Sustainability transition and digital trasformation: an agent-based perspective

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Abstract Digital transformation and sustainability transition are complex phenomena characterized by fundamental uncertainty. The potential consequences deriving from these processes are the subject of open debates among economists and technologists. In this respect, adopting a modelling and simulation approach represents one of the best solution in order to forecast potential effects linked to these complex phenomena. Agent-based modelling represents an appropriate paradigm to address complexity. This research aims at showing the potential of the large-scale macroeconomic agent-based model Eurace in order to investigate challenges like sustainability transition and digital transformation. This paper discusses and compares results of previous works where the Eurace model was used to study the digital transformation, while it presents new results concerning the framework on the sustainability transition, where a climate agent is introduced to account the climate economy interaction. As regards the digital transformation, the Eurace model is able to capture interesting business dynamics characterizing the so-called increasing returns world and, in case of high rates of digital technological progress, it shows a significant technological unemployment. As regard the sustainability transition, it displays a rebound effect on energy savings that compromises efforts to reduce green house gases emissions via electricity efficiency improvements. Furthermore, it shows that a carbon tax could be not sufficient to decouple economy from carbon consumption, and that a feed-in tariff policy fostering renewable energy production growth may be more effective.

Keywords Sustainability · Climate change mitigation policies · Digital Transformation · Technological unemployment · Agent-Based Modelling

1 Introduction

Climate change and digital transformation represent real challenges for our society. Climate change is mainly caused by anthropogenic green house gases (GHGs) emissions and, if uncontrolled it threatens human life on earth (IPCC (2014)). Paris agreement article 2 set the goal to hold the increase in the global average temperature below 2°C (UNFCC (2015)). Attaining this goal requires a large scale transition to a low or zero carbon economy. According to the UNEP emission gap report (UNEP (2019)), the current national determined contributions of the Paris agreement signatories are not sufficient to avoid a global warming greater than 3°C by 2100.

Climate change involves different physical phenomena such as global warming, sea level rise, change in oceans circulation, rainfall pattern shift, rise of extreme weather events frequency, etc. Furthermore, it has diverse and severe consequences on our society, for instance: harvest destruction, impacts on health, reduction and volatility of economic growth and negative effects on distribution of income and wealth (Krogstrup and

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Oman (2019)). Climate change, and more in general the Earth system evolution, is characterized by different interlinked tipping points. As some authors suggest (Lenton et al. (2019)), passing one of them could trigger a global cascade of tipping points. However, physical risks are not the only source of uncertainty associated to climate change. In fact, the way and pace at which the required green transition is realized could cause financial instability and economic losses, see Carney (2015). Both physical and transition risks affect the evaluation of costs and benefits of mitigation interventions. By virtue of the unpredictable nature of the physical processes and their strict relation with humans' reaction, the future climate state and the potential impacts of climate change are difficult to be evaluated.

As regards the digital transformation, during the last thirty years, digital technologies have been interested by a significant improvement. The advent of new digital technologies, e.g. artificial intelligence (AI), and their applications make economists and technologists ponder on potential effects deriving from a continuous technological progress in this research field. Since the first industrial revolution, technological progress has always generated apprehension among economic agents, especially among the working class. Although the debate on possible effects of technological progress is still open, most of economists agree on distinguishing between short and long run effects. In particular, in the short term, technological progress determines a decrease in the employment level and wages, whereas in the long run, higher productivity levels could lead to an increase of these economic variables, see Mokyr et al. (2015). Obviously, technological progress can involve different outcomes. In particular, we can distinguish between two different typologies of technological innovation, i.e. product and process innovation. Edquist et al. (2001); Vivarelli and Pianta (2000) highlight and underpin the positive effects of product innovation on labour demand: it can determine the opening of new markets leading to an increase in the production and employment level. On the other hand, process innovation leads to higher levels of productivity involving a higher unemployment within the production system. According to the so-called compensation theory, these negative effects on employment are counteracted by various economic forces triggered by the innovation process itself. Vivarelli (2014) identifies six forces, namely the compensation mechanisms "via additional employment in the capital goods sector", "via decrease in prices", "via new investments", "via decrease in wages", "via increase in incomes" and "via new products". According to Vermeulen and Pyka (2014), by virtue of this compensation mechanisms, the diffusion of robots and AI is causing a typical structural change rather than the so-called "end of work". However, the nature of the new digital technological progress, linked for instance to AI and its applications, is different from that of previous technological waves. In this regard, Brynjolfsson and McAfee (2014) argue that humans are experiencing a new technological revolution, the so-called "second machine age". According to these authors, traditional technologies, deriving from the steam engine perfected by James Watt, allowed human beings to overcome the limits imposed by our physical force, whereas through the adoption of new digital instruments, we are able to surmount limits imposed by our mind. In fact, the main purpose of AI is represented by the automation of decision making process and this makes us ponder on its potential consequences on economy, especially on the labour market. In case of further developments in AI and computation, some authors prospect the hypothesis of a technological singularity, associated to disruptive economic consequences, see Aghion et al. (2017); Good (1966); Nordhaus (2015). It is worth noting that the economic dynamics characterizing digital technologies developers are completely different from those of traditional bulk production systems. In this regard, according to Arthur (1996), we can distinguish between two different worlds, namely the increasing returns world, to which digital technologies developers belong, and the diminishing returns one. Differently from the latter, the increasing returns world is characterized by strong mechanisms of feedback that lead to disequilibrium and instability. Markets ruled by increasing returns are characterized, for instance, by unpredictability, instability, network effects, winner-take-most and technology lock in phenomena.

Both the sustainability transition and the digital transformation needs effective tools of analysis. So far, to evaluate policies potential impact diverse modeling approaches have been used in the economics literature.

Concerning the climate economics, Integrated assessment models (IAM) and computable general equilibrium (CGE) models are among the most used. IAMs (Nordhaus and Sztorc (2013), Hope (2006), Tol (1997)) are optimization models in which the economy and climate dynamics are coupled. The climate is represented as a system of interacting layers (atmosphere and oceans) each with its own temperature and stock of carbon. Economic activities produce GHGs emissions leading to an atmospheric temperature increase, the climate damages the economy destroying a fraction of the output determined by a non linear function of the atmospheric temperature. System evolution is obtained by maximizing the discounted value of social welfare with respect to the consumption path, under the economic and climatic constraints of the model. CGE models represent the whole economy as system of different interacting sectors (Households, firms, etc.) composed by rational and optimizing agents. Sectors represent aggregates of agents performing the same type of economic activity;

assuming homogeneity of agents along a sector it is possible to describe its behavior through aggregated equations (representative agent). The evolution is governed by equations whose parameters and initial conditions are calibrated with empirical data (social accounting matrices), that account for the relations between the various economic sectors and are based on the assumptions that almost all markets are in equilibrium. They are extensively used also to study the digital transformation, see Acemoglu and Restrepo (2018d).

One of the main limitation of traditional tools of analysis is the representative agent approach. Economy is a complex system, i.e. a system characterized by heterogeneous interacting entities, non-linear feed-backs, out of equilibrium behavior and strong path dependence (Arthur (2013)). These characteristics make difficult the study of the economy with traditional instruments such as general equilibrium models, since they rely on equilibrium and homogeneity assumptions as said above. Thus, to deal with complex systems alternative approaches should be devised. Among the other agent-based modelling (ABM) represents an appropriate paradigm of simulation to address complexity, see Gallegati (2018); Hommes and LeBaron (2018); North and Macal (2007). While traditional approach focuses on relevant variables characterizing a system and aims to write down a system of equations to represents its evolution, ABM represents explicitly individual agents and their interaction in the abstract model of the target system (Borrill and Tesfatsion (2011), Galán et al. (2009)). Once agents and interaction rules are written on a computer, system evolution is studied analyzing the output of several simulations in search for macroscopic regularities (Epstein (2006)).

The aim of this paper is to show the potential of agent-based modelling to investigate challenges like the sustainability transition and the digital transformation. For this analysis the Eurace model has been used. It was developed at the end of a three years European project started in 2006. It was the first attempt at representing a complete economy that comprises all the main markets and mechanism existing in the real world. Motivated by the need of new tools to understand phenomena not captured by mainstream economics, such as the 2008 global financial crisis, it is characterized by non-clearing market and heterogeneous agents with bounded rationality and adaptive expectations and it provides a suitable environment to study non-equilibrium transitory dynamics triggered by changes in policy parameters. It has been used to study and to give insights about different economic challenging themes such as the relation between the amount of credit money in an economy and its macroeconomic instability (Cincotti et al. (2010) and Raberto et al. (2011)), the relation between different capital adequacy requirements and the main economic indicators (Teglio et al. (2012)), the role of resource efficiency investment in industrial sustainability (Tonelli et al. (2016)), the sustainability transition in the energy sector (Ponta et al. (2018)), the effect of austerity measures in crisis times (Teglio et al. (2019)), the housing market (Ozel et al. (2019)) and the role of discriminating bank regulation policies in fostering green investments (Raberto et al. (2019)).

