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# Systemic modelling tools to assess the green economy transition

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# 1 Introduction

The socio-economic and environmental performance of a given system, such as a country, region, or city, is determined at any point in time by competing forces, represented by opportunities to grow and emerging constraints to such growth. Practically, society is in constant transition, influenced by well-known dynamics as well as external, unexpected events.

## 1.1. Rationale of the report

Several concurrent changes are taking place in today's society. This calls for the identification and assessment of new policy interventions. Two main reasons can be identified for this:

(i) emerging new drivers of change, including population ageing and the growing speed of the development and adoption of technology; and
(ii) the understanding of the concepts of sustainability and wellbeing, two factors at the core of public decision making, is evolving.

These two reasons are connected, meaning that our understanding of the world we live in changes based on our experience, or the recognition that new trends are emerging, and known ones disappearing.

For the public sector, this leads to concerns about fiscal sustainability. If governments are not able to allocate investment to ensure the wellbeing of their citizens, they fail in their mission. The concerns are based on two main emerging dynamics of revenues and costs. An ageing population is likely to lead to reduced tax revenues and increasing expenditure; the development and adoption of technology can lead to increased revenues from economic growth but also higher unemployment and subsequent growing public expenditure; energy use and the resulting increase in air pollution could lead to revenues from environmental taxation while at the same time higher costs for health care (see ETC/WMGE, 2017 and 2018; EEA, 2020).

Several methodological frameworks and tools can support policy makers in analysing these issues by assessing competing and complementary approaches and the likely outcomes of their implementation. On one hand, the need to assess systemic issues and solutions calls for the use of integrated models; on the other, most of the methods and tools currently being used are designed for and focus on specific areas of analysis, performing economic, social, environmental or governance assessments. As a result, two solutions emerge:

(i) existing simulation models can be improved and expanded to capture different dimensions of sustainable development, or embed the three macro trends described above more explicitly; or
(ii) new simulation models, designed to capture systemic change with feedback loops, delays and non-linearity, could be developed.

Both options are explored in this report, after a review of available methods and models, using a qualitative systemic approach to analyse the simultaneous impact of social, economic and environmental variables on a system's performance, as well as a computable general equilibrium (CGE) model to forecast the impacts of an ageing population, technological change and environmental policies on fiscal sustainability and macroeconomic performance.
The outlook is complex, as is sustainability, which embodies social, economic and environmental considerations. As a result, the modelling approaches used and the analysis resulting from the simulation of such models are complex. What emerges is:

(i) the standard policy design approach is no longer adequate for facing these emerging challenges;
(ii) approaches to policy formulation are likely to address one issue, not the systemic nature of the issues with which we are currently confronted, leading to suboptimal outcomes; and

(iii) new, systemic thinking is required to identify, assess and prioritise policy interventions to deliver on the goal of fiscal, social and environmental sustainability.

### 1.2. Population ageing

Population ageing is an emerging challenge that grows stronger each year. 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 has accelerated. According to the World Health Organization (WHO), the proportion of over 60 year-olds in the world's population is expected to nearly double between 2015 and 2050, from 12 to 22 per cent (WHO, 2015). This demographic trend will impact all countries, but particularly developed ones: some European Union (EU) Member States are particularly at risk.

According to a recent European Commission (EC) report, 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, those aged 15–64, will decrease significantly from 333 million in 2016 to 299 million in 2050 due to a reduction in fertility rates and low immigration flows (EC, 2018a). Over the same period the proportion of young people aged 0–14 is projected to remain almost constant, falling from 16 to 15 per cent of the total population. Those aged over 65, however, will represent a growing share, rising from 19 to 29 per cent, while the proportion of those aged 80+ will become almost as large as the young population, increasing from 5 to 11 per cent. Conversely, the working-age population will decrease substantially, declining from 65 to 57 per cent of the total population and, as a result, the old-age dependency ratio is projected to rise from 29.6 to 50.4 per cent on average across the EU between 2016 and 2050 (EC, 2018a).

This trend has severe implications. First, an increase in the elderly population will lead to a rise in expenditure on healthcare and pensions – for example, public pension expenditure in the EU is projected to increase from 8.6 per cent of gross domestic product (GDP) in 2016 to 9.5 per cent in 2050 (EC, 2018a).

A second impact is that the decrease in the number of working people will bring a reduction of direct tax payments with two indirect consequences, a stagnation in labour productivity and a contraction of resources required to sustain the social welfare system.

A third impact will be variations in the composition of the consumption basket because preferences are different among different age groups. At a general level, an ageing society will result in a contraction of total consumption expenditure, with a direct negative impact on aggregated demand and an indirect negative impact of taxation revenues arising from value- added tax (VAT).

A fourth impact is associated with a possible negative impact on disposable income of the working population that might bring to a further decline in fertility rates, with an aggravation of the negative vicious cycle (Hock and Weil, 2012; Hughes Hallet et al., 2019).

### 1.3. Technological advances

Together with demographic trends, the development and adoption of technology have recently emerged as being responsible for shaping socio-economic trends. This is particularly the case for developed economies, as shown in many recent debates in the EC (EC, 2019; EC, 2018b).

Technological progress is leading to massive implementation of automation in production systems, which is increasingly influencing the way people work and live, and may curb some of the undesirable trends triggered by population ageing, for example by increasing productivity in several sectors, including manufacturing, healthcare and energy generation (EC, 2019; Government Office for Science, 2016). At the same time, the introduction of automation in production systems may affect employment, with workers being replaced by more efficient and less costly machines. This, in turn, may have other economic impacts in terms of job losses and difficulties in creating opportunities for unskilled workers (EC, 2019; Arntz et al., 2016).

The productivity of computers has grown extremely rapidly in the past five decades, and innovation associated with machine learning and artificial intelligence (AI) is replacing an increasing number of human tasks. This has mainly been made possible by the significant reduction in the cost of a standard computation that has declined at an average annual rate of 53 per cent over the past sixty years (Nordhaus, 2015). The greatest concern related to this is the potential job losses associated with the replacement of the human brain with AI. There are also fears about negative impacts associated with the combination of an ageing society and automation given that in a typical political-economy game, older voters are more likely to express a preference for shorter-term investments in, for example, healthcare and pensions, rather than forward-looking ones, such as in education. With the substantial penetration of automation in production processes, reduced spending on education will not provide adequate skills for the workforce, especially qualifications for middle-skill jobs, bringing the potential of non-neutrality of digital divide in the labour market. The polarisation of labour markets, especially in richer countries, might produce a decline in the share of employment in those branches of the job market that deliver mid-income jobs, and thereby increase income disparities (Dellot and Wallace-Stephens, 2017).

### 1.4. Environmental protection

Together with concerns associated with an ageing society and the costs and opportunities arising from the widespread adoption of new technologies in production systems as well as daily life, the EU has increasingly focused on achieving challenging environmental-sustainability targets, above all a deep decarbonisation of the whole of society. According to the EC (2019), sustainable development – development that meets the needs of present generations without compromising the ability of future generations to meet theirs – is increasingly rooted in the European institutional framework, combining physical targets in terms of environmental protection with socio-economic concepts of societal wellbeing, inclusion and cohesion. It is noteworthy that, over the past 20 years, the EU has set some of the highest social and environmental standards, and put in place some of the most ambitious policies to protect human health, and has also become a global champion in the fight against climate change setting itself some of the world's most challenging decarbonisation targets.

As advantages and disadvantages are often jointly provided, the impacts of environmental protection action on socio-economic systems remain a matter of debate. By analysing such impacts with a special eye on their potential interaction with ageing and technological change, direct and indirect effects emerge.

Firstly, by achieving strict environmental targets, an ecosystem will become safer and negative impacts on human health lowered, thereby reducing healthcare expenditure.

