input of production (exceptions are Gerst et al. (2013) and Wolf et al. (2013)), while no model combines energy and financial systems.

In the light of this, we modify an agent-based model developed in Safarzynska and van den Bergh (2017) to study macroeconomic impacts of policies aimed at guiding the economy along sustainable trajectories. The model conceptualizes relevant feedback mechanisms between technological evolution, labor and interbank markets, and the electricity sector. In the model, four populations, namely of heterogeneous consumers, producers, power plants and banks, interact through interconnected networks. The modeling of sustainability policies requires several changes in the earlier model. In particular, we modify the model to explicitly account for: subsidies and investments in different energy mixes in electricity production; energy efficiency measures; energy taxation, whose revenues are used to reduce the tax burden on labor; and redistributive policies. We show that sustainability policies affect the relationship between the interbank connectivity and the probability of bank failures, which has not been considered so far in the literature. For instance, policies increasing the share of renewable energy in electricity production reduce the interbank connectivity, increasing the probability of bank failures; while raising energy taxes acts in the opposite way. So far, no study has examined this effect either empirically or theoretically.

A main insight of our study is that a too quick transition to renewable energy can pose a serious burden on the financial system. Investments in renewable energy increase the price of electricity, and hence profits and ability to re-pay debts of incumbent power plants. However, if the share of renewable increases too quickly, financial stability may be at stake as the burden of financing investments in expensive renewable power plants offsets the improved profitability of gas power stations. This is because the costs of constructing a renewable power plant per MW installed capacity is still considerably higher than that of a fossil-fuel power station. The detrimental effect of investments on the financial sector is especially pronounced in coal-dependent economies because investments required to set-up a coal power plants are larger than of CCGT. We will see that a solution is to combine renewable energy with combined cycle gas turbines (CCGT) in electricity production. This can improve the stability of the financial system.

The reminder of this paper is organized as follows. In Section 2, we describe the basic setup of the model and present a set of policy scenarios. Section 3 reports simulation results and interpretations. Section 4 concludes.

2. Model description

In this section, we describe the basic assumptions of, and modifications in, the model of Safarzynska and van den Bergh (2017). Fig. 1 presents a schematic structure of the model that highlights its modules and the described interactions between energy, labor and financial subsystems. We consider a product market with many firms producing highly differentiated goods. A technological trajectory arises from the interplay between incremental innovation and the search for new product designs by individual firms. This approach follows the seminal work by Nelson and Winter (1982). Evolving consumer preferences determine the direction of firms' innovative activities, giving rise to demand-supply coevolution.

On the supply side, firms decide about a desirable level of production and associated use of inputs (labor, capital and electricity). Product quality changes over time as a result of learning-by-doing (experience). The effect of incremental improvements in product design on sales is uncertain. As a result of a change in product quality a firm can attract new consumers, while it may lose others. In addition, every period a new firm offering a new product design tries to enter the market. It asks a randomly chosen bank for a start-up loan. Similarly, incumbent firms can ask banks for loans, for instance, to invest in capital expansion. The loans are granted, and new firms can enter the market, if two conditions are satisfied: (1) a bank has sufficient liquidity or is capable of raising finance in the interbank lending market and (2) the debt-to-equity ratio of a firm asking for a loan does not exceed some critical value.

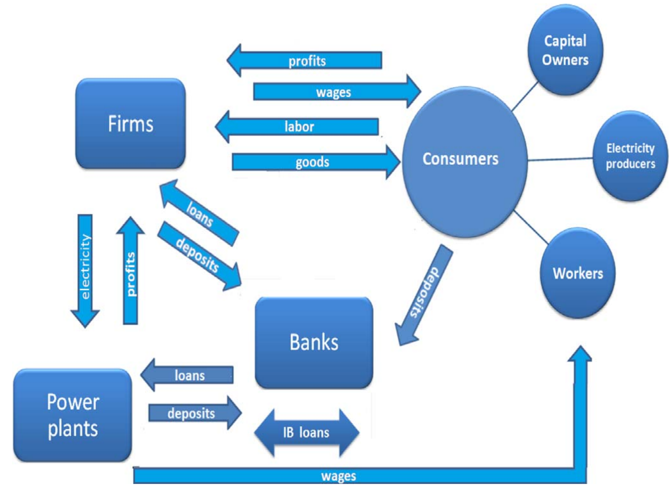


Fig. 1. Schematic representation of the model. Source: Safarzynska and van den Bergh (2017).

In the model, electricity is assumed to be an important input to the production of consumer goods, along with capital and labor. This is illustrated by electricity being essential to manufacturing: it can reach up to 95% of total energy use for production (Steinbucks, 2010). The electricity market is modeled as composed of energy companies with heterogeneous plants producing electricity from diverse energy sources, namely combined cycle gas turbines (CCGT), coal and nuclear energy. We model energy transitions as occurring through the installation of new power plants and the exit of obsolete plants. A plant is closed after reaching its maximum lifespan, and a new plant enters the market. The size of a new power plant and the type of energy technology it employs are chosen based on the discounted value of future investments. In addition, each new plant receives a loan, which has to be re-paid by the end of its lifecycle. Credit connections between banks and firms, including power plants, develop as a result of activities in the real economy. The basic model of Safarzynska and van den Bergh (2017) distinguishes between three abstract fuels. For the current analysis, parameters describing each energy technology are calibrated using data for the electricity industry in the UK between 1990 and 2002, following an earlier study (Safarzynska and van den Bergh, 2010a, 2010b). This period is relevant as it constituted a major transition of the British electricity sector from coal to gas. Installation costs and parameters describing changes in fuel prices were re-scaled by a factor 1/10 to match demand for electricity in the market for consumer products.