The paper is organized as follows. In section 2 an overview of the literature on modelling the sustainability transition and the digital transformation is presented. Section 3 provides a description of the baseline version of the Eurace model. Section 4 presents a review of the extensions of the baseline version of Eurace model together with the results of computational experiments on the digital trasformation. Section 5 describes the work on the sustainability transition. In particular, the subsection 5.1 presents the extensions of Eurace model, describing those used in the previous works Ponta et al. (2018) and Raberto et al. (2019), and the new ones introduced in this work. In the subsection 5.2, the results of computational experiments are reported. Finally, section 6 concludes the paper.

2 Literature Review

2.1 Modelling the Digital Transformation: a literature overview

From a quantitative point of view, using a modelling approach results to be crucial in order to investigate the potential consequences deriving from the digital transformation, e.g. unemployment increase, productivity change and wage inequality. In this regard, the debate on how to represent the impact of technological advanced digital assets on our economy is still open. Current literature presents different methodologies that have been used in order to model digital technologies and their technological progress.

DeCanio (2016); Hanson (2001); Lankisch et al. (2019) include AI in the production function as a new input factors, whereas various researchers have modelled digital technological progress as factor augmenting, namely through an increase in factor productivity, see Acemoglu (2003). In this respect, Graetz and Michaels (2018); Nordhaus (2015); Sachs and Kotlikoff (2012) represent automation, AI and their technological progress as a capital-augmenting technical change, while Bessen (2016, 2018, 2019) frame automation as labour-augmenting.

However, Acemoglu and Restrepo (2017, 2018a,b,c,d) highlight several weaknesses characterizing the factor augmenting approach in equilibrium model. In particular, Acemoglu and Restrepo (2018d) argue that this approach is not able to frame a significant characteristic of automation, namely the substitution of humans with machines in a growing set of tasks. Moreover, according to these authors, factor augmenting approaches “have a limited scope to reduce the demand for labor" and “relate the impact of technology on the labor share on the elasticity of substitution between capital and labor". By virtue of these considerations, they adopt a task-based approach[1] which “always reduces the labor share and it reduces labor demand and the equilibrium wage unless the productivity gains from automation are sufficiently large". Using this particular approach, digital technological progress is represented through an increase in the range of tasks performed by machines. The criticisms by Acemoglu and Restrepo about factor augmenting technical change nevertheless concerns equilibrium models and they can not be directly addressed to disequilibrium ones, as the agent-based model Eurace presented in the next section[2].

A task-based approach is also used by Aghion et al. (2017) to model AI and its progress.

2.2 Modelling the Sustainability Transition: a Literature Overview

Sustainability transitions are socio-technical transformations that lead to more sustainable modes of production and consumption (Markard et al. (2012)). They are long term processes that involve profound changes at the social, technical, political, institutional, material and organizational level. Sustainability challenges can be found in different domains such as the energy production, transportation, water supply and sanitation. There are different types of sustainability as shown by the 17 sustainable development goals established by the United Nation (UN (2015)). This paper is mainly focused on environmental sustainability and in particular on the sustainable transition in the energy sector.

As mentioned in the introduction, the models most used in climate policy analysis are IAMs and CGE (see Wei et al. (2015)). In IAMs, green transition is modeled looking only at GHGs emissions of the economy and climate policies are modelled only as interventions on the emissions reduction rate. IAMs give the optimal path of emissions reduction and they can be used to compute the social cost of carbon (see below for its definition). But its responses have proven to be very dependent on the choice of parameters and assumptions, as the prescriptionist-descriptionist debate on the discount rate shows (see Arrow et al. (1996)). For instance, the DICE model uses a higher discount rate than that used in the PAGE model in Stern (2008) and then it finds a reduction path that requires lesser efforts for present generation. Although they do not account explicitly for the climate-economy feed-back, CGE models offer a richer representation of policies and they are used to study the propagation through the economic sectors of the effects of policies such as carbon pricing or green subsidies (Gottinger (1998), Liang and Wei (2012)).

Regarding agent-based models, an analogous richness of representation of the climatic transition is found in literature (see Castro et al. (2020)). There are models that explicitly represents the climate economy interaction and could be classified as integrated assessment ABM (Lamperti et al. (2018), Lamperti et al. (2020), Lamperti et al. (2021)). With respect traditional IAMs, being agent based they could deal with heterogeneity of agents and out of equilibrium dynamics; further they use a local damages function that allows to study different channels through which climate affects economy. There are models that represent the whole economy (Gerst et al. (2013), Monasterolo and Raberto (2018) and the above cited IAMs among others) while others examine a single sector (Jonson et al. (2020), Shi et al. (2020)). Often in ABM works there are two or more types of power producers, when the energy sector is present, or firms more in general that differ for the input or machinery type used in the production process in an environment where there are green and brown inputs or machines. The transition is then considered realized when the green inputs or capital use are predominant. Moreover, there are several policy instruments that can be used to foster the ecological transition required by the climate change problem, see for example Krogstrup and Oman (2019). Carbon tax is one of the first measure proposed to combat climate change and it is retained an indispensable part of a policy action aimed to reduce GHGs emissions Stiglitz et al. (2017). Today some form of carbon price is in place or under development in 46 national and 32 subnational jurisdiction (Wordl Bank and Economics (2020)). Carbon tax is grounded on externality theory, according to which climate change can be viewed as an unwanted cost of the production

[1] The task based approach proposed by Acemoglu and Restrepo (2018d) is based on the pioneering contribution of Zeira (1998).

[2] In this respect, the main purpose of equilibrium models is to determine the vector of prices which equals agent's demand and supply, whereas agent-based modelling investigates how agent's actions, strategies and expectations vary out-of-equilibrium and the aggregate dynamics of the system emerging from agents interactions at the micro level, see Arthur (2006, 2010).

and consumption of carbon intensive goods imposed on societies. To eliminate an externality, under efficient market hypothesis it is sufficient to impose a price on the activity that generate the externality equal to its marginal cost. The marginal cost of climate change is called the social cost of carbon (SCC) and it is defined as the change in the discounted value of social welfare caused by an additional unit of GHG emissions (Nordhaus (2017)). However this approach has been criticized because estimates of climate impacts, and then of the SCC, are largely affected by uncertainty. Further, other market failures and distortions prevent the corrective mechanism to succeed (Stiglitz (2019)). There is broad consensus on the fact that carbon tax should be coupled with other policies measures (Stiglitz et al. (2017), Acemoglu et al. (2012)). Among others, feed-in tariff has proven to be one of the most efficient way to speed up the transition in the energy sector Couture and Gagnon (2010). Although there are different implementation scheme, the general purpose of a FIT is to remunerate the renewable energy producer with a guaranteed price for fixed periods. Finally some model consider only fiscal policies, others assess policy mix where financial and or monetary measures stand besides fiscal ones (Monasterolo and Raberto (2016), Monasterolo and Raberto (2018), Lamperti et al. (2021)).

3 The Eurace Model

3.1 The Baseline Version of Eurace

A detailed description of the baseline version of Eurace has been presented in Teglio et al. (2019). The Eurace model encloses various types of heterogeneous economic agents, characterized by bounded rationality, which interact through both centralized and decentralized markets. Moreover, one of its most significant features is represented by stock-flow consistency: each economic agent is represented by a dynamic balance sheet accounting all its assets and liabilities, see Godley and Lavoie (2012). In particular, the base Eurace model is composed by households, consumption goods producers, commercial banks, capital goods producers and two policy makers: the central bank and the government.
In the following the main features of the Eurace agents are summarized.

Households (HHs): they act as investors, workers and consumers. As traders, they invest in Government bonds and stocks emitted by firms and banks. As workers, they can be employed earning a monthly wage in the public or private sector. The latter is represented by firms producing both consumption and capital goods. The sum between the monthly wage and the returns on financial assets, i.e. bonds and stocks, represents the total income on which households determine their consumption budget. In particular, along the line of the buffer-stock saving behaviour theory, the consumption budget is defined according to a target wealth to income ratio, see Carroll (2001).

Consumption goods producers (CGPs): they produce and sell homogeneous consumption goods to households. In order to perform their production processes, firms demand input factors, i.e. labour and capital. The demand of production factors is based on estimates taking into account past sales. In particular, after having calculated the new desired production target, each firm determines the labour demand: if the number of workers actually employed is higher compared to the required employment level, the firm fires extra workers, otherwise it enters the labour market trying to hire additional workers posting new vacancies. For the first round of hiring, the firm sets a starting wage offer. In case of failure in hiring the amount of employees needed, the starting wage offer is increased by a fixed thick and the firms starts a second hiring round. In case of unsuccess, the firm exits the labour market increasing the wage offer a second time: this will represents the starting wage offer for the next hiring session. As for the labour demand, the decision of investments in new capital is strictly linked to the production target. The purchase of new capital is financed following the pecking order theory: first through retained earnings, then debt, then equity. If rationed, the firm decreases its costs to make the total financial needs consistent with the available resources. Moreover, in case of insolvency, the firm defaults and undergoes a restructuring process to increase the equity over debt ratio.