Secondly, the development and diffusion of green technologies and production and consumption behaviour will encourage the creation of new green job opportunities, partly offsetting the negative impact on unemployment brought about by automation and skill-biased technical change.

Thirdly, the fiscal revenues generated by the implementation of environmental taxes are a positive element for the sustainability of the public budget, at least partly compensating the revenue reduction caused by an ageing society.

Lastly, drawbacks may arise if the cost of implementing an environmental policy is so high that it curbs the economic growth process, as would be the case of a too ambitious carbon tax.

### 1.5. Fiscal sustainability

An ageing population, the accelerated development and adoption of technology, and the growing interest in environmental sustainability have many implications.

The first one is that an increase in the number of older people leads to a rise in expenditure on healthcare and pensions. In the EU, public health expenditure amounted to 6.8 per cent of GDP in 2016 and is projected to rise to 7.8 per cent in 2050 as a result of demographic ageing. Public pension expenditure over the same period is projected to increase from 8.6 to 9.5 per cent of GDP (EC, 2018a).

The second implication concerns the overall reduction in the number of working people and the consequent decrease in direct tax payments due to a shrinking of the tax base. This typically leads to two negative impacts: a decline in labour productivity and a fall in available resources for financing the welfare system. At the same time, an ageing population may lead to an increase in health care and pension expenditure. Furthermore, additional impacts of changes in the age-group distribution affect consumption patterns as consumption preferences are varied among different age groups. This influences the structure of demand and hence production patterns of economic systems, and, in the case of an ageing society, negatively impacts consumption expenditure. This last effect, if no tax reforms are implemented, will lead to a reduction in VAT revenues.

It follows that, by reducing economic growth and simultaneously increasing the fiscal deficit, population ageing could result in an increase in the deficit to GDP ratio. This is particularly important for EU Member States that must respect the 3 per cent threshold level requested by the Stability and Growth Pact (SGP) rules set out in Article 121 of the Treaty of the Functioning of the European Union and the political basis of which was settled by the Resolution of the European Council on the Stability and Growth Pact in 1997. Further, a high old-age dependency ratio is expected to reduce the disposable income of the working population and lead to a further decline in the fertility rate, thus worsening an already critical situation (Hock and Weil, 2012).

A third implication originates from the increasing attention being paid to environmental sustainability, especially in relation to climate change and energy emissions. On one hand, climate policies may bring additional costs to societies that undertake structural changes in production and consumption; on the other hand, carbon taxes, or more general environmental taxes, might increase public revenues and, at least partly, counterbalance fiscal pressure exacerbated by an ageing population. As highlighted in a recent EC report on taxation (2018b), the reduction of revenues from labour taxation can be balanced by an increase from other forms of taxes. Among these, a crucial role could be played by environmental taxation, which could also contribute to the achievement of environmental policy goals, providing a double dividend. Accordingly, such a tax shift towards other revenue sources could be introduced to stimulate growth, increase employment and investment, and offset negative effects on fiscal sustainability associated with the reduction in direct taxation on labour due to ageing trends.

The positive effect of introducing an environmental tax, however, is not straightforward. Firstly, it might undermine economic competitiveness especially for more carbon-intensive and trade-exposed industries, producing, in the short/medium-term at least, a further reduction in employment. Secondly, if an environmental policy is effective in reaching its primary target of reducing greenhouse gas emissions, in the medium-term the tax base (emission level) will be reduced along with the corresponding tax revenue – always assuming that the unitary tax remains unchanged.

Even though the issues of an ageing population, technological change and environmental policies are widely investigated in scientific literature in silos, to the best of our knowledge there are no analytical contributions that combine these three aspects in order to disentangle links and feedback loops that might mutually influence one another.

# 2. Literature review

There are many methods and models that can be used to qualitatively and quantitatively analyse the impact of macro trends on sectoral performance. This section provides an overview of several options and describes in more detail causal loop diagrams (CLDs) and computable general equilibrium (CGE) models.

## 2.1. Decision tree

A decision tree (DT), also called a classification and regression tree (CART), is a decision-support tool that uses a binary tree-like graph or model to identify and map the relationship between inputs and outputs (Liu, et al., 2013). This methodology was first developed by Breiman et al. in the 1980s (Breiman, et al., 1984) and was then applied to the energy field by Wehenkel et al. in 1989 (Wehenkel, et al., 1989).

A DT explicitly maps the structure of a system and related intervention options. Starting from the indicator that is directly affected by the policy to be analysed, each branch of the tree diagram corresponds to a possible outcome (Covaliu, 2001). As the tree diagram expands, these branches represent direct, indirect and induced policy outcomes.

## 2.2. Causal loop diagrams

A causal loop diagram (CLD) is a map of the system analysed, or, rather, a way to explore and represent the connections between key indicators in the analysed sector or system (Probst and Bassi, 2014). As indicated by Sterman, "a *causal diagram consists of variables connected by arrows denoting the causal influences among the variables. The important feedback loops are also identified in the diagram. Variables are related by causal links, shown by arrows. Link polarities describe the structure of the system. They do not describe the behaviour of the variables. That is, they describe what would happen if there were a change. They do not describe what actually happens. Rather, it tells you what would happen if the variable were to change."* (Sterman, 2000).

Causal loop diagrams include variables and arrows (causal links), with the latter linking the variables with a "+" or "−" on each link, indicating a positive or negative causal relationship. A causal link from variable A to variable B is positive if a change in A produces a change in B in the same direction. A causal link from variable A to variable B is negative if a change in A produces a change in B in the opposite direction. Circular causal relationships between variables form causal, or feedback, loops. There are two types of feedback loops: reinforcing and balancing ones. The former can be found when an intervention in the system triggers other changes that amplify the effect of that intervention, thus reinforcing it. The latter, balancing loops, tend towards a goal or equilibrium, balancing the forces in the system (Forrester, 1961).

By highlighting the drivers and impacts of the issue to be addressed and by mapping the causal relationships between key indicators, CLDs support the identification of policy outcomes using a systemic approach (Probst and Bassi, 2014). They can in fact be used to create storylines corresponding

to the implementation of policy interventions, by highlighting direct, indirect and induced policy outcomes across social, economic and environmental indicators.
The creation of a CLD has several purposes: it combines the team's ideas, knowledge, and opinions; it highlights the boundaries of the analysis; and it allows all stakeholders to achieve basic-to-advanced knowledge of the dynamics underlying the sector or system analysed.

CLDs use a systems approach and are highly compatible with and complementary to other methods. But like every other method, CLDs also have some shortcomings. Firstly, the effectiveness of a CLD is directly related to the quality of the work and the knowledge that goes into developing the diagram. Multi-stakeholder perspectives should be incorporated and cross-sectoral knowledge is essential to correctly identify the causes of the problem and design effective interventions. Secondly, the boundaries of the system and the relationships between the key variables have to be correctly identified. Errors in creating the diagram may lead to biased assessments of policy outcomes, overstating or underestimating some of the impacts across sectors and actors. Thirdly, the estimation of the strength of causal relations, even if these are correctly identified, cannot be guaranteed as the causal diagram is a qualitative tool.

### Box 2.1: Introduction to systems thinking

Systems thinking (ST) is an approach that allows better understanding and forecasting of outcomes of decisions across sectors and among economic actors, over time and in space (Probst and Bassi, 2014). It emphasises the system, made up of several connected parts, rather than focusing on its individual parts.

As ST is an approach, there are several methodologies and tools that support its implementation and hence the identification of the underlying functioning mechanisms of a system, and their quantification and evolution over time. In general terms, it can be said that the identification of the components of a system and the relationships existing among these, carried out through, for example, the use of CLDs, represents the *soft* side of ST, while attempts to quantify these links and forecast how their strength might change over time through, for example, SD models, represent the *hard* side of ST.