On the demand side, consumers imitate choices of others within their social networks. We distinguish three consumer classes based on the source of their income, namely owners of the factors capital and energy, and workers. This allows us to study the impact of distributive policies on financial and economic stability. Energy owners can be thought of as shareholders of energy utilities or oil and gas companies, while capital owners may be regarded as small producers who own productive machinery. In the model, consumers evaluate the attractiveness of a product based on its quality, price and whether others in their socio-economic class have already adopted it. The stronger brand loyalty, the more likely consumer choices cluster around similar products. In addition, energy and capital owners derive disutility from buying products that are frequently bought by workers, which we refer to as a snob effect. Consumer differentiation is one factor behind income inequality, while the degree to which consumers imitate others in their social networks determines the extent of market competition.

In modeling the interbank lending market, we build upon Thurner and Polenda (2013). New firms entering the market ask a bank for a startup loan. If banks have insufficient liquidity, they ask other banks for loans in the interbank lending network. The bankruptcy of a bank can arise due to failures of loan repayments triggered by bankruptcy of firms or other banks (Thurner and Polenda, 2013). If a bank goes bankrupt, its loans at the interbank market are written off, while consumers' and firms' savings are reallocated to a randomly chosen other bank.

In Safarzynska and van den Bergh (2017), we showed that brand loyalty, captured by a network externality on the demand side, can increase the likelihood of bankruptcies of banks. In particular, if the network effect is strong, new firms have difficulty in competing with incumbents because consumers tend to prefer established products. In turn, under the weak network effect, new firms can easily attract consumers if they outcompete existing products with respect to quality. As a result, the market resembles the fashion market with many firms competing for adoption. In turn, intense market competition causes many firms to be unable to re-pay any debts, for instance, once demand for their products suddenly diminishes due to a new, more attractive products appearing on the market. This increases the probability of cascades of bank failures.

In our model, there are three main channels through which energy markets affect financial stability and inequality. First, the degree of concentration of loans to energy companies determines the probability of the cascades of bank failures. In particular, we find that if large loans are concentrated in few banks, this is conducive to bankruptcies of banks as risk becomes unevenly spread in the financial sector. Second, energy prices affect the distribution of wealth among owners of different factors of production (workers, capital owners, and owners of energy companies), which generates inequalities. Third, an increase in the price of energy drives the prices of final products up. As a result, wages of workers may become insufficient to buy manufacturing products every period, undermining demand. This in turn reduces firms' profits, increasing the probability of their bankruptcies. In addition, an increase in energy prices may cause firms to be unable to repay their loans, further contributing to the likelihood of their bankruptcies.

Using the above described model, in this paper, we study macroeconomic impacts for six scenarios of energy and social policies that can foster a transition to a low-carbon economy. We focus on traditional energy policies: energy subsidies, energy taxes and improving energy efficiency, and their interactions with social policies:

(1) *Investments in renewable energy:* in the baseline scenario, the size and type of energy technology embodied in a new power plant is chosen based on the discounted value of investments. We compare simulations where we impose a rule that with a certain probability investments are made in a new nuclear power station, regardless of the discounted value of investments. In addition, we examine the evolution of the system under the following conditions: with a certain probability investments are made in a nuclear power plant, while with the remaining probability a new coal station is installed. Nuclear stations are, like certain renewable energy technologies, characterized by high fixed and installation costs, and low or no fuel costs. This allows us to generalize our results based on nuclear energy to renewable energy. We investigate the impact of increasing the share of renewable energy from 5% to 20%, which is motivated by the EU baseline target of 20% by 2020, and the USA's national renewable energy target (RET) of 20%.
(2) *A tax on electricity use:* We model an energy tax in a way that all revenues from it are equally distributed among workers. This can be interpreted as a tax shift from labor to energy, motivated by the goals of encouraging more employment and reducing greenhouse emissions. We examine the macroeconomic effects of imposing a tax from 0.1 to 0.35.
(3) *A reduction in the probability with which consumers purchase durable goods:* Much has been written about excessive consumption putting pressure on the environment (Arrow et al., 2004). In the future, the environmental impact of overconsumption may escalate because of population growth and growing real incomes in developing countries. Can reducing consumption help create a more sustainable world? We examine the macroeconomic consequences of scenarios in which the probability that a consumer buys a product with a probability between 50–90%. To illustrate, reducing demand by 50% implies that consumers buy manufacturing products on average every second period (which can be interpreted as year) instead of every period in the baseline. This policy is motivated by the burgeoning literature on degrowth as a solution to the triple environmental, social and economic crisis (Schneider et al., 2010). Degrowth implies downscaling of production and consumption so as to increase human well-being and enhance ecological conditions. We offer a first test of its macroeconomic impacts.
(4) *Improvements in energy efficiency:* In the baseline scenario, firms invest in either energy efficiency or labor productivity, depending on the relative prices of both inputs. The labor and energy productivity frontiers determine the maximum values of these variables at a given time by incumbent firms, which evolve over time because of technological progress. All new firms start with the same labor and energy efficiency. We study the evolution of the system for different values of the maximum energy efficiency reachable (see the Appendix).
(5) *Equitable redistribution of income:* all outlays by firms on energy, capital and labor are equally distributed among input owners (shareholders or workers). While the link between inequality, financial stability and economic growth has received much attention (e.g. King and Levine, 1993; Beck et al., 2007), the relationship between distributive and energy policies has not achieved much attention. Formally, all expenses of firms on different factors of production are distributed equally among consumers regardless of their type (among workers, energy and capital owners), thus every consumers receives the same income. We compare outcomes of this scenario to the baseline, where all payments by firms to production factors are distributed equally among consumers, regardless of whether they are workers, capital owners or owners of energy companies. We compare outcomes of this scenario to the baseline, where wages of workers are determined by labor supply and demand, while expenses of firms on energy (capital) are redistributed equally among energy (capital) owners. In line with this, in the baseline, wages, rents of capital and of energy owners are heterogeneous and evolving over time.
(6) *Equitable redistribution and energy policies:* In particular, we run additional simulations, where we combine the redistributive policy with the energy tax (*Policy 5 and 4*) and with a double value of the maximum energy efficiency compared to the baseline case (*Policy 5 and 2*).

3. Results

We use the model to simulate the macroeconomic effects of different energy and social policies during 1000 time steps. The reported results are averages over 100 identical simulations. Mean results and standard deviations for each simulation setting are reported in the Appendix A. In Appendix D, we report parameter values used in the baseline scenario. Parameters in the baseline were chosen so that the model replicates a wide spectrum of stylized facts. In particular, our model is capable of generating capital growth combined with business cycles, while employment and total debt in the economy are procyclical, and loan losses (as a percentage of total loans) in the economy are countercyclical – as shown in Safarzynska and van den Bergh (2017).

We evaluate different policy scenarios with respect to financial stability, socio-economic consequences, and whether they reduce energy use compared to the baseline. As a measure of financial stability, we report the number of banks in the last period, following Tedeschi et al. (2012). Fewer banks surviving by the end of a simulation is indicative of the severity of the cascades of bank failures during simulations. We do not assume this to be a measure of general stability of the financial sector, as a banking sector with only one bank can be stable, but as an indicator of cascades of bank failures. In addition, we observe the evolution of connectivity at the interbank market, inequality of wealth over time, the mean consumption of electricity and employment, and the mean values of the electricity price (see the Appendix A). The connectivity measure is defined as the average number of loans per bank in the interbank lending market. In turn, inequality is measured using the coefficient of variation, σ_t/μ_t, with σ_t the standard deviation of wealth (consumers' bank deposits) and μ_t mean wealth at time t. We report also the mean value of the Herfindahl index (H-index, reported in the table in the Appendix) as a measure of concentration of firms on the market, which is computed as: $\sum_j m^2{}_{jt}$ with m_{jt} the market share of firm j at time t. Finally, we provide the mean values of M1, which is a measure of money created in the economy, namely total reserves + loans. Since we keep total reserves constant throughout the entire simulations, mean values of M1 are indicative of total debt in the economy.

Fig. 2 illustrates results from model simulations with energy subsidies, which differ with respect to the share of nuclear energy in electricity production. In particular, Fig. 2(a) depicts mean electricity, and Fig. 2(b) the number of surviving banks in 100 simulations for each policy scenario. We find that the effect of increasing the share of nuclear energy on financial stability and energy use depends on whether coal or CCGT dominates electricity production. In the baseline scenario, CCGT constitutes a dominant fuel in electricity production as CCGT is the cheapest to install. Increasing the share of nuclear energy in the electricity sector, up to 10%, increases the price of electricity at first, benefiting existing CGGT power plants (see Table A in the Appendix). This is because the cost of producing electricity from nuclear energy is high due to its high installation costs. An increase in electricity price as a result of entry of nuclear stations makes it easier for incumbent CCGT plants to repay their loans. In addition, an increase in the price of electricity causes firms to substitute electricity for labor in production, thus limiting energy consumption and emissions from burning fossil fuels (Fig. 2(a)).

However, if the share of nuclear energy exceeds a certain threshold, their high installation costs create tensions in the financial system. This is because such cost are considerably higher than those of conventional power plants relying on fossil fuels. Increasing the share of nuclear energy in the energy mix poses especially a burden on the financial system in coal-dependent economies. Coal power stations are nearly twice as expensive to install as gas-powered plants, which means that larger loans are required to cover their initial investments. In turn, the concentration of large loans in few banks causes risk to become unevenly spread across the financial sector, increasing the probability of bank failures. Adding nuclear energy in electricity production reliant on coal merely exaggerates systemic risk. Moreover, investing too much in nuclear energy causes crowding-out of investments in the manufacturing sector. As a result, interbank connectivity is much lower in coal- than in gas-dependent systems.