Commercial banks (Bs): they provide credit to CGPs and HHs. After having evaluated the loan and mortgage requests, banks eventually lend money to requiring agents at a price that depends on the default risk of the firm or on the creditworthiness of the household. Each bank is constrained in lending: its capacity is limited by the obligation to respect a capital adequacy ration (CAR). Furthermore, it is worth underling the endogenous money creation which characterizes Eurace: every time a bank issues new credit, new deposits are created.

Capital good producer (KGP): in the base version of Eurace, it produces and sells complete capital goods to CGPs that include both hardware and software. As mentioned previously, capital goods together with workers represent the input factors of CGPs. In order to produce capital goods, the KGP employs only workforce performing the same labour procedures used by CGPs and explained above to hire workers.

Policy makers: Government (G) and Central Bank (CB) are responsible for fiscal and monetary policy, respectively. Government ensures a welfare system managing incomes and expenditures: the former derive from taxation on corporate earnings, consumption (VAT), financial and labour income, whereas the latter are linked to public sector wage bills, unemployment benefits, transfers and interests on debt. If in short of liquidity, G emits perpetuities, that pay a monthly fixed coupon, in order to finance its activity. As far as CB is concerned, it acts as a lender of last resort providing a infinite liquidity to Bs. Moreover, it also sets the policy rate and the capital requirement for Bs.

In the next sections, detailed descriptions concerning the sustainability transition and digital transformation extensions are reported.

4 Modelling the digital transformation in Eurace: a review

In this subsection, a general description of the extension of the Eurace model concerning the digital transformation is presented. For a more detailed presentation please refer to Bertani et al. (2020a,b, 2021).

In order to evaluate the potential consequences deriving from digital transformation, the Eurace model has been endowed with a new population of agents, namely the digital assets developers (DADs). These firms develop and supply a new typology of productive capital which is required by CGPs in order to improve their economic performances. This new digital capital is then integrated within the hard capital goods produced by the KGP. Indeed, in this specific framework, investment goods produced by the KGP are considered as the physical part of a generalized mean of production. In other words, these hard capital goods represent the hardware part of computerized numerical control machines, robots, computer, communication equipment, etc. By virtue of the intrinsic complementarity characterizing hardware and software, capital goods produced by the KGP must be combined together with digital technologies, or software, produced by DADs. Therefore, each unit of hard capital is integrated with a digital asset (or software) license. The presence of this new type of capital good implies the existence of a new market in which DADs compete in order to increase their market share. In fact, digital assets are heterogeneous; in particular, they differ for the productivity or elasticity of substitution associated to their adoption, depending on the framework developed as it is explained below. Moreover, the heterogeneity is also linked to their price. In fact, each DAD varies the price of its products according to a specific strategy: in case of an increase in the amount of licenses sold, it rises the prices exploiting the expansionary phase, otherwise it opt for a price reduction in order to attract new customers.

In this regard, each CGP can adopt only one digital asset at a time and it has the possibility to change the technology adopted. CGPs perform a costs and benefits analysis to evaluate the existence of an effective economic convenience in switching technology. Besides prices, this economic convenience is also related to the ability of the various workers to manage the various software available on the market. In fact, each household is endowed with a set of “digital technologies" skills[3] representing their ability to handle the different kinds of digital assets present in the economy. Therefore, in case of switching, the company must bear training costs for those workers that are not capable to use the new digital technology: the higher the number of employees to train, the higher the switching costs. Training courses are provided by the reference DADs.

Through this assumption we are able to model the presence within the Eurace model of an indirect network effect[4]. In fact, both DADs and CGPs benefits from the “digital technologies" skills of workers. As regards DADs, the higher the number of workers capable of using their assets, the higher the probability to sell their products. As far as CGPs are concerned, during the assessing of a possible digital asset change, the higher the number of workers with that particular digital skill, the lower the transition costs to that alternative technology.

[3] The set of “digital technologies" skills can be as large as the number of DADs present in the economic system.

[4] Economic benefits emerge indirectly from the interaction between different groups, see Belleflamme and Peitz (2018); Farrell and Klemperer (2007).

In this extension, DADs represent the engine of the technological progress within the Eurace model: they embody the essence of Schumpeterian entrepreneurship. In fact, each month, they invest a fixed fraction of their revenues to hire researchers performing R&D activities in order to develop improved versions of their software. Differently from CGPs that hire workers disregarding their education level, DADs employ only graduated workers performing the same labour market procedures of CGPs and the KGP[5].

The probability to develop a more performing version of digital assets is given by the following increasing monotone function with decreasing returns to scale:

$$prob = 1 - \frac{1}{1+\eta M} \tag{1}$$

where M is the cumulated person months since the latest version development and η represents the shape parameter of the probability function. Although η does not represent the rate of technological progress, it influences the innovation process within the economic system in a significant way: the higher the value of η, the higher the probability to develop an improved version of the digital assets and, therefore, the higher the endogenous rate of digital technological progress. It is worth pointing out that the R&D is modelled as an uncertain activity. In fact, a successful development of more performing digital assets is not granted in principle: the probability is equal to 1 only asymptotically for an infinite value of person months.

Being Eurace a versatile model, it leaves room to experiment and implement different approaches to asses possible effects on the production system deriving from the digital transformation. In this respect, two different frameworks have been realized in order to represent the influence of digital technological progress on production processes. In the first framework presented in Bertani et al. (2020a,b), a total factor augmenting approach is used. In this case, technological progress linked to digital assets determines an increase of the total factor productivity (TFP). As regards the second framework, which is presented in Bertani et al. (2021), it has been used an innovative approach, namely the elasticity augmenting approach: technological progress involves an increase in the elasticity of substitution between capital and labour. In other words, digital innovation increase the degree of substitutability between machines and workforce.

In the total factor augmening framework, the technological progress influences the TFP of CGPs production processes. This modelling assumption is underpinned by the empirical analysis carried out in Bertani et al. (2020b). In particular, along the line of the analysis presented in Haskel and Westlake (2017), it has been performed a correlation analysis between growth rates of different measures of productivity and investments for a sample of fifteen countries[6]. Through this investigation, it emerges a highly significant and positive correlation between ICT capital investments (or ICT&Soft&DB investments[7]) and TFP growth rates. Moreover, the analysis highlights also a significant and positive correlation between R&D investments and TFP growth rates. By virtue of these considerations, we have linked the digital technological progress to an increase in the TFP of CGPs production processes, each of which is modelled through a Cobb-Douglas production technology with constant returns to scale:

$$Y_f = \gamma_f N_f^{\alpha} K_f^{1-\alpha} \tag{2}$$

where N_f and K_f are the workforce employed and the capital endowment owned by a generic firm f, respectively. γ_f represents the TFP, which is heterogeneous acress CGPs. The latter is modelled as follows[8]:

$$\gamma_f = \exp(1 + \eta_\gamma \kappa_d) \tag{3}$$

where η_γ is a scale parameter homogeneous across firms and κ_d represents an index number which is representative of the technological progress of the digital assets adopted. A successful R&D activity, performed by

[5] HHs are characterized by five different education level. DADs hire workers with a high degree of education, i.e. from the third upward. Although CGPs hire workers disregarding their education level, they prioritized highly educated workers during the labour market sessions

[6] The fifteen countries considered are: Italy (IT), Germany (DE), Netherlands (NL), United Kingdom (UK), United States (USA), France (FR), Sweden (SW), Spain (ES), Denmark (DK), Portugal (PT), Austria (AT), Finland (FI), Ireland (IE), Greece (GR) and Luxembourg (LU). The analysis is focused on a time period of twenty-two years, namely, from 1995 to 2016. Moreover, the time span is also divided in a pre and post crisis time period, i.e., from 1995 to 2007 and from 2008 to 2016.

[7] ICT capital investments are composed by tangible investments in ICT equipment and intangible investments in software and database. The combination between these two typologies of investments results to be crucial by virtue of the intrinsic complementarity characterizing hardware and software: the hardware is useless without software and vice versa. Through the combination of these investments we are capable to evaluate the effective importance that digital technologies have on our productive system.

[8] The TFP shape has been modelled as exponential in order to represent a significant influence of digital technological progress on our economy. Moreover, OECD data on TFP growth rates suggest a long-term exponential trend of TFP, albeit with a declining rate (https://stats.oecd.org).

the reference DAD d, determines an update of the digital assets adopted by the CGP f. In particular, κ_d is increased by a fixed tick equal to δ_κ. Alternatively, the firm could increase its TFP adopting more technologically advanced digital assets, namely changing its digital assets supplier.