On the *soft* side of ST, CLDs allow the creation of a shared understanding of how the system works, and hence identify effective entry points for (human) intervention, such as public policies. When this is done using a participatory approach, it helps to bring people together, creating the required building blocks for the co-creation of a shared and effective theory of change.

On the *hard* side, SD models allow the quantification of policy outcomes across social, economic and environmental indicators (UNEP, 2014), providing insights on the relative strength of various drivers of change (scenario analysis) and supporting the identification and prioritisation of policy intervention (policy analysis). These models can be bottom-up or top-down (Probst and Bassi, 2014; UNEP, 2011).

In the context of this research, the role of ST is to assess the extent to which the main drivers of the change considered – in this case, population ageing, technological change and fiscal sustainability – can shape future trends, affect existing policy effectiveness and require future intervention. This in turn allows the identification of a system's safe operating space and limits, anticipating the emergence of side effects across social, economic and environmental indicators.

An example of the use of CLDs is the analysis of the power sector of Mauritius (Deenapanray and Bassi, 2015). This CLD, which later served as guideline for the development of a system dynamics (SD) simulation model that supported the formulation of the Long-term Energy Policy 2009–2025 (RoM, 2009), was conceptualised with decision makers from the Ministry of Renewable Energy and Public

Utilities. Developing the CLD together with local stakeholders contributed to the acceptance and ownership of the simulation model, and enhanced both its quality validation.

### 2.3. Macro-econometric models

Econometric models function by collecting historical data on a range of variables and using economic theory and statistical techniques to determine how a change in one variable is correlated with changes in others. Data on past correlations are then used to project future changes. A macro-econometric model applies this approach to macroeconomic variables. As a result, this type of model is not based on an attempt to theorise about how an economy works, rather it measures how an economy has evolved based on actual data. The reliance on data is certainly a strength, but also a weakness: past relationships may not accurately capture current or future ones; and a more sophisticated attempt to model pathways of causation could take a range of factors not captured by past data into account.

### 2.4. Partial equilibrium models

Partial equilibrium (PE) models are a family of models that cover a single sector, generally at a high level of detail when compared to economy-wide ones such as CGE models. They range from single-sector single-country models to single-sector multi-country models (FAO, 2006) and typically use a bottom-up approach, placing emphasis on individual technologies and estimating the impacts that the adoption of these technologies could have on demand and production in a given sector.

At their simplest level, PE models can be conceptualised as the interaction of supply and demand in a single market. In this market, the model estimates the effect that certain policy options could have on the sector's performance. Based on a new situation and specific elasticities for demand and supply, the PE model calculates a new equilibrium for the sector and provides output on a range of indicators.

Partial equilibrium models can primarily use optimisation and simulation to model the development and adoption of a technology. These models are generally faster to customise and are less data intensive than macroeconomic assessments – or, at the very least, data collection is limited to a single sector. Energy systems PE models are an example of ones that focus on energy demand and/or supply, but do not include macroeconomic dynamics such as GDP and income.

The policy impacts that can be assessed using PE models differ depending on the model. In addition to the detailed presentation of variables in the sector analysed, coverage of environmental, economic and social indicators can also be found in PE models.

### 2.5. Computable general equilibrium (CGE) models

A general equilibrium approach models supply and demand behaviour across all markets in an economy (Lofgren and Diaz-Bonilla, 2010). Computable general equilibrium models are a standard tool of empirical analysis and are widely used to analyse the aggregate welfare and distributional impacts of policies the effects of which may be transmitted through multiple markets, or contain menus of different tax, subsidy, quota or transfer instruments.

Computable general equilibrium models optimise utility for economic actors, and the three conditions of market clearance, zero profit and income balance are employed to simultaneously solve the set of prices and the allocation of goods and factors that support general equilibrium. The CGEs are first solved in a base year, by deriving parameters consistent with historical data and optimisation assumptions. The model is then 'shocked' by changing policy or economic conditions allowing economic modellers to observe quantitative changes in the outputs, which provide an estimate of long-term outcomes.

These models are in general 'top-down', meaning that variables such as energy consumption are determined by parameterised equations, rather than by considering individual technologies. They estimate all direct and indirect impacts, and follow these through time, allowing for a distinction between first-, second- and third-order effects. On this basis, the World Bank argues that general equilibrium analysis is the most appropriate way to estimate the macroeconomic impacts of subsidies and their reform (World Bank, 2010). In general, the advantage of a general equilibrium approach is that it allows for indicators on a full set of impacts across an economy – not only household incomes, but also macroeconomic effects, such as inflation, and estimates on how specific economic sectors will be affected.

The main limitation of CGE models is the assumption about optimisation and how closely this mirrors reality. Two additional limitations regard employment and productivity. Regarding the former, CGE models normally work under the assumption of full employment, with salaries and wages changing depending on the performance of the economy. This is an important limitation for policies that could lead to job losses or stimulate employment creation. For productivity, CGE models generally do not incorporate social and human capital as a key factor of production, so as a result, with a few exceptions including the World Bank's MAMS model, changes in health and education are not shown to affect economic productivity and production.

One of the key aspects of CGE models is that they are suitable for investigating the economic impacts of policies by taking the interactions between different agents and markets into account. Accordingly, applications of CGE models include the examination of policies in the fields of international trade; public finance (tax reforms); agriculture; transportation; changes in world prices; welfare; economic growth and income distribution; changes in public expenditure; and energy and environmental policies, especially those involving the introduction of carbon taxes (Mezenes et al., 2006). Given the main subject of this report, the focus here is on CGE models applied to the issues of the environment, technology, population ageing and taxation.

Environmental and technology issues are currently among the most studied through the use of CGE models. Many studies rely on the Inter-temporal Computable Equilibrium System (ICES) model, a CGE model developed by the Fondazione Eni Enrico Mattei (FEEM) to "assess impacts of climate change on the economic system and to study mitigation and adaptation policies" ([1]). It is a dynamic, multi-regional CGE model derived from the GTAP-EF (Bigano et al., 2008), a modified static version of the CGE GTAP-E model (Burniaux and Troung, 2002), which in turn is an extension of the basic GTAP model (Hertel, 1997). It is characterised by the inclusion of sustainability issues through the introduction of 28 indicators related to the 17 Sustainable Development Goals (SDGs). Consequently, it is mainly used to study mitigation policies (Michetti and Parrado, 2012; Bosello et al., 2010) and adaptation (Carraro and Sgobbi, 2007). Furthermore, it has been used for studies on climate change and technology (Parrado and De Cian, 2014). In this respect, technical changes in ICES are modelled through a set of technology

[1] http://www.feem-web.it/ices

parameters and are considered in terms of changes in productivity, and renewable and clean technologies. For the former, estimates of labour and land productivity are obtained from the G-Cubed model (McKibbin and Wilcoxen, 1998) and the IMAGE model (IMAGE, 2001), respectively, while for the latter, wind, solar and hydro-electricity are split off from the original power sector, allowing for fossil-based electricity to be substituted with renewable sources.

Recently, mitigation policies and land use have been investigated through a CGE model developed by the International Food Policy Research Institute (IFPRI): the IFPRI-MIRAGE, particularly suitable to assess the impact of EU biofuels policies (Laborde et al., 2014; Malins, 2011) and derived from the Modelling International Relationships in Applied General Equilibrium (MIRAGE ) model developed at Centre d'Études Prospectives et d'Informations Internationales (CEPII) (Decreux and Valin, 2007; Bchir et al, 2002) and based on the *Global Trade Analysis Project* (GTAP) database. Originally developed to analyse trade policies, further extensions of the MIRAGE model also embrace an updated version, called MIRAGE-e, which includes a more detailed description of energy and carbon dioxide emissions (Fontagné et al., 2013).

