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A dynamic CGE model for jointly accounting ageing population, automation and environmental tax reform. European Union as a case study

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ABSTRACT

We develop a dynamic Computable General Equilibrium model based on the combination of different versions of GTAP utilities where alternative scenarios on ageing population trends are combined with projections on the incidence of automation into production processes and the adoption of unilateral decarbonisation policies. By simultaneously controlling for these different challenges that especially developed countries should face in the next decades, it is possible to disentangle non-linear mechanisms that will influence sustainability of public budget when the three issues are jointly combined. The European Union is taken as a case study. The first result is that ageing trends will impact fiscal sustainability reducing the EU capacity to respect the Stability and Growth Pact parameters. Second, when also considering technical change related to automation and robotics in the production process, fiscal sustainability will improve only in the case of input-neutral technological change. On the contrary, if biased technical change produces unemployment impact, negative impacts of ageing population are reinforced by automation. Third, the adoption of an environmental tax, here modelled in the form of a carbon price, leads to an improvement in environmental sustainability but has non-linear effects of fiscal sustainability.

1. Introduction

Population ageing is a key challenge the world is going to face. This is a long-term issue, mostly due to the combination of a decrease in fertility rates and an increase in life expectancy (Beard et al., 2016). During recent decades, the pace of population ageing is much faster than in the past. According to the World Health Organization (WHO, 2015), between 2015 and 2050, the proportion of the world's population over 60 years is expected to nearly double (from 12% to 22%). This demographic trend will characterise all countries, with a stronger impact in developed countries. Among these, the European Union (EU) is an area particularly at risk.[1]

According to the recent report published by the European Commission (EC, 2018a), the total population in the EU is projected to increase from 511 million in 2016 to 528 million over the next three decades, but the working-age population (within the age group of 15–64 years) will decrease significantly from 333 million in 2016 to 299 million in 2050 due to a reduction in fertility rates, an increase in life expectancy and low immigration flows. The proportion of young people (0–14 years) is projected to remain almost constant in the EU, falling from 16% to 15% of total population. The individuals over 65 years will become a much larger share, rising from 19% to 29%, while the share of those aged 80 years and over will increase from 5% to 11%, becoming almost as large as the young population. Conversely, the working-age population will become substantially smaller, declining from 65% to 57% of the total population. As a result, the old-age dependency ratio is projected to rise significantly across the EU, from 29.6% in 2016 to 50.4% in 2050 on average.[2]

This trend in population has many implications on economic systems. The first one is that the increase in old population leads to a rise of expenditures for healthcare and pensions. In the EU, public health expenditures amount to 6.8% of Gross Domestic Product (GDP) in 2016 and are

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[1] In what follows we refer to the European Union including the 28 members forming the EU up to December 2018.

[2] The old-age dependency ratio is defined as the ratio between the number of people aged 65 years and older and the working-age population (i.e. people aged in the 15–64 years group).

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projected to become 7.8% of GDP in 2050 only due to demographic ageing. Public pension expenditure is projected to increase from 8.6% in 2016 to 9.5% of GDP in 2050 (EC, 2018a).

The second implication refers to the overall reduction in number of working people and the consequent decrease in direct tax payments due to a smaller tax base, that typically causes two negative impacts: a decline in labour productivity, and a fall in available resources for financing the welfare system. At the same time, ageing might imply a raise in expenditures especially due to health care and pensions.

Thirdly, additional impacts of changes in population structure are related to variations in consumption patterns since consumption preferences are differentiated among different age groups. This influences the structure of demand and hence production patterns of economic systems, and negatively impacts consumption expenditure levels. This last effect, if no tax reforms are implemented, brings to a reduction in revenues from Value Added Tax (VAT) that might strongly influence the amount of available public budget.

Consequently, by reducing economic growth and jointly increasing deficit level, this could result in an increase of the deficit/GDP ratio, particularly important for EU countries that must respect the 3% threshold level as requested by the Stability and Growth Pact (SGP) rules (set by art. 121 of the Treaty of the Functioning of the European Union and whose political basis was settled by the Resolution of the European Council on the Stability and Growth Pact in 1997).

Together with demographic trends there are two aspects recently characterising socio-economic evolution, especially in developed economies, that are often accounted jointly with ageing population because of their potential positive impacts on economic systems that could counterbalance selected negative effects of ageing.

The first issue refers to the role of technological progress in leading to a massive implementation of automation in production systems. This would contribute to influencing the way people work and live and might smooth negative effects of ageing population, for example by increasing productivity levels in several sectors including manufacturing, healthcare, and energy (EC, 2019; Government Office for Science, 2016).

Despite such positive impact, if the introduction of automation in production systems affects employment levels as workers can be replaced by more efficient and less costly machines, this could result into additional negative impacts on economic systems related to job losses especially for unskilled workers (Arntz et al., 2016). More importantly, if an economy-wide perspective is adopted, there could be non-linear effects associated to the introduction of automation on economic dimensions as the public budget itself. As an example, technical change may increase labour productivity and consequently wages. If from the one side this may bring to augmenting the revenues from direct taxation, on the other side also the value of pensions might arise, with an unpredictable impact on fiscal sustainability.

The second issue is the increasing attention to environmental aspects, especially related to climate change and the energy sector, since environmental taxes are often considered as an alternative source of revenues that could, at least partly, counterbalance fiscal pressure due to ageing. As highlighted by the EC (2018b), the reduction of revenues from labour taxation can be balanced by the increase of other forms of taxation, and environmental taxation is expected to contribute both to the achievement of environmental targets and to sustainability of public budget. In a typical Environmental Tax Reform (ETR) approach, revenues from environmental taxation might replace revenues from other sectors (typically, direct cost payed by firms for employees) thus reducing the labour cost and stimulating economic growth, employment and investments to offset negative effects associated with ageing trends (Ekins et al., 2011).

Nonetheless, the positive effect of introducing environmental tax is not straightforward. First, it might undermine economic competitiveness especially of dirtier industries, producing at least in the short/medium-term a further reduction in employment levels and a contraction in value added. Second, if the environmental policy is effective in reaching its primary target (that is reducing polluting emissions), in the medium-term the tax base (emissions level) will be reduced thus bringing to a decreasing environmental tax revenue if unitary tax remains unchanged.

A direct consequence of such contrasting effects associated to the introduction of massive automation and the adoption of environmental taxes is that the combination with the issue of ageing might produce unpredictable results on economic systems, or in other words the cure might be worse than the disease. Accordingly, it is necessary to address all interactions and feedback loops in a systemic way taking into account as many linkages as possible in a highly integrated international context implemented in a temporal dynamic framework.

Even if the issues of ageing population, automation and environmental policies are widely investigated by the scientific literature, to the best of our knowledge there are no analytical contributions that combine these three aspects in a systemic way. The novelty of our contribution is to build a simple but comprehensive methodological tool in order to disentangle linkages and feedback loops that might mutually influence each other these three aspects. In so doing, we select the EU as a case study since the three issues are already highly debated, but no systematic analysis taking into account them jointly is available. The research purpose is to investigate if and to what extent automation and environmental taxes in an ageing society context impact those economic dimensions highly influenced by demographic trends, providing a first broad quantitative framework for policy evaluation. The model developed for this analytical purpose is based on a dynamic Computable General Equilibrium (CGE) model that allows adopting a long-term perspective.

The rest of the paper is structured as follows: Section 2 provides a literature review on main contributions modelling economic implications of ageing population, automation and environmental taxes; Section 3 describes the dynamic CGE structure and main mechanisms that can be captured, the baseline and the alternative scenarios investigated; Section 4 discusses main results; Section 5 provides some conclusions, policy recommendations and future research developments.

2. Literature review

The issue of ageing population has been widely debated over last years. From an economic point of view, most scholars have investigated the role that this phenomenon can have in influencing the economic system. In particular, literature is mainly focused on the analysis of the impacts of ageing population on selected aspects as human capital trends and the consequent impacts on labour market, changes in public social expenditure flows, and changes in consumption behaviours and patterns (Nagarajan et al., 2016). Although some of these dynamics are widely recognized, the final impact on the entire economic system is not straightforward to predict. The net effect might be positive or negative depending on the interaction of many factors both at the domestic and international level, including adaptation policies and reforms designed to manage such complexity (Bloom et al., 2011; Sukpaiboonwat et al., 2014).

The first and immediate consequence of ageing population is on human capital, through a decrease in labour force. Many scholars argue that a lower labour force would have negative effects on economic growth due to a reduction in productivity levels (Lisenkova et al., 2013; Narciso, 2010). However, such negative effects might be counterbalanced by the positive impact of immigration flows and the introduction of automation processes (Bloom et al., 2010; Peng and Fei, 2013). According to Elgin and Tumen (2012), modern economies are going to rely more on machines than on labour force. This replacement of workers by machines will then compensate the reduction of labour supply, without significant effects on productivity or, as stated by the International Federation of Robotics (IFR), with positive effects on productivity and a resulting job creation (IFR, 2017). This is not a shared conclusion, as demonstrated by another strand of literature, according to which the risks associated to the introduction of robotics exceed the advantages, especially as a consequence of the substitution of workers by robots that would lead to increasing unemployment (Brynjolfsson and McAfee, 2012; Frey and Osborne, 2017). Arntz et al. (2016) conclude that automation would destroy a large number of jobs (about 9% in OECD countries), and low qualified workers are particularly at risk. According to Freeman (2015), a crucial aspect is related to who owns the new technologies: if replaced workers owned the technologies that have substituted them (e.g., by owning shares of the firm, holding stock options or being paid in part from the profits), they would be better off, enjoying more leisure time while still gaining. More broadly, since automation is a slow process, the main challenge for the years to come is to adjust labour market to the new reality. Indeed, the introduction of automation requires parallel innovation in business models, organizational processes structures, institutions and skills in order to allow the whole job market to adapt (Brynjolfsson and McAfee, 2012).

Notwithstanding the effects on productivity levels, without specific adjustments in the tax system, the reduction of labour force necessarily leads to a decrease in revenues arising from labour taxation (Goudswaard and Van de Kar, 1994). This, in turn, exacerbates the difficulties of governments in providing additional services needed by an older population, mainly represented by the increase in government expenditures on health care and pensions (Elmeskov, 2004; Marešová et al., 2015).

As highlighted by the WHO (2015), the use of healthcare services rises with age and per capita expenditures on medical care are relatively higher among older people. Consequently, one of the main challenges for the future is to cope with non-communicable diseases[3] (Bloom et al., 2011) and to reach the so-called "Health Ageing", i.e., the process of developing and maintaining the functional ability that enables well-being in older age, reflecting the interactions between individuals and the environments they inhabit (Beard et al., 2016). Indeed, increased longevity without an improvement in health conditions leads to higher demand for health services over a longer period of the lifetime, increasing total health care spending (Breyer et al., 2010; Zweifel et al., 2005).

Similarly, the increase in old-age dependency ratio also raises the expenditure for pensions (EC, 2018a; Verbič, 2014), hampering the compliance with the fiscal sustainability rules (Beetsma and Oksanen, 2007). Consequently, there is the widespread necessity to implement specific policies, such as to finance and reconfigure health and long-term care provisions, increase labour force participation, raise the age at retirement, counteract population ageing (e.g., by encouraging higher fertility and permitting more immigration) or to reform the pension system (Bongaarts, 2004; Harper, 2014). In this respect, many countries adopted deep reforms of the pension system over the last decade (OECD, 2017), because the commonly adopted pay-as-you-go system over past decades, if not complemented with additional measures such as public pension reserve funds, would provoke an increasing deficit in government budgets (Elmeskov, 2004; Tosun, 2003). In particular, Díaz-Giménez and Díaz-Saavedra (2009) consider the crucial role played by the retirement of high-skilled workers in the rise of government deficit. According to them, skilled workers pay higher taxes during their working lives and hence they receive greater pensions when they retire, implying to almost double the government's expenditure for pensions.

However, some scholars argue that the negative effects of ageing population on the pension systems strongly depend on the types of retirement policies adopted by governments. According to Aguila (2011), personal retirement account systems implemented by some countries instead of pay-as-you-go systems would enable retirees to be more independent. In this respect, it is also worth mentioning the role of an ageing society on political decisions and public investments. As highlighted by Jäger and Schmidt (2016), the ageing electorate values future payoffs less than young people and hence demands less investment spending. Consequently, public investment tends to decline in ageing societies, especially in terms of expenditures for education (Harris et al., 2001; Poterba, 1997).

Although such divergences in predicted impacts from ageing population, at the EU level demographic change seems to have prevailing negative implications in terms of fiscal sustainability, mainly due to increasing expenditure for pensions and healthcare and decreasing tax revenues from direct taxation on labour force (EC, 2018a). Given that it is almost impossible to smooth the increasing trend from the expenditure side, scholars are focusing on different proposals to reform the tax system in order to increase revenues required to sustain the public budget (Lawton and Silim, 2012). An ETR can be a possible response to the fiscal sustainability challenge because taxes on environmentally-damaging activities can be recycled for reducing conventional taxes (EEA, 2005; Ekins et al., 2011; Pearce, 1991; Speck, 2017). Revenues from environmental taxation can be used to reduce labour taxes, thus favouring employment, or to address broad fiscal priorities and to finance other policies and government expenditures contributing to compensating the reduction of revenues from labour taxation due to ageing trends (EC, 2018b; Gonand and Jouvet, 2015; Marron and Morris, 2016). However, successfully reducing emissions policy will lower the tax base for environmental taxes in future thus turning back to a danger of fiscal unsustainability. Accordingly, the design of a resilient fiscal system for the long-term, jointly taking into account the demographic transition and the evolution in environmental policies is highly recommended (EEA, 2016).

Another economic impact associated to ageing population is related to changes in consumption behaviours. Old people tend to reduce their consumption both because of a different life style and because of a lower level of disposable income (Hock and Weil, 2012). In addition, demographic change also leads to different propensities to consume as old people direct their expenses towards specific sectors (Aguila, 2011). Household expenditures for health increase due to ageing. Elderly households tend to consume more energy, as a consequence of an increasing demand for heating and cooling due to their less active lifestyles and prolonged permanence at home (Atkinson and Hayes, 2010; Deutsch and Timpe, 2013; Romanach et al., 2017). On the contrary, food consumption is lower, especially among households headed by over 75 years-old people. Similarly, old people reduce their consumption of clothing, transports, alcoholic drinks, housing and fuel, communication, education and restaurants. At the same time, while the level of food consumption by households headed by old people is lower, the relative share of expenditures spent on food with respect to the disposable budget is higher, revealing a significant change in consumption propensity for old people (Aigner-Walder and Döring, 2012; Mao and Xu, 2014).

According to Willis et al. (2011), old people are also less likely to adopt new technologies, both because they are more sensitive to their higher capital costs and because they are less inclined to changes. The combination of an increasing consumption propensity for energy sources required for household services and the reduced propensity to adopt clean energy technologies is a typical example of non-linear effects when effects of an ageing society are combined with other elements, such as clean energy policies (Aslam and Ahmad, 2018; Harper, 2013).

Regarding the interactions between ageing society and energy issues, according to Kim and Seo (2012), while residential energy consumption increases due to ageing, the industrial one decreases. Indeed, ageing population causes a decline of productivity in the economy that makes energy demand decrease faster as ageing proceeds.

Several additional aspects might influence consumption patterns, such as socio-demographic transformations (smaller family size), economic transformations (changes in job market, income distribution) or changes in lifestyle and environmental attitudes (Bardazzi and Pazienza, 2017).

[3] According to Bloom et al. (2011), the most important non-communicable diseases are cancer, diabetes, cardiovascular and chronic respiratory disease. These diseases are characterised by the fact of sharing four modifiable risk factors (i.e., tobacco use, physical inactivity, unhealthy diets and the harmful use of alcohol) and one non-modifiable risk factor: age.

3. Model description

3.1. General model settings

The analysis here proposed is based on simulation results obtained by developing an original version of the GTAP model, hereafter referred to GDynEP-AG. It is based on a recursive dynamic CGE model that allows the representation of long-term policies as well as the capital accumulation function. It results from merging the GDynE (the energy version of the dynamic GDyn) developed by Golub (2013) and improved by Markandya et al. (2015) with the GTAP-Power (Peters, 2016), which introduces for the first time in GTAP a detailed representation of the renewable electricity sector. In addition, a specific module for modelling changes in consumption patterns driven by alternative demographic trends has been developed and included in expenditure function specification.

GDynEP-AG is based on the last version of the GTAP-Database (GTAP-Database 9.1, updated to 2011) and integrates it with the GTAP-Power that distinguishes several energy-generating technologies and introduces supply from different renewable energy sources. Combustion-based CO_2 emissions are also included at the sector level.[4]

As for the country and sector coverage, we consider 19 regions and 22 sectors. With regard to the former, we have six regions formed by advanced economies (European Union, United States, Russian Federation, Rest of Europe, Rest of OECD East, Rest of OECD West) and 13 regions representing the rest of the world (Brazil, China, India, Asian Energy Exporters, Continental Asia, Rest of South Asia, South East Asia, African Energy Exporters, Western Africa, East and South Africa, American Energy Exporters, South America, Central America and Caribbean).

The 22 sectors represent the whole economy, with a greater emphasis on energy commodities and manufacturing industries: Agriculture; Food, beverages and tobacco; Textile; Wood; Pulp and paper; Chemical and petrochemical; Non-metallic Minerals; Metals; Other metals[5]; Machinery equipment; Transport equipment; Other manufacturing industries; Transport; Water Transport; Air transport and Services; Energy (divided into Coal, Oil, Gas, Oil products, Electricity from fossil and nuclear sources, Electricity from renewable sources).[6]

The use of a CGE model, if from the one side presents several concerns given the required theoretical assumptions for simplifying relationships in order to reach the equilibrium solution, from the other side allows taking into account a high number of bilateral relationships at the sector and country/region level, determined by the input-output structure of the production and demand functions. Accordingly, by detailing a multi-region and multi-sector model we can retain the heterogeneity in bilateral relationships that a two-region model two-sector model would impede. This modelling choice allows better capturing driving factors activated by ageing society, automation and environmental policies that have divergent impacts on different sectors (given the specific input mix in the production function) and on different countries (given the specific impact of demographic trend and age composition).[7]

In terms of the temporal dimension (*t*), we consider a time horizon from 2011 to 2050, divided in eight steps, the first one in the time span 2011–2015, and the following seven of five years each. This modelling choice allows to fully calibrate data at 2015 with historical information, especially with respect to data provided by EUROSTAT for the EU. The EU region in GDynEP-AG corresponds to the EU28 aggregate-current composition available in EUROSTAT database.[8]

The scenario building approach starts from the baseline and adds first alternative scenarios for ageing projections, then introduces the impact of automation with different assumptions in terms of productivity and labour market effects and, finally simulates the impact of introducing an environmental policy (here modelled as a carbon tax). By introducing the three different issues one by one it is possible to better distinguish: i) which mechanisms the dynamic CGE is able to capture with respect to the existing literature on impacts of ageing on economic systems; ii) if and to what extent the automation process or the introduction of an environmental tax are effective in contrasting negative impacts of ageing; iii) which mechanisms and effects prevail if all three issues are simultaneously simulated.

Fig. 1 synthesises the most relevant mechanisms operating in GDynEP-AG. For the sake of simplicity, we organise comments on two core impacts, first fiscal sustainability and then environmental sustainability (both represented in bold letters in Fig. 1).

Ageing population plays a direct role in increasing government expenditures due to health and pensions while it has an indirect impact on the revenue side due to a reduction in consumption expenditures that leads to lowering other tax revenues.

The decrease in total labour force due to ageing society influences the revenue side in different directions. First, a reduction in number of workers due to ageing directly reduces the tax basis with a negative effect on fiscal sustainability. Second, the reduction in labour supply directly increases wages and salaries thus increasing the amount of direct taxation payed for each employee.

Ageing population also impacts consumption expenditures. In this case the composition of the consumption basket changes, and the total amount of expenditures generally declines (given that pensions are reduced with respect to the wage level). Even in this case, there are two effects, which are in the same direction. From the one hand a reduction in consumption expenditures negatively impacts the aggregated demand, thus reducing labour demand by firms with a consequent reduction in wage levels. This brings to a reduction in revenues from direct taxation from each employee (with an opposite effect w.r.t. the impact of the reduction in labour supply as previously mentioned). From the other side, a reduction in consumption expenditures is also associated to a reduction in other tax revenues (VAT above all), driving down the total amount of tax revenues and again negatively impacting fiscal budget

[4] According to the GTAP-Power specification, energy data include electricity generating technologies as: Coal, Gas, Oil, Hydro, Wind, Solar, Nuclear and Other Power sources. Gas, Oil, Hydro and Solar generating technologies are further divided between Base and Peak Load.