The impact of increasing the share of renewable energy on the electricity price is not straightforward. In general, economic theory predicts that the increase of the share of renewable energy in electricity production may reduce the price of electricity in the short run, which is also known as the merit-order effect (Jensen and Skytte, 2002). This is because renewable energy technologies are characterized by lower marginal costs than conventional (fossil-fuel) technologies. Yet, it is still more expensive to generate electricity with renewable energy than it is with conventional technologies. Countries that have succeeded in increasing their renewable capacities have done so by implementing costly policies. In particular, in most countries, the diffusion of renewable energy has been driven by public renewable support schemes - financed by increasing the final electricity price paid to consumers (Moreno et al., 2012). Our model captures two mechanisms through which increasing the share of renewable energy in electricity production affects the electricity price. In the short run, renewable energy plants that employ energy technologies characterized by low marginal costs produce more electricity (Eq. (24) in the Appendix), which lowers the electricity price (Eq. (22) in the Appendix). However, as a result of lower electricity prices, the newly installed power plants become smaller in size (Eq. (29)). This is because the size of newly installed power plants is determined by their future expected profits given the current price of electricity. In turn, less installed capacity translates into less electricity produced, and thus a higher electricity price.

How does interconnectedness between banks affect systemic risk? This constitutes an important topic in the literature on financial contagion (Kirman, 2016). In particular, models of financial contagion show that the high interbank connectedness helps to spread the risk evenly over all other banks, causing the impact of shocks to be easily absorbed (Allen and Gale, 2000). Our results demonstrate that investing too much and too fast in renewable energy increases the chances of cascades of bank failures. This has not been realized so far in the

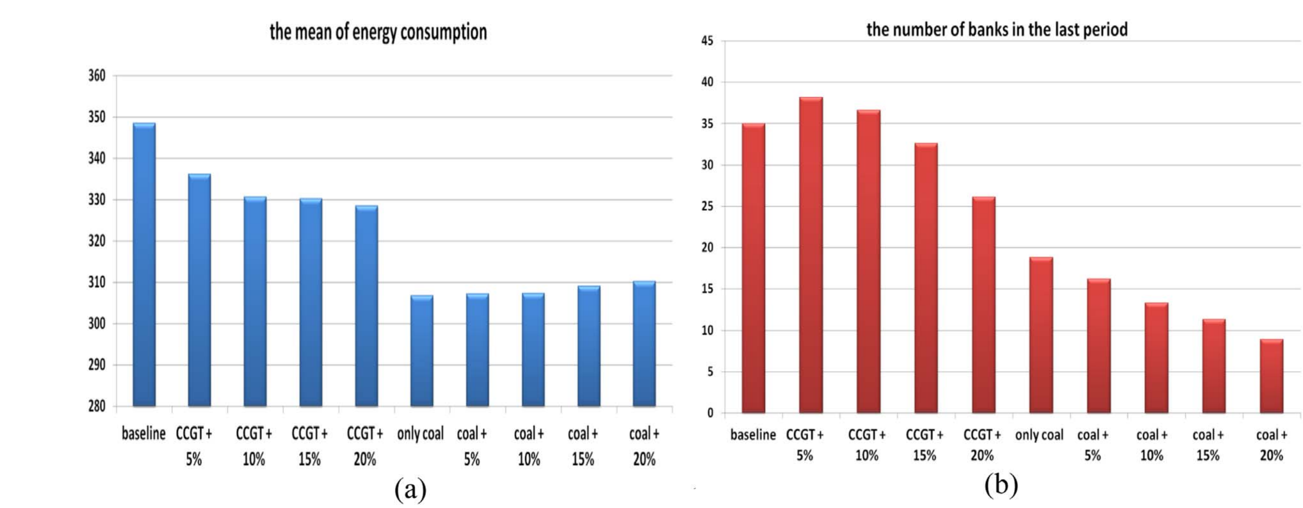


Fig. 2. Macroeconomic impacts of increasing the share of nuclear energy in economies, where electricity production relies on CCGT or coal. (a) summarizes mean electricity use in the manufacturing sector for different energy mixes, in particular for increasing shares of investments in renewable energy in the economy reliant on gas (5 bars on the left) or on coal (5 bars on the right). (b) shows the corresponding number of banks operating in the final period of the simulations, as a measure of financial stability.

literature. In particular, increasing shares of renewable energy decreases the interbank connectivity by causing the concentration of large loans to energy utilities in few banks. This translates into fewer banks surviving by the end of the simulation period (see the Appendix).

Fig. 3 shows the mean interbank connectedness over time and the number of banks in the last period for different policy scenarios. The figure illustrates that the relationship between two variables is influenced by energy policies. In particular, an increase in the energy tax increases the mean connectivity of banks, but has only a negligible effect on the number of banks surviving in the last period. The enlarged connectivity can be explained by the fact that the energy tax increases values of loans required to expand production by firms in the manufacturing sector. In turn, the negligible effect of taxes on the financial sector is due to tax revenues being redistributed among workers, with limited impact on consumer demand or the ability of firms to repay their debts.