In line with ICES and MIRAGE, several other CGE models have been developed and applied tin environmental studies based on the GTAP database and basic model. Firstly, the GDyn model (Ianchovichina and McDougall, 2000) includes dynamic behaviour, while an energy-environmental version of the static GTAP model (GTAP-E) was developed by Burniaux and Truong (2002), with the inclusion of energy substitution and carbon emissions from fossil fuels. By combining these two extended versions, the GDynE, developed by Golub (2013) and improved by Markandya et al. (2015), represents the energy version of the dynamic GDyn. Finally, the merging of GDynE with the new GTAP-Power database, with the inclusion of a detailed disaggregation of the electricity sector, gave rise to the GDynEP version of the model (Antimiani et al., 2017). As for the fields of application, GTAP models and their extensions have been used to analyse the impacts of climate change on forestry (Rive et al., 2005) and other sectors (Berrittella et al., 2006), mitigation and energy transformation (Cai et al., 2015). They also include analyses of mitigation policies and the role of the Green Climate Fund (GCF) in climate negotiations (Antimiani et al., 2017); interactions between European low-carbon policies for mitigation, energy efficiency and the use of renewables through green technologies (Corradini et al., 2018); and the impacts of climate change damages on economies (Costantini et al., 2018).

With respect to climate damage, its impact has also been analysed through the application of the ICES model (Bosello et al., 2012; Eboli et al., 2010; Carraro and Sgobbi, 2007) and through the ENV-Linkages model, developed by the Organisation for Economic Co-operation and Development (OECD). In particular, it has been applied to shed light on the impacts of climate change on economic growth (OECD, 2015; Dellink et al., 2014). The ENV-Linkages model is a recursive dynamic neo-classical CGE (Chateau et al., 2014), originally developed to support governments in identifying least-cost environmental policies, including mitigation and environmental tax reform (Chateau et al., 2018). The model also takes into account technological progress through an annual adjustment of productivity parameters, including autonomous energy efficiency and labour productivity improvements.

Indeed, all these CGE models dealing with environmental issues also entail technical change. Consequently, CGE models have recently also been used to specifically investigate the role of automation processes, as in the case of a report on the impacts of AI on labour productivity and product enhancement, on GDP at a global level, in specific geographical regions as well as within specific industry sectors through a spatial CGE (S-CGE) model (Gillham et al., 2018).

Together with environmental and automation issues, population ageing represents another challenge for the world, and in particular the EU. Accordingly, several studies are investigating this aspect and CGE models are a key instrument for such studies requiring simulation analyses. Among these, in the Environmental Outlook to 2050 (OECD, 2012), the ENV-Linkage model is used to study the socioeconomic developments, describing current demographic trends and corresponding baseline projections, especially in terms of population growth and composition, including ageing and urbanisation. It then delineates economic trends and projections, including economic growth and its drivers, such as labour and capital.

Many EU studies use the overlapping generations CGE model (OLG-CGE). Following the tradition of Auerbach and Kotlikoff (1987), it combines CGE elements with overlapping generations' characteristics – people live for a limited period of time and overlap with other individuals' lives. It has been typically applied to study demographic change and public policy (Fehr et al, 2013; Georges et al, 2013; Sánchez-Romero et al., 2013; Börsch-Supan et al., 2006), in particular to examine the economic effects of population ageing, especially on the labour market (Lisenkova et al., 2013), the pension system and fiscal sustainability (Lisenkova and Bornukova, 2017). Further improvements have been made by Georges et al. (2016), who include consumption per age group and age-variable rates of time preference, and in the European Work Package 5 (WP5) with the development of a simulation OLG-CGE model based on national transfer accounts (NTA) data in order to evaluate the impact of ageing on the sustainability of public finances (Abio et al., 2014).

In this regard, most of the studies using CGE models to investigate the effects of ageing dynamics also often examine the relationship between ageing and fiscal sustainability (Honkatukia and Marttila, 2009; Aaberge et al., 2007; Pedersen, 2002). In fact, it is worth noting that environmental and technological issues are usually analysed together, while studies of ageing often include fiscal sustainability considerations.

An attempt to combine environmental issues with ageing dynamics is represented by Wei et al. (2018), who conducted an analysis of the relationship between an ageing population, economic growth and climate issues in China: the idea is that ageing may impact the economy and energy-related emissions extensively, potentially affecting the global economy and climate. This analysis used a model of Global Responses to Anthropogenic Change in the Environment (GRACE), which is a global CGE model (Aaheim and Rive, 2005). The study, however, neither took technological improvements into account nor provided in-depth analysis of fiscal sustainability.
While CGE models have been extensively used to examine the environment, automation, ageing and fiscal sustainability, the four dimensions under investigation in this report, so far and to the best of our knowledge, there are no studies that combine them in a CGE model. Consequently, given the strict connections occurring among these issues, we have developed a CGE model that aims to simultaneously investigate them, as described in the following chapters.

### 2.6. System dynamics

Created by Jay W. Forrester in the late 1950s, SD is an integrated quantitative modelling approach utilised to understand (complex) real world issues and guide decision making over time for achieving sustainable long-term solutions (Probst & Bassi, 2014).

It is a flexible methodology that allows the integration of social, economic and environmental indicators in a single framework of analysis. System dynamics models are based on the assumption that structure drives behaviour and use causal relationships to link variables. Models can be customised to analyse the socioeconomic implications of different action across social, economic and environmental sectors and actors, such as households, the private sector and government, within and across countries. In fact, SD models can be top-down or bottom-up, general or partial equilibrium ones.

The pillars of SD models are feedback, delays and non-linearity. The former are identified through the creation of causal maps, or CLDs. A CLD has several purposes:

1) it brings the ideas, knowledge and opinions of the participants together;
2) it highlights the boundaries of the analysis;
3) it allows all stakeholders to reach a basic-to-advanced knowledge of the systemic properties of the issues analysed.

Having a shared understanding is crucial for solving problems that touch upon several sectors or areas of influence, which are normally found in complex systems (Rouwette and Franco, 2014; Sterman, 2000). Delays and non-linearity are captured through the creation of a quantitative model, which includes stocks and flows.

System dynamics models, as opposed to CGE and energy systems ones, do not aim at optimising the behaviour of a system. Rather than developing policies that optimise a certain aspect, SD models support the development of integrated policies that contribute to long-term stability of a system through what-if scenarios. Thus, instead of providing a policy for optimising energy supply, SD aids the formulation of a set of policy measures that may improve several indicators at once, such as providing affordable energy while generating employment and reducing air pollution. As a result, SD models inform both policy formulation and assessment, as well as monitoring and evaluation.

A high degree of customisation is common in SD models. This is done to account for:

(i) local circumstances;
(ii) the tacit and explicit local knowledge (2); and
(iii) the priorities of local decision makers.

Specifically, it is crucial to use local knowledge in the identification of causal relationships and feedback loops. Further, being a tool to inform local decision making, the analysis must provide information on indicators that local decision makers deem important. It is therefore recommended that the model is customised in close cooperation with decision makers and local stakeholders (Rouwette and Franco, 2014).

[2] "Local knowledge refers to information and understanding about the state of the bio-physical and social environments that has been acquired by the people of a community which hosts (or will host) a particular project or programme." Baines et al. (2000).