[5] Metals includes ferrous metals (iron and steel: basic production and casting) and non-ferrous metals (production and casting of copper, aluminum, zinc, lead, gold, and silver); Other metals includes fabricated metal products (sheet metal products, but not machinery and equipment).

[6] See Tables B.1–B.4 in Appendix B for further details on scenario settings.

[7] We describe two examples related to the empirical exercise carried in this analysis to highlight the benefits from a multi-country and multi-sector model.1) Concerning a multi-region approach: the simulation with ageing population is based on the UNDESA scenario where demographic trends are highly heterogeneous across countries. Such divergences in population growth and composition are responsible for two main driving factors: the number of employees (labour force) and the number of households (country-based demand for distinguished sectors). Given that the aggregated demand for each country is composed by domestic and external consumption, changes in external demand in different countries (let's say China and the US) will impact differently on the EU production given that trade (input-output) relationships are different across countries.2) Concerning a multi-sector approach: literature provided evidence that ageing population is responsible for changes in the composition of the consumption basket, which in turn directly impacts on demand for different goods. By changing demand structure according to different consumption behaviour for different goods, it is possible to disentangle the impact of ageing via the demand channel on economic performance. This is exactly what emerges from the comparison of the two simulation LF15 and LF15C, where the latter shows a large (negative) impact on economic performance associated to changes in consumption behaviour.

[8] All details required for replicating model simulation for baseline and alternative scenarios are provided in a Data-in-Brief document with a link to a dedicated folder containing files for the shocks, the Tablo with all equations, the parameters and simulation details. The model can be replicated only by owners of RunDynam and Gempack valid licences.

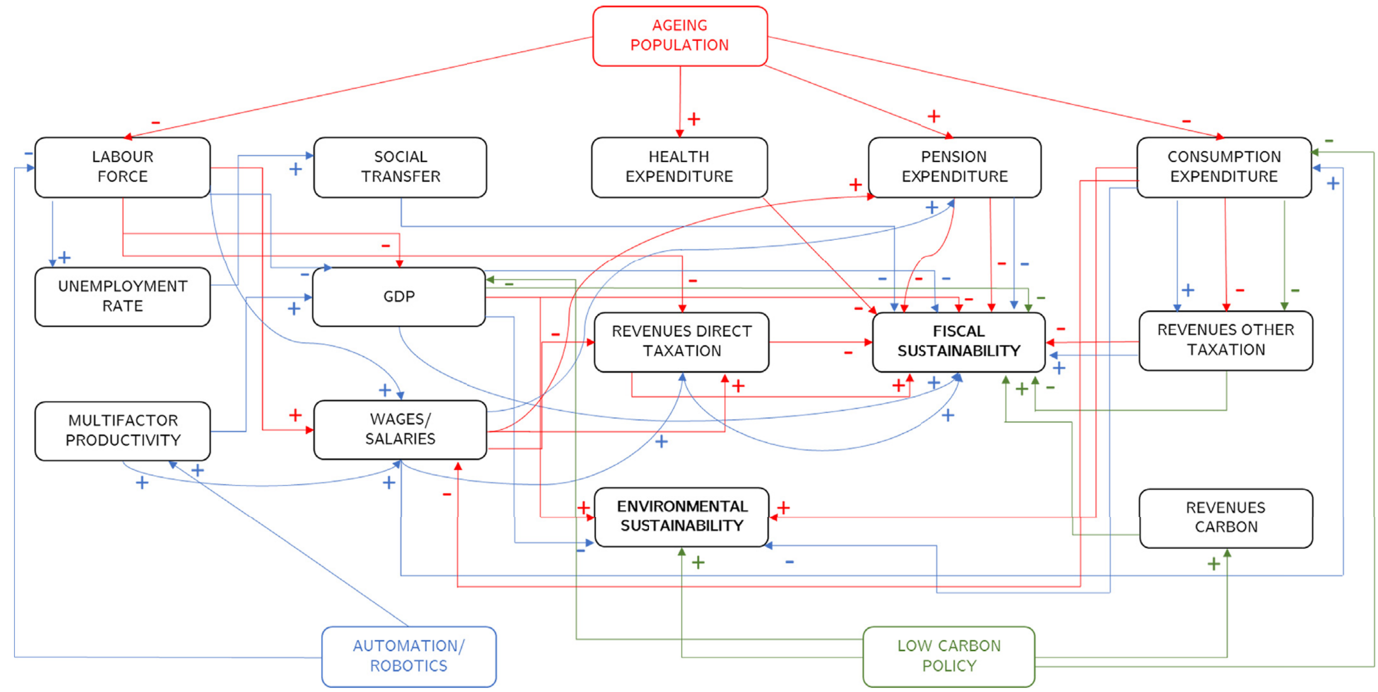

Fig. 1. Main mechanisms influencing environmental and fiscal sustainability: unveiling the black box in GDynEP-AG.

levels.

At the same time, the increase in wages is responsible for a further increase in unitary pensions as they are direct function of salary levels, reinforcing pressure on government expenditures.

When we include the impacts of automation, the framework becomes more complex. The increase in multifactor productivity positively influences GDP growth thus reducing, *ceteris paribus,* the deficit/GDP ratio. The increase in multifactor productivity determines (given fixed labour supply) an increase in wages that in turns has three effects: an increase in household consumption that induces other tax revenues to grow thus improving fiscal sustainability; an increase in direct taxation revenues that help fiscal sustainability; an increase in unitary cost of pensions that in turn is detrimental for fiscal sustainability. If the introduction of automation in productive processes is also responsible for an increase in unemployment, other mechanisms enter into force. The reduction in number of employees further increases wage levels, reinforcing the positive impact on direct and other tax revenues already described, but at the same time it also impacts negatively in terms of increasing expenditures for the pension system and for social transfers. In addition, the reduction in labour force also brings to a reduction in GDP thus negatively affecting the deficit/GDP ratio.[9] When introducing the issue of environmental policy, selected impacts are remarkable. Focusing on carbon taxation on combustion-based CO_2, we have a direct control on multiple effects thanks to the direct impact of this fiscal instrument on energy consumption.

If a pure environmental sustainability goal is under the lens of policy impact evaluation, then a carbon tax policy is certainly successful in mitigating emissions. If, on the other hand, environmental policies are considered as an instrument to contrast negative impacts of ageing on fiscal sustainability, the net outcome in terms of improving public budget sustainability is uncertain.

A first positive impact is an increase in revenues from carbon taxation that increase the overall public budget and, *ceteris paribus*, reduces the deficit. On the contrary, the contraction in consumption expenditures at the household level hampers revenues from other taxation, with an opposite effect on fiscal sustainability via a reduction in VAT revenues. The increase in the cost of the energy inputs also negatively affects GDP growth, reinforcing pressure on fiscal sustainability.

3.2. *The baseline scenario*

The baseline case corresponds to a Business As Usual (BAU) scenario, which assumes that there will be no significant changes in demographic composition, technology, economics, policies or people's attitudes. To this end, projections for macroeconomic variables are given by the combination of several sources. In particular, GDP projections are based on the average values of four sources: the OECD Long Run Economic Outlook, the GTAP Macro projections, the IIASA projections used for the OECD EnvLink model, and the CEPII macroeconomic projections used in the GINFORS model.[10] Population projections are taken from the United Nations Statistics (UNDESA). By taking into account the projections associated to the definition of the five Shared Socioeconomic Pathways (SSP) as developed by Dellink et al. (2017) and O'Neill et al. (2017), it is worth noting that the GDP in BAU scenario for the EU corresponds to SSP4 OECD-ENV Link, the scenario without mitigation policies.[11]

Population in BAU is calibrated on the basis of data from UNDESA medium scenario.[12] We choose to rely on UNDESA data and projections

[9] It is worth mentioning that in this modelling framework labour force is exogenously given. Accordingly, when automation induces unemployment, there is no feedback loop in terms of pushing down salaries and reabsorbing unemployed workers. Although this is a strong assumption, it is also worth mentioning that literature suggests that most negative effects on labour market provoked by automation are on unskilled workforces, partly justifying the growth in unitary wage levels that is mainly correlated with growing scarcity of skilled employees.

[10] In BAU the growth rate is exogenous while in alternative scenarios it is endogenously calculated as a result of simulations. This is a standard modelling choice. See Table C.7 in Appendix C for GDP projections in BAU for all regions.

[11] See OECD Env-Growth model (Dellink et al., 2017) from SSP database, and Appendix A for further details on the concept of SSP.

[12] United Nations, Department of Economic and Social Affairs, Population Division (2017). World Population Prospects: The 2017 Revision, DVD Edition. (Population by Age Groups - Both Sexes, available online last download on 28th January 2019, https://esa.un.org/unpd/wpp/Download/Standard/Population/.

for population in order to correctly calibrate the model, which requires to have a common data source for all regions at the global level.[13] For this reason, some small differences arise with respect to data provided by the EC in its last report on ageing population for what concerns the distribution across age ranges of the total population up to 2050 (EC, 2018a).[14] In terms of SSP, EU population in BAU corresponds to an intermediate level between SSP3 and SSP4 (Table 1).[15]

Labour force is modelled as skilled and unskilled workers separately. Projections up to 2050 are built by using labour force projections provided by ILO (which result as aggregate but are recent), GTAP Macro projections (where skilled and unskilled workers are disentangled but data where calculated before 2011) and UNDESA projections on active population defined in the age range 15–64 years (medium variation scenario). Starting from ILO projections, for each region (r) in each temporal step (t) we compute the share of labour force ($q_{r,t}$) with respect to active population (population in the 15–64 age group), as in eq. (1):

$$q_{r,t} = \frac{LF\_BAU_{r,t}}{POP(15-64)\_BAU_{r,t}} \tag{1}$$

where ($q_{r,t}$) changes over time while it is constant among scenarios. Labour force (LF) is then calculated as follows:

$$LF_{r,t} = POP(15-64)_{r,t} \cdot q_{r,t} \tag{2}$$

where data on active population (age group 15–64 years) comes from UNDESA projections. In the BAU case the LF remains as given by the ILO projections, while in scenarios with changes due to ageing population, the LF changes according with changes in active population of the selected UNDESA scenario.

In order to distinguish between skilled and unskilled labour, starting from GTAP Macro projections, we compute the share of skilled and unskilled labour force:

$$sk_{r,t} = \frac{skilled_{r,t}}{LF\_BAU_{r,t}} \tag{3}$$

$$unsk_{r,t} = \frac{unskilled_{r,t}}{LF\_BAU_{r,t}} \tag{4}$$

Then, the number of skilled (SK) and unskilled (UNSK) workers is found by applying the respective shares to labour force data:

$$SK_{r,t} = LF_{r,t} \cdot sk_{r,t} \tag{5}$$

$$UNSK_{r,t} = LF_{r,t} \cdot unsk_{r,t} \tag{6}$$

Consequently, we suppose that the shares of skilled and unskilled labour change over time and across regions but do not change among different scenarios, while differences across scenarios are due to changes in total labour force according to changes in population in the age 15–64 as given by eq. (2).[16]

Following this approach, in the BAU scenario we obtain that the EU labour force registers a 7.3% decrease between 2015 and 2050 (Table 2), coherently with the results presented in the last EC report in 2018.[17]

As for the calibration of CO_2 emissions, the baseline case corresponds to a BAU scenario in which the distribution of emissions is assigned among regions according to projections provided by the International Energy Agency (IEA, 2017). Such a distribution represents the effects of only those policies and measures adopted by mid-2015.

In order to calibrate GDynEP-AG data regarding fiscal sustainability and public budget with respect to the EU aggregate, we have made several controls and adjustments.

First, we have calculated the labour tax rate in 2015 for the EU in GDynEP-AG reaching an average value between skilled and unskilled labour force equal to 25%, which is quite close to the 24% EU average tax rate provided by EUROSTAT (2018) for the same year.[18] Second, we checked for consistency of the tax burden in the EU from historical data and the total tax revenue to GDP ratio resulting from GTAP data is very closed to current EU data (about 41% in GTAP w.r.t. a 40% in EUROSTAT).

Third, GDynEP-AG results are expressed in constant 2015 USD. The exchange rate to convert them in constant 2015 Euro has been calculated as the average value of monthly values in the time span 2011–2015 in order to neutralise fluctuations.[19] It is worth noting that in this way the GDP value in 2015 Euro for the EU aggregate obtained in GDynEP-AG is perfectly in line with GDP figures provided by EUROSTAT for the same year. The exchange rate has been adopted to convert all scenario results expressed in monetary terms for all temporal steps, given that they are all expressed at constant 2015 monetary values.[20]

3.3. Alternative scenarios for ageing

We distinguish between three simulation groups. The first aims at investigating the impact of ageing population. The second one introduces the impact of automation in production processes, while the third group examines the impact of an environmental taxation applied to carbon emissions. The third group includes scenarios with ageing population and with the impact of automation both excluded and included. In this way it is possible to disentangle the specific mechanisms arising if environmental taxation is interpreted as a potential remedy for negative impacts of ageing.

As a first general remark, projections for GDP adopted in BAU, for population and labour force adopted in BAU and in alternative scenarios are assigned to all regions forming the current setting of GDynEP-AG, thus obtaining a global perspective of the economic and demographic evolution, bearing in mind that no migration flows are allowed across regions. Secondly, in the simulation groups dealing with automation and carbon tax we assume a unilateral shock valid only for the EU aggregate, while other regions have no constraints. Accordingly, given the structure of the CGE model here adopted, the final results in terms of economic and fiscal sustainability impacts on the EU aggregate must be interpreted as the joint contribution of internal mechanics directly linked to the simulated shock and the indirect effects associated to interaction channels

[13] For full information on population trends in BAU and alternative scenarios for all regions, see Tables C.1–C.3 in Appendix C.

[14] https://ec.europa.eu/info/publications/economy-finance/2018-ageing-report-economic-and-budgetary-projections-eu-member-states-2016-2070_en.

[15] According to BAU assumptions, GDP and population are not calibrated directly on the basis of SSP data, but they come from the described sources and then compared to SSP projections.

[16] Within each scenario, we assist to an allocation of labour force over time so that the number of skilled workers increases between 2015 and 2050, while the number of unskilled workers decreases. For full details on projections of skilled and unskilled labour force for all regions in BAU and alternative scenarios see Tables C.4–C.6 in Appendix C.

[17] See Table III.1.28 in EC (2018a).

[18] It is given by the ratio between "Employers' social contributions and other labour costs paid by employer" and "Total labour costs" from http://ec.europa.eu/eurostat/data/database (Labour cost levels by NACE Rev. 2 activity).

[19] The applied exchange rate between USD and Euro is equal to 0.7653, obtained as the average value of maximum and minimum values for each month in the period 2011–2015. The statistical source is: https://www.x-rates.com.

[20] Summing up, the statistical sources for macro projections and calibration are: CEPII macroeconomic projections (Fouré et al., 2013); EUROSTAT (2018) online databases; GTAP macro projections (Chappuis and Walmsley, 2011); IEA (2017) combustion-based CO_2 emissions; IIASA projections used for the OECD EnvLink (Dellink et al., 2017); ILO Labour force projections (ILO, 2017); OECD Long Run Economic Outlook (OECD, 2014); UNDESA Population projections (UN, 2017).

Table 1
Population trend in the EU (Mln) - BAU.

	2015	2020	2025	2030	2035	2040	2045	2050
SSP3	506	506	504	498	491	483	473	461
SSP4	508	512	515	515	515	514	511	506
BAU (UNDESA)	**507**	**511**	**512**	**513**	**512**	**510**	**507**	**503**

Note: Bold figures are those used for BAU scenario in GDynEP-AG.
Source: UNDESA medium scenario and IIASA-WIC POP model (KC and Lutz, 2017) from SSP database.

Table 2
Labour force in the EU (Mln) - BAU.

	2015	2020	2025	2030	2035	2040	2045	2050
ILO (15+)	244	247	243	**239**				
GDynEP-AG BAU	243	244	242	238	234	230	227	225
Skilled	*93*	*99*	*103*	*107*	*111*	*115*	*123*	*128*
Unskilled	*150*	*144*	*139*	*131*	*123*	*115*	*105*	*97*

Source: own elaborations on GTAP, ILO and UNDESA data.

depending on international linkages (mainly represented by trade and capital flows).[21]

The first set of scenarios simulates an increase in the dependency ratio through a reduction in labour force up to 2050. In this respect, two alternative patterns are tested:

1. **LF10:** change in labour force for world regions according to UNDESA, corresponding to a 10% reduction of EU labour force in 2050 w.r.t. 2015 (according also to EC, 2018a).
2. **LF15:** change in labour force for world regions according to UNDESA, corresponding to a 15% reduction of EU labour force in 2050 w.r.t. 2015 (according also to EC, 2018a).

In both cases, skilled and unskilled labour force decrease proportionally given that UNDESA projections are available only for active population and aggregate labour force. In particular, the reduction in labour force is obtained by applying to all regions the steps described in the BAU case as in eqs. (1)–(6), where data on active population correspond to the UNDESA "No change" scenario (LF10) and "Low variant" scenario (LF15).[22] The alternative scenarios describe a situation in which all regions face a change in labour force trend according to UNDESA projections for active population, and specifically for the EU in 2050 labour force decreases by 10% and 15% w.r.t. 2015 according to projections provided by EC (2018a).

As illustrated in Table 3, in the LF10 scenario the EU population decreases compared to BAU, but the composition among age groups does not change: natality decreases while life expectancy remains stable and, in fact, the number of people over 65 years decreases.

As for the LF15, even if the level of population is quite the same (slightly lower) compared to the LF10 scenario, labour force decrease is sharper. Indeed, we assist to a change in the composition of population compared to BAU: natality decreases as in LF10 but life expectancy increases so that the number of people aged 65 years and over is higher than LF10, quite in line with the BAU scenario. Accordingly, also the share of inactive population (65+) increases with respect to total population. The resulting demographic composition brings to a reduction in labour force by −15% in 2050 w.r.t. 2015 that is substantially higher than in the BAU case with a −7.3%.[23]

When comparing old age dependency ratio for the three scenarios, in BAU there is an increase from 29% in 2015 to 53% in 2050, while in LF10 there is still a positive trend with a lower increase (reaching a 45% by 2050), and finally in LF15 we face the highest increase with a 57% old age dependency ratio by 2050. Accordingly, we start from this last scenario to examine the impact of ageing population on consumption patterns by developing an additional scenario only for the EU as:

3. **LF15C:** equal to LF15 with an additional change in consumption propensity shares as a consequence of ageing population only for the EU.

The LF15C scenario entails the overall effects of an ageing population for the EU with a 15% reduction in labour force and changes in the distribution of consumption quotas for households. In order to maintain the core demand-supply system in the CGE model, we model change in the propensity to consume for different goods, where the consumption level remains an endogenous output of the model.

In order to modify the consumption propensity, we rely on selected contributions in the existing literature that specifically analyse the effects of ageing population on consumption in selected EU countries.[24] Accordingly, we consider a reduction of the propensity to consume in the sectors of transports (transport equipment included) and textile; conversely, we suppose an increase in the propensity to consume associated to the sectors of services, coal, gas, electricity (from fossil fuel and renewable sources) and food (Aigner-Walder and Döring, 2012; Marešová et al., 2015; Nagarajan et al., 2016).[25] Such adjustments on consumption propensity have been introduced only for the EU region starting from 2020, when population trend beguines differentiating from BAU given that most of empirical studies are based on EU countries. The parameters have been calibrated in order to obtain an increase (decrease) in consumption share in quantitative terms by a maximum of +5% (-5%)

[21] The extension of automation in the form of productivity increases to the other regions in alternative scenarios would produce an impact not only on domestic markets but, given the nature of the CGE based on bilateral input-output flows (including trade), the economic impacts would indirectly affect also the EU results. The mechanisms and linkages in this case would be unpredictable and difficult to be interpreted under our research framework. The next step in our research agenda is to build a "global" scenario where migration, automation and environmental policies will be tested for all regions forming the model.

[22] See Tables C.1–C.3 in Appendix C for full details on world population projections in alternative scenarios.