We find that policy mixes, which involve an equitable redistribution of incomes, ensure high connectivity at the interbank market as well as the highest number of banks in the last period, thus the most stable financial system (Fig. 3(b)). This is in line with previous studies, which suggest that uneven income distribution and a financial crisis are two sides of the same coin (Tridico, 2012). Recently, a number of authors used agent-based models to explore the link between inequality and financial instability (Russo et al., 2013; Cardaci and Saraceno, 2015). The main result from this line of research is that increased inequality contributes to macroeconomic volatility, and may cause large unemployment crisis and lower output growth. This is confirmed by our model simulations (see Appendix A).

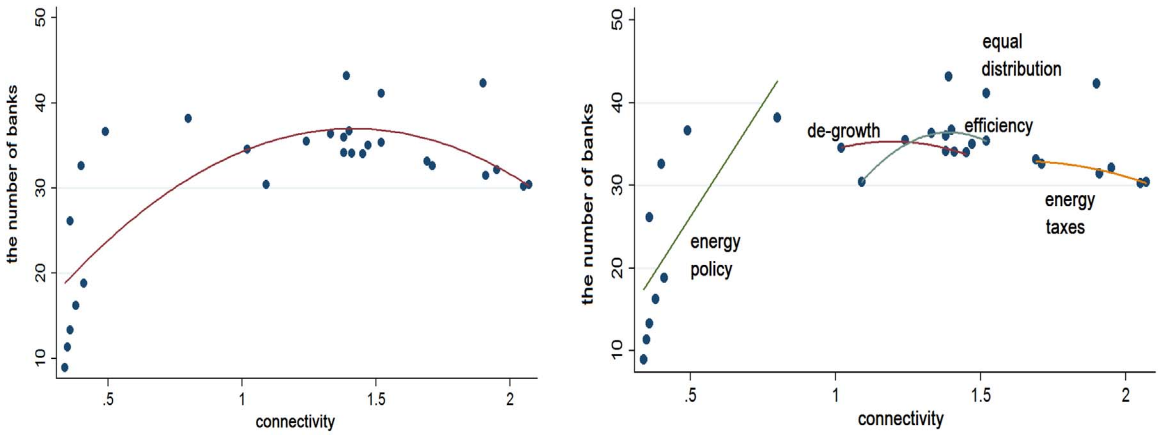
Some have argued that a transition to a low-carbon economy is not feasible without behavioral changes (Jackson et al., 2004; Beddoe et al., 2009). In particular, growth in disposable income has been considered as driving consumption to unprecedented, unsustainable levels (Witt, 2011). In this context, the concept of reducing or controlling consumption has attracted much attention as a solution to environmental problems (Schneider et al., 2010; Jackson and Victor, 2016). It is often understood in terms of downscaling consumption and production. We examine the macroeconomic implications of this in our model simulations. In the baseline, each consumer attempts to buy the product which yields the highest utility given its disposable income. In the third policy scenario, we introduced a probability with which a consumer attempts to buy a product, varying from 0.5 to 1. As opposed to previous studies (e.g., Tokic, 2012) we do not find evidence for reduction of consumption being detrimental to financial stability. In fact, the larger the reduction in demand, the lower connectivity on the interbank market, and the more banks survive by the end of simulations. This can be explained by the fact that lower demand makes firms produce less, reducing their need to take loans from banks, which reduces also systemic risk. However, reduction of consumption has a cost in terms of a significant reduction in employment, associated with a slower economic growth. Surprisingly, the degrowth scenario reduces inequalities (see Appendix A). In our model, inequality is driven mostly by large income differences between distinct consumers' classes. In case firms produce fewer products, energy and capital rents are reduced significantly as their values depend on the total outlays by firms divided by the number of input owners. The latter does not change during model simulations, thus reductions in outlays by firms translate into lower rents, reducing disparities in income between workers and affluent classes. This explains why inequality is reduced under degrowth.

So far, the links between energy and financial markets have not achieved much attention in the theoretical analysis, despite increasing concerns that changes in energy sectors can affect systemic risk (Battiston et al., 2017; ESRB, 2016). We therefore use the model to examine the relationship between electricity prices and interbank connectedness. Previous analysis with the basic model (Safarzynska and van den Bergh, 2017), in the absence of policies, showed that higher electricity prices drive connectivity in the interbank market up. This is because higher electricity prices cause firms to request larger loans to expand their production. With the current analysis we find that in the presence of energy and social policies, the link between the electricity prices and interbank connectivity is U-shaped (Fig. 4). Some policies such as improvements in energy efficiency, reduction of consumption or equitably redistributing incomes do not affect the price of electricity but only interbank connectivity, thus reducing systemic risk. This is an unexpected result. On the other hand, policies such as stimulating investments in renewable energy result in higher electricity prices, in turn reducing interbank connectivity. Hence, investments in renewable energy contribute to systemic risk, increasing the probability of cascades of bank failures. Finally, an increase in the energy tax translates into more expensive electricity as well as better interbank connectivity, yet the impact of such a tax on systemic risk is low. This is because tax revenues are redistributed among consumers. As a result, the energy tax has a negligible impact on overall demand, ergo it does not compromise the ability of firms to repay their debts.