# 3. Description of a system dynamics model applied to population ageing and technological change

### 3.1. Population ageing

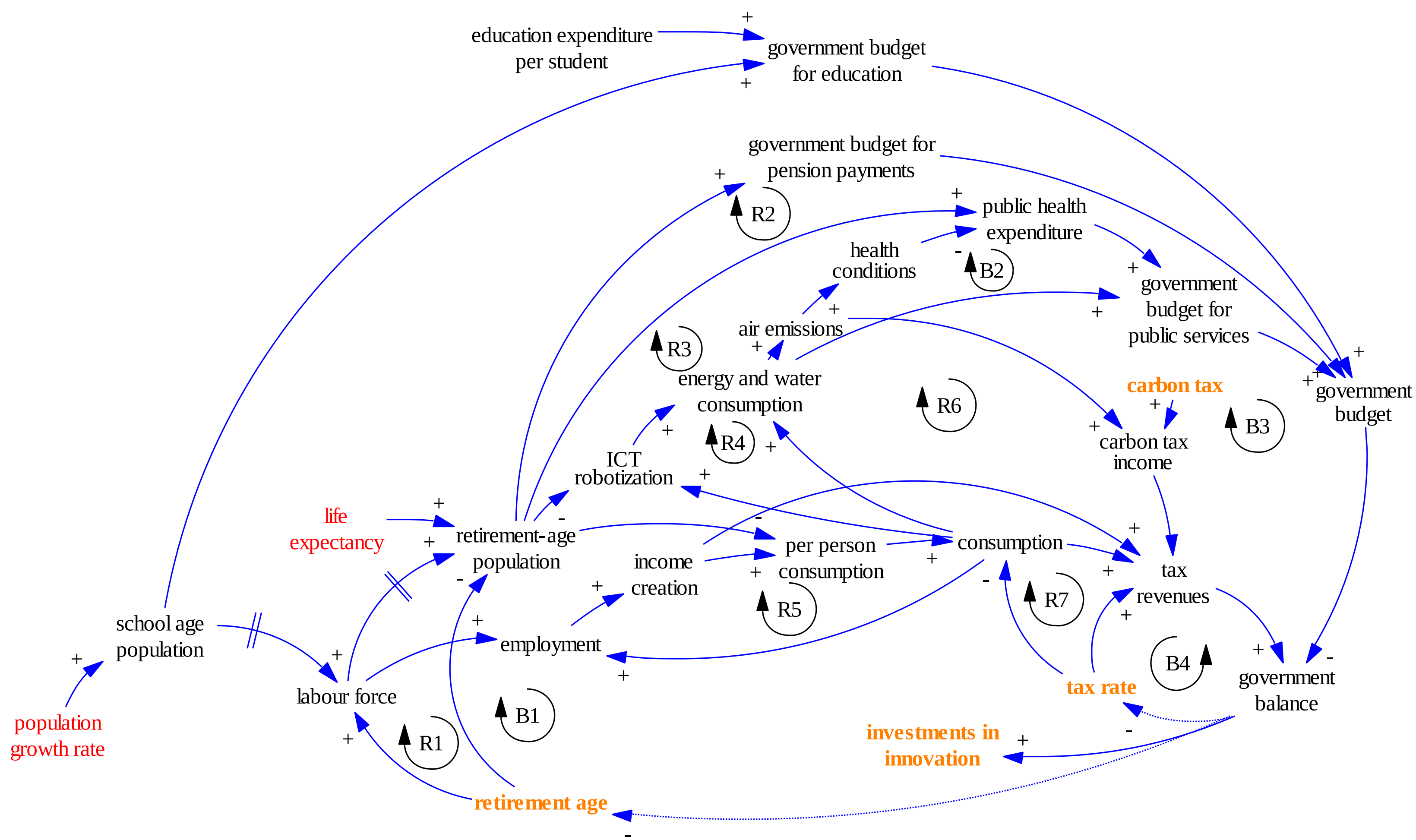
Population ageing affects several dynamics in an economy. First, it increases the public budget due to the need to provide more services and pension while tax revenues decline as a consequence of reduced/changed consumption. If population ageing is driven both by increased life expectancy and reduced fertility, the cost of education may decline, but only in the medium to longer term. As a result, fiscal sustainability could be challenged, especially in the short to medium term.

Specifically, public expenditure, including pensions and health care expenditure, increases as the number of retirees grows. At the same time, the spending power of the population decreases due to reductions in income and changes in lifestyles, which changes and reduces consumption for households and tax revenues for the government. This is a particular problem for consumption-driven economies, in which the challenge is to maintain the fiscal balance by finding ways to finance additional expenditure in the face of comparatively lower revenues. This is coupled with a relatively slower rate of adaptation of retirees to technological innovation, for example, in the context of energy consumption, which may render certain policy interventions, such as incentives to encourage energy efficiency and the use of renewable energy, ineffective and hence limit the potential to reduce other budgetary items. There are, on the other hand, several options to counter the negative (or undesirable) effect of population ageing. To provide two examples, to improve fiscal sustainability, the retirement age could be extended and/or tax rates could be increased. The outcomes of such interventions are not trivial, as presented by the many variables and feedback loops included in the CLD (**Error! Reference source not found.**3.1).

Changes towards the ageing of population reduce tax revenues (R1) and increase public expenditure (R2, R3 and R4). These are four reinforcing feedback loops, indicating an increasingly challenging outlook if action is not taken; positive developments however emerge if action is taken, either by increasing the retirement age or increasing tax rates. Income and consumption (e.g. VAT) tax are expected to decline, or increase less than in a baseline scenario, due to lower labour income and domestic consumption with population ageing (B1 and R5). Furthermore, an increase of public expenditure would be the result of higher pension payments (R2), health care expenditure (R3) and public services (R4).

If the retirement age and/or the tax rate are increased, several desired and undesired outcomes emerge. An increase in the tax rate affects both government revenues, through a balancing loop (B4), and consumption, through a reinforcing loop (R7). This indicates that, depending on the reliance of an economy to consumption, triggering R7 could lead to the creation of a virtuous or a vicious cycle. When the retirement age is changed instead, two main dynamics are triggered: a reinforcing loop (R1) is strengthened, as more people stay in the labour force; and simultaneously a balancing loop is triggered (B1), as fewer people flow, or will do so at a slower pace, temporarily, into the cohort of retired people.

Figure 3.1 Causal loop diagram of ageing population



### 3.2. Technological change

Technological change represents an important opportunity for economic development and for reducing the impact of human activity on the environment, but it also creates challenges, especially at the social level. **Error! Reference source not found.**3.2 illustrates how the adoption of technology affects the labour market and the government's fiscal balance, and, in turn, how these developments influence investment in innovation and technology.

In general terms, it can be seen that there are various potential outcomes for the government from the adoption of information and communications technology (ICT) and robotisation. On the side of public revenues, there could be (a) an increase of productivity and production, leading to more income creation and tax revenue, as well as (b) a potential reduction in employment, and hence comparatively lower tax income from labour and consumption. On the expenditure side, there could be both (i) a reduction in health care expenditure and (ii) the potential creation of technological unemployment, leading to higher welfare costs. Further, if ICT and robotisation are used to modernise production processes and reduce energy consumption, or promote fuel switching toward less carbon intensive energy sources, the potential to improve the fiscal balance through environmental taxation could be challenged.

The adoption of technology and the growing efficiency improvements brought about by ICT and robotisation have historically increased industrial productivity and production, leading to higher GDP and income tax revenues (R4). Further, the adoption of technology can contribute to improving health conditions, reducing public health care expenditure (R3). On the other hand, technological advancement improves productivity, often leading to a reduction in labour intensity. This can result in comparatively lower labour demand and employment, for example relative to a situation with less robotisation. When this leads to technological unemployment the cost to the government increases through, for example, higher welfare payments. The challenge is to balance the potential decline in tax revenues with the potential increase resulting from a growth in productivity and profit for companies.