[23] In Appendix C we report demographic trends for all regions at the general level (total population). Data on distinguished age groups for all regions adopted in different scenarios are available upon requests from the authors.

[24] All scenarios except for LF10 and LF15 are carried assuming that only the EU faces the difference in projections while all the other regions move according to model functioning.

[25] To this end, we include a new variable describing changes in consumption quota of commodities and a new parameter which takes value −1 (+1) for sectors whose propensity to consume increases (decreases) as a consequence of ageing population. Equations programmed in the GEMPACK language Tablo file are available upon request from the authors.

Table 3
Population in the EU (Mln).

Scenario		2015	2020	2025	2030	2035	2040	2045	2050
BAU	Total	507	511	512	513	512	510	507	503
	0–14	*79*	*78*	*76*	*74*	*73*	*72*	*72*	*72*
	15–64	*332*	*327*	*321*	*312*	*303*	*295*	*288*	*281*
	65+	*97*	*106*	*115*	*126*	*135*	*142*	*147*	*149*
LF10	Total	507	509	506	501	494	486	476	465
	0–14	*79*	*78*	*75*	*72*	*69*	*68*	*67*	*66*
	15–64	*332*	*327*	*320*	*311*	*301*	*291*	*282*	*274*
	65+	*97*	*104*	*112*	*119*	*125*	*127*	*127*	*125*
LF15	Total	507	510	510	509	502	493	481	469
	0–14	*79*	*77*	*74*	*71*	*68*	*67*	*66*	*65*
	15–64	*332*	*327*	*321*	*312*	*299*	*285*	*271*	*257*
	65+	*97*	*106*	*115*	*125*	*135*	*141*	*145*	*147*

Source: UNDESA scenarios: Medium change (BAU); No change; (LF10); Low variant (LF15).

Table 4
Ch. in consumption share on household expenditure in the EU (LF15C w.r.t. BAU, %).

Sectors[a]	2020	2025	2030	2035	2040	2045	2050
Coal	−0.04	−0.07	0.66	1.39	2.12	2.85	3.58
Oil	−0.04	−0.07	−1.80	−3.50	−5.17	−6.83	−8.45
Gas	−0.04	−0.07	0.66	1.39	2.12	2.85	3.58
Oil prod.	−0.04	−0.07	−2.52	−4.92	−7.26	−9.55	−11.78
Electr. Foss_Fuel	−0.04	−0.07	0.66	1.39	2.12	2.85	3.58
Electr. Renw.	−0.04	−0.07	0.66	1.39	2.12	2.85	3.58
Agriculture	0.12	−0.13	−2.21	−4.99	−8.04	−11.85	−15.50
Food	0.06	0.04	1.31	2.48	3.59	4.54	5.44
Textile	0.07	0.06	−2.43	−4.87	−7.23	−9.50	−11.71
No-metal prod.	−0.01	−0.01	−1.65	−3.25	−4.83	−6.34	−7.82
Wood	−0.01	−0.02	−1.67	−3.33	−4.99	−6.67	−8.37
Pulp & paper	−0.01	0.00	−1.60	−3.18	−4.74	−6.26	−7.75
Chemicals	−0.01	−0.01	−1.67	−3.30	−4.90	−6.44	−7.97
Metals	−0.01	−0.02	−1.72	−3.38	−5.01	−6.55	−8.06
Other metals	0.00	0.01	−1.62	−3.21	−4.78	−6.27	−7.74
Transport eq.	0.00	0.01	−2.36	−4.67	−6.91	−9.07	−11.18
Machinery	0.00	0.02	−1.65	−3.26	−4.84	−6.33	−7.81
Other manuf.	−0.01	0.00	−1.67	−3.30	−4.89	−6.43	−7.96
Road transp.	−0.01	−0.01	−2.39	−4.70	−6.97	−9.13	−11.24
Air transp.	−0.01	−0.02	−1.72	−3.38	−5.00	−6.54	−8.06
Water transp.	−0.02	−0.03	−1.74	−3.41	−5.04	−6.60	−8.12
Services	−0.02	0.00	0.87	1.76	2.63	3.54	4.46

[a] For details on sector composition and definition see Tables B.2–B.4 in Appendix B.
Source: our elaboration on GDynEP-AG results.

in 2050. These upper and lower bounds result from computing the average change obtained by comparing the empirical results of the aforementioned scientific contributions. In Table 4 we report the resulting change in consumption shares in monetary terms in the LF15C scenario w.r.t. BAU disentangled by sectors.

It is worth mentioning that changes in consumption shares in monetary terms depend on the combination of exogenous changes in consumption propensity at the quantitative levels and of endogenous changes in expenditure structure in monetary terms that are induced by the demographic shock. The highest variations are related to the sectors of agriculture, transport and textile, which register a reduction of their share of about 15% and 11% respectively as a consequence of ageing population, and food and services, for which the share of consumption increases. This reflects the fact that elder people tend to reduce their use of transports, while their need of services increases (e.g., health care services, or domestic care assistance). Moreover, in line with Engel's rule, the reduction in their income due to retirement entails a larger consumption quota directed towards basic needs such as food (+5.44%), and a smaller one for less necessary commodities (e.g., textile −11.71%).

This modelling choice for changes in household consumption basket structure is constrained by the lack of complexity in household demand specification, given that it is formed by one representative agent. Future research will focus on a more complex structure of the demand system with heterogeneous agents, starting from the structure developed for the GTAP-POV module for world income distribution.

Since the LF15C scenario provides a more comprehensive description compared to LF15, we will start from this when introducing the role of automation and environmental policies.[26]

3.4. Alternative scenarios for ageing and automation

Starting from LF15C, we look at the second set of scenarios in which, in addition to ageing population, an automation process takes place only in the EU region, while all other regions react to this EU-specific shock endogenously.

First, we assume that by starting to invest specifically into massive introduction of automation and robotics in production processes in 2020, changes in economic system will occur in the next temporal step, in this case by 2025.

Second, by assuming neutral technical change (w.r.t. factor specific productivity) we simulate two distinguished ways in which investments in automation are transformed into increasing productivity: one acting on Total Factor Productivity (TFP) at the national level, and the other one

[26] Although we acknowledge the close relation between ageing and migration, we do not include a scenario with migration flows in this study, since the main purpose is to investigate the economic effects of ageing through the developed CGE model. Indeed, since migration could (at least partly) compensate the effects of an ageing society, we do not include it in order to isolate the economic impacts of the ageing population alone. We thank an anonymous reviewer for addressing this point suggesting the direction for future research analyses.

influencing multifactor productivity in a homogeneous way w.r.t. different factors but differently at the sector level.

Third, we test the potential impact of massive automation if biased technological change is occurring, by modelling a relatively higher increase in capital productivity w.r.t. labour productivity, thus inducing an increase in unemployment (Doraszelski and Jaumandreu, 2018). Accordingly, three additional scenarios are investigated:

4. **LF15CR:** equal to LF15C plus technical change in production process. The introduction of automation results in an increase of TFP, as the sum of input and output productivity so that its effects are generalized to the whole economy without any difference across sectors. We assume that investments in automation will produce a 1% annual increase in TFP according to OECD (2018).[27]
5. **LF15CRS:** equal to LF15CR with the productivity impacts of the automation process differentiated across sectors on the basis of their relative capital intensity. Capital intensity is given by the ratio between the value added of capital w.r.t. the value added associated to all endowments at 2015. To differentiate productivity impacts across sectors, we calculate the share of capital intensity in each sector w.r.t. the capital intensity of all sectors. Finally, we use this share to allocate the 1% annual increase in TFP among sectors, in order to obtain a scenario fully comparable with LF15CR.[28]
6. **LF25CRS:** equal to LF15CRS but we suppose that the automation process acts as a biased technical change that negatively impacts on labour productivity and consequently increases unemployment level. We suppose a 10% reduction of employment due to automation (Arntz et al., 2016). Given that GDynEP-AG works with full employment, the unemployment caused by automation can be modelled as a proportional reduction in labour force. Accordingly, in this scenario we assist to a 25% reduction of the EU labour force in 2050 w.r.t. 2015: a 15% reduction due to ageing population plus a 10% reduction due to automation entailing an additional proportional decrease of both skilled and unskilled workers.[29]

In Table 5 we show labour force trends for the EU in alternative scenarios as resulting from the implementation of eqs. (1)–(6) when the demographic structure changes and also when the automation process is responsible for unemployment.[30]

It is noteworthy that in this modelling approach we consider technical change as exogenous. Further development on this topic would require the introduction of a specific sector producing new technologies, in order to model innovation as endogenously determined by investment choices, thus better capturing also trade-offs and crowding out effects with other sectors.[31]

According to Disney (2007), together with the old age dependency ratio it is also interesting to look at the inverse of the support ratio, that describes the number of pensioners to workers. It is obvious that not all people of working age work, and also that some older people may not be eligible for a pension and/or may still be working. Consequently, we have precise data for pensioners and workers for the EU28 aggregate only for 2015 year from EUROSTAT, namely around 122.561 million pensioners and 215.244 million employees. Given that in GTAP active population coincides with total employment, we compute here the inverse of the support ratio by using active population data from EUROSTAT in 2015. In 2015 it is about 51%, perfectly in line with GTAP data. Looking at projected values for this ratio, in BAU it reaches an 84% by 2050, while in LF15 it amounts at 91%.

By combining trends in old age dependency ratio and in the inverse of the support ratio, it is clear that, *ceteris paribus*, an increase in the tax rate will be required to finance social security benefits and, very likely, there will be an increase of the size of the overall welfare system. Literature has recently emphasised that the correlation between ageing and welfare spending is ambiguous and depends on the demographic structure and the composition of the welfare system. From the one side, ageing contributes in increasing the share of beneficiaries of the two largest welfare programs, social security and health care. If the entitlements to these welfare programs are not modified, spending grows due to the increasing number of recipients. From the other side, according to Razin et al. (2002), changes in demographic structure due to ageing also bring to substantial modification of voting behaviours and equilibria. At least in the short-term, the reduction in young voters might reduce pressure for the portion of welfare system devoted to education, thus partly counterbalancing the increase in welfare spending size due to pensions and health care (Hughes Hallett et al., 2019). Given that the reduction in education spending is found to be mainly a short-term effect in shaping political economy decisions, given the long-term horizon of this work we ignore here the potential effects of changes in welfare composition due to different voting equilibria. Nonetheless, in ex-post calculations we disentangle these three welfare program expenditures (health, social security and education) assuming that they are not influenced by changes in voting preferences due to ageing but only related to changes in demographic structure.

3.5. Alternative scenarios for ageing and environmental taxation

Finally, in order to analyse the role played by environmental tax revenues on negative impacts of ageing, we develop four scenarios characterised by the implementation of a unilateral carbon tax in the EU from 2020 onwards, while all other regions are free to emit without any mitigation constraint. The abatement policy is here represented by a carbon tax applied to combustion-based CO_2 emissions. The carbon tax unitary level per ton of CO_2 emitted is exogenously modelled in GDynEP-AG based on a recent World Bank report (World Bank, 2017) where a comparison of several carbon prices resulting from many different models is provided. This modelling choice relies on three main reasons. First, the adoption of a mitigation measure on CO_2 emissions allows covering the whole economy, since each production sector as well as

[27] Given the structure of GDynEP-AG, in order to simulate the economic impacts of adopting automation technologies into the production system, it is necessary to inform the model with coefficients that allow transforming investments in automation into productivity improvements. In this work, we consider an average 1% gain in TFP each year as a simple average improvement of productivity of all factors, relying on the calculation of the multifactor productivity by OECD, which is in the range of 0%–2% per year (for a comparison for OECD countries see: https://data.oecd.org/lprdty/multifactor-productivity.htm; https://ec.europa.eu/info/sites/info/files/ip060_en_iii_tfp_growth.pdf).

[28] Given that we simulate the influence on factor productivity within the production process, we assume that efficiency gains in the energy sectors arise in the phase of the production function when energy is used as an input. Accordingly, energy sectors (that produce energy as an output) are not included in the computation of the distribution of productivity gain due to double counting. As an example, given that in GDynEP-AG CO_2 emission are directly linked to fossil fuels, if we include crude oil among sectors arising the factor productivity, the model produces a huge increase in emissions over time.

[29] Given that we have no information regarding the proportion of the impact of automation on the two labour force types, skilled and unskilled, we assume here a homogeneous biased technical change. We acknowledge that recent literature is dealing with skill-biased technical change that will be part of our future research agenda.

[30] In order to maintain all scenarios as fully comparable without adopting subjective assumptions not based on empirical contributions, we assume that the shares of skilled and unskilled workers on total labour force are independent from the adopted scenario and remain constant across scenarios also in the case of technology-driven unemployment.

[31] In particular, the assumption of exogenous technical change implies that the positive economic impacts on those sectors experiencing innovation are overestimated, given that no capital diversion from other sectors is modelled. Future research activities will focus on modelling the introduction of automation and robotics in production processes and in services as endogenous.

Table 5
Labour force projections for the EU (Mln).

	2015	2020	2025	2030	2035	2040	2045	2050
BAU	242.76	243.57	241.70	238.19	233.93	230.31	227.39	225.01
skilled	*149.59*	*144.45*	*138.98*	*131.37*	*122.84*	*115.00*	*104.84*	*97.46*
unskilled	*93.17*	*99.12*	*102.71*	*106.82*	*111.09*	*115.31*	*122.54*	*127.55*
LF10	242.76	240.88	237.94	233.48	228.81	224.87	220.94	218.00
skilled	*149.59*	*142.85*	*136.82*	*128.77*	*120.15*	*112.28*	*101.87*	*94.43*
unskilled	*93.17*	*98.03*	*101.12*	*104.71*	*108.66*	*112.59*	*119.07*	*123.57*
LF15C	242.76	241.11	238.53	234.48	227.65	220.23	211.99	204.03
skilled	*149.59*	*142.99*	*137.16*	*129.32*	*119.54*	*109.96*	*97.74*	*88.38*
unskilled	*93.17*	*98.12*	*101.37*	*105.15*	*108.11*	*110.27*	*114.24*	*115.65*
LF25CRS	242.76	241.11	226.60	211.84	204.77	197.10	188.78	180.70
skilled	*149.59*	*142.99*	*130.30*	*115.10*	*106.39*	*97.87*	*87.67*	*77.77*
unskilled	*93.17*	*98.12*	*96.30*	*96.74*	*98.38*	*99.24*	*101.11*	*102.93*
Unemployment	-	-	*11.93*	*22.64*	*22.88*	*23.12*	*23.21*	*23.33*

*LF15C data for labour force also apply to LF15CR, LF15CRS, LF15CTXL, LF15CTXH. LF25CRS data for labour force also apply to LF25CRSTXL and LF25CRSTXH.

Table 6
Carbon tax applied in EU (EUR per tCO_2).

Carbon Tax	2020	2025	2030	2035	2040	2045	2050
Low Price	31	34	38	43	48	54	60
High Price	61	68	77	86	96	107	119

Note. Data are converted from USD to Euro by applying a constant 2015 exchange rate equal to 0.7653.
Source: World Bank (2017).

households are responsible for such emission type, thus ensuring the largest tax base. Second, the adoption of an exogenous carbon price (while abatement target is endogenous) allows to simulate a policy design mechanism in a more realistic way, where policy makers decide the unitary tax level that is uniformly applied to all sectors. Third, the adoption of an average carbon price value that results from the comparison of several different scenarios and models ensures to be on track with respect to projections provided by bottom-up energy models that are more accurate in shaping technological patterns w.r.t. global CGEs like GDynEP-AG.[32]

According to the World Bank report, we consider two carbon price patterns that represent the upper and lower bound of carbon prices obtained as the mean of carbon tax values deriving from the climate-economic models included in the report (Table 6). Each carbon price pattern is tested on two scenarios, the LF15C without automation and the LF25CR with automation and unemployment.

7. **LF15CTXL:** this scenario replicates the LF15C one (15% labour force reduction in 2050 w.r.t. 2015 due to ageing population), with the addition of a carbon tax in line with data from World Bank (2017), low price (Table 6).
8. **LF15CTXH:** the scenario replicates the LF15C one (15% labour force reduction in 20150 w.r.t. 2015 due to ageing population), with the addition of a carbon tax in line with data from World Bank (2017), high price (Table 6).
9. **LF25CRSTXL:** the starting point is the LF25CRS Scenario. Accordingly, we have a 25% labour force reduction in 2050 w.r.t. 2015 due to ageing population and automation. The mitigation policy is given by the introduction of a carbon tax in line with the World Bank Report (World Bank, 2017), low price (Table 6).
10. **LF25CRSTXH:** assumptions are the same as in LF25CRSTXL, but the carbon tax corresponds to the highest value indicated in World Bank (2017), high price (Table 6).

The last two scenarios, by testing together all investigated issues, allow assessing the direction and magnitude of all mechanisms and feedback loops and, in the case of non-linear effects as highlighted in Fig. 1, the relative net impact on economic dimensions as growth and fiscal sustainability.[33]

4. Results

Results for the different scenarios are compared according to distinguished topics, in order to have a complete framework across all scenarios for all dimensions investigated. We start with the analysis of the economic impacts of population ageing and how these impacts are influenced if automation process is also modelled. Then we introduce the role played by an environmental policy (in the form of a carbon tax) in the case of ageing population and also if massive technological change occurred in the production system. The dimensions we focus on are mainly represented by the economic growth performance and the fiscal sustainability of the public budget on the economic side and CO_2 emissions on the environmental sustainability side.

4.1. Impacts on economic growth

In Table 7 we report results from simulations in terms of the total level of GDP in the EU and the average yearly growth rate for the whole period 2015–2050, while in Table 8 we report GDP per capita.[34] Not

[32] It is noteworthy that we introduce a unilateral climate policy given the interest in understanding the potential contribution of an environmental tax on fiscal sustainability in the EU, without any ambition of assessing the effectiveness and impact of such a policy on the international scale.

[33] In terms of the contribution to the ETR debate, it is noteworthy that we model the carbon tax revenue as a lump sum in welfare computation. Accordingly, in what follows we only consider the counterbalancing effect of increasing environmental tax revenues when there is a decrease in direct tax revenues coming from labour force due to ageing population. In this way, we can treat both revenues as determined by exogenously given tax rates, resulting into scenarios that are fully comparable. Future development from the modelling side on this topic would include two issues: i) the potential contribution of environmental tax revenues in reducing labour taxation within the double dividend debate; ii) the effect of investing environmental tax revenues in new energy technologies within the optimal policy mix design debate (Corradini et al., 2018), by treating green energy technologies as endogenously determined in line with the automation issue.

[34] Original GDynEP-AG results are expressed in USD. All monetary values here reported have been converted into Euro. It is worth mentioning that the calibration process for the BAU scenario brings to a GDP value for 2015 that is perfectly in line with Eurostat data (http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nama_10_gdp&lang=en), while from 2020 onwards data are expressed in Euro constant 2015, by applying the 2011–2015 average exchange rate (the applied exchange rate is equal to 0.7653, obtained as the average value between maximum and minimum for each month in the period 2011–2015). Data from https://www.x-rates.com/average/?from=USD&to=EUR&amount=1&year=2010. This is applied to all monetary variables.

Table 7
GDP in the EU (Mln EUR, constant 2015 for BAU and % change w.r.t to BAU).