Much has been written on the relationship between equality and economic growth. But the impact of equality on energy use and financial stability has received no attention. To address this gap, below we study it. Fig. 5 compares the macroeconomic consequences of an equal income distribution with those of combinations of equitable redistribution and energy policies. Fig. 5(a) illustrates that combing an equal distribution of incomes with doubling of energy efficiency ensures the most stable financial system. In turn, Fig. 5(b) shows that energy use is minimized under improvements in energy efficiency alone. To assess if differences in the number of banks between different policy scenarios are statistically significant, we collected data from 100 simulations from each policy scenario (total 600 simulations). We then regressed, using OLS, dummies corresponding to each policy scenario on the number of banks in the last period, without a constant. Afterwards, we tested if differences in coefficients between each pair of coefficients were significantly different from each other. Table 1 reports the corresponding F-statistics. These indicate that the number of banks are statistically different from each other between policy scenarios, with the exception of the baseline scenario and the scenario with improvements in energy efficiency, and the baseline scenario and the scenario with a mix of an energy tax and equal income distribution. Tables D1 and D2 in the Appendix provide F-statistics corresponding to differences in mean labor and energy use between every pair of policy scenarios, illustrating that all differences are statistically significant.

Statistical significance in outcomes between different policy scenarios does not reveal causation between variables. To study determinants of energy use and financial stability in the presence of energy and distributive policies, Table 2 reports results from a logit panel regression with the dependent variable taking value 1 if a single bank collapsed at time t in Models 1–2; and from the random-effects model with the dependent variable computed as the log of total energy use at time t in Model 3. The sample includes data from 600 simulations between 1st and 250th round.[1] We include as depended variables dummies corresponding to each policy treatment, and additionally lagged values of: wages; the electricity price; the Herfindahl index; and the logarithm of money supply M1. In addition, we examine the impact of inequalities on the probability of bank failures in Model 1–2. In Model 3, we added a lagged value of growth of inequality instead of the measure of inequality. This is motivated by the fact that inequality is correlated with energy use. In particular, energy rent received by owners of energy companies depends on how much energy is employed for production in the manufacturing sector. In turn, inequality depends on relative income of different consumer classes: workers, capital

[1] Due to computational limits of the statistical software, we could not include data from all 1000 rounds for the 600 simulations.



(a) Baseline simulations with policies (b) fitting policies

Fig. 3. The link between connectivity and the number of banks in the final period. (a) shows a regression line fitted to the data, illustrating the positive relationship between connectivity and the number of banks. (b) plots regressions for each policy scenarios separately, indicating that the relationship between the probability of bank failures and interbank connectivity is influenced by energy policies.

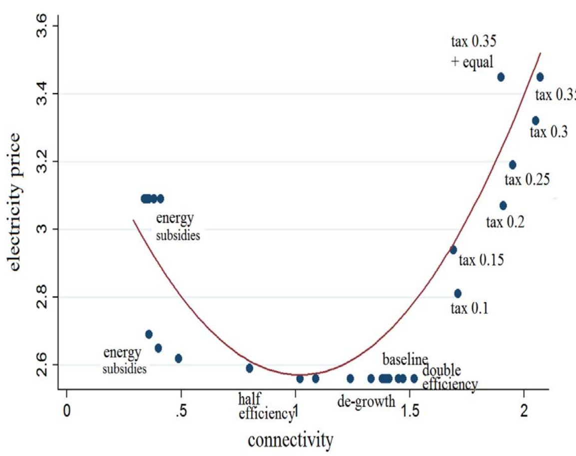
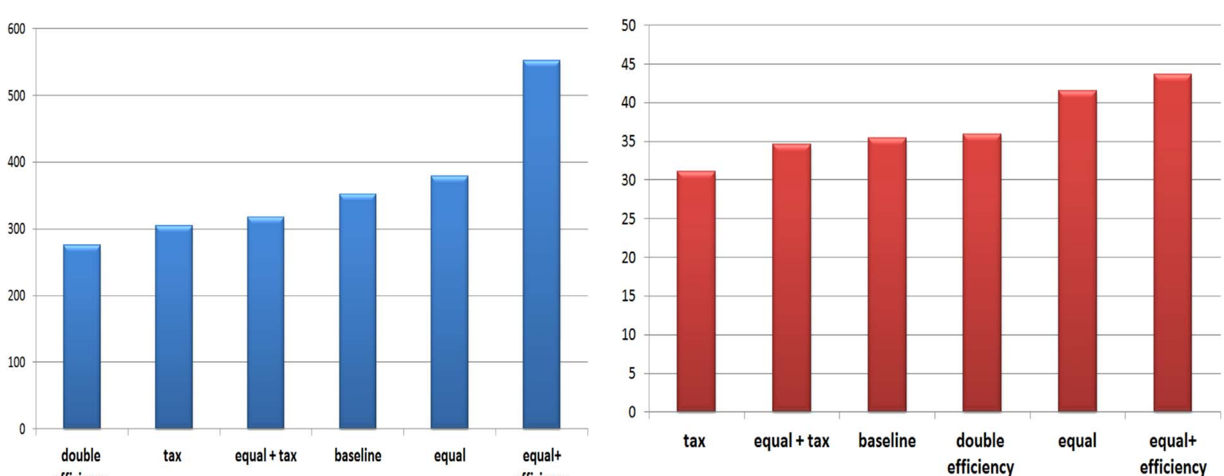