**Error! Reference source not found.**3.2 includes two possible intervention options: environmental taxation – carbon and energy taxes – and investment in energy efficiency and smart technologies. Investment in innovation, especially in smart technologies and smart services, is expected to improve health conditions of the population (R2) and lower public expenditure in the short term. This investment counters the reluctance of the elderly to adopt new technologies, as presented in the ageing population CLD. There are additional outcomes of this investment: (i) an increase in life expectancy and (ii) growth in the required public budget for pensions (B2), social services (B3), and health care (B6).

Increasing environmental taxation generates additional tax revenues (R4 and R5), but also simultaneously affects the economic performance of the private sector. In fact, a tax on environmental performance represents extra costs and lower profits, thereby reducing income tax revenues (B7 and B8), or consumption and hence VAT if the costs are passed on to consumers.
No intervention has been analysed so far to tackle technological unemployment directly in the CLDs. On the other hand, the concept of increasing environmental taxation has emerged as being an important outcome of the improvement and increased adoption of ICT and robotisation, especially in relation to ageing. This is depicted in balancing loops B1 and B3 (**Error! Reference source not found.**3.2) as a constraint to growth – countering the growth of consumption and creating stress on fiscal sustainability. The dynamics of technological unemployment are not trivial: the retirement age can be extended to

reduce the number of retirees when fiscal sustainability demands higher contributions from the working population; however this increases the labour force, creating more unemployment if demand for labour does not increase as well. When this take place in conjunction with the growing adoption of ICT and robotisation, unemployment could increase further because ICT and robotisation may reduce demand for labour.

The consequence would be a positive short-term reduction in pension payments, followed by an undesirable medium- to longer-term increase in welfare payments due to unemployment in a larger labour force, and hence possibly affect the younger cohort – youth unemployment – and older age cohorts that are most likely to be displaced by the adoption of new technology. The macroeconomic consequences of both higher unemployment and higher retirement rates include a reduction of consumption and tax revenues.

### 3.3. Fiscal sustainability

Fiscal sustainability has become a very important goal in the last decade, both to maintain macroeconomic stability and to ensure the effective allocation of public resources for the provision of public services. Maintaining fiscal stability is, however, not easy because public revenues and expenditure are affected by several dynamics, involving social, economic and environmental indicators.

Among the factors that affect government revenues are the implementation of environmental taxes, taxes on personal income, consumption and corporate profits. Among the factors influencing government expenditure are investments in energy supply, energy imports, the possible provision of energy subsidies and carbon-related impacts resulting from the use of fossil fuels. The government budget is only affected by reinforcing loops, indicating that challenges may get harder and harder to solve, while government revenues are mostly impacted by balancing loops, indicating that the more the economy grows and the greener economy investment, such as in energy efficiency, is made, the less the revenue that can be expected from environmental taxation. Exceptions emerge from the most traditional macroeconomic feedback loops, where investment leads to more economic growth, and hence more investment and consumption. These are positive reinforcing loops, which counter, and historically have dominated, the reinforcing and balancing loops mentioned above.

In **Error! Reference source not found.** 3.3, the CLD illustrates how green economy investment in, for example, energy efficiency, removal of fossil fuel subsidies or the introduction of a carbon tax, can contribute to fiscal sustainability. First, it is assumed that fiscal sustainability enables governments to invest in green economy interventions and stimulate the adoption of energy-efficient technologies. Improving energy efficiency reduces energy consumption and hence reduces the required power-generation capacity (R1), energy imports (R2) and adverse health impacts from emissions (R3). Furthermore, a reduction in energy consumption tends to reduce the price of electricity, or certainly its cost, which has beneficial effects for the economy and yields additional tax revenues (R5).

On the other hand, the reduction in energy consumption from investment in energy efficiency reduces energy tax revenues (B1) and revenues from environmental taxes such as a carbon tax (B2). This indicates the need to assess the likely outcomes of green economy policy impacts carefully, since investment in energy-efficient technologies would both impact government revenues and expenditure.

Figure 3.2 Causal loop diagram of technology adoption

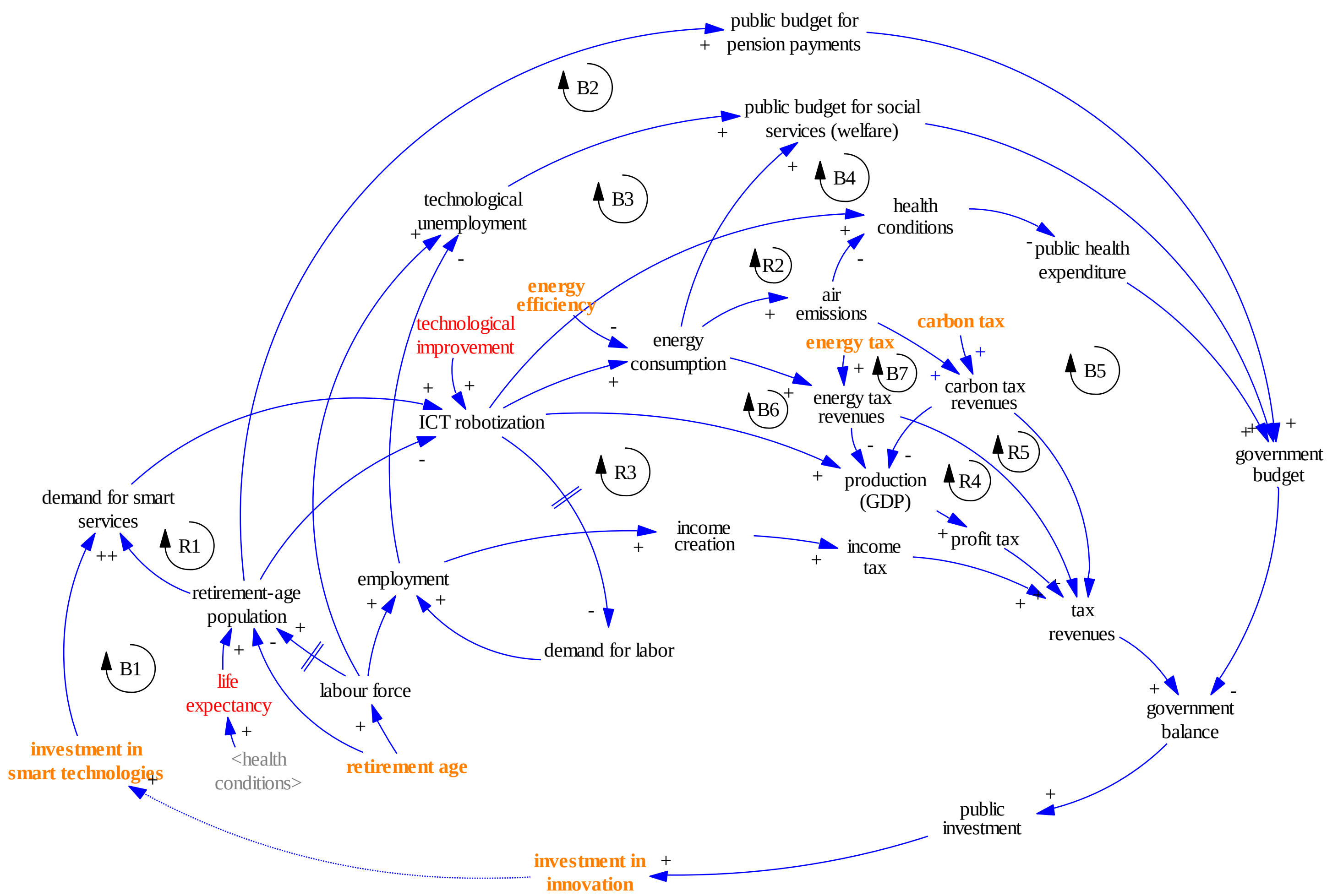
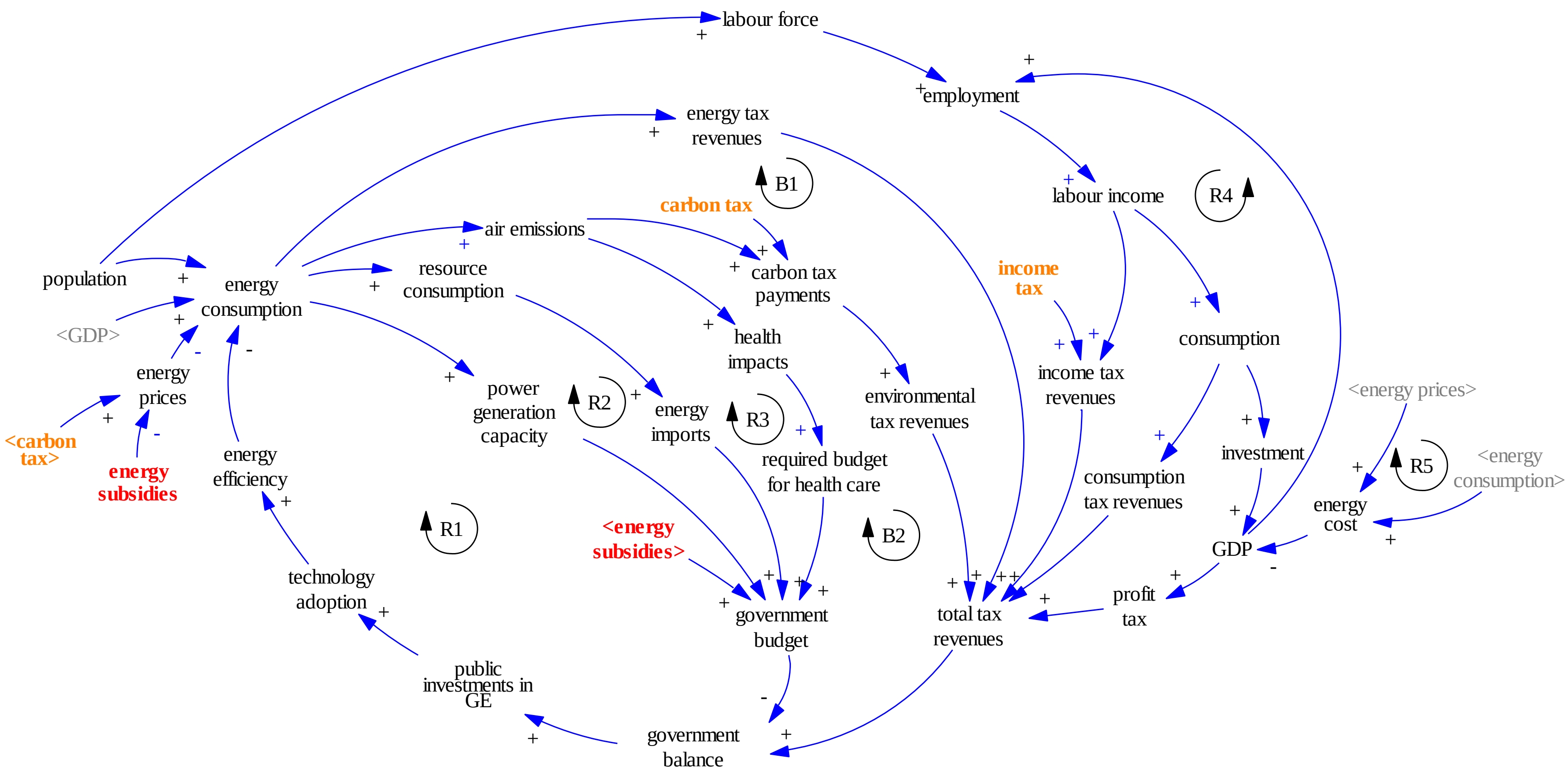