	2015	2020	2025	2030	2035	2040	2045	2050	Av. growth per year
BAU	14,808,018	16,274,803	17,956,967	19,818,745	21,881,282	24,163,062	25,764,348	27,482,057	1.77%
LF10	14,808,018	−0.64%	−0.97%	−1.29%	−1.52%	−1.79%	−2.34%	−2.91%	1.68%
LF15	14,808,018	0.00%	0.00%	−0.01%	−0.76%	−2.08%	−3.86%	−5.88%	1.59%
LF15C	14,808,018	−0.59%	−0.82%	−1.91%	−3.50%	−5.52%	−8.08%	−10.97%	1.43%
LF15CR	14,808,018	−0.59%	−0.72%	−0.66%	−0.51%	−0.56%	−0.09%	0.02%	1.77%
LF15CRS	14,808,018	−0.59%	0.59%	1.36%	1.91%	1.48%	1.73%	1.23%	1.80%
LF25CRS	14,808,018	−0.59%	−2.56%	−4.46%	−6.12%	−6.69%	−6.57%	−7.28%	1.55%
LF15CTXL	14,808,018	−1.01%	−1.92%	−3.80%	−6.21%	−8.98%	−12.20%	−15.65%	1.28%
LF15CTXH	14,808,018	−1.44%	−2.96%	−5.49%	−8.49%	−11.77%	−15.38%	−19.15%	1.16%
LF25CRSTXL	14,808,018	−1.01%	−3.65%	−6.31%	−8.75%	−10.08%	−10.68%	−12.04%	1.40%
LF25CRSTXH	14,808,018	−1.44%	−4.67%	−7.96%	−10.97%	−12.81%	−13.87%	−15.62%	1.28%

Note: LF10-10% reduction of EU labour force; LF15-15% reduction of EU labour force; LF15C-15% reduction of EU labour force + change in consumption; LF15CR-15% reduction of EU labour force + change in consumption + uniform change in TFP; LF15CRS-15% reduction of EU labour force + change in consumption + change in sector productivity; LF25CRS-15% reduction of EU labour force + change in consumption + change in sector productivity +10% unemployment; LF15CTXL-15% reduction of EU labour force + change in consumption + low carbon price; LF15CTXH-15% reduction of EU labour force + change in consumption + high carbon price; LF25CRSTXL-15% reduction of EU labour force + change in consumption + change in sector productivity +10% unemployment + low carbon price; LF25CRSTXH-15% reduction of EU labour force + change in consumption + change in sector productivity +10% unemployment + high carbon price.
Source: our elaboration on GDynEP-AG results.

Table 8
GDP per capita in the EU (EUR, constant 2015 for BAU and % change w.r.t. BAU).

	2015	2020	2025	2030	2035	2040	2045	2050	Av. growth per year
BAU	29,179	31,852	35,054	38,670	42,770	47,408	50,841	54,662	1.79%
LF10	29,179	−0.22%	0.21%	0.91%	1.89%	3.01%	4.00%	5.07%	1.93%
LF15	29,179	0.16%	0.39%	0.70%	1.05%	1.23%	1.20%	0.96%	1.82%
LF15C	29,179	−0.42%	−0.42%	−1.22%	−1.75%	−2.33%	−3.25%	−4.50%	1.66%
LF15CR	29,179	−0.42%	−0.33%	0.04%	1.30%	2.80%	5.17%	7.30%	1.99%
LF15CRS	29,179	−0.42%	0.99%	2.07%	3.76%	4.91%	7.08%	8.59%	2.03%
LF25CRS	29,179	−0.42%	−2.17%	−3.78%	−4.41%	−3.54%	−1.66%	−0.54%	1.78%
LF15CTXL	29,179	−0.84%	−1.53%	−3.13%	−4.51%	−5.91%	−7.58%	−9.52%	1.51%
LF15CTXH	29,179	−1.27%	−2.58%	−4.82%	−6.83%	−8.79%	−10.93%	−13.27%	1.39%
LF25CRSTXL	29,179	−0.84%	−3.27%	−5.65%	−7.09%	−7.04%	−5.98%	−5.64%	1.63%
LF25CRSTXH	29,179	−1.27%	−4.29%	−7.31%	−9.35%	−9.87%	−9.34%	−9.48%	1.51%

Note: LF10-10% reduction of EU labour force; LF15-15% reduction of EU labour force; LF15C-15% reduction of EU labour force + change in consumption; LF15CR-15% reduction of EU labour force + change in consumption + uniform change in TFP; LF15CRS-15% reduction of EU labour force + change in consumption + change in sector productivity; LF25CRS-15% reduction of EU labour force + change in consumption + change in sector productivity +10% unemployment; LF15CTXL-15% reduction of EU labour force + change in consumption + low carbon price; LF15CTXH-15% reduction of EU labour force + change in consumption + high carbon price; LF25CRSTXL-15% reduction of EU labour force + change in consumption + change in sector productivity +10% unemployment + low carbon price; LF25CRSTXH-15% reduction of EU labour force + change in consumption + change in sector productivity +10% unemployment + high carbon price.
Source: our elaboration on GDynEP-AG results.

surprisingly, we assist to a reduction in GDP values due to a decrease in labour force. The higher the labour force reduction, the larger the negative economic impact. When the impacts on consumption patterns due to ageing are also included, the average GDP annual growth rate over the period 2015–2050 is even lower (1.43%) loosing 0.16 percentage points comparing with the LF15 case. The divergence is even larger if we compare results for the end year of simulation as by 2050 the reduction in GDP w.r.t. almost doubles when changes in consumption behaviours are accounted. The use of a multi-sector CGE in this case is extremely relevant for catching the divergent behaviour in consumption patterns determined by ageing society and the relative impacts on economic performance.

The introduction of automation, on the other hand, entails an increase in factor productivity that contributes increasing the level of GDP, reaching values close to the BAU case.[35] As a sensitivity analysis for testing non-linear effects associated to ageing and automation as visualised in Fig. 1, we have run a simulation with the same increase in TFP as in LF15CR scenario but excluding ageing impacts, resulting in a BAU case plus automation. By looking at impacts on total GDP, the sum of the effects ascribed to ageing and automation w.r.t. BAU taken separately brings to an average yearly growth rate of 1.81%, compared with the 1.77% obtained in the LF15CR case where non-linear impacts are addressed. Such differences are even much larger if we look at results in the long-term. The difference between BAU and the linear sum of ageing and automation by 2050 is 1.48%, while addressing for non-linearity brings to a difference equal to 0.02% in the same year.[36]

When factor productivity improvement due to the introduction of robotics/automation is differentiated among sectors according to the relative capital intensity, the economy reaches the highest level of GDP and an average growth rate higher than the BAU case (1.80%). Nevertheless, if automation is simulated as input non-neutral generating a reduction in employment rate (scenario LF25CRS), GDP value decreases again reaching a value that is quite close to the GDP value with the maximum ageing population case without automation improvements.

Results related to the role played by technical change must be interpreted with care given that we assume that the introduction of automation occurs in the EU region only. In this way we obtain the direct and net effect in terms of GDP growth (when neutral technical change is modelled) because in the rest of the world technology remains

[35] Since the investments in automation produce effects on productivity levels from 2025, up to that point the three scenarios with automation correspond to the LF15C scenario.

[36] Non-linearity in feedback loops when addressing ageing and automation for GDP is only an example of the complexity in such mechanisms here commented for sensitivity analysis. Full results for these additional simulations are available upon request from the authors.

unchanged and international relationships don't play (significant) influence on the domestic mechanisms. Accordingly, the technological pattern of the EU has a direct effect in terms of increasing multifactor productivity at the domestic level, and an indirect effect related to the improvement of revealed comparative advantages in trade patterns thanks to a higher factor efficiency w.r.t. the rest of the world. Future research should include a comparison with scenarios where technological change related to automation is shaped for all regions at the world level, also taking into account potential impacts on unemployment for all regions, and consequently on costs for social protection and fiscal sustainability.

When we introduce a mitigation policy in the form of a carbon price, the economy faces an additional cost and the level of GDP further decreases, reaching the lowest level in the LF15CTXH case, where more challenging abatement measures are implemented in the form of a higher carbon tax level while no productivity gain is embedded due to automation investments.

Also in this case it is noteworthy that the negative impact on GDP is also driven by the assumption that the EU adopts a unilateral carbon policy while the rest of the world has no abatement constraints, thus bringing to an overestimation of abatement costs for the EU and a corresponding lower bound in terms of GDP reduction, according to what literature defines within the carbon leakage concept (Antimiani et al., 2013, 2016; Böhringer et al., 2012). In other words, the carbon tax imposes an additional cost to firms and households related to the use of fossil fuel-based energy thus reducing competitiveness on the international markets, while all other regions may easily increase their use of polluting energy sources since there is no carbon price on them. This fully explains why in those scenarios with ageing population and carbon price without investments in automaton, the GDP level for the EU is lower while in the other regions slightly grows.[37]

When looking at the effects in terms of GDP per capita (Table 8), among alternative scenarios without automation, the LF15C has the highest reduction in GDP per capita. Indeed, in this scenario the reduction of total population is mainly due to a decrease in active population, thus reducing the level of production with respect to the LF10 scenario (for which the total number of EU people is quite the same but it is due to a reduction of the individuals over 65 years, with a corresponding increase in average yearly growth rate w.r.t. the BAU case, due to the reduction of total population that overwhelms the reduction in labour force).

When automation is introduced (LF15CR), thanks to the positive effects on productivity, the GDP per capita increases, overcoming the LF10 scenario. Nevertheless, when also unemployment impacts are taken into account (LF25CRS), we assist to a reduction in GDP per capita. When environmental policy is modelled with ageing (LF15CTXL and LF15CTXH), a further contraction of the economy is registered so that the GDP per capita reaches its lowest level. If all dimensions are jointly taken, the abatement costs combined with the negative effects associated to unemployment neutralise the positive impacts of automation almost completely (LF25CRSTXL and LF25CRSTXH).

4.2. Tax revenues, public expenditures, environmental and fiscal sustainability

Table 9 compares alternative scenarios according to the revenues arising from different sources of taxation, in terms of direct (labour) and indirect taxation.[38]

First, it is worth mentioning that total revenues registered at the starting point of our simulations (2015) are fully in line with data used in the EC report (EC, 2018b). In fact, in GDynEP-AG total revenues in 2015 correspond to 41% of GDP, compared to about 40% as reported by the EC report.[39]

As for future dynamics, scenarios with lower labour force register lower revenues compared to BAU, especially as a consequence of a reduction of direct taxation flows. It is also worth noting that in all cases higher revenues arise from taxation on skilled labour, but the highest growth over the whole period is always from unskilled workers.

Two reasons are behind this effect. First, in GDynEP-AG the tax rate is the same for skilled and unskilled labour force but the total amount of taxation is also dependent on unitary wage value that in turns changes across different scenarios due to the labour market mechanism of demand and supply equilibrium. The second reason is the change in relative shares of skilled and unskilled on total labour force over time: the reduction of unskilled workers share brings to changing equilibrium price on labour market, with a resulting increase in wage level. Given that total wages are the base for direct taxation, when simulating all these mechanisms in the dynamic CGE, the net effect on wages is positive, meaning that the shortage in labour supply is stronger in directing labour market price equilibrium w.r.t. the reduction in labour demand via the consumption expenditures channel. Nonetheless, the net effect on direct tax revenue in LF15C scenario is negative, meaning that the reduction in tax base overwhelms the increase in unitary tax (associated to wage levels).

Turning to the aggregate of revenues from other taxation that in GTAP computation includes VAT, it is strongly influenced by ageing dynamics, especially when changes in consumption structure is accounted. By comparing values for other taxation in BAU, LF15 and LF15C, the sharper decrease is faced when changes in consumption structure is included (LF15C). When automation is included, things change (Table 10). The total amount of revenues increases as a consequence of a rise in revenues from both direct and indirect taxation, especially when automation results in an increase of productivity differentiated among sectors. Conversely, if automation also entails an additional reduction in labour force (LF25CRS), the collapse of revenues from direct and other taxation aggregates generates a sharp decrease of total revenues, below the BAU case. It is noteworthy that, since the "Other taxation" component includes revenues from VAT, it is the one which contributes the most to total revenues due to a reduction on aggregated demand associated with a lower disposable income for consumers.

The same table is replicated to investigate what happens when environmental taxation is modelled (Table 11). In this case there is an additional component of the public budget given by the revenues arising from carbon taxation (CTR), calculated as follows:

$$CTR_{r,t} = CT_{r,t} \cdot CO2_{r,t} \tag{7}$$

where (CT) is the exogenous per unit tax that corresponds to the carbon price (low and high) values according to World Bank (2017) as reported in Table 5, and applied unilaterally for the EU. CO_2 emissions are endogenously determined and are different across scenarios according to the carbon price adopted as well as the other characteristics as automation and unemployment.

Revenues from carbon taxation are higher in those scenarios entailing higher per unit carbon tax levels (LF15CTXH and LF25CRSTXH)

[37] All results for all regions included in this GDynEP-AG model version are available upon request from the authors.

[38] In GDynEP-AG direct taxation corresponds to labour taxation. More precisely, it corresponds to the difference between the gross labour cost payed by the firm and the net salary perceived by the employee. In a system with full employment and no tax evasion it corresponds to the sum of the income tax payed by the employee and the labour cost payed by the firm. Indirect taxation refers to ordinary tax payed by firms on the use of intermediate goods. Residual taxation (Other tax) includes tax on private consumption (VAT, Value Added Tax) and on government consumption plus taxation payed by firms for the use of endowments (labour excluded). The tax rate is given by the difference between values at market price and at agent price in the starting year. Tax rate is fixed over time. The tax base is determined on value added and consumption.

[39] See Graph 2.28 (EC, 2018b, p. 62).

Table 9
Tax revenues with ageing in the EU (Mln EUR, constant 2015).

Scenario		2015	2020	2025	2030	2035	2040	2045	2050
BAU	Total revenues	6,182,644	6,845,631	7,530,600	8,247,565	8,976,148	9,685,353	10,072,245	10,416,398
	Rev. from direct tax	1,708,181	1,858,443	2,032,177	2,214,796	2,409,349	2,621,965	2,730,968	2,845,058
	Direct skilled	*1,017,100*	*1,116,401*	*1,229,132*	*1,349,603*	*1,479,100*	*1,620,590*	*1,704,039*	*1,785,817*
	Direct unskilled	*691,082*	*742,042*	*803,045*	*865,193*	*930,248*	*1,001,375*	*1,026,930*	*1,059,241*
	Rev. from indirect tax	761,958	828,296	897,515	965,711	1,037,809	1,117,522	1,154,013	1,194,135
	Rev. from other tax	3,712,505	4,158,892	4,600,909	5,067,059	5,528,989	5,945,866	6,187,264	6,377,205
LF10	Total revenues	6,182,644	6,791,852	7,411,008	8,010,888	8,614,845	9,168,347	9,393,963	9,570,795
	Rev. from direct tax	1,708,181	1,844,958	2,010,768	2,184,663	2,371,658	2,574,080	2,665,356	2,759,724
	Direct skilled	*1,017,100*	*1,108,175*	*1,216,076*	*1,331,100*	*1,455,731*	*1,590,497*	*1,661,873*	*1,730,498*
	Direct unskilled	*691,082*	*736,783*	*794,692*	*853,563*	*915,927*	*983,583*	*1,003,483*	*1,029,226*
	Rev. from indirect tax	761,958	822,391	887,772	951,627	1,020,445	1,096,764	1,127,879	1,161,819
	Rev. from other tax	3,712,505	4,124,502	4,512,468	4,874,598	5,222,742	5,497,503	5,600,728	5,649,253
LF15	Total revenues	6,182,644	6,845,804	7,485,191	8,214,209	8,924,607	9,573,013	9,884,550	10,103,930
	Rev. from direct tax	1,708,181	1,858,943	2,033,237	2,216,731	2,392,306	2,566,272	2,623,379	2,673,729
	Direct skilled	*1,017,100*	*1,118,352*	*1,232,146*	*1,353,948*	*1,471,648*	*1,588,150*	*1,641,897*	*1,677,605*
	Direct unskilled	*691,082*	*740,591*	*801,091*	*862,782*	*920,658*	*978,123*	*981,482*	*996,124*
	Rev. from indirect tax	761,958	828,127	897,548	966,085	1,029,787	1,092,910	1,106,439	1,118,819
	Rev. from other tax	3,712,505	4,158,734	4,554,407	5,031,394	5,502,514	5,913,831	6,154,731	6,311,383
LF15C	Total revenues	6,182,644	6,804,170	7,421,774	8,030,446	8,597,127	9,143,840	9,363,064	9,506,389
	Rev. from direct tax	1,708,181	1,846,201	2,014,147	2,170,228	2,321,152	2,471,681	2,504,848	2,529,776
	Direct skilled	*1,017,100*	*1,108,925*	*1,218,111*	*1,323,147*	*1,426,395*	*1,529,695*	*1,564,948*	*1,589,785*
	Direct unskilled	*691,082*	*737,276*	*796,037*	*847,081*	*894,757*	*941,986*	*939,900*	*939,991*
	Rev. from indirect tax	761,958	822,960	889,481	958,068	1,023,949	1,091,504	1,110,363	1,128,112
	Rev. from other tax	3,712,505	4,135,009	4,518,145	4,902,151	5,252,026	5,580,656	5,747,853	5,848,501

Note: LF10-10% reduction of EU labour force; LF15-15% reduction of EU labour force; LF15C-15% reduction of EU labour force + change in consumption; LF15CR-15% reduction of EU labour force + change in consumption + uniform change in TFP; LF15CRS-15% reduction of EU labour force + change in consumption + change in sector productivity; LF25CRS-15% reduction of EU labour force + change in consumption + change in sector productivity +10% unemployment; LF15CTXL-15% reduction of EU labour force + change in consumption + low carbon price; LF15CTXH-15% reduction of EU labour force + change in consumption + high carbon price; LF25CRSTXL-15% reduction of EU labour force + change in consumption + change in sector productivity +10% unemployment + low carbon price; LF25CRSTXH-15% reduction of EU labour force + change in consumption + change in sector productivity +10% unemployment + high carbon price.
Source: our elaboration on GDynEP-AG results.

Table 10
Tax revenues with ageing and automation in the EU (Mln EUR, constant 2015).

Scenario		2015	2020	2025	2030	2035	2040	2045	2050
LF15CR	Total revenues	6,182,644	6,824,845	7,497,499	8,192,232	8,959,268	9,663,904	10,129,145	10,535,782
	Rev. from direct tax	1,708,181	1,846,201	2,016,355	2,202,385	2,402,973	2,616,546	2,748,640	2,876,840
	Direct skilled	*1,017,100*	*1,108,925*	*1,219,475*	*1,343,192*	*1,477,622*	*1,620,725*	*1,719,678*	*1,811,067*
	Direct unskilled	*691,082*	*737,276*	*796,880*	*859,193*	*925,351*	*995,821*	*1,028,962*	*1,065,773*
	Rev. from indirect tax	761,958	822,960	890,297	969,906	1,053,902	1,144,734	1,200,322	1,257,658
	Rev. from other tax	3,712,505	4,155,685	4,590,848	5,019,941	5,502,393	5,902,625	6,180,183	6,401,284
LF15CRS	Total revenues	6,182,644	6,824,845	7,573,396	8,335,156	9,119,651	9,810,325	10,265,595	10,618,812
	Rev. from direct tax	1,708,181	1,846,201	2,042,684	2,240,540	2,445,867	2,643,797	2,757,741	2,855,734
	Direct skilled	*1,017,100*	*1,108,925*	*1,235,825*	*1,366,801*	*1,504,025*	*1,636,853*	*1,724,383*	*1,796,225*
	Direct unskilled	*691,082*	*737,276*	*806,859*	*873,738*	*941,841*	*1,006,945*	*1,033,358*	*1,059,509*
	Rev. from indirect tax	761,958	822,960	900,357	984,437	1,070,665	1,156,812	1,206,922	1,254,407
	Rev. from other tax	3,712,505	4,155,685	4,630,355	5,110,179	5,603,119	6,009,716	6,300,932	6,508,670
LF25CRS	Total revenues	6,182,644	6,822,778	7,366,939	8,029,273	8,587,937	9,191,739	9,541,599	9,786,424
	Rev. from direct tax	1,708,181	1,846,201	1,969,880	2,099,860	2,240,557	2,422,863	2,526,888	2,608,205
	Direct skilled	*1,017,100*	*1,108,925*	*1,190,619*	*1,279,235*	*1,375,725*	*1,498,880*	*1,578,971*	*1,639,355*
	Direct unskilled	*691,082*	*737,276*	*779,261*	*820,626*	*864,831*	*923,982*	*947,917*	*968,851*
	Rev. from indirect tax	761,958	822,960	872,669	931,065	992,018	1,069,745	1,111,827	1,149,176
	Rev. from other tax	3,712,505	4,153,617	4,524,390	4,998,348	5,355,363	5,699,131	5,902,885	6,029,043

Note: LF10-10% reduction of EU labour force; LF15-15% reduction of EU labour force; LF15C-15% reduction of EU labour force + change in consumption; LF15CR-15% reduction of EU labour force + change in consumption + uniform change in TFP; LF15CRS-15% reduction of EU labour force + change in consumption + change in sector productivity; LF25CRS-15% reduction of EU labour force + change in consumption + change in sector productivity +10% unemployment; LF15CTXL-15% reduction of EU labour force + change in consumption + low carbon price; LF15CTXH-15% reduction of EU labour force + change in consumption + high carbon price; LF25CRSTXL-15% reduction of EU labour force + change in consumption + change in sector productivity +10% unemployment + low carbon price; LF25CRSTXH-15% reduction of EU labour force + change in consumption + change in sector productivity +10% unemployment + high carbon price.
Source: our elaboration on GDynEP-AG results.

revealing that the reduction in tax base (total emission level as in Table 12) is more than compensated by the higher unit tax applied to each ton of CO_2.[40]

However, these scenarios register lower levels of total revenues compared to those with a low carbon price. This is mainly due to the sharp economic contraction characterizing these scenarios (Tables 7 and

[40] These two scenarios also correspond to an almost complete achievement of abatement targets for the EU by 2050 coherently with the EU commitment within the Paris Agreement (PA) as in Table 12 row EU target PA (Corradini et al., 2018).