Through a total factor augmenting approach, technological progress affects input factor equally. An increase of the TFP, related to the adoption of more technologically advanced digital assets, determines a decrease in the amount of inputs needed, both capital and labour, which in turn leads to a production costs reduction. This fact is then reflected by a decrease in the consumption goods sales price. Therefore, digital technological progress allows firms to save money to compete in the consumption goods market. Indeed, the lower the price, the higher the probability to sell their products, since the price is assumed as discriminating factor in the consumption goods choice by households.

4.1 The new Elasticity Augmenting Approach

In the second framework developed, to analyze long term consequences related to the digital transformation, we replace the Cobb-Douglas function used to model CGPs production processes with a Leontief technology, in which input factors are represented by complementary organizational units[9] (OUs). In turn, the contribution of each unit is given by the combination between labour and capital.

Moreover, in this case, the digital technological progress affects the elasticity of substitution between input factors, i.e. labour and capital, within organizational units. In this regard, an increase in the value of the elasticity of substitution σ determines a change of the shape of the isoquant curves, as shown in Fig. 1. The elasticity σ influences the isoquant shape, but it is not a measure of its curvature. Rather than a curvature parameter, de La Grandville (1997) suggests to characterize it as an efficiency parameter: fast economic growths could be related to high value of elasticity. According to de La Grandville (1989), the higher the value of the elasticity of substitution, the higher the benefit (in terms of additional output) linked to a relative input price change and, in turn, the faster the potential growth that an economy could experience.

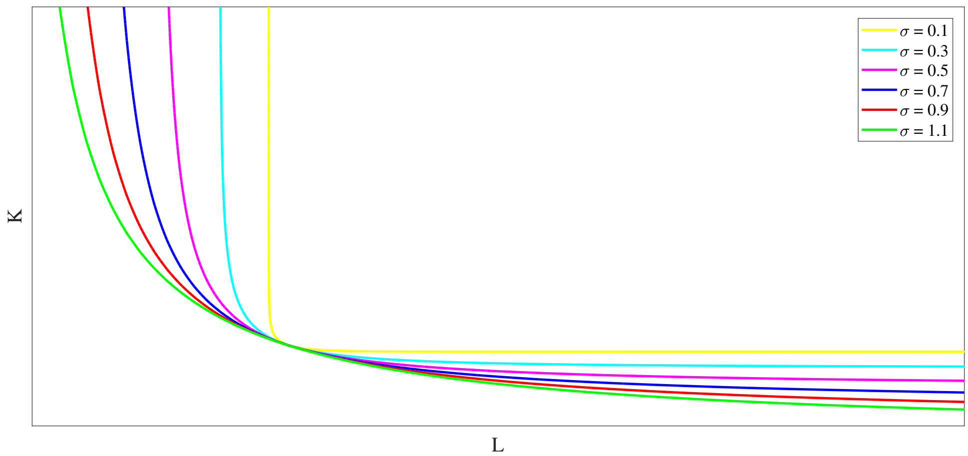

Fig. 1 The figure displays the shape of an isoquant curve of a CES production function for different values of the elasticity of substitution σ.

This innovative approach represents a new consistent way to model the influence of digital technologies on our production system. In particular, for those models in which tasks performed by workers are not heterogeneous, it can be considered as a valid alternative to the so-called task-based approach: an increase in the elasticity of substitution can be seen as an increase in the range of tasks in which machines can replace

[9] An organizational unit represents a group of workers organized according to a specific criterion. According to Mintzberg (1979), we can distinguish between two different criteria in order to group employees, i.e. the functional criterion and the divisional one. In the first case, workers are grouped by knowledge, skills, work process or function, while in the second case human resources are grouped to produce (or provide) a specific product (or service) or to serve a specific area or client.

workers. Besides these new modelling assumptions, this second framework has maintained the same characteristics of the total factor augmenting one.

From a theoretical point of view, the production of a generic firm can be represented by the interaction between OUs according to the following function:

$$Y = min[\gamma_1 Y_{OU_1}, \gamma_2 Y_{OU_2}, ..., \gamma_n Y_{OU_n}] \tag{4}$$

where Y_{OU_i} is the contribution provided by the i-th OU to the production Y, while γ_i represents the coefficient of production of the OU considered. The firm complexity is given by the number of the OUs: the higher the number of OUs, the higher the firm complexity since the number of the interactions required in order to coordinate the production increases. A regards the reasoning behind the complementarity assumption, it is related to the irreplaceable nature of OUs tasks, especially in case of a functional grouping; for instance, the function performed by the manufacturing OU can not be performed by the marketing or R&D unit, and vice versa. By virtue of this reasoning, in this particular Leontief function, the concept of complementarity applies to knowledge, and not to labour and capital.

The contribution Y_{OU_i} of each OU can be represented combining capital K and labour L through a constant elasticity of substitution (CES) production technology with constant returns to scale, see Arrow et al. (1961):

$$Y_{OU_i} = [\alpha_i K_i^{\frac{\sigma_i - 1}{\sigma_i}} + (1 - \alpha_i) L_i^{\frac{\sigma_i - 1}{\sigma_i}}]^{\frac{\sigma_i}{\sigma_i - 1}} \tag{5}$$

where α_i represents the distribution parameter and σ_i the elasticity of substitution between K and L.

Eq. 4 allows to represent the overall production process of companies in a more realistic way, allowing to distinguish between the different activities carried out and education levels featuring the workforce. For this reason, in the Eurace model, we integrate this conceptual production function to represent production within CGPs. In particular, for the sake of simplicity, we model each CGP production process considering only two functional OUs:

$$Y = min[\gamma_1 Y_{OU_1}, \gamma_2 Y_{OU_2}] = min\Big\{\gamma_1 [\alpha K^{\frac{\sigma-1}{\sigma}} + (1-\alpha) L_u^{\frac{\sigma-1}{\sigma}}]^{\frac{\sigma}{\sigma-1}}, \gamma_2 L_g\Big\} \tag{6}$$

The first organizational unit OU_1 is representative of the manufacturing process inside the company and it includes only undergraduate workers L_u, characterized by a low degree of education. This OU is endowed with hard capital goods K on which digital assets are integrated[10]. Graduate workers L_g with a high educational level are grouped within a second unit, i.e OU_2, in which all the intellectual tasks are performed. In this unit, we do not consider the presence of machinery in order to perform their work. Therefore, the technological progress study is focused only on the manufacturing process.

Within each CGP, if the reference DAD manages to improve its software, the elasticity of substitution σ increases by a fixed thick equal to δ_σ. Alternatively, as in the total factor augmenting framework, CGPs can increase their σ adopting a more technologically advanced digital technology.

4.2 Results on Digital Transformation: an Overview

Results on the digital transformation are summarized in Table 1.

Both the Eurace frameworks developed are able to capture interesting features belonging to the increasing returns world described by Arthur. In particular, the model displays the so-called winner-takes all effect: in the long-term a market leader emerges within the digital technologies market detaining most of the market shares. This phenomenon is strictly related to the competitive behavior displayed by DADs that compete on the market adopting an aggressive pricing strategy and trying to develop improved versions of their software. Moreover, this economic dynamics is also related to the presence of indirect network effects within the system, as mentioned in the previous section.

The total factor augmenting framework is investigated with two different pricing mechanisms, namely a collusive pricing mechanism and a competitive pricing one. In the “price collusion" regime, DADs adopt the

[10] As mentioned previously, each unit of hard capital is combined with a software license.

Table 1 The table summarizes most relevant results concerning the two Eurace frameworks related to the digital transformation.

Total factor augmenting framework	Low rates of digital technological progress in case of collusive behaviors
	Presence of increasing returns world phenomena (market instability, unpredictability, winner-takes all, indirect network effects, etc.)
	High unemployment levels for high rates of digital technological progress: compensation mechanisms are not able to absorb all the technological unemployment
	Converse concentration effect: low prices with high market concentrations

Elasticity augmenting framework	Presence of increasing returns world phenomena (market instability, unpredictability, winner-takes all, indirect network effects, etc.)
	High unemployment levels for high rates of digital technological progress: compensation mechanisms are more effective but not able to absorb all the technological unemployment. This phenomenon affects only employees characterized by a low education levels
	Productivity trends aligned with empirical evidence: increase in the labor productivity and decrease in the capital productivity

same license price over time, whereas, in presence of competitive behavior, DADs can freely manage prices according to their business strategies[11]. In case of collusion, the economy experiences low rates of digital technological progress: the absence of a competitive behavior among DADs does not stimulate the innovation process within the economic system. Indeed, in the "price competition" regime, the system is characterized by higher level of digital technological progress.

The "price competition" regime is also characterized by the presence of an emerging phenomenon that we call "converse concentration effect". The latter leads to "competitive concentrations" in the digital assets industrial sector, according to which very concentrated markets present lower average license prices by virtue of aggressive decision making strategies.