Fig. 4. The relationship between mean connectivity on the interbank market and mean electricity price.

owners and owners of energy companies, thus on energy rent and wages. Finally, connectivity at the interbank market is added to Model 3, but has not been included in Models 1–2. This is because we identified nonlinear relationships between connectivity, electricity price and number of surviving banks (i.e. the dependent variable) above.

We find that inequality increases the probability of bankruptcies of banks, contributing to financial frictions, which confirms previous findings (e.g. Russo et al., 2013). In turn, increasing inequality considerably reduces total energy used in the production of manufactured goods (Model 3). In our model, a more equal distribution of incomes ensures that more consumers can afford to buy products, which fuels demand, employment and growth. In turn, expanding production to meet new demand requires additional energy. The opposite is true for more uneven societies.

Table 2 shows results that indicate the positive and significant impact of the Herfindahl index on energy use, and its negative impact on the probability of banks failures. A higher value of this index implies less competition, while a value of 1 indicates that the market is a monopoly. The more firms compete on the market, the higher the probability becomes that some of them will go bankrupt, failing to re-pay debts, which in turn increases the probability of cascades of bank failures. Other results in Table 2 indicate that bankruptcies of banks are preceded by the growth in total debt. In particular, the logarithm of M1, measuring reserves and money generated due to loans, has a positive and statistically significant impact on the probability of bankruptcies of banks.



(a) Mean electricity consumption (b) Financial stability (mean number of banks in the final period)

Fig. 5. Impact of policy mixes on financial stability, employment and energy markets. (a) shows the mean number of workers and electricity consumption for the six policy scenarios, and (b) the number of banks in the last period.

Table 1
Significant differences in the number of banks in the last period between policy scenarios. In the table we report F(1,594)-statistics.

Policy scenario	Tax 0.35	Double efficiency	Equal distribution	Equal distribution+double efficiency	Equal distribution+tax 0.35
Baseline	48.14***	0.63	93.80***	167.44***	1.82
Tax 0.35		59.79***	276.34***	395.15***	31.23***
Double efficiency			79.05***	147.53***	4.59**
Equal distribution				10.59***	121.76***
Equal distribution+double efficiency					204.19***

Notes: *** indicates variable significant at 0.01 level, ** at 0.05 and * at 0.1 level.

Table 2
Results from the logit panel regression with the dependent variable taking value 1 if a single bank collapsed in time period *t* in Column 2; from the random-effects model with the dependent variable as the total employment in Column 3.

(Model) Dependent variable	**(Logit panel model) Banks collapse**		**(Random-effects model) Log of tot energy**
	Model 1	Model 2	Model 3
Electricity price $_{t-1}$	−0.54*** (0.19)	0.42*** (0.06)	
Wage $_{t-1}$	−0.09** (0.04)	−0.11*** (0.04)	0.32*** (0.001)
H-index $_{t-1}$	−3.05*** (0.19)	−2.97*** (0.19)	0.62*** (0.01)
Growth of Inequality $_{t-1}$			−1.08*** (0.01)
Inequality $_{t-1}$	0.67*** (0.05)	0.69*** (0.05)	
Bank connectivity $_{t-1}$			0.004*** (0.001)
Ln(M1) $_{t-1}$	7.00*** (0.46)	0.70*** (0.05)	3.28*** (0.03)
Dummy tax	0.51** (0.18)		−0.23*** (0.01)
Dummy double efficiency	0.05 (0.52)		−0.002 (0.01)
Dummy equal distribution	−0.34** (0.14)		0.06 (0.001)
Dummy equal distribution +double efficiency	−0.78*** (0.15)		0.32*** (0.001)
Dummy equal distribution+tax	1.29*** (0.18)		−0.17*** (0.001)
Constant	−92.71** (5.96)	−85.80*** 5.85	−38.07*** (0.36)
Nr. of observations	149,300	149,300	149,297
Nr. of groups	600	600	600
Wald Chi2	1709.13	1315.10	148,382.03
R2 within			0.50
between			0.69
overall			0.51

Notes: standard deviation in parenthesis; *** indicate variables significant at 1% level, ** 5%, and *** at the 10% level.