Table 11
Tax revenues with carbon pricing in the EU (Mln EUR, constant 2015).

Scenario		2015	2020	2025	2030	2035	2040	2045	2050
LF15CTXL	Total revenues	6,182,644	6,808,445	7,443,988	8,040,418	8,633,728	9,158,492	9,383,083	9,515,828
	Rev. from direct tax	1,708,181	1,834,409	1,986,116	2,122,589	2,251,436	2,378,125	2,391,517	2,397,351
	Direct skilled	*1,017,100*	*1,101,691*	*1,200,925*	*1,293,868*	*1,383,364*	*1,471,712*	*1,494,194*	*1,506,742*
	Direct unskilled	*691,082*	*732,719*	*785,191*	*828,721*	*868,073*	*906,412*	*897,323*	*890,609*
	Rev. from indirect tax	761,958	831,475	904,339	977,435	1,046,515	1,116,793	1,134,818	1,151,378
	Rev. from carbon tax	0	83,674	83,037	83,391	83,962	85,701	86,171	88,154
	Rev. from other tax	3,712,505	4,058,888	4,470,497	4,857,002	5,251,815	5,577,874	5,770,578	5,878,945
LF15CTXH	Total revenues	6,182,644	6,790,299	7,399,442	7,965,432	8,524,444	9,008,056	9,218,967	9,350,169
	Rev. from direct tax	1,708,181	1,823,592	1,962,086	2,083,609	2,196,805	2,307,889	2,309,434	2,304,562
	Direct skilled	*1,017,100*	*1,095,003*	*1,186,116*	*1,269,835*	*1,349,591*	*1,428,173*	*1,442,964*	*1,448,600*
	Direct unskilled	*691,082*	*728,589*	*775,970*	*813,774*	*847,214*	*879,716*	*866,470*	*855,962*
	Rev. from indirect tax	761,958	838,285	914,432	988,673	1,057,229	1,125,980	1,140,601	1,153,446
	Rev. from carbon tax	0	152,754	142,994	139,490	135,548	132,995	131,449	131,384
	Rev. from other tax	3,712,505	3,975,669	4,379,930	4,753,660	5,134,863	5,441,193	5,637,484	5,760,777
LF25CRSTXL	Total revenues	6,182,644	6,808,445	7,344,711	7,916,331	8,481,739	9,047,964	9,359,204	9,562,641
	Rev. from direct tax	1,708,181	1,834,409	1,942,354	2,053,570	2,173,176	2,331,715	2,414,315	2,474,397
	Direct skilled	*1,017,100*	*1,101,691*	*1,173,749*	*1,250,805*	*1,334,170*	*1,442,409*	*1,508,642*	*1,555,306*
	Direct unskilled	*691,082*	*732,719*	*768,605*	*802,764*	*839,006*	*889,306*	*905,673*	*919,091*
	Rev. from indirect tax	761,958	831,475	887,283	949,841	1,013,734	1,094,366	1,136,349	1,173,569
	Rev. from carbon tax	0	83,674	82,026	81,739	82,133	84,708	87,028	90,720
	Rev. from other tax	3,712,505	4,058,888	4,433,048	4,831,181	5,212,696	5,537,176	5,721,511	5,823,955
LF25CRSTXH	Total revenues	6,182,644	6,790,299	7,301,019	7,864,104	8,395,282	8,923,677	9,221,815	9,413,777
	Rev. from direct tax	1,708,181	1,823,592	1,918,758	2,015,697	2,120,341	2,263,116	2,332,346	2,379,847
	Direct skilled	*1,017,100*	*1,095,003*	*1,159,215*	*1,227,475*	*1,301,536*	*1,399,893*	*1,457,429*	*1,495,934*
	Direct unskilled	*691,082*	*728,589*	*759,543*	*788,222*	*818,804*	*863,222*	*874,916*	*883,913*
	Rev. from indirect tax	761,958	838,285	897,213	960,760	1,024,112	1,103,485	1,142,570	1,176,551
	Rev. from carbon tax	0	152,754	141,261	136,781	132,733	131,718	133,218	135,828
	Rev. from other tax	3,712,505	3,975,669	4,343,787	4,750,866	5,118,097	5,425,359	5,613,682	5,721,550

Note: LF10-10% reduction of EU labour force; LF15-15% reduction of EU labour force; LF15C-15% reduction of EU labour force + change in consumption; LF15CR-15% reduction of EU labour force + change in consumption + uniform change in TFP; LF15CRS-15% reduction of EU labour force + change in consumption + change in sector productivity; LF25CRS-15% reduction of EU labour force + change in consumption + change in sector productivity +10% unemployment; LF15CTXL-15% reduction of EU labour force + change in consumption + low carbon price; LF15CTXH-15% reduction of EU labour force + change in consumption + high carbon price; LF25CRSTXL-15% reduction of EU labour force + change in consumption + change in sector productivity +10% unemployment + low carbon price; LF25CRSTXH-15% reduction of EU labour force + change in consumption + change in sector productivity +10% unemployment + high carbon price.
Source: our elaboration on GDynEP-AG results.

Table 12
Combustion-based CO_2 emissions in the EU (Mtoe).

Scenario	2015	2020	2025	2030	2035	2040	2045	2050
BAU	3201	3123	3027	2950	2853	2789	2708	2682
EU target PA	3201	2732	2353	1999	1660	1376	1135	941
LF10	3201	3112	3011	2929	2828	2760	2674	2642
LF15	3201	3122	3027	2950	2839	2747	2629	2557
LF15C	3201	3112	3013	2942	2841	2762	2658	2597
LF15CR	3201	3112	3015	2968	2904	2869	2829	2834
LF15CRS	3201	3112	3033	2997	2937	2892	2837	2822
LF25CRS	3201	3112	2976	2880	2771	2717	2663	2646
LF15CTXL	3201	2733	2411	2179	1959	1777	1608	1477
LF15CTXH	3201	2495	2099	1823	1581	1390	1227	1100
LF25CRSTXL	3201	2733	2382	2136	1916	1757	1624	1520
LF25CRSTXH	3201	2495	2074	1787	1549	1377	1243	1138

Note: LF10-10% reduction of EU labour force; LF15-15% reduction of EU labour force; LF15C-15% reduction of EU labour force + change in consumption; LF15CR-15% reduction of EU labour force + change in consumption + uniform change in TFP; LF15CRS-15% reduction of EU labour force + change in consumption + change in sector productivity; LF25CRS-15% reduction of EU labour force + change in consumption + change in sector productivity +10% unemployment; LF15CTXL-15% reduction of EU labour force + change in consumption + low carbon price; LF15CTXH-15% reduction of EU labour force + change in consumption + high carbon price; LF25CRSTXL-15% reduction of EU labour force + change in consumption + change in sector productivity +10% unemployment + low carbon price; LF25CRSTXH-15% reduction of EU labour force + change in consumption + change in sector productivity +10% unemployment + high carbon price.
Source: our elaboration on GDynEP-AG results and Corradini et al. (2018) for the EU target PA calculation.

8) that leads to lower revenues from other forms of taxation. For the same reason, in most cases total revenues registered in scenarios with CO_2 mitigation are lower than those observed in the corresponding scenarios without abatement policies. As a clear example of non-linear effects, carbon tax revenues are higher in the case of LF25CRSTXL and LF25CRSTXH w.r.t. the corresponding LF15CTXL and LF15CTXH given the same carbon price as in Table 5. This is due to differences in CO_2 emission levels (Table 12) that are higher in scenarios with automation also accounting for technology-driven unemployment. According to this results, *ceteris paribus*, it is noteworthy that by including the impacts of automation the positive impacts on public budget in terms of increased revenues associated to environmental taxation are reinforced by the negative impacts of automation of emission levels.

This means that for an exogenously determined mitigation policy in the form of a carbon tax instrument, the amount of revenues is strictly dependent on the economic structure under scrutiny. If ageing population is considered, CO_2 emissions are lower than in the BAU case, meaning that the total CTR will be reduced for a given carbon price. Two reasons are behind this specific result. First, the EU economy faces a strong contraction as a consequence of the reduction in labour force with a reduction in both production and consumption. This results in a decreasing energy consumption, and consequently in a reduction in CO_2 emissions. Second, in line with Kim and Seo (2012), a progressive ageing society impacts on energy consumption both through a reduction in consumption levels across all commodities at the household level, and by changing energy consumption share in the commodity basket. On the contrary, when also automation is included, productivity gains bring CO_2 emissions up and consequently also CTR increases.[41] Trends in CO_2 emissions suggest that if environmental sustainability is the only policy target under consideration, ageing population plays a positive role while technological innovation is detrimental for such objective, bringing to opposite conclusions w.r.t. the economic growth dimension. Thus, if a sustainable growth pattern is the long-term policy goal for the EU, such complexities and contrasting forces should be carefully considered in an optimal policy mix design exercise.

Together with economic growth and environmental sustainability, a further aspect to be addressed is fiscal sustainability. Indeed, changes in population structure and production processes also entail changes in revenues from direct and indirect taxation and a simultaneous increase of public expenditure to sustain inactive population (e.g., higher health and pensions expenditures).

Starting from GDynEP-AG results, we perform ex-post calculations on selected expenditure lines in the public welfare system which are not detailed in model structure. We start from the variable derived from the model describing the government expenditure (G) whose value in BAU case at 2015 corresponds to the sum of final consumption, consumption of fixed capital and changes in inventories and acquisitions less disposals of valuables from the public sector according to EUROSTAT COFOG data.

In order to obtain the total EU government expenditure (*GovExp*), we apply a coefficient (ϕ) describing the share of G w.r.t. total government expenditure, as follows[42]:

$$Gov\_Exp_{r,2015} = \frac{G_{r,2015}}{\phi_{r,2015}} \tag{8}$$

where (ϕ) is equal to 0.49 for the EU aggregate according to EUROSTAT data.

Then we calculate the amount of government expenditure allocated towards different purposes only for the EU aggregate.[43] We first obtain the expenditures for health, education and pensions in 2015 in absolute values starting from the total government expenditure obtained in eq. (8) as:

$$Health_{2015} = GovExp_{2015} \cdot h \tag{9}$$

$$Education_{2015} = GovExp_{2015} \cdot \varepsilon \tag{10}$$

$$Pensions_{2015} = GovExp_{2015} \cdot \rho \tag{11}$$

where h, ε and ρ come from EUROSTAT data and describe the share of total government expenditure that EU directs towards health ($h = 0.15$), education (ε=0.10) and pensions ($\rho = 0.22$), respectively.[44]

In order to approximate how expenditure evolves over time, we apply two different methods, one for health and education, and a different one for pensions.

Regarding health, we start from computing two aggregates of public health expenditure divided by age group summing all age group under 64-year old and leaving the 65 + age group alone. The shares of health expenditure for age groups for the year 2015 are taken from OECD data obtaining[45]:

$$Health(0-64)_{2015} = Health_{2015} \cdot \psi \tag{12}$$

$$Health(65+)_{2015} = Health_{2015} \cdot \omega \tag{13}$$

with $\psi = 58.9\%$ and $\omega = 41.1\%$. We then compute the per capita public expenditure (*Hpc*) in 2015 as for age group 0–64 years:

$$Hpc(0-64)_{2015} = \frac{Health(0-64)_{2015}}{POP(0-64)_{2015}} \tag{14}$$

and for age group over 65 years:

$$Hpc(65+)_{2015} = \frac{Health\_Exp(65+)_{2015}}{POP(65+)_{2015}} \tag{15}$$

given that per capita health expenditure for elderly people is much higher than for the other age groups (Breyer et al., 2010). Then for each scenario (s), we compute how *Hpc* evolves over time, taking into account different demographic trends and age structures. The per capita health expenditures grow over time proportionally to the increase in population share of people over 65 years. In this way, the per capita expenditure for health increases with ageing population, according to empirical findings on OECD countries provided by Sanz and Velázquez (2007). We then calculate the amount of total public expenditure for health (H) over time considering the increase of the unitary cost due to the composition of population. Moreover, the total expenditure for health over time is indexed to +1% per year to take into account changes in the cost of health care services due to for instance the adoption of new technologies or the replacement of medical equipment, as follows:

$$H_{s,t} = \left[\left(Hpc(0-64)_{2015} \cdot POP(0-64)_{s,t}\right) + \left(Hpc(65+)_{2015} \cdot POP(65+)_{s,t}\right)\right] \cdot (1+0.01)^{(t-t_0)} \tag{16}$$

Regarding education, starting from the aggregate expenditures as calculated in eq. (10) we compute the per capita public expenditure (*Epc*) in 2015 as for age group 0–64 years:

$$Epc_{2015} = \frac{Education_{2015}}{POP(0-64)_{2015}} \tag{17}$$

Once the per capita expenditure is obtained, we project the total expenditure for education up to 2050 by considering the different

[41] In this modelling exercise BAU is the only case in which emissions are exogenously given according to IEA projections. Conversely, in all scenarios the level of emissions is endogenous. In addition, also in the case of introducing automation, we assume neutrality in terms of input augmenting technical change and no specific investments in green energy technologies. This means that energy efficiency improves as all the other inputs' efficiency and that there are no changes regarding convenience in producing energy from renewable sources w.r.t. to traditional fossil fuel due to specific investments directed toward renewables.

[42] Data for government expenditures for the EU are taken from EUROSTAT database on government expenditure main aggregates http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=gov_10a_main&lang=en. Total general government expenditure corresponds to COFOG code TE, final consumption expenditure to COFOG code P3, consumption of fixed capital to COFOG code P51C, changes in inventories to COFOG code P52 and acquisitions less disposals of valuables from the public sector to COFOG code P53.

[43] Given the focus on the EU, in what follows ex-post calculations are referred to the EU region only, but they can be applied to each region forming the model if appropriate information on the composition of public budget is available.

[44] Data on general government expenditure by function (COFOG) is directly extracted from EUROSTAT database available at: http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=gov_10a_exp&lang=en. Data for health expenditures correspond to the code COFOG GF07 (Health). Data for education expenditures correspond to the code COFOG GF09 (Education). Data for pension expenditures correspond to the code COFOG GF1002 (Old age).

[45] Data on expenditure by disease, age and gender are extracted by OECD database on the System of Health Accounts (SHA) Framework available online https://stats.oecd.org/index.aspx?DatasetCode=EBDAG.

evolutions of demographic structure designed by scenarios and also indexing it with a +1% per year increase to take into account changes in the cost of education function as for health expenditures[46]:

$$E_{s,t} = \left[\left(Epc_{2015} \cdot POP(0-64)_{s,t}\right)\right] \cdot (1+0.01)^{(t-t_0)} \quad (18)$$

Regarding pensions, we first compute the unitary cost of pensions for the EU (*Ppc*) in 2015, given by the ratio between the amount of public budget directed to pensions provided by EUROSTAT and the number of people over 65 years:

$$Ppc_{2015} = \frac{Pensions_{2015}}{POP(65+)_{2015}} \quad (19)$$

The unitary cost of pensions evolves over time on the basis of wage increase. In particular, in a defined contribution pension scheme, if wages increase, also pensions rise, even if not proportionally (Díaz-Giménez and Díaz-Saavedra, 2009). Given the wide differences across pension schemes in EU countries, simplifying assumptions are required. In particular, we consider the current average cost of pension systems on average for the all EU countries and we assume no reforms in terms of funding systems and age retirement rules. More importantly, even if there is a high heterogeneity in retirement age, given that the employment rate for people in the age 65–69 is very low for most countries in the EU, we assume an average retirement age of 64. This allows considering 65 + people as automatically retired across all EU, obtaining a full correspondence between demographic and retirement trends. The evolution of the unitary pension is as follows:

$$Ppc_{s,t} = Ppc_{s,t-1} \cdot (1 + r_{s,t}) \quad (20)$$

where (*r*) is the growth rate of pensions, here assumed to be a function of the wage growth rate in monetary terms (net of inflation since monetary values are all expressed in constant 2015 EUR). In this way, we adjust the unitary cost of pensions according to change in the level of wages starting from a unitary value at 2015 that is calibrated with EU data. This allows accounting for two mechanisms associated to projected demographic and labour market trends as emphasised in Díaz-Giménez and Díaz-Saavedra (2009). First, wages and salaries are expected to increase with the growing proportion of skilled workers in the labour market. Second, with ageing population labour supply will decrease and wage levels will increase. As a benchmark for calibration of parameter (*r*) we have considered the most recent OECD publication on pensions with a comparative approach (OECD, 2017), where the unitary cost of pension across OECD countries (net of inflation) on average increases by a 1.25% per year due to the effect of increasing value of wages and salaries. In our modelling exercise the yearly growth rate is assumed to be on average 0.8% for the period 2015–2050 for the BAU case representing the lower bound value, while the upper bound is a yearly average growth rate of 1.22% for the LF15CRS scenario corresponding to the highest projected increase in wage values. Accordingly, in any case, values for (*r*) are below the OECD average, in order to adopt the most conservative assumption (with a resulting underestimated pressure on public budget due expenditure flow for pension).

Finally, we compute the total public expenditure for pensions (*P*) over time:

$$P_{s,t} = Ppc_{s,t} \cdot POP(65+)_{s,t} \quad (21)$$

The remaining government expenditure for 2015 is classified as "Other" and it is the complement to *GovExp* in eq. (8) w.r.t. to health, education and pensions as:

$$Other_{2015} = Gov\_Exp_{2015} - Health_{2015} - Education_{2015} - Pensions_{2015} \quad (22)$$

Starting from the value for 2015 which is equal for all scenarios, the evolution over time of other government expenditures for all scenarios is proxied by the variation rate of variable *G* in model results for each temporal 5-year step (here defined as $g_{s,t-(t-1)}$) that is endogenously determined by the model as:

$$Oth\_Exp_{s,t} = Oth\_Exp_{s,t-1} \cdot \left(1 + g_{s,t-(t-1)}\right) \quad (23)$$

The evolution over time of total government expenditure is the simple sum of expenditure lines according to the scenario under scrutiny as:

$$Gov\_Exp_{s,t} = H_{s,t} + E_{s,t} + P_{s,t} + Oth\_Exp_{s,t} \quad (24)$$

Once we have defined the government expenditure value and its composition, we compute the current deficit as:

$$DEFICIT_{s,t} = GovExp_{s,t} - REV_{s,t} \quad (25)$$

where (*REV*) is the sum of total revenues arising from all forms of taxation that is endogenously calculated in GDynEP-AG for all scenarios directly by the model optimization procedure. The deficit to GDP ratio is then available for all scenarios over the temporal horizon 2015–2050:

$$\frac{DEFICIT_{s,t}}{GDP_{s,t}} \cdot 100 \quad (26)$$

Tables 13–15 summarize these results for ageing, automation and environmental policy related scenarios, respectively.

The first and most straightforward consequence of ageing population is that a reduction in labour force entails a contraction of the economic system and hence a decrease in revenues arising from direct taxation and a reduction in GDP level. We also observe that in the case of a more pronounced level of ageing population (i.e. 15% reduction of labour force) government expenditures are higher, due to health and pensions. Regarding pensions, together with the impact associated to an increased number of retired workers, the increase in total expenditure is also associated to the increase in wages due to the mechanisms acting on the labour market, bringing to an increase in unitary pensions as they are direct function of salary levels, reinforcing pressure on government expenditures.