From a macroeconomic perspective, for high rates of digital technological progress, the economy experiences huge levels of unemployment: compensation mechanisms are not able to counteract all the technological unemployment caused by the technologically advanced digital assets within CGPs. In particular, Eurace displays two different compensation mechanisms: the mechanism "via decrease in prices" and the "via additional employment in the capital goods sector" one. According to the former, the technological progress allows CGPs to reduce production costs and sell their products at a lower price. In turn, this fact leads to an increase in sales that determines an increase in the demand of labour by firms. As regards the latter, it is linked to the increase in the employment level within companies producing capital goods, namely the KGP and the DADs. However, DADs are not able to absorb all the technological unemployment caused by their digital assets within CGPs, and this fact leads to an explosion of unemployment in the economic system.

As far as the unemployment level is concerned, the two frameworks show a significant difference. In fact, through a total factor augmenting approach, the technological progress affects in the same way the input factors productivity, leading to a decrease in the demand of both labour and capital. In this case, the compensation mechanism "via additional employment in the capital goods sector" works only within DADs that are able to increase their revenues over time varying their prices.

In the elasticity augmenting framework, the digital technological progress determines a replacement of human beings with machines because of the increase in the degree of substitutability between production factors within OU_1. Indeed, from a financial perspective, the adoption of capital results to be more convenient. In this regard, if the adoption of capital is cheaper, the ratio between the theoretical optimum quantities[12] of capital $\hat{K}$ and labor $\hat{L}$ increases exponentially with the elasticity of substitution σ, see Fig. 2. For this reason,

[11] In case of an increase in sales, each DAD raises its price trying to exploit a potential expansionary phase, otherwise it opts for a price reduction in order to increase its market share. In fact, a lower price could determine an increase in the number of users (see Bertani et al. (2020a) for further details).

[12] The optimum quantities of both capital and labour in order to meet the planned production are determined through the mathematical optimization methods of Lagrange multipliers, see Bertani et al. (2021) for further details.

the economy experiences an increase in the demand of capital and a decrease in the demand of labour within CGPs industrial sector. The ratio between the optimum quantities of capital $\hat{K}$ and labor $\hat{L}$ is reported in the following equation:

$$\frac{\hat{K}}{\hat{L}} = \frac{(\alpha w)^{\sigma}}{(\beta r c_K)^{\sigma}} \tag{7}$$

where α and β are the distribution parameters of the CES production function, w is the average wage within OU_1, r and c_K represent the rental rate proxied by the corporate loan rate and the unit cost of the capital[13].

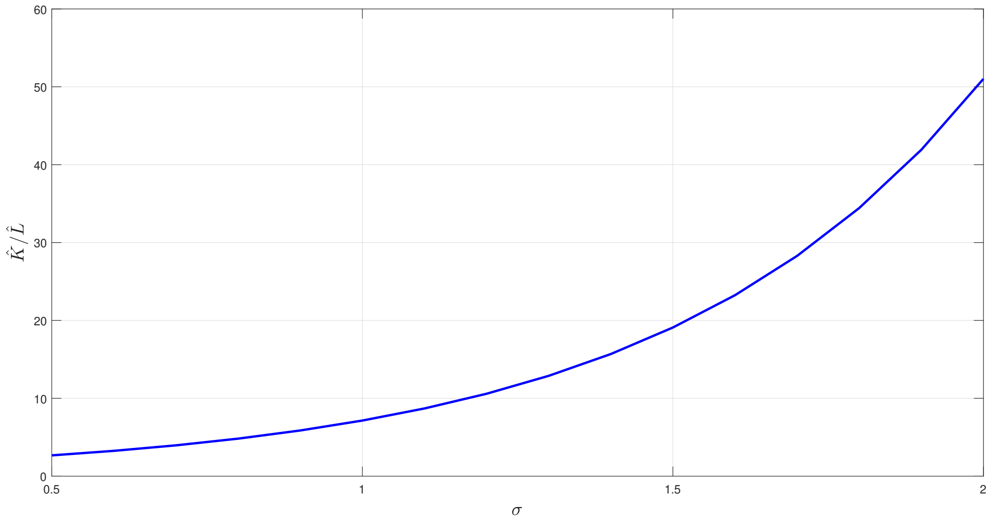

Fig. 2 The figure shows the variation of the ratio between the optimum quantities of labour and capital to meet the planned production with the elasticity of substitution σ.

In this second framework, the compensation mechanism "via additional employment in the capital goods sector" functions more effectively, namely it works within both the KGP and DADs, and for high values of η, i.e. the shape parameter of the innovation probability function (Eq. 1), the unemployment is lower compared to the total factor augmenting framework[14].

Furthermore, in the elasticity augmenting approach, the system shows a decrease in the capital productivity and an increase in the labour productivity over time. This trend is representative of what is really experienced by our economy: in most of OECD countries, empirical evidences show that the capital productivity has been decreasing over the past twenty years, whereas the labour productivity has been growing even if faintly, see Bertani et al. (2021); OECD (2019).

5 Modelling the sustainability transition in Eurace: new results

5.1 Model improvements

In order to study the sustainable transition an integrated assessment framework of Eurace model is developed starting from the Eurace model described in Ponta et al. (2018) and in Raberto et al. (2019). In Ponta et al. (2018) the base line of Eurace is extended adding an energy sector that supplies the electricity demanded on a monthly basis by CGPs (electricity is introduced as a third input factor of the production process of CGPs). The energy sector was composed by:

[13] The values used in order to obtain Fig. 2 are: $\alpha = 0.3$, $\beta = 0.7$, $w = 1$, $r = 0.03$, $c_K = 2$

[14] As mentioned previously, η does not represent the rate of technological progress within the economy. However, it influences the innovation rate significantly. Indeed, the higher the value of η, the higher the endogenous rate of technological progress.

Renewable power producer (RP) It uses capital goods (solar panel) to produce electricity from renewable sources. The electricity produced is directly proportional to the number of solar panel installed. The RP decides on a monthly basis the quantity of new solar panels to buy evaluating the net present value of the additional earnings implied by the investment. The new solar panels eventually bought are immediately delivered by the KGP agent.

Non renewable power producer (PP) It produces electricity using a non renewable sources, oil, according to a decreasing return to scale production function. Since in the model it is assumed that RP has grid priority, the electricity produced by the PP is the difference between the electricity demanded and that produced by the RP; the oil consumed is determined accordingly.

Foreign economy (FE) It is a stylized foreign country that exports the oil needed by the PP agent. It sets the oil price and collects oil payment that accumulates as liquidity.

In order to investigate the sustainability transition, in this paper, the Eurace version presented in Ponta et al. (2018) has been enriched introducing a climate agent, that receives greenhouse gases emissions coming from economic activities, updates its internal variables, and then causes physical damages to the economy.

Further,with respect to the version presented in Raberto et al. (2019), the capital good sector has been enhanced adding a new type of producer, and the investment decision rule of the CGPs is modified to account for the new capital goods sector structure.

Climate Box Following Nordhaus' DICE model (see Nordhaus and Sztorc (2013)), the climate is represented as a three homogeneous layers system, the atmosphere, the upper oceans and the lower oceans, each with its own temperature and stock of carbon. The layers are overlapping and each one exchanges masses of carbon and heat only with its adjacent layers; the atmosphere receives in addition emissions coming from economic activities. Carbon stocks and temperatures are updated every five years. The stocks evolution is represented as the linear system

$$M_{at}(t+1) = M_{at}(t)b_{11} + M_u(t)b_{21} + E(t) \tag{8}$$

$$M_u(t+1) = M_{at}(t)b_{12} + M_u(t)b_{22} + M_l(t)b_{32} \tag{9}$$

$$M_l(t+1) = M_u(t)b_{23} + M_l(t)b_{33} \tag{10}$$

where M_{at}, M_u and M_l are the stocks of carbon of respectively the atmosphere, the upper and lower oceans, E represents quinquennial CO_2 emissions and $b_{i,j}$ expresses the fraction of carbon that layer i transfers to layer j. The accumulation of GHGs in the atmosphere influences the atmospheric temperature. Following again Nordhaus, to represent temperature evolution, the atmosphere and the upper oceans layers are considered as a single layer. Calling T_{at} and T_{oc} the variation of temperature with respect to pre-industrial level of respectively the atmosphere and the lower oceans, the temperature dynamic is given by

$$T_{atm}(t+1) = T_{atm}(t) + c_1\left(F(t+1) - T_{atm}(t)\frac{f_{CO_2}}{tx_{2CO_2}}\right) - c_3(T_{atm}(t) - T_{oc}(t)) \tag{11}$$

$$T_{oc}(t+1) = T_{oc}(t) + c_4(T_{atm}(t) - T_{oc}(t)) \tag{12}$$

where c_1 is the inverse of thermal capacity of the atmosphere; the constants c_3 and c_4 are related to thermal capacities and rates at which heat is exchanged between the two layers; F is the additional forcing due to changes in CO_2 concentration in the atmosphere and it is given by

$$F(t) = f_{CO_2} log_2\left(\frac{M_{at}(t)}{M_{at}^{1750}}\right) \tag{13}$$

where f_{CO_2} is the additional energy per unit time and surface that the atmosphere absorbs after a doubling of CO_2 concentration with respect to pre-industrial level. Finally, tx_{2CO_2} is a feedback parameter used to calibrate the model, that represent the temperature increase due to a doubling of CO_2 concentration. Initial values of stocks and temperatures and parameters are picked from Nordhaus and Sztorc (2013).