We expected that the higher price of electricity would increase the probability of bank failures by causing some firms to become unable to repay their loans. However, in the presence of energy polices, the impact of the price of electricity on the probability of bank failures is significant and negative, indicating that higher prices of electricity improve financial stability (Model 1 in Table 2). Only in the absence of dummies corresponding to different energy policies (Model 2 in Table 2), the impact of the price of electricity on the probability of bankruptcies of banks becomes negative, confirming findings in Safarzynska and van den Bergh (2017). The fact that the coefficient corresponding to the price of electricity changes its sign depending on whether dummies corresponding to different policies are added to the regressions is indicative of these policies being a mediating factor between the price of electricity and the likelihood of bank failures. In turn, higher wages translate into a lower probability of bank failures in both Models 1–2. This result is intuitive as higher wages allow workers to buy more products, which improves firms' profits and reduces the likelihood that they would be unable to re-pay their debts.

Table 2 shows results suggesting that most policy mixes involve a trade-off between financial stability and energy savings as compared to the baseline. The results in the table confirm that an equal distribution of income alone as well as in combination with doubling of energy efficiency improve stability of the financial system (Fig. 5(a)). In particular, dummies corresponding to these policy scenarios have a negative and significant impact on the probability of bank failures in Model 1 in Table 2. However, these dummies have also a positive impact on energy use in the economy (Model 3 in Table 2). Because of policies reducing inequalities, more workers can afford to buy products, improving demand. As a result, firms produce more and use more energy in the process.

As another example, improving energy efficiency alone reduces energy consumption but also generates unemployment (see Appendix A). Although improvements in energy efficiency translate into more labor and capital in the manufacturing sector, if technology in the manufacturing sector is more energy efficient, firms in the energy sector need to employ fewer inputs in production as a result of lower demand for electricity. The latter results in less total employment in the economy, which may undermine also demand for, and thus employment associated with manufacturing goods. On the other hand, improvements in energy efficiency are too insignificant to explain the probability of bank failures (in Model 1, as well as in Table 1). In turn, imposing a tax on electricity reduces energy use and boosts employment. However, this comes at the price of financial stability. The coefficient corresponding to this policy has a positive and statistically significant impact on the probability of bank failures in Model 1. In fact, none of policy dummies has a significant and negative impact on the probability of bank failures and simultaneously a negative impact on energy use in Table 2. Thus, no single policy balances two policy goals perfectly. Nevertheless, combining the energy tax with a redistributive policy boosts employment and reduces energy use compared to the baseline with a slight decline in financial stability (see Table A1 in the Appendix), and thus can be considered the best compromise between different objectives.

4. Conclusions and policy implications

This paper has presented novel insights about effective energy policies using an agent-based model. The model captures the coevolutionary nature of interactions between energy, technology and financial sectors, which allows us to study a broader than usual set of macroeconomic impacts of energy policies. Our results contribute to the debate on optimal timing and magnitude of investments in renewable energy. The power sector is currently responsible for nearly 40% of global carbon emissions (Williams et al., 2012), and it relies greatly on coal (IEA, 2014). Investing in low-carbon technologies is key to mitigating climate change. So far, there is no agreement over the optimal time of phasing out of coal power, as well as over its immediate replacement. It is evident that any energy transition will ultimately require decommissioning of fossil fuel-fired power plants and a major shift to a renewable energy. However, in the short run it is uncertain whether it is wise to retire generating capacity of coal. In addition, the question arises whether or not coal should first be substituted by gas and only later by renewable energy.

Different approaches have been adopted in the literature to address these questions. Using IPCC carbon budgets, which define allowable carbon gas emissions over time, Preffeir et al. (2016) show that investment in renewable power should start before coal and gas resources are phased out to reach the 2 °C target, or that even existing electricity infrastructure needs to be retired early to meet this target. Looking at the optimal path towards carbon-free economy in the Ramsey model, van der Ploeg and Withagen (2014) show that if the initial oil stock is small, the socially optimal path consists of an initial fossil fuel-only phase followed by a renewable-only phase. Similar conclusions have been reached by Chakravorty et al. (2008). However, all these studies neglect the impact of investments in the electricity sector on systemic financial risk.

Instead, our study sheds light on the impact of different investment strategies on the financial system. We find that substituting coal by gas, and then gas by renewable energy may be a safer option from the perspective of financial stability. This is because coal is more expensive to install than gas power plants. Moreover, coal generates more CO_2 emissions per unit of (net) useful energy delivered. One should also not forget that in many countries coal mines face financial difficulties, being at the edge of bankruptcy. Nevertheless, the cost of investments in a new renewable power plant is still considerably higher than that of fossil fuel generators. As a result, combing unprofitable coal with renewable energy creates a too high burden on the financial sector. Our analysis indicates that there exists an optimal combination of gas (notably CCGT) and renewable energy in electricity production which does not compromise the financial system. In addition, we showed that improvements in energy efficiency, reduction of consumption or equitably redistributing incomes do not affect the price of electricity, but may reduce systemic risk. In turn, investments in renewable energy result in higher electricity prices which can increase the probability of cascades of bank failures, depending on the initial mix of energy in the electricity production and how fast the share of renewable energy is increased. All in all, our study provides a starting point for further systemic analysis of sustainability policies, offering practitioners and policy makers a simulation environment in which to test impacts of policy packages on equity, employment, financial stability and the climate.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.enpol.2017.05.042.

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