In this respect, we can observe that pension expenditures at 2050 are similar to the projections provided by the EC Report in the same year in GDP terms, with a 10.8% of GDP obtained by GDynEP-AG compared to the 9.5% projected by EC (2018a). In addition, our results show a 5.7% of GDP directed to health expenditures in 2050, against a 7.8% in EC (2018a). Nevertheless, it is worth noting that our results are strongly influenced by the assumptions made to build the scenarios and to calculate ex-post variables. Consequently, they must not be interpreted as projections, but rather as an indication of the direction and trend of a phenomenon. These changes in the economic structure together with the effects on the economic system, also modify the ability of the EU to respect the SGP parameters.

Indeed, Table 13 shows that when a process of ageing population is taken into account (LF15C), from 2035 the EU will not be able to respect the SGP target of holding the deficit/GDP ratio below 3%. Turning to the impact of automation, it generally improves fiscal sustainability. In

[46] For the sake of simplicity per capita expenditure for education is here computed on the largest age group 0–64 as an aggregate, and accordingly we also considered the largest COFOG code for education that includes all forms of expenditures for all education levels from pre-primary to continuous training for workers. In this work, we are not interested in analyzing different structures of allocation of public expenditures according to different bargaining outcomes between voters belonging to different age groups when choosing allocation of government expenditures to different functions (typically health and pensions vs. education). Accordingly, the evolution of total expenditures for health, education and pensions only depends on demographic structure changes across scenarios. This assumption is consistent with Sanz and Velázquez (2007) results since the negative influence on education expenditures performed by elderly people seems to be confined into the short term, while in our analysis a long term perspective is adopted.

Table 13
Fiscal sustainability with ageing in the EU (Mln EUR, constant 2015).

Scenario		2015	2020	2025	2030	2035	2040	2045	2050
BAU	Total revenues	6,182,644	6,845,631	7,530,600	8,247,565	8,976,148	9,685,353	10,072,245	10,416,398
	Total gov. exp.	6,505,150	7,199,500	7,908,093	8,653,511	9,421,697	10,171,871	10,588,068	10,959,151
	Health	*975,772*	*1,116,786*	*1,218,500*	*1,328,333*	*1,431,589*	*1,505,574*	*1,553,301*	*1,578,590*
	Health+65	*400,067*	*457,882*	*525,069*	*601,596*	*681,433*	*753,206*	*816,721*	*872,357*
	Education	*663,525*	*688,566*	*708,846*	*725,972*	*741,923*	*761,283*	*783,901*	*809,246*
	Pensions	*1,431,133*	*1,624,399*	*1,863,075*	*2,138,725*	*2,429,082*	*2,689,159*	*2,851,004*	*2,973,989*
	Other gov. exp.	*3,434,719*	*3,769,748*	*4,117,672*	*4,460,480*	*4,819,103*	*5,215,855*	*5,399,862*	*5,597,326*
	Deficit	−322,506	−353,869	−377,492	−405,945	−445,549	−486,518	−515,822	−542,754
	Deficit/GDP %	−2.18	−2.17	−2.10	−2.05	−2.04	−2.01	−2.00	−1.97
LF10	Total revenues	6,182,644	6,791,852	7,411,008	8,010,888	8,614,845	9,168,347	9,393,963	9,570,795
	Total gov. exp.	6,505,150	7,139,957	7,766,431	8,398,668	9,030,634	9,621,197	9,860,805	10,048,773
	Health	*975,772*	*1,102,939*	*1,179,467*	*1,254,906*	*1,316,281*	*1,343,708*	*1,343,029*	*1,321,157*
	Health+65	*400,067*	*452,205*	*508,249*	*568,341*	*626,546*	*672,227*	*706,161*	*730,095*
	Education	*663,525*	*687,122*	*704,667*	*718,109*	*729,717*	*743,807*	*759,961*	*777,509*
	Pensions	*1,431,133*	*1,606,796*	*1,807,446*	*2,026,328*	*2,239,941*	*2,405,919*	*2,469,782*	*2,489,687*
	Other gov. exp.	*3,434,719*	*3,743,100*	*4,074,852*	*4,399,325*	*4,744,696*	*5,127,763*	*5,288,031*	*5,460,420*
	Deficit	−322,506	−348,105	−355,423	−387,780	−415,789	−452,851	−466,841	−477,978
	Deficit/GDP %	−2.18	−2.15	−2.00	−1.98	−1.93	−1.91	−1.86	−1.79
LF15	Total revenues	6,181,583	6,845,804	7,485,191	8,214,209	8,924,607	9,573,013	9,884,550	10,103,930
	Total gov. exp.	6,505,150	7,201,959	7,888,308	8,673,747	9,444,922	10,154,175	10,502,914	10,762,205
	Health	*975,773*	*1,115,819*	*1,216,270*	*1,324,172*	*1,424,534*	*1,494,102*	*1,535,066*	*1,550,112*
	Health+65	*400,067*	*457,486*	*524,108*	*599,711*	*678,074*	*747,466*	*807,133*	*856,620*
	Education	*663,525*	*687,287*	*705,620*	*719,976*	*725,236*	*729,010*	*732,478*	*737,395*
	Pensions	*1,431,133*	*1,637,834*	*1,887,158*	*2,181,700*	*2,499,451*	*2,789,123*	*2,993,865*	*3,149,785*
	Other gov. exp.	*3,434,720*	*3,761,018*	*4,079,260*	*4,447,899*	*4,795,702*	*5,141,939*	*5,241,505*	*5,324,914*
	Deficit	−322,506	−356,155	−403,117	−459,539	−520,315	−581,161	−618,364	−658,275
	Deficit/GDP %	−2.18	−2.20	−2.26	−2.36	−2.46	−2.55	−2.61	−2.69
LF15C	Total revenues	6,182,644	6,804,170	7,421,774	8,030,446	8,597,127	9,143,840	9,363,064	9,506,389
	Total gov. exp.	6,505,150	7,181,153	7,882,599	8,571,732	9,242,449	9,851,572	10,108,349	10,281,263
	Health	*975,773*	*1,115,819*	*1,216,270*	*1,324,172*	*1,424,534*	*1,494,102*	*1,535,066*	*1,550,112*
	Health+65	*400,067*	*457,486*	*524,108*	*599,711*	*678,074*	*747,466*	*807,133*	*856,620*
	Education	*663,525*	*687,287*	*705,620*	*719,976*	*725,236*	*729,010*	*732,478*	*737,395*
	Pensions	*1,431,133*	*1,632,619*	*1,878,920*	*2,160,601*	*2,465,310*	*2,741,748*	*2,930,193*	*3,069,977*
	Other gov. exp.	*3,434,720*	*3,745,428*	*4,081,789*	*4,366,982*	*4,627,370*	*4,886,712*	*4,910,611*	*4,923,779*
	Deficit	−322,506	−376,983	−460,825	−541,286	−645,322	−707,732	−745,285	−774,874
	Deficit/GDP %	−2.18	−2.33	−2.59	−2.78	−3.06	−3.10	−3.15	−3.17

Note: LF10-10% reduction of EU labour force; LF15-15% reduction of EU labour force; LF15C-15% reduction of EU labour force + change in consumption.
Source: our elaboration on GDynEP-AG results.

particular, we assist to a lower deficit/GDP ratio especially in the LF15CRS scenario. This is mainly driven by the higher GDP characterizing the economy as a consequence of automation (Table 7).

To this sense, it is worth mentioning that the expenditures for pensions increase when automation is included, especially when improvements in factor productivity are assigned to more capital-intensive sectors. If from the one side this brings to the highest impact in terms of GDP growth, it also leads to increasing demand for the labour factor. Given that labour supply is constrained by ageing population (and no migration), labour market reacts with increasing wage levels. This in turn will push up pensions level according to eq. (20). At the same time, given that direct taxation is a positive function of wages in monetary terms, the increase in work force remuneration raises revenues from labour taxation, with a positive impact on fiscal sustainability. However, when input biased-technical change is under scrutiny, if non-neutrality negatively impacts employment level as in LF25CRS scenario, additional government expenditures in the form of social transfers for unemployment arise while labour tax revenues decrease w.r.t. to the neutral technical change comparable case (LF15CRS).

To this end, we start from EUROSTAT data on total EU expenditure for unemployment (*UnemExp*, equal to 194,379 Mln EUR)[47] and on the number of unemployed people in 2015 (*Unem*, equal to 22,989 individuals in 2015).[48] We then calculate the government expenditure per unemployed person per year (*Upc*, equal to about 8490 EUR) as follows:

$$Upc_{2015} = \frac{UnemExp_{2015}}{Unem_{2015}} \tag{27}$$

Finally, supposing that the *Upc* changes over time as for the per capita health expenditure, the social transfer for unemployment is obtained for each period by applying the unitary cost to the number of unemployed people, given by the difference between labour force associated to LF15C scenario and labour force in the LF25CRS (as provided in Table 5)[49]:

$$SocialTransf_t = Upc_{2015} \cdot (1 + 0.01)^{t-t_0} \cdot (LF_{LF15C,t} - LF_{LF25CRS,t}) \tag{28}$$

Accordingly, other expenditures variable for 2015 as given by eq. (22) becomes:

$$Other_{2015} = Gov\_Exp_{2015} - Health_{2015} - Education_{2015} - Pensions_{2015} - UnemExp_{2015} \tag{29}$$

while its evolution over time is given by eq. (23).

[47] Data for government expenditures for unemployment correspond to the EUROSTAT code COFOG GF1005 (Unemployment) http://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do.

[48] Data for unemployment are available on EUROSTAT within the Labour Force Survey database at: http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=une_rt_a&lang=en.

[49] We acknowledge that the computation of social transfer over time is quite simple and ignores two relevant issues: i) the unitary social transfer per person evolves over time independently from trends in monetary wages; ii) once a worker exits from the job market we don't consider the temporal profile of social benefits (the age of the worker at the time unemployment begins and the consequent duration of transfers). In our ex-post calculation, we consider only the cost of social benefits of unemployment on average on total unemployed workers in each period.

Table 14
Fiscal sustainability with ageing and automation in the EU (Mln EUR, constant 2015).

Scenario		2015	2020	2025	2030	2035	2040	2045	2050
LF15CR	Total revenues	6,182,644	6,824,845	7,497,499	8,192,232	8,959,268	9,663,904	10,129,145	10,535,782
	Total gov. exp.	6,505,150	7,181,153	7,887,478	8,643,302	9,425,028	10,175,589	10,657,363	11,066,956
	Health	*975,773*	*1,115,819*	*1,216,270*	*1,324,172*	*1,424,534*	*1,494,102*	*1,535,066*	*1,550,112*
	Health+65	*400,067*	*457,486*	*524,108*	*599,711*	*678,074*	*747,466*	*807,133*	*856,620*
	Education	*663,525*	*687,287*	*705,620*	*719,976*	*725,236*	*729,010*	*732,478*	*737,395*
	Pensions	*1,431,133*	*1,632,619*	*1,879,882*	*2,175,633*	*2,507,153*	*2,820,391*	*3,068,762*	*3,274,464*
	Other gov. exp.	*3,434,720*	*3,745,428*	*4,085,706*	*4,423,521*	*4,768,105*	*5,132,085*	*5,321,057*	*5,504,985*
	Deficit	*−322,506*	*−356,308*	*−389,978*	*−451,070*	*−465,759*	*−511,684*	*−528,219*	*−531,174*
	Deficit/GDP %	*−2.18*	*−2.20*	*−2.19*	*−2.29*	*−2.14*	*−2.13*	*−2.05*	*−1.93*
LF15CRS	Total revenues	6,182,644	6,824,845	7,573,396	8,335,156	9,119,651	9,810,325	10,265,595	10,618,812
	Total gov. exp.	6,505,150	7,181,153	7,953,653	8,744,252	9,548,095	10,272,917	10,735,816	11,095,233
	Health	*975,773*	*1,115,819*	*1,216,270*	*1,324,172*	*1,424,534*	*1,494,102*	*1,535,066*	*1,550,112*
	Health+65	*400,067*	*457,486*	*524,108*	*599,711*	*678,074*	*747,466*	*807,133*	*856,620*
	Education	*663,525*	*687,287*	*705,620*	*719,976*	*725,236*	*729,010*	*732,478*	*737,395*
	Pensions	*1,431,133*	*1,632,619*	*1,895,354*	*2,204,180*	*2,548,257*	*2,861,759*	*3,114,583*	*3,315,773*
	Other gov. exp.	*3,434,720*	*3,745,428*	*4,136,408*	*4,495,923*	*4,850,069*	*5,188,046*	*5,353,689*	*5,491,953*
	Deficit	−322,506	−356,308	−380,257	−409,096	−428,445	−462,592	−470,222	−476,421
	Deficit/GDP %	−2.18	−2.20	−2.11	−2.04	−1.92	−1.89	−1.79	−1.71
LF25CRS	Total revenues	6,182,644	6,822,778	7,366,939	8,029,273	8,587,937	9,191,739	9,541,599	9,786,424
	Total gov. exp.	6,505,150	7,178,118	7,873,633	8,587,571	9,214,032	9,863,539	10,255,571	10,536,135
	Health	*975,773*	*1,115,819*	*1,216,270*	*1,324,172*	*1,424,534*	*1,494,102*	*1,535,066*	*1,550,112*
	Health+65	*400,067*	*457,486*	*524,108*	*599,711*	*678,074*	*747,466*	*807,133*	*856,620*
	Education	*663,525*	*687,287*	*705,620*	*719,976*	*725,236*	*729,010*	*732,478*	*737,395*
	Pensions	*1,431,133*	*1,629,583*	*1,835,277*	*2,072,914*	*2,335,134*	*2,581,584*	*2,774,264*	*2,918,365*
	Social transfer	*0*	*0*	*111,835*	*223,105*	*236,988*	*251,721*	*265,512*	*280,514*
	Other gov. exp.	*3,434,720*	*3,745,428*	*4,004,631*	*4,247,404*	*4,492,141*	*4,807,122*	*4,948,251*	*5,049,749*
	Deficit	−322,506	−355,340	−506,694	−558,299	−626,095	−671,800	−713,972	−749,711
	Deficit/GDP %	−2.18	−2.20	−2.90	−2.95	−3.05	−2.98	−2.97	−2.94

Note: LF15CR-15% reduction of EU labour force + change in consumption + uniform change in TFP; LF15CRS-15% reduction of EU labour force + change in consumption + change in sector productivity; LF25CRS-15% reduction of EU labour force + change in consumption + change in sector productivity +10% unemployment.
Source: our elaboration on GDynEP-AG results.

Table 14 summarizes this ex-post computation through an additional row under the LF25CRS scenario, describing the social transfer provided by the government to support technology-driven unemployed people.

Despite this additional expense, the total amount of government expenditure remains low, as a consequence of the general contraction of the economy characterizing this scenario, as also demonstrated by the low level of GDP. Nevertheless, in addition to a low GDP, this scenario also registers a reduction of revenues due to labour taxation. Consequently, this is the case in which the EU might incur in deep fiscal sustainability problems, from 2035 onwards, with a deficit/GDP ratio going beyond the 3% threshold.

In Table 15 we report results for fiscal sustainability when an environmental policy is adopted through the introduction of a carbon tax. If we compare mitigation scenarios with the corresponding ones without

Table 15
Fiscal sustainability with carbon pricing in the EU (Mln EUR, constant 2015).

Scenario		2015	2020	2025	2030	2035	2040	2045	2050
LF15CTXL	Total revenues	6,182,644	6,808,445	7,443,988	8,040,418	8,633,728	9,158,492	9,383,083	9,515,828
	Tot Gov Exp	6,505,150	7,162,492	7,832,058	8,478,047	9,095,824	9,646,056	9,878,941	10,019,437
	Health	*975,773*	*1,115,819*	*1,216,270*	*1,324,172*	*1,424,534*	*1,494,102*	*1,535,066*	*1,550,112*
	Health+65	*400,067*	*457,486*	*524,108*	*599,711*	*678,074*	*747,466*	*807,133*	*856,620*
	Education	*663,525*	*687,287*	*705,620*	*719,976*	*725,236*	*729,010*	*732,478*	*737,395*
	Pensions	*1,431,133*	*1,623,452*	*1,856,894*	*2,121,791*	*2,405,702*	*2,659,124*	*2,825,750*	*2,944,044*
	Other gov. exp.	*3,434,720*	*3,735,933*	*4,053,275*	*4,312,107*	*4,540,353*	*4,763,820*	*4,785,647*	*4,787,886*
	Deficit	−322,506	−354,047	−388,070	−437,629	−462,097	−487,564	−495,858	−503,608
	Deficit/GDP %	−2.18	−2.20	−2.20	−2.30	−2.25	−2.22	−2.19	−2.17
LF15CTXH	Total revenues	6,182,644	6,790,299	7,399,442	7,965,432	8,524,444	9,008,056	9,218,967	9,350,169
	Tot Gov Exp	6,505,150	7,143,487	7,784,384	8,394,384	8,971,241	9,479,246	9,694,735	9,830,377
	Health	*975,773*	*1,115,819*	*1,216,270*	*1,324,172*	*1,424,534*	*1,494,102*	*1,535,066*	*1,550,112*
	Health+65	*400,067*	*457,486*	*524,108*	*599,711*	*678,074*	*747,466*	*807,133*	*856,620*
	Education	*663,525*	*687,287*	*705,620*	*719,976*	*725,236*	*729,010*	*732,478*	*737,395*
	Pensions	*1,431,133*	*1,615,066*	*1,838,100*	*2,090,145*	*2,359,063*	*2,597,037*	*2,749,708*	*2,854,993*
	Other gov. exp.	*3,434,720*	*3,725,315*	*4,024,394*	*4,260,091*	*4,462,409*	*4,659,097*	*4,677,483*	*4,687,877*
	Deficit	−322,506	−353,188	−384,942	−428,952	−446,798	−471,190	−475,768	−480,208
	Deficit/GDP %	−2.18	−2.20	−2.21	−2.29	−2.23	−2.21	−2.18	−2.16
LF25CRSTXL	Total revenues	6,182,644	6,808,445	7,344,711	7,916,331	8,481,739	9,047,964	9,359,204	9,562,641
	Tot Gov Exp	6,505,150	7,159,985	7,827,851	8,505,080	9,086,705	9,685,501	10,030,363	10,265,160
	Health	*975,773*	*1,115,819*	*1,216,270*	*1,324,172*	*1,424,534*	*1,494,102*	*1,535,066*	*1,550,112*
	Health+65	*400,067*	*457,486*	*524,108*	*599,711*	*678,074*	*747,466*	*807,133*	*856,620*
	Education	*663,525*	*687,287*	*705,620*	*719,976*	*725,236*	*729,010*	*732,478*	*737,395*
	Pensions	*1,431,133*	*1,620,945*	*1,817,397*	*2,043,769*	*2,292,118*	*2,523,486*	*2,701,854*	*2,831,861*
	Social transfer	*0*	*0*	*111,835*	*223,105*	*236,988*	*251,721*	*265,512*	*280,514*
	Other gov. exp.	*3,434,720*	*3,735,933*	*3,976,730*	*4,194,059*	*4,407,829*	*4,687,182*	*4,795,454*	*4,865,278*
	Deficit	−322,506	−351,539	−483,140	−588,750	−604,966	−637,537	−671,160	−702,519
	Deficit/GDP %	−2.18	−2.18	−2.79	−3.17	−3.03	−2.93	−2.92	−2.91

(*continued on next page*)

Table 15 (*continued*)

Scenario		2015	2020	2025	2030	2035	2040	2045	2050
LF25CRSTXH	Total revenues	6,182,644	6,790,299	7,301,019	7,864,104	8,395,282	8,923,677	9,221,815	9,413,777
	Tot Gov Exp	6,505,150	7,141,641	7,784,400	8,430,711	8,977,247	9,538,925	9,850,907	10,055,003
	Health	*975,773*	*1,115,819*	*1,216,270*	*1,324,172*	*1,424,534*	*1,494,102*	*1,535,066*	*1,550,112*
	Health+65	*400,067*	*457,486*	*524,108*	*599,711*	*678,074*	*747,466*	*807,133*	*856,620*
	Education	*663,525*	*687,287*	*705,620*	*719,976*	*725,236*	*729,010*	*732,478*	*737,395*
	Pensions	*1,431,133*	*1,613,219*	*1,802,224*	*2,019,951*	*2,258,182*	*2,479,244*	*2,648,195*	*2,769,329*
	Social transfer	*0*	*0*	*111,835*	*223,105*	*236,988*	*251,721*	*265,512*	*280,514*
	Other gov. exp.	*3,434,720*	*3,725,315*	*3,948,451*	*4,143,507*	*4,332,308*	*4,584,848*	*4,669,656*	*4,717,653*
	Deficit	−322,506	−351,342	−483,381	−566,608	−581,965	−615,248	−629,092	−641,227
	Deficit/GDP %	−2.18	−2.19	−2.82	−3.11	−2.99	−2.92	−2.83	−2.77

Note: LF15CTXL-15% reduction of EU labour force + change in consumption + low carbon price; LF15CTXH-15% reduction of EU labour force + change in consumption + high carbon price; LF25CRSTXL-15% reduction of EU labour force + change in consumption + change in sector productivity +10% unemployment + low carbon price; LF25CRSTXH-15% reduction of EU labour force + change in consumption + change in sector productivity +10% unemployment + high carbon price.
Source: our elaboration on GDynEP-AG results.

mitigation, we see that the level of deficit is always lower when we introduce abatement measures. Indeed, even if mitigation entails a general contraction of the economy and hence a reduction of revenues and also a decrease in GDP, also public expenditure decreases. Consequently, SGP targets are always respected, especially in the LF15CTXH case, where we assist to a 15% labour force reduction due to ageing population, the absence of automation and the implementation of a high carbon price. Apparently, the adoption of an environmental tax policy seems to be successful in contrasting the negative impacts of ageing on fiscal sustainability. At the same time, the whole economy faces a sharp decrease in GDP levels, that might induce a further contraction if investment flows into key sectors as technologies and infrastructures will be decreased. In this model version the allocation of investment is endogenously determined only for private sectors (firms) while public investment is not shape in capital stock accumulation. Further research is still required to fully represent potential crowding out effects in the investment decisions by the government.