To model how climate affects economy we have followed the approach outlined in Lamperti et al. (2018). The climate causes damages to every firm destroying a fraction of its capital stock. Fractions are picked up from a probability density function whose properties are dependent on the temperature. It sends numbers in the range $[0;1]$ that stand for the fraction of the damaged target, i.e. a firm receiving a damage s on its capital stock K will see a reduction of its capital stock

$$\Delta K = -sK \tag{14}$$

Damages are picked up from a beta distribution

$$f(s;a,b) = \frac{1}{B(a,b)} s^{a-1}(1-s)^{b-1} \tag{15}$$

where $B(a,b)$ is the beta function. The parameters a and b regulate the mean and the right tail of the distribution and are functions of the atmospheric temperature increase and variability (variance of previous ten records).

5.1.1 PP and KGP improvements

With respect to the model in Ponta et al. (2018), the PP agent, burning oil to produce energy, also produces GHGs emissions according to the following formula:

$$\mathcal{E} = i_{CO_2} O \tag{16}$$

where O is the oil burned and i_{CO_2} is the carbon intensity that characterizes the energy production process. It represents the emissions produced burning one unit of oil. The carbon intensity is constant during all the simulation time of the experiments performed. Its value is chosen such that emissions of the first five years are equal to those relative of the period 2015-2020 as given in Nordhaus and Sztorc (2013).

In Raberto et al. (2019) the Eurace model is charactherized by capital goods heterogeneity with respect to electrical intensity, i.e. the electricity used to produce a unit of consumption good. Every month the KGP supplies new capital with electrical intensity decreased by 2% with respect to the its previous month value. When CGPs invests in new capital their capital stock composition changes and the average electrical intensity decreases. In this paper, the capital goods sector is composed by two types of KGP, i.e. green and brown. The green KGP uses only a $1-dv$ fraction of its workforce to the production process while the remaining workers improve the intensity of the new machines by a 2% every month. The brown KGP devotes all its workforce to the production without changing electricity intensity. Since KGPs set the capital price putting a mark-up on unitary costs and since labor is the only input of their production process the price is given by

$$p_k = (1-\mu_k)\frac{w}{\gamma_k(1-dv)} \tag{17}$$

where μ_k, the mark-up, and γ_k, the labor productivity, are equal for both KGPs; w is the mean wage. Since dv is zero for the brown KGP, the price of brown capital goods is lower (if wages payed by the KGPs are equal). The advantage of green capital goods due to the implied energy saving on the unit of output is counterbalanced by increased price due to greater unitary costs.

Every quarter CGPs can chose to buy new capital goods in order to meet the new production plans, determined on expected demand evaluation. The new investment implies a change in the electricity intensity i of a firm dependent on the its previous intensity and on the intensity of the new machines:

$$i(t+1) = \frac{K(t)}{K+\Delta K} i(t) + \frac{\Delta K}{K+\Delta K} i_{KGP}(t) \tag{18}$$

where $K(t)$ is the capital of the firm before the investment, ΔK is the new capital bought and $iKGP$ is the electrical intensity of the capital bought. With respect to the work in Raberto et al. (2019) the intensity decreases only if green KGP is chosen.

CGPs select one of the KGPs randomly assigning probabilities through a logit model based on the net present value of additional earnings implied by the two types of new capital, for instance the probability of choosing the green KGP P_g is given by

$$P_g = \frac{1}{1 + e^{\gamma(NPV_b - NPV_g)}} \tag{19}$$

where NPV_b and NPV_g are the NPVs associated respectively to the brown and green capital goods.

As explained in Raberto et al. (2019), the NPV of new investment is the sum of 4 terms: new capital cost, additional revenues due to the increased production, additional electricity cost due to the increased production and electricity savings or additional costs due to the change in electricity intensity of capital stock. Since the second term do not depend on capital price or intensity, it is equal for the NPVs associated to the KGPs. Then, NPV difference is determined only by the difference between capital prices and the difference between intensities of the new capital goods.

5.1.2 Policies

In this paper a comparison between a carbon tax and a feed-in tariff is investigated. The feed-in tariff scheme considers the government that sets a guaranteed price p_E^r for renewable energy. The government finances through its tax revenues the difference with the market energy price for every unit of energy sold by the RP. See Ponta et al. (2018) for further details.

The carbon tax policy considers the government that sets a price p_{CO_2} on the unit of GHGs emission and collects the corresponding revenues $p_{CO_2}\mathscr{E}$. Since the PP is the only GHGs emitter it is also the only agent that pays the tax.

Both the guaranteed price and the carbon price are set exogenously and kept constant during a single experiments; they are the parameters that characterize our experiments.

The carbon price values used have been chosen in order to produce predetermined values of the ratio between the carbon tax payed and the PP revenues, that is given by

$$\frac{p_{CO_2}\mathscr{E}}{p_E E} \simeq \frac{p_{CO_2} i_{CO_2}}{(1+\mu_E)(p_O + p_{CO_2} i_{CO_2})} \tag{20}$$

where p_O is the price of oil and μ_E is the mark-up that the PP puts on unitary cost to determine the energy price.

The carbon tax revenues are not devoted to any particular use, they are summed to the government budget.

5.2 **Computational results**

The methodology of this study is based on Monte Carlo computational experiments. Each of the five scenarios considered is simulated with ten different seeds of the pseudo-random number generator. Table 2 summarizes the parameters values defining each scenario considered, while results are shown in Fig. 3 - 6.

Scenario	*Symbol*	p_E^r	p_{CO2}
(i)	BAU	0	0
(ii)	F1	0.05	0
(iii)	F2	0.1	0
(iv)	CT1	0	16
(v)	CT2	0	27

Table 2 The table reports the parameters values characterizing the scenarios studied together with the symbols used to label them in the figures from 3 to 6

Scenario (i) is the business as usual case (BAU in figures). It has no policies implemented. In scenarios (ii) and (iii) a feed-in tariff mechanism is implemented. In scenarios (iv) and (v) a carbon tax is implemented. Simulations across different scenarios differ only for the values of the guaranteed renewable energy price p_E^r and for the carbon price value p_{CO_2} that are held constant during all the 20 years time span of each simulation.

Figures from 3 to 6 show the boxplots of the distributions of the relevant economic and climate variables. In particular, except for those relative to atmospheric temperature and carbon stock, all the boxplots show the distribution of the temporal averages over the entire time of simulations obtained for every seed. Concerning temperature and carbon stock, boxplots show the distribution of their final value. On each box the red line indicates the median of the distribution, the lower and higher extremes of the blue box represent respectively the 25^{th} and 75^{th} percentile, the dashed line extends from the minimum to the maximum value not considered outliers. Finally, outliers,if any, are represented individually with the + symbol.

Figure 3 shows that a feed-in tariff scheme is effective in reducing GHGs emissions: the scenario with the higher p_E^r leads to significant lower value of atmospheric temperature, panel (a), atmospheric carbon stock, panel (b) and emissions, panel (c), with respect to the BAU case and the other scenarios. Furthermore, panel (d) shows that the feed-in tariff is effective in greening the energy sector. The table 3 reports the mean and the standard deviation across all the seeds of the final year value of total fraction of damaged capital for every scenario considered. Although the standard deviations are high and similar, under the higher feed-in tariff scenario the mean value is lower with respect to all the other cases but the higher carbon tax scenario. As concern its fiscal impact, figure 5(c) and 6(a) and (b) show that the feed-in tariff do not lead to an increase of the general tax rate (VAT and labor), nor it has remarkable effects on government deficit and debt. These may be explained arguing that the cost of the policy is small compared to GDP, see panel (c) of fig6. However, we expect a different picture for higher values of the guaranteed price p_E^r as outlined in Ponta et al. (2018).

Scenario	μ_{CD}(%)	σ_{CD}(%)
(i)	41	11
(ii)	42	9
(iii)	34	10
(iv)	41	14
(v)	34	10

Table 3 The table reports the mean μ_{CD} and the standard deviation σ_{CD} across all the seeds of the final year value of total fraction of damaged capital for every scenario considered. The subscript CD stands for climate damages.