Figure 3.3 Causal loop diagram of fiscal sustainability



### 3.4. Integration and macro performance

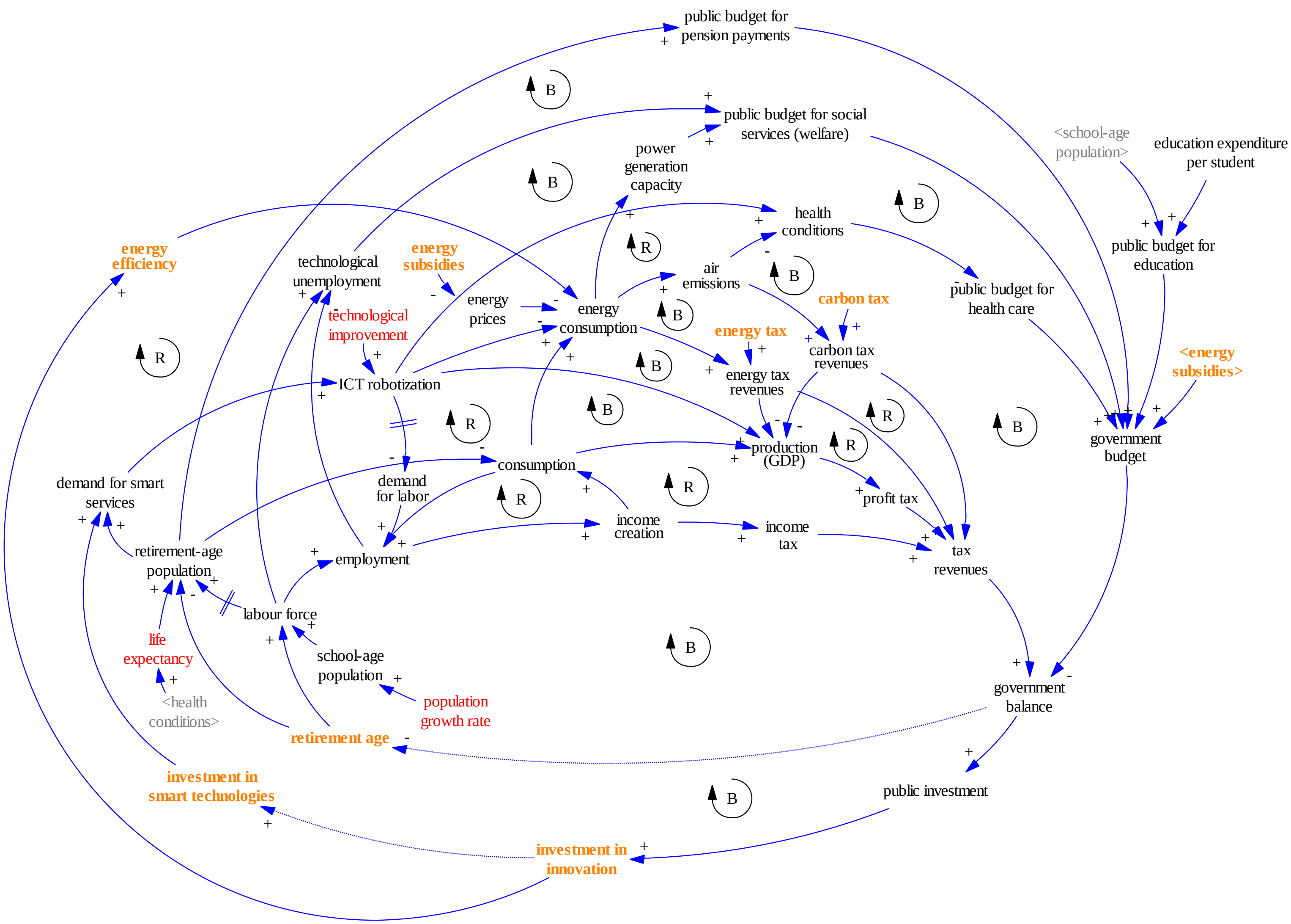
Population ageing, technological change and fiscal sustainability are deeply connected. This emerged very clearly from the analysis presented above, with the three individual CLDs. Figure 3.4 illustrates an attempt to integrate these diagrams, to highlight, with a higher level of aggregation and in a simplified manner, the causal relations that exist between the three key drivers of change.