Fig. 2 provides a graphical representation of the effects of the investigated scenarios on fiscal sustainability. When accounting for ageing population, the higher the reduction in labour force (LF15 and LF15C scenarios), the higher the risk of not being compliant with SGP rules. A precise specification of the impacts of ageing on household consumption behaviour appears to be crucial since changing the structure of the consumption basket shares significantly pull down the deficit/GDP ratio. The introduction of automation seems to improve the sustainability of the public deficit, at least in the case of a labour-neutral technical change (LF15CR and LF15CRS). On the contrary, when biased technical change is introduced, at least in the medium-term (up to 2035) automation negatively impacts fiscal sustainability. This is a clear sign of non-linear impacts associated to multiple forces acting on the economic system. When an environmental taxation is introduced, there emerges a positive (counterbalancing) effect w.r.t. negative impacts of ageing only if no automation process is modelled. In the case of simultaneous processes the picture is more complex since non-linear effects arise. By comparing fiscal sustainability in LF25CRS and LF25CRSTXH there are three temporal points when the relation between the deficit/

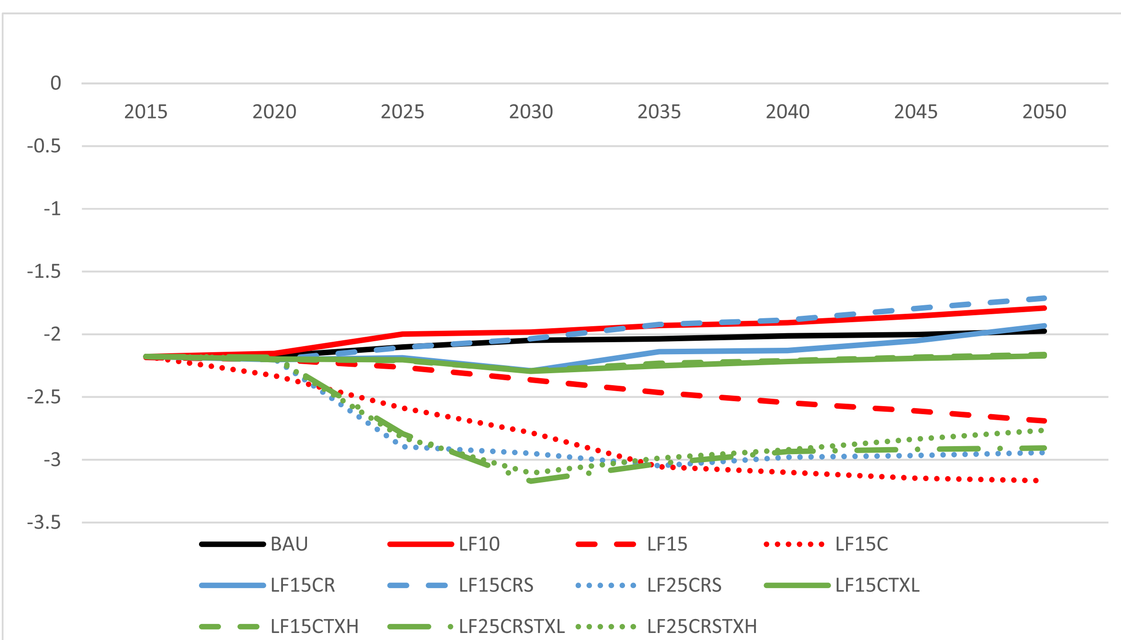

Fig. 2. Fiscal sustainability 2015–2050 (Deficit/GDP ratio, %). Source: our elaboration on GDynEP-AG results. Note: LF10-10% reduction of EU labour force; LF15-15% reduction of EU labour force; LF15C-15% reduction of EU labour force + change in consumption; LF15CR-15% reduction of EU labour force + change in consumption + uniform change in TFP; LF15CRS-15% reduction of EU labour force + change in consumption + change in sector productivity; LF25CRS-15% reduction of EU labour force + change in consumption + change in sector productivity +10% unemployment; LF15CTXL-15% reduction of EU labour force + change in consumption + low carbon price; LF15CTXH-15% reduction of EU labour force + change in consumption + high carbon price; LF25CRSTXL-15% reduction of EU labour force + change in consumption + change in sector productivity +10% unemployment + low carbon price; LF25CRSTXH-15% reduction of EU labour force + change in consumption + change in sector productivity +10% unemployment + high carbon price.

GDP ratios in the two scenarios is inverted.

5. Conclusions and policy implications

This paper provides a first attempt to model in a dynamic CGE setting different linkages and feedback loops arising when ageing society, deep introduction of automation in production processes and environmental taxation are jointly considered. The original contribution of the analysis relies on the effort of jointly modelling the multiple impacts and the potential reinforcing or contrasting mechanisms in an ad hoc dynamic CGE GTAP-based model. In so doing, such mechanisms are evaluated under the lens of two policy objectives applied to the EU case study: i) the fulfilment of the Sustainable and Growth Pact rule related to the respect of the fiscal sustainability of public budget with a deficit/GDP ratio below the threshold of 3%; ii) the achievement of an environmental sustainability in the long-term specifically looking at the decarbonisation trend by 2050.

In addition, by adopting a modelling approach that includes the global economy, together with the specific effects related to the three scrutinised challenges, results also depend on the economic interactions at the global level thanks to the general equilibrium approach applied to an international context with inter-country flows of commodities and investments.

When accounting for demographic trends in an ageing society scenario, the deep reduction in active population might impact the EU capacity to respect the fiscal sustainability criteria under the SGP rules due an increase in public expenditures, a reduction in tax revenues and a contraction of GDP. If automation is taken into account, technical change provides positive effects that help counterbalancing negative impact of ageing only if it is modelled as input-neutral. On the contrary, when also the role of automation is considered, fiscal constraints seem to relax but only in the case of labour-neutral technical change. If input-biased technical change induces an additional outflow of workers from the job market, increasing unemployment produces an additional cost to public budget for social transfers and a simultaneous reduction in production activities, undermining the capacity to be compliant with the SGP rules again.

Environmental taxation might provide a positive impulse to reducing the deficit/GDP ratio, but it is not sufficient to be fully compliant with the SGP rules. If non-neutral technical change is also modelled, the economic system faces a huge contraction in GDP values and fiscal sustainability is again at risk.

This work is a first attempt to identify and quantify mechanisms driving selected objectives as environmental and fiscal sustainability when policy mix design faces complex interactions. Far from being exhaustive, we consider results described in this analysis as a stimulus to go further in developing complex modelling approaches that combine multiple driving forces and analyse reinforcing and contrasting mechanisms when multiple policy objectives are jointly part of a policy mix design.

Examples of future model developments are: the adoption of a labour mobility assumption to allow for migration flows to partly compensate ageing population; a demand structure with heterogeneous households for the assessment of distribution impacts; the parametrisation of input-augmenting technical change due to automation for all regions in order to better capture the role of international linkages in comparative advantages; the adoption of and endogenous technical change approach for all technologies (including the green ones); a better model specification of the welfare computation in order to directly include specific functions as education, health, pensions, social transfers in model equilibrium, in order to capture feedback loops on human capital, consumption patterns and also labour productivity; the introduction of public investment decisions in capital stock accumulation for accounting the impact of the political economy of government decisions on economic growth patterns.

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Appendix A. Shared Socioeconomic Pathways (SSP)

SSP1: Sustainability - Taking the green road. Low challenges for mitigation (resource efficiency) and adaptation (rapid development) (Fig. A.1).

SSP2: Middle of the road. The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns.

SSP3: Regional rivalry - A rocky road. High challenges for mitigation (regionalized energy/land policies) and adaptation (slow development).

SSP4: Inequality - A road divided. Low challenges for mitigation (global high tech economy), high for adaptation (regional low tech economies).

SSP5: Fossil-fueled development - Taking the highway. High challenges for mitigation (resource/fossil fuel intensive) and low for adaptation (rapid development).

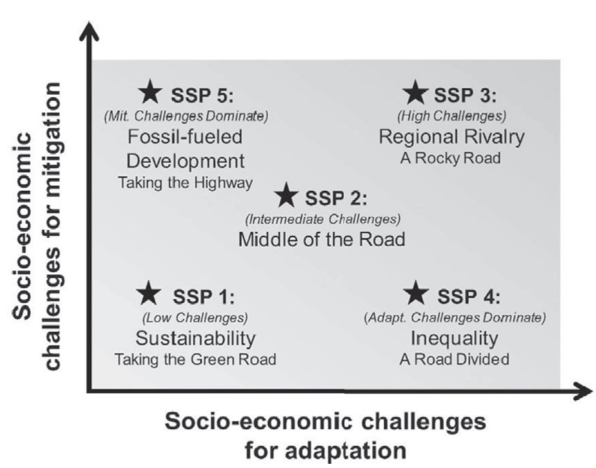

Fig. A.1. Shared Socioeconomic Pathways (SSP).
Source: O'Neill et al. (2017).

Appendix B. Model settings

Table B.1
List of GDynEP-AG Regions.

	GTAP code	Description
1	EU28	European Union
2	USA	United States
3	ROECD1	Rest of OECD East
4	ROECD2	Rest of OECD West
5	BRA	Brazil
6	CHN	China
7	IND	India
8	RUS	Russian Federation
9	REU	Rest of Europe
10	AS1	Asian Energy Exporters
11	AS2	Continental Asia
12	AS3	Rest of South Asia
13	AS4	South East Asia
14	AF1	African Energy Exporters
15	AF2	Western Africa
16	AF3	East and South Africa
17	LAM1	American Energy Exporters
18	LAM2	South America
19	LAM3	Central America and Caribbean Islands

Table B.2
List of GDynEP-AG aggregates.

	Sector	Description
1	coal	Coal
2	oil	Oil
3	gas	Gas
4	oil_pcts	Petroleum, coal products
5	ely_f	Electricity from fossil and nuclear energy sources
6	ely_rw	Electricity from renewable energy sources
7	agr	Agriculture
8	food	Food
9	textile	Textile
10	nometal	Non-metallic mineral products
11	wood	Wood
12	paper	Pulp and paper
13	chemical	Chemical and petrochemical
14	basicmet1	Metals
15	basicmet2	Other metals
16	transeqp	Transport equipment
17	machinery	Machinery and equipment
18	oth_Manuf	Other manufacturing industries
19	transport	Transport
20	air_trans	Water Transport
21	water_trans	Air Transport
22	services	Services

Table B.3
List of GDynEP-AG countries.

GTAP code	Code	Country	GTAP code	Code	Country	GTAP code	Code	Country
EU28	aut	Austria	REU	xee	Rest of Eastern Europe	AF2	bfa	Burkina Faso
EU28	bel	Belgium	REU	xer	Rest of Europe	AF2	cmr	Cameroon
EU28	cyp	Cyprus	REU	xsu	Rest of Former Soviet	AF2	civ	Cote d'Ivoire
EU28	cze	Czech Republic	REU	tur	Turkey	AF2	gha	Ghana
EU28	dnk	Denmark	REU	xtw	Rest of the World	AF2	gin	Guinea
EU28	est	Estonia	AS1	kaz	Kazakhstan	AF2	sen	Senegal
EU28	fin	Finland	AS1	bhr	Bahrain	AF2	tgo	Togo
EU28	fra	France	AS1	irn	Iran Islamic Republic	AF2	xwf	Rest of West Africa
EU28	deu	Germany	AS1	kwt	Kuwait	AF3	eth	Ethiopia
EU28	grc	Greece	AS1	omn	Oman	AF3	ken	Kenya
EU28	hun	Hungary	AS1	qat	Qatar	AF3	mdg	Madagascar
EU28	irl	Ireland	AS1	sau	Saudi Arabia	AF3	mwi	Malawi
EU28	ita	Italy	AS1	are	United Arab Emirates	AF3	mus	Mauritius
EU28	lva	Latvia	AS2	mng	Mongolia	AF3	moz	Mozambique
EU28	ltu	Lithuania	AS2	npl	Nepal	AF3	rwa	Rwanda
EU28	lux	Luxembourg	AS2	pak	Pakistan	AF3	tza	Tanzania
EU28	mlt	Malta	AS2	kgz	Kyrgyztan	AF3	uga	Uganda

(*continued on next column*)

Table B.3 (*continued*)

GTAP code	Code	Country	GTAP code	Code	Country	GTAP code	Code	Country
EU28	nld	Netherlands	AS2	arm	Armenia	AF3	zmb	Zambia
EU28	pol	Poland	AS2	aze	Azerbaijan	AF3	zwe	Zimbabwe
EU28	prt	Portugal	AS2	geo	Georgia	AF3	bwa	Botswana
EU28	svk	Slovakia	AS2	jor	Jordan	AF3	nam	Namibia
EU28	svn	Slovenia	AS2	xws	Rest of Western Asia	AF3	zaf	South Africa
EU28	esp	Spain	AS3	xoc	Rest of Oceania	AF3	xsc	Rest of South Africa
EU28	swe	Sweden	AS3	xea	Rest of East Asia	LAM1	mex	Mexico
EU28	gbr	United Kingdom	AS3	brn	Brunei Darussalam	LAM1	arg	Argentina
EU28	bgr	Bulgaria	AS3	khm	Cambodia	LAM1	ecu	Ecuador
EU28	hrv	Croatia	AS3	lao	Lao People's Dem. Rep.	LAM1	ven	Venezuela
EU28	rou	Romania	AS3	phl	Philippines	LAM2	bol	Bolivia
USA	usa	United St of Am.	AS3	vnm	Viet Nam	LAM2	chl	Chile
ROECD1	aus	Australia	AS3	xse	Rest of Southeast Asia	LAM2	col	Colombia
ROECD1	nzl	New Zealand	AS3	bgd	Bangladesh	LAM2	pry	Paraguay
ROECD1	jpn	Japan	AS3	lka	Sri Lanka	LAM2	per	Peru
ROECD1	kor	Korea	AS3	xsa	Rest of South Asia	LAM2	ury	Uruguay
ROECD2	can	Canada	AS4	twn	Taiwan	LAM2	xsm	Rest of South Am.
ROECD2	xna	Rest of North Am.	AS4	idn	Indonesia	LAM3	cri	Costa Rica
ROECD2	che	Switzerland	AS4	mys	Malaysia	LAM3	gtm	Guatemala
ROECD2	nor	Norway	AS4	sgp	Singapore	LAM3	hnd	Honduras
ROECD2	xef	Rest of EFTA	AS4	tha	Thailand	LAM3	nic	Nicaragua
ROECD2	isr	Israel	AF1	egy	Egypt	LAM3	pan	Panama
BRA	bra	Brazil	AF1	mar	Morocco	LAM3	slv	El Salvador
CHN	chn	China	AF1	tun	Tunisia	LAM3	xca	Rest of Centr. Am.
CHN	hkg	Hong Kong	AF1	xnf	Rest of North Africa	LAM3	dom	Dominican Rep.
IND	ind	India	AF1	nga	Nigeria	LAM3	jam	Jamaica
RUS	rus	Russian Federation	AF1	xcf	Central Africa	LAM3	pri	Puerto Rico
REU	alb	Albania	AF1	xac	South Central Africa	LAM3	tto	Trinidad & Tobago
REU	blr	Belarus	AF1	xec	Rest of Eastern Africa	LAM3	xcb	Caribbean
REU	ukr	Ukraine	AF2	ben	Benin			

Table B.4
List of GDynEP-AG commodities and aggregates.

Sector	Code	Products	Sector	Code	Products
agri	pdr	paddy rice	basicmet_1	i_s	ferrous metals
agri	wht	wheat	basicmet_1	nfm	metals nec
agri	gro	cereal grains nec	basicmet_2	fmp	metal products
agri	v_f	vegetables, fruit, nuts	transeqp	mvh	motor vehicles and parts
agri	osd	oil seeds	transeqp	otn	transport equipment nec
agri	c_b	sugar cane, sugar beet	macheqp	ele	electronic equipment
agri	pfb	plant-based fibers	macheqp	ome	machinery and eq nec
agri	ocr	crops nec	oth_man_ind	omf	manufactures nec
agri	ctl	bovine cattle, sheep and goats, horses	services	TnD	transmission and distr
agri	oap	animal products nec	ely_f	NuclearBL	nuclear power
agri	rmk	raw milk	ely_f	CoalBL	coal-fired power
agri	wol	wool, silk-worm cocoons	ely_f	GasBL	gas-fired power (base load)
agri	frs	forestry	ely_rw	WindBL	wind power
agri	fsh	fishing	ely_rw	HydroBL	hydro power (base load)
Coal	coa	coal	ely_f	OilBL	oil-fired power (base load)
Oil	oil	oil	ely_rw	OtherBL	other power
Gas	gas	gas	ely_f	GasP	gas-fired power (peak load)
nometal	omn	minerals nec	ely_rw	HydroP	hydro power (peak load)
food	cmt	bovine cattle, sheep and goat meat pr.	ely_f	OilP	oil-fired power (peak load)
food	omt	meat products	ely_rw	SolarP	solar power
food	vol	vegetable oils and fats	gas	gdt	gas manufacture, distrib
food	mil	dairy products	services	wtr	water
food	pcr	processed rice	services	cns	construction
food	sgr	sugar	services	trd	trade
oth_man_ind	ofd	food products nec	transport	otp	transport nec
food	b_t	beverages and tobacco products	wat_transp	wtp	water transport
textile	tex	textiles	air_transp	atp	air transport
textile	wap	wearing apparel	services	cmn	communication
textile	lea	leather products	services	ofi	financial services nec
wood	lum	wood products	services	isr	insurance
paper	ppp	paper products, publishing	services	obs	business services nec
oil_pcts	p_c	petroleum, coal products	services	ros	recreational and other serv
chem	crp	chemical, rubber, plastic products	services	osg	public admin.
nometal	nmm	mineral products nec	services	dwe	ownership of dwellings

Appendix C. Exogenous projections for scenario setting

Table C.1
Population in BAU Scenario (Mln.).