Figure 4(c) shows that the higher carbon tax is effective in electricity intensity improvements with respect to BAU case. The tax determines a higher energy price, see fig.4(a), that increases the relative weight of energy savings in the NPV evaluation by CGPs. Consequently, the fraction of capital bought from the green KGP over the total capital delivered increases with respect to the BAU case, as shown in panel (b), particularly under the higher carbon tax scenario, when the green investments clearly exceeds brown ones. However, we observe a rebound effect on energy savings, since the energy consumption do not decrease despite the intensity reduction, as shown in panel (d). These effect determines carbon tax performance on climate mitigation as shown in figure 3; both temperature anomaly, atmospheric carbon stock and GHGs emissions under a carbon tax scenario are quite similar to those under BAU. Moreover, since the only channel through which the carbon tax could affect the share of renewable energy is via reduction of the total energy consumption, the rebound effect makes negligible the contribution of the policy in changing the composition/share of energy source used in the economy, as shown in fig.3(d). Figures 5(c) and 6(a) and (b) show that, as for the feed-in tariff, the carbon tax has no pronounced effects on general tax rate and on government deficit and debt. This is due to the fact that carbon tax revenues are negligible compared with the GDP, as shown in panel (d) of fig6. As regards the economic impact, fig.5(d) indicates that the policy does not reduce the GDP; furthermore, it does not lead to unemployment increase with respect to the BAU scenario, as panel(a) of fig.5 indicates.

6 Conclusion

ABM models allow the study of complex phenomena such as the digital transformation and the sustainable transition.

In order to show how ABMs helps in understanding these themes the EURACE model have enriched adding new agents with respect to the base version presented in section 3.1. In particular to study the sustainable transition a climate agent to account for climate economy feed-back have been introduced. GHGs emissions produced from fossil fuels combustion used by the PP accumulates on the atmosphere causing a temperature increase. The climate affects every firm with different intensities, destroying a random fraction of the capital stock.

Moreover also the capital good sector has been enriched adding a green KGP that devotes a fraction of its

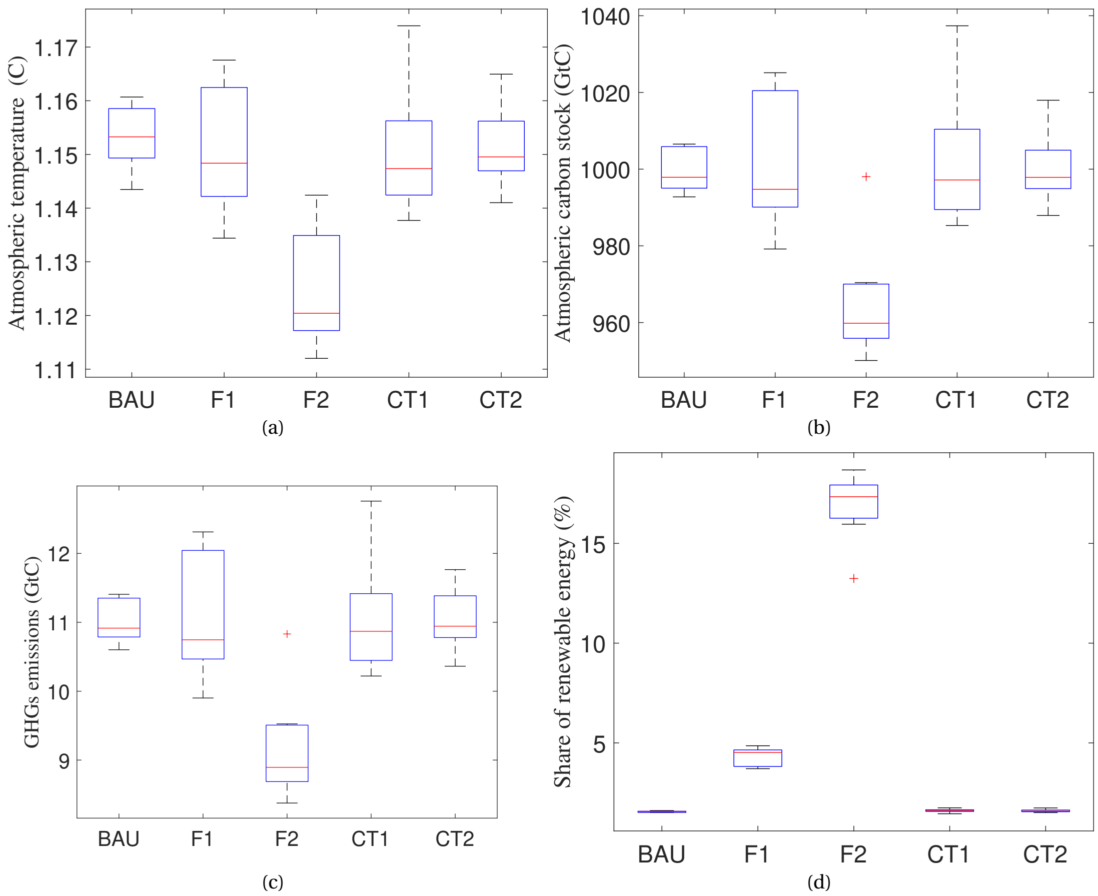

Fig. 3 The figure shows various boxplots for the five scenarios considered. In particular it shows the distribution of the final value of (a) atmospheric temperature and (b) atmospheric carbon stock, and the distribution of the time averages of (c) the annual GHGs emissions and (d) the share of renewable energy.

employees to improve electrical efficiencies of the new capital goods produced. CGPs chose one of the KGP to buy new capital evaluating the net present value of the additional earnings associated with the machine type.

To deal with the digital transformation we have enriched the base version of the Eurace model with a new population of agents, namely the digital assets developers. These agents develop and supply a new type of capital, which is integrated by consumption goods producers within the hard capital (produced by the capital goods producer) in order to perform their manufacturing processes. In particular, we have developed two different frameworks. In the first case, digital technological progress affects the total factor productivity of consumption goods producers, whereas, in the second case, it influences the elasticity of substitution between capital and labour.
The results show that while a feed-in tariff with a sufficiently high guaranteed price is effective in greening the energy sector and then in reducing GHGs emissions, carbon tax seems unable to change the emissions path. In particular we observe a rebound effect on energy savings: the expected savings due to electricity intensity reduction are counterbalanced by an increase in energy consumption.

As regards the digital transformation, in both frameworks interesting phenomena characterizing the so-called increasing returns world occurs, e.g. the winner takes most phenomenon.
In case of high rates of technological progress, the Eurace model displays a significant increase in the unemployment level. In this respect, although the model captures the presence of the compensation mechanisms "via decrease in prices" and "via additional employment in the capital goods sector", these are not sufficient to counteract all the technological unemployment caused by technologically advanced digital assets within consumption goods producers. However, it is worth highlighting that this result is also influenced by the absence of other compensation mechanisms, as the "via new products" one, which represents one of the most effective forces in counteracting process innovation.

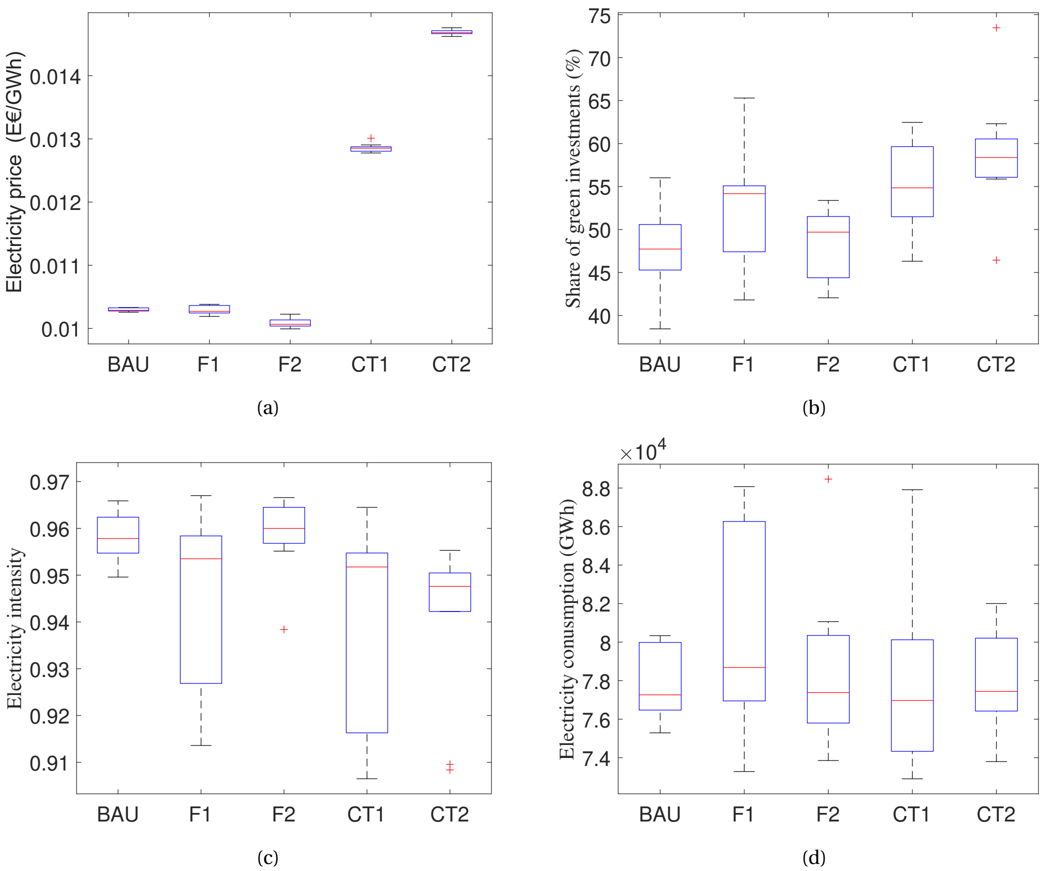

Fig. 4 The figure shows various boxplots for the five scenarios. In particular it shows the distribution of the time averages of: (a) market energy price, (b) share of green investments, (c) total electricity intensity and (d) electricity consumption.