The main dynamics emerging from this integrated CLD are as follows.

- Population ageing primarily strengthens reinforcing (R) loops. This highlights that action needs to be taken, otherwise growing costs and declining public revenues will create a vicious cycle in which resources will not be available for the modernisation of the economy. In other words, population ageing creates considerable challenges for fiscal sustainability.
- Technological change has both pros and cons. On the downside, the adoption of ICT and robotisation may lead to the creation of technological unemployment, exacerbating the issues emerging with population ageing of extra public costs, including for welfare. This could also lead to reduced consumption and public revenues, with the possible creation of a vicious cycle, creating challenges for fiscal sustainability. On the upside, however, ICT and robotisation also carry the potential to increase economic productivity, leading to higher GDP, and hence possibly triggering the creation of new jobs, and thereby higher tax revenues. In other words, if economic growth offsets the negative impacts of technological unemployment and consumption, ICT and robotisation could have a positive impact on fiscal sustainability and mitigate the outcomes of population ageing.
- Fiscal sustainability is directly impacted by population ageing and ICT/robotisation, but it is also impacted by public and private investment in, for example, energy efficiency. Here it can be seen that population ageing could reduce the uptake of new technology or stimulate it, especially in the context of smart services. The same goes for ICT, which may introduce new appliances and services that require additional electricity and hence increase energy consumption, on top of and above a baseline scenario, as, for example, the use of mobile phones and smartphones has increased electricity use, or modernise and replace existing tasks/processes, lowing energy needs. What can be observed is that the performance of environmental taxation is uncertain, and that a green economy, if implemented effectively through, for example, increasing energy efficiency, may reduce the potential role of environmental taxation in supporting fiscal sustainability.

When it comes to specific interventions that could be implemented to counter some of the undesirable outcomes of population ageing, technological change and fiscal sustainability, again the pros. and cons., or the potential emergence of side effects over time, need examination. For instance, changing the retirement age would reduce stress on the fiscal balance, but this would only be a temporary effect. Investment in innovation and technology would allow a reduction of costs and boost productivity, but might also lead to technological unemployment and reduced public revenues from environmental taxation. Market distortions could be removed, such as harmful energy subsidies, which would lead improve the fiscal balance and raise energy prices. and thereby stimulate energy efficiency and reduce health costs.
As a result, it is critical to assess the likely outcomes of interventions across dimensions of development and for different economic actors, both in the short, medium and longer term to anticipate potential side effects and improve policy effectiveness.

Figure 3.4 Integrated causal loop diagram



### 3.5. Performance monitoring and evaluation

The creation of CLDs and the analysis of feedback loops supports the identification of dominance in the system. In other words, some feedback loops are stronger than others, and therefore steer the system in a specific direction. For ageing, technology adoption and fiscal sustainability, the dynamics to consider are as follows.

- Population ageing primarily strengthens reinforcing (R) loops. This highlights that action needs to be taken, otherwise growing costs and declining public revenues will create a vicious cycle for fiscal sustainability. The main impacts include reduced tax revenues (R) and increased public expenditure for higher pension payments (R), health care expenditure (R) and public services (R). Consumption is also expected to decline, or increase less than in a baseline scenario, due to lower labour income and domestic consumption caused by population ageing (B and R).
    - The dynamics to observe are:
      (1) the annual rate of change of tax revenues, especially from labour income;
      (2) the extent to which public expenditure increases, especially for budget items related to pensions and health care; and
      (3) the consumption trend and eventual changes in the consumption basket.

- The adoption of technology and the growing efficiency improvements brought about by ICT and robotisation have advantages and disadvantages. While they trigger growth through improved productivity (R), they may, on the other hand, lead to the creation of technological unemployment, exacerbating the issues emerging with population ageing – extra public costs, for example for welfare (B). The challenge is to balance the potential decline in tax revenues with potential growth resulting from the increase in productivity and company profits.
    - The dynamics to observe include:
      (1) trends in fixed capital investment, labour productivity and labour costs; as precursor of
      (2) technological unemployment, paying particular attention to youth unemployment and among the higher-age cohorts of the labour force.

- Fiscal sustainability is impacted by population ageing and ICT/robotisation as described above, through both reinforcing and balancing loops. Further, green economy investment in, for example, energy efficiency, or the removal of fossil fuel subsidies and the introduction of a carbon tax, have two opposite outcomes on financial sustainability. On one hand, there are cost reductions (R) such as in public expenditure for the health sector as a result of energy efficiency, and higher revenues (R), due, for example, to reduced reliance on energy and increased profitability, competitiveness, and hence higher GDP and income. On the other hand, the reduction in energy consumption from investment in energy efficiency reduces energy tax revenues (B) and revenues from environmental taxes such as a carbon tax (B). It can thus be concluded that the performance of environmental taxation is uncertain, and that a green economy – if implemented effectively – may reduce the potential role of environmental taxation in supporting fiscal sustainability.
    - The dynamics to observe are those related to:
      (1) government revenues; and
      (2) government expenditure.
      The former could be monitored through changes in economic activity, both production and consumption; the latter is primarily impacted by ageing, unemployment and the health impacts of environmental degradation, such as a growing incidence of respiratory diseases.

These feedback loops provide useful information to aid the selection of indicators for monitoring and evaluation (M&E). Practically, there are three types of indicators to monitor:

(i) those that are directly impacted by policy interventions;
(ii) those that form critical feedback loops; and
(iii) those that belong to several feedback loops – crucial nodes in the system.

The first group of indicators is relevant because it supports the analysis of policy effectiveness, and shows whether the implemented interventions are leading to the intended or expected outcomes. The second group is critical because changes in the trend of these indicators indicates that policy impacts are not only direct, but also indirect and induced, and can propagate through the dominating feedback loops – those affected by policy interventions. The third group could anticipate change in the whole system as these indicators are precursors of systemic change, and allows determining whether side effects will emerge or whether the implemented policy will have lasting positive (desired) effects.

It is evident that M&E for dynamics and integrated systems has to be carried out at different levels, considering:
(1) the shocks introduced in the system, as a starting point, through policy interventions;
(2) system responses within sectors or thematic areas; and finally
(3) whole system responses across sectors, economic actors and dimensions of development and over time.

A similar approach was first proposed by the United Nations Environment Programme (UNEP) in the context of their Green Economy Advisory Services (UNEP, 2014b), with emphasis on the need to use indicators for issue identification, policy formulation and assessment, and M&E.

From a review of the integrated CLD presented in Figure 3.4 the main M&E indicators for the three groups are as follows, considering population ageing as a starting point (with the selection of key indicators being, at least for Group 1, policy or problem driven.

- Group 1, based on the focus area of ageing population:
    - retirement-age population and annual rate of retirement;
    - labour force and annual net change, considering declining fertility and longer life expectancy;
    - public budget for pension payments and health.

- Group 2, based on key feedback loops:
    - employment and unemployment, consumption, income tax and VAT, government revenues;
    - school-age population and education expenditure, government budget.

- Group 3, based on whole system performance:
    - labour force, employment and unemployment, especially technology related and age cohorts affected;
    - tax revenues and government budget;
    - energy consumption and air emissions, as proxies for the impact of environmental degradation on government expenditure, such as on health, and revenues, from, for example, fuel or carbon taxes.

In concluding, it is important to mention that indicators have to be assessed in relation to the feedback loops to which they belong. This is because the system-wide impact of an increase in a given indicator is determined by whether it is embedded in a reinforcing loop, and hence growth