POP TOT	2015	2020	2025	2030	2035	2040	2045	2050
EU28	507.49	510.95	512.26	512.51	511.60	509.69	506.76	502.76
USA	319.93	331.43	343.26	354.71	365.03	374.07	382.06	389.59
ROECD1	206.98	208.24	208.42	207.73	206.20	203.89	201.11	198.15
ROECD2	57.86	60.78	63.54	66.13	68.50	70.66	72.68	74.60
BRA	205.96	213.86	220.37	225.47	229.20	231.60	232.72	232.69
CHN	1404.27	1432.10	1446.60	1449.17	1441.64	1425.67	1402.59	1372.71
IND	1309.05	1383.20	1451.83	1512.99	1564.57	1605.36	1636.50	1658.98
RUS	143.89	143.79	142.61	140.54	138.08	135.84	134.13	132.73
REU	199.59	207.45	211.43	214.69	217.73	220.18	221.99	222.95
AS1	149.81	160.83	169.13	175.72	181.15	185.91	190.09	193.23
AS2	344.81	377.29	412.27	445.26	477.04	508.19	537.98	565.49
AS3	525.12	556.54	587.53	615.53	640.09	661.26	679.10	693.41
AS4	386.56	381.09	395.54	408.38	418.82	426.70	432.13	435.23
AF1	579.57	653.93	733.02	817.27	907.36	1002.90	1102.22	1203.70
AF2	194.26	222.38	253.39	287.35	324.22	363.71	405.44	448.89
AF3	419.14	474.81	534.23	597.22	663.34	731.82	801.96	872.97
LAM1	216.61	229.89	242.13	253.17	262.91	271.32	278.38	284.06
LAM2	119.75	125.78	131.22	136.00	140.03	143.29	145.80	147.55
LAM3	88.72	93.59	98.19	102.46	106.20	109.42	112.09	114.17
WORLD	7379.40	7767.92	8156.99	8522.29	8863.70	9181.48	9475.73	9743.86

Source: UNDESA – Medium change Scenario.

Table C.2
Population in LF10 Scenario (Mln.).

POP TOT	2015	2020	2025	2030	2035	2040	2045	2050
EU28	507.49	508.78	506.22	501.38	494.50	485.94	475.87	464.54
USA	319.93	330.61	340.62	349.46	356.49	361.80	365.90	369.51
ROECD1	206.98	207.18	205.52	202.39	198.00	192.67	186.80	180.62
ROECD2	57.86	60.71	63.30	65.59	67.57	69.33	70.95	72.50
BRA	205.96	214.01	220.57	225.35	228.29	229.51	229.16	227.35
CHN	1414.79	1437.68	1440.89	1427.90	1402.87	1366.97	1319.58	1261.78
IND	1309.05	1386.67	1461.93	1532.11	1594.24	1647.88	1695.42	1738.11
RUS	143.89	142.81	139.95	136.19	132.18	128.16	124.07	119.84
REU	199.59	207.33	211.09	214.16	217.11	219.51	221.31	222.41
AS1	149.81	161.46	170.69	178.37	184.92	190.66	195.62	199.51
AS2	344.81	380.65	422.14	464.70	509.24	557.12	608.93	664.79
AS3	531.77	558.74	593.85	628.01	660.71	692.15	722.91	753.48
AS4	386.56	388.88	398.10	412.86	425.40	435.70	444.03	450.84
AF1	579.57	657.69	745.18	843.34	954.46	1081.06	1225.42	1389.95
AF2	194.26	223.64	257.63	296.75	341.65	393.24	452.67	521.27
AF3	419.14	477.97	545.37	621.57	706.88	802.65	911.15	1034.70
LAM1	216.61	230.70	244.48	257.61	269.84	281.15	291.59	301.19
LAM2	102.15	107.81	113.22	118.21	122.64	126.52	129.90	132.86
LAM3	88.72	94.01	99.39	104.68	109.67	114.43	119.01	123.47
WORLD	7378.96	7777.36	8180.15	8580.63	8976.65	9376.44	9790.29	10228.72

Source: UNDESA – No change Scenario.

Table C.3
Population in LF15 Scenario (Mln.).

POP TOT	2015	2020	2025	2030	2035	2040	2045	2050
EU28	507.49	510.10	510.24	508.93	502.47	493.03	481.44	468.69
USA	319.93	330.54	340.82	350.04	355.37	357.80	358.17	357.87
ROECD1	206.98	207.82	207.58	206.38	202.84	197.69	191.58	185.33
ROECD2	57.86	60.38	62.68	64.71	65.99	66.75	67.14	67.36
BRA	205.96	213.86	220.36	225.45	227.09	226.21	223.39	219.49
CHN	1404.27	1432.32	1447.29	1450.43	1431.05	1397.89	1355.12	1306.63
IND	1309.05	1383.96	1453.36	1515.38	1554.78	1574.65	1578.87	1574.43
RUS	143.89	143.64	142.29	140.00	136.08	131.87	128.02	124.56
REU	199.59	207.13	211.63	215.09	216.60	216.41	214.89	212.50
AS1	149.81	161.09	168.96	175.23	179.22	182.55	185.35	187.08
AS2	344.81	378.07	413.29	447.05	476.48	502.27	524.45	543.74
AS3	525.12	557.36	589.53	618.98	639.45	652.79	660.34	664.35
AS4	386.56	381.11	395.68	408.64	415.65	417.88	416.18	412.05
AF1	579.57	654.32	734.07	819.11	904.66	991.37	1078.07	1164.98
AF2	194.26	222.57	253.86	288.17	323.62	360.16	397.48	435.71
AF3	419.14	474.97	534.65	597.96	660.28	721.45	781.07	840.07

(continued on next column)

Table C.3 (*continued*)

POP TOT	2015	2020	2025	2030	2035	2040	2045	2050
LAM1	216.61	229.96	242.29	253.45	261.11	265.97	268.51	269.58
LAM2	119.75	125.87	131.41	136.33	139.31	140.76	140.98	140.45
LAM3	88.72	93.80	98.65	103.19	106.32	108.28	109.29	109.71
WORLD	7379.40	7768.88	8158.62	8524.53	8798.35	9005.78	9160.32	9284.59

Source: UNDESA – Low variant Scenario.

Table C.4
Labour force in BAU Scenario (Mln.).

Region	Labour force	2015	2020	2025	2030	2035	2040	2045	2050
EU28	skilled	93.17	99.12	102.71	106.82	111.09	115.31	122.54	127.55
	unskilled	149.59	144.45	138.98	131.37	122.84	115.00	104.84	97.46
USA	skilled	70.37	75.79	82.02	89.02	96.68	104.87	113.16	121.20
	unskilled	124.56	125.49	124.08	122.24	120.21	117.28	113.31	108.58
ROECD1	skilled	36.98	39.63	41.19	42.27	42.76	42.68	42.64	42.60
	unskilled	70.43	67.13	63.66	59.48	55.03	50.62	46.80	43.33
ROECD2	skilled	8.78	9.37	9.82	10.21	10.64	11.13	11.67	12.21
	unskilled	19.13	19.13	18.85	18.63	18.58	18.56	18.46	18.27
BRA	skilled	23.49	26.73	30.39	34.40	38.92	43.24	47.35	51.37
	unskilled	80.43	83.19	83.60	81.72	77.84	72.85	66.93	60.33
CHN	skilled	50.77	58.96	64.98	71.03	78.94	87.01	93.93	100.63
	unskilled	804.77	812.05	819.00	820.59	808.42	783.55	747.29	700.53
IND	skilled	54.60	66.44	79.55	93.87	108.73	123.79	138.59	152.54
	unskilled	567.36	606.02	640.18	667.40	686.26	695.18	693.14	681.43
RUS	skilled	21.64	21.80	21.67	22.11	23.02	23.81	24.13	24.16
	unskilled	55.41	51.77	48.16	45.11	41.96	38.39	34.65	31.19
REU	skilled	11.91	13.09	14.17	15.38	16.70	18.05	19.40	20.71
	unskilled	85.31	83.61	81.53	79.26	76.67	73.38	69.49	65.48
AS1	skilled	26.84	36.68	41.92	48.42	55.46	61.93	66.83	70.55
	unskilled	83.97	81.64	82.67	82.28	79.48	74.03	66.93	58.74
AS2	skilled	27.84	34.01	40.95	49.04	58.44	68.72	79.38	90.26
	unskilled	129.60	141.08	152.64	163.51	172.53	179.01	182.99	184.59
AS3	skilled	29.79	35.60	42.22	49.46	57.39	65.68	73.66	81.76
	unskilled	247.32	263.58	277.66	288.63	296.06	299.82	300.35	297.48
AS4	skilled	36.28	43.04	49.93	57.11	64.91	72.53	79.50	86.62
	unskilled	172.77	177.15	179.74	180.06	177.55	173.24	168.16	161.67
AF1	skilled	24.84	30.76	38.06	47.22	58.17	70.57	84.02	98.85
	unskilled	166.92	185.37	206.44	229.69	252.12	273.30	293.15	311.62
AF2	skilled	2.06	2.75	3.66	4.87	6.39	8.26	10.53	13.25
	unskilled	81.73	94.34	108.96	124.94	141.87	159.37	177.13	194.92
AF3	skilled	18.43	23.88	30.90	39.78	50.76	62.56	78.01	96.06
	unskilled	197.39	225.87	257.01	289.71	322.84	347.06	377.20	404.65
LAM1	skilled	20.29	23.81	27.52	31.39	35.59	38.70	42.57	46.44
	unskilled	77.05	80.22	82.69	84.33	84.45	81.01	78.55	75.40
LAM2	skilled	12.97	15.37	17.84	20.37	23.05	25.68	28.27	30.78
	unskilled	46.45	48.60	49.81	50.27	49.99	49.09	47.59	45.56
LAM3	skilled	10.43	12.84	15.62	18.73	22.26	25.48	29.17	32.91
	unskilled	34.65	36.62	38.03	38.96	39.24	37.81	36.14	33.65
WORLD	skilled	581.47	669.67	755.12	851.50	959.91	1070.02	1185.34	1300.44
	unskilled	3194.85	3327.31	3453.69	3558.21	3623.92	3638.53	3623.10	3574.90

Source: own elaborations on ILO projections, GTAP Macro projections, and UNDESA projections on active population.

Table C.5
Labour force in LF10 Scenario (Mln.).

Region	Labour force	2015	2020	2025	2030	2035	2040	2045	2050
EU28	skilled	93.17	98.03	101.12	104.71	108.66	112.59	119.07	123.57
	unskilled	149.59	142.85	136.82	128.77	120.15	112.28	101.87	94.43
USA	skilled	70.37	74.38	79.20	84.23	90.41	97.65	106.92	116.03
	unskilled	124.56	123.16	119.82	115.66	112.40	109.20	107.06	103.94
ROECD1	skilled	36.98	39.33	40.71	41.90	42.62	42.48	42.67	42.73
	unskilled	70.43	66.62	62.92	58.97	54.84	50.38	46.83	43.46
ROECD2	skilled	8.78	9.45	10.04	10.57	11.22	11.96	12.76	13.51
	unskilled	19.13	19.31	19.28	19.28	19.59	19.95	20.19	20.23
BRA	skilled	23.49	26.57	29.83	33.52	38.10	42.78	47.11	51.09
	unskilled	80.43	82.66	82.04	79.64	76.20	72.07	66.60	59.99
CHN	skilled	50.77	57.71	62.42	66.34	70.96	75.97	81.93	87.95
	unskilled	804.77	794.81	786.70	766.42	726.68	684.12	651.85	612.29
IND	skilled	54.60	66.65	79.35	92.69	107.73	124.34	142.04	159.76
	unskilled	567.36	607.87	638.58	658.98	679.97	698.26	710.39	713.72
RUS	skilled	21.64	21.89	21.93	22.71	24.36	25.62	26.35	26.54

(continued on next column)

Table C.5 (*continued*)

Region	Labour force	2015	2020	2025	2030	2035	2040	2045	2050
	unskilled	55.41	51.99	48.74	46.34	44.39	41.30	37.83	34.28
REU	skilled	11.91	13.64	15.13	16.85	18.95	21.21	23.51	25.75
	unskilled	85.31	87.12	87.01	86.82	87.04	86.22	84.21	81.42
AS1	skilled	26.84	36.91	42.33	49.01	56.81	64.65	71.27	76.96
	unskilled	83.97	82.14	83.48	83.29	81.42	77.28	71.38	64.08
AS2	skilled	27.84	34.22	41.61	50.21	61.12	74.23	88.97	105.37
	unskilled	129.60	141.95	155.09	167.39	180.44	193.36	205.08	215.50
AS3	skilled	29.79	35.35	41.76	48.69	56.86	66.17	75.87	86.22
	unskilled	247.32	261.74	274.60	284.13	293.32	302.07	309.37	313.70
AS4	skilled	36.28	41.42	46.84	53.39	60.86	68.63	76.14	84.08
	unskilled	172.77	170.49	168.63	168.33	166.48	163.92	161.06	156.94
AF1	skilled	24.84	31.12	38.62	48.11	60.28	75.20	92.71	113.74
	unskilled	166.92	187.51	209.49	234.01	261.28	291.19	323.47	358.57
AF2	skilled	2.06	2.78	3.71	4.94	6.60	8.76	11.58	15.22
	unskilled	81.73	95.35	110.33	126.86	146.41	169.13	194.83	223.81
AF3	skilled	18.43	24.06	31.02	39.74	51.28	66.19	85.05	108.53
	unskilled	197.39	227.57	258.00	289.45	326.14	367.22	411.22	457.18
LAM1	skilled	20.29	24.11	27.93	31.92	36.64	41.58	46.76	52.26
	unskilled	77.05	81.24	83.92	85.77	86.93	87.02	86.28	84.86
LAM2	skilled	12.97	15.19	17.49	19.82	22.47	25.35	28.23	31.10
	unskilled	46.45	48.02	48.82	48.91	48.75	48.46	47.53	46.03
LAM3	skilled	10.43	12.61	14.96	17.42	20.39	23.82	27.64	31.70
	unskilled	34.65	35.97	36.43	36.24	35.94	35.35	34.25	32.42
WORLD	skilled	581.47	665.40	745.97	836.76	946.32	1069.18	1206.56	1352.13
	unskilled	3194.85	3308.37	3410.71	3485.25	3548.38	3608.79	3671.28	3716.85

Source: own elaborations on ILO projections, GTAP Macro projections, and UNDESA projections on active population.

Table C.6
Labour force in LF15 Scenario (Mln.).

Region	Labour force	2015	2020	2025	2030	2035	2040	2045	2050
EU28	skilled	93.17	98.12	101.37	105.15	108.11	110.27	114.24	115.65
	unskilled	149.59	142.99	137.16	129.32	119.54	109.96	97.74	88.38
USA	skilled	70.37	74.44	79.37	84.54	89.84	95.50	102.49	109.05
	unskilled	124.56	123.26	120.07	116.08	111.70	106.80	102.62	97.69
ROECD1	skilled	36.98	39.36	40.80	42.06	42.45	41.71	41.15	40.50
	unskilled	70.43	66.67	63.06	59.19	54.62	49.47	45.16	41.19
ROECD2	skilled	8.78	9.46	10.06	10.60	11.11	11.62	12.09	12.49
	unskilled	19.13	19.32	19.32	19.35	19.41	19.38	19.13	18.71
BRA	skilled	23.49	26.60	29.93	33.75	37.86	41.52	44.36	46.51
	unskilled	80.43	82.76	82.33	80.18	75.71	69.95	62.71	54.61
CHN	skilled	50.77	57.76	62.54	66.55	70.51	74.49	79.08	83.33
	unskilled	804.77	795.58	788.16	768.87	722.07	670.78	629.14	580.11
IND	skilled	54.60	66.74	79.67	93.40	107.10	120.55	133.12	144.20
	unskilled	567.36	608.78	641.18	664.02	675.98	676.95	665.81	644.19
RUS	skilled	21.64	21.94	22.05	22.94	24.55	25.72	26.20	25.98
	unskilled	55.41	52.10	49.02	46.82	44.74	41.47	37.62	33.55
REU	skilled	11.91	13.66	15.18	16.96	18.84	20.63	22.19	23.46
	unskilled	85.31	87.23	87.31	87.37	86.52	83.86	79.50	74.19
AS1	skilled	26.84	36.94	42.43	49.23	56.13	62.22	66.30	68.70
	unskilled	83.97	82.21	83.68	83.66	80.43	74.37	66.40	57.21
AS2	skilled	27.84	34.25	41.73	50.50	60.27	70.70	80.98	91.08
	unskilled	129.60	142.09	155.56	168.36	177.92	184.17	186.67	186.28
AS3	skilled	29.79	35.84	42.44	49.63	57.02	64.45	70.98	76.95
	unskilled	247.32	265.38	279.05	289.60	294.15	294.18	289.45	279.97
AS4	skilled	36.28	40.73	46.99	53.71	60.34	66.25	70.94	75.28
	unskilled	172.77	167.63	169.17	169.35	165.05	158.25	150.06	140.51
AF1	skilled	24.84	31.18	38.87	48.75	60.45	73.73	88.02	103.91
	unskilled	166.92	187.90	210.85	237.17	262.02	285.50	307.13	327.58
AF2	skilled	2.06	2.78	3.74	5.02	6.64	8.63	11.04	13.96
	unskilled	81.73	95.63	111.29	129.01	147.49	166.61	185.80	205.30
AF3	skilled	18.43	24.20	31.43	40.64	51.76	64.94	80.14	97.54
	unskilled	197.39	228.92	261.43	295.99	329.23	360.27	387.47	410.87
LAM1	skilled	20.29	24.13	28.00	32.07	36.21	39.90	43.15	46.14
	unskilled	77.05	81.31	84.12	86.16	85.91	83.52	79.61	74.92
LAM2	skilled	12.97	15.22	17.49	19.80	22.02	24.09	25.82	27.24
	unskilled	46.45	48.13	48.83	48.86	47.76	46.05	43.46	40.32
LAM3	skilled	10.43	12.63	15.01	17.54	20.17	22.85	25.46	27.89
	unskilled	34.65	36.01	36.55	36.48	35.56	33.90	31.54	28.51
WORLD	skilled	581.47	666.00	749.09	842.84	941.38	1039.77	1137.76	1229.87
	unskilled	3194.85	3313.91	3428.13	3515.83	3535.82	3515.45	3467.03	3384.08

Source: own elaborations on ILO projections, GTAP Macro projections, UNDESA projections on active population and EC (2018a, 2018b) projections on labour force.

Table C.7
GDP in BAU (Mln. USD)

	2015	2020	2025	2030	2035	2040	2045	2050
EU28	19,353,092	21,265,177	23,463,146	25,895,805	28,590,782	31,572,228	33,664,520	35,908,934
USA	16,289,736	18,339,311	20,140,781	22,123,037	24,305,032	26,705,397	28,761,445	30,984,417
ROECD1	9,796,909	11,356,185	12,534,843	13,835,083	15,272,825	16,863,031	17,976,834	19,174,091
ROECD2	3,703,241	4,419,152	5,024,090	5,711,184	6,492,188	7,380,320	8,026,098	8,731,110
BRA	3,060,053	3,597,581	4,169,273	4,834,272	5,606,160	6,500,679	7,105,372	7,768,588
CHN	9,790,362	14,105,366	17,347,202	21,311,038	26,169,955	32,137,751	34,824,146	37,710,720
IND	2,496,845	3,438,030	4,559,344	6,043,958	8,009,030	10,612,685	12,692,559	15,147,554
RUS	2,216,498	2,649,202	2,942,999	3,265,669	3,621,562	4,016,493	4,195,549	4,386,698
REU	1,476,342	1,838,474	2,189,365	2,606,637	3,101,976	3,689,893	4,135,300	4,632,901
AS1	2,586,353	3,062,009	3,672,788	4,404,481	5,278,947	6,324,917	7,095,988	7,955,028
AS2	859,600	1,061,348	1,306,562	1,604,601	1,969,102	2,416,817	2,897,981	3,475,404
AS3	924,027	1,136,101	1,396,699	1,716,180	2,108,104	2,589,279	3,105,659	3,724,679
AS4	2,936,980	3,938,461	4,938,397	6,192,404	7,760,631	9,720,500	11,444,723	13,466,089
AF1	1,637,961	1,984,995	2,516,577	3,192,656	4,052,502	5,145,826	6,028,284	7,060,447
AF2	201,232	268,204	367,308	503,212	689,451	944,624	1,264,436	1,692,574
AF3	808,487	1,056,386	1,349,300	1,723,043	2,199,361	2,806,318	3,580,778	4,570,254
LAM1	2,651,383	3,166,069	3,798,301	4,555,379	5,462,172	6,549,363	7,622,149	8,878,126
LAM2	1,075,059	1,282,782	1,538,223	1,845,190	2,213,361	2,654,550	3,090,587	3,600,626
LAM3	586,437	700,247	841,178	1,010,600	1,213,033	1,454,112	1,692,513	1,969,189
WORLD	82,450,596	98,665,081	114,096,378	132,374,429	154,116,174	180,084,786	199,204,921	220,837,429

Source: own elaborations from IIASA projections for OECD-ENV Link model, GTAP Macro projections, CEPII projections for GINFORS model.

Appendix D. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.econmod.2019.08.004.

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