Comparing the two frameworks developed, for high rates of digital technological progress, the total factor augmenting framework shows a higher level of unemployment compared to the elasticity augmenting one. In fact, influencing the total factor productivity, the technological progress determines a decrease of the demand of both labour and capital, while affecting the elasticity of substitution it determines a replacement of workers with machines by virtue of the lower costs of capital. Therefore, in the elasticity augmenting framework, the compensation mechanism “via additional employment in the capital goods sector" functions more effectively because it affects also the hard capital good producer.

Future research on the sustainable transition will investigate the long term impacts of the policies considered here, in order to improve the evaluation of the economic costs of each measure. Further, we will include in our analysis other policy measures aimed to financing the environmental transition, such as green bonds or green quantitative easing. Further developments on the digital transformation will be related to the introduction of specific policy interventions, e.g. the so-called robot tax or a reduction of the working hours, aimed at counteracting the massive technological unemployment which occurs for high rates of digital technological progress.

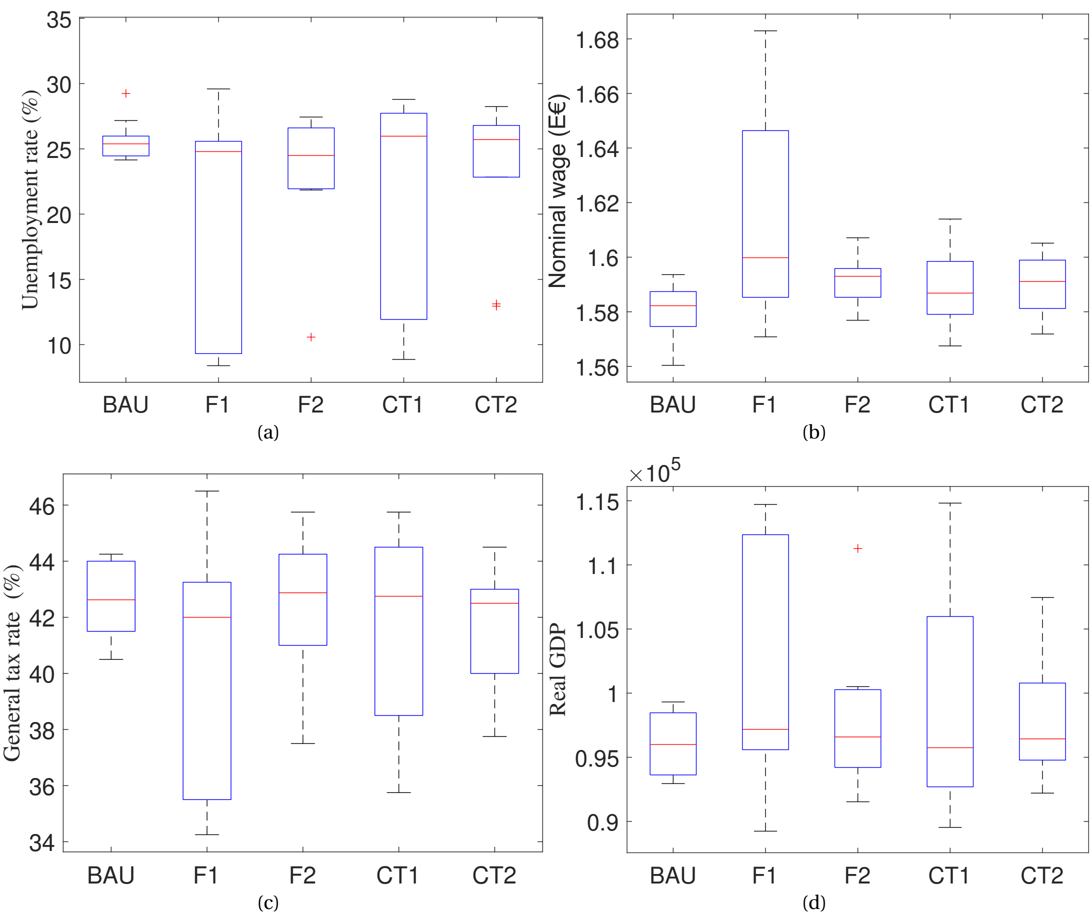

Fig. 5 The figure shows various boxplots for the five scenarios considered. In particular it shows the distribution of the time averages of: (a) unemployment rate, (b) nominal wage, (c) general tax rate and (d) real GDP.

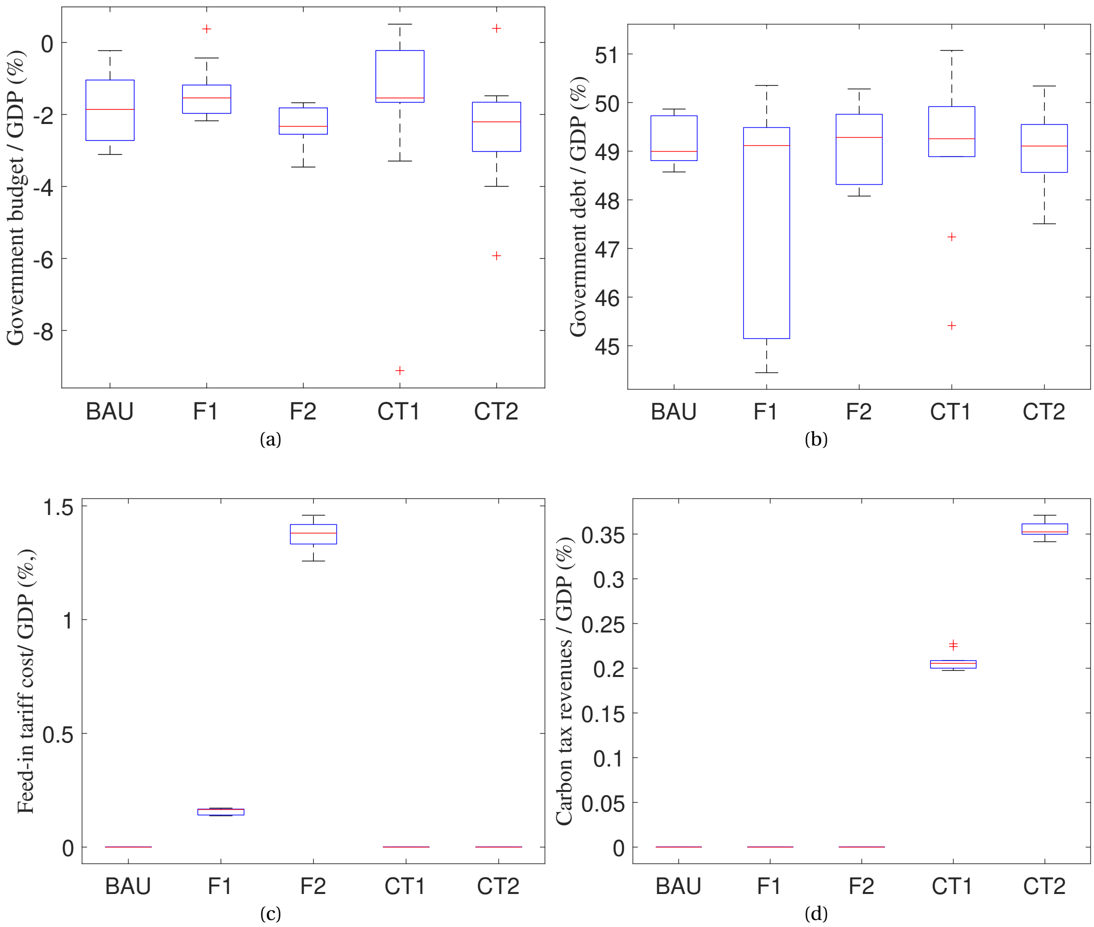

Fig. 6 The figure shows various boxplots for the five scenarios considered. In particular it shows the distribution of the time averages of: (a) government deficit over GDP, (b) government debt over GDP, (c) feed-in tariff cost over GDP and (d) carbon tax revenues over GDP.

Conflict of interest

The authors declare that they have no conflict of interest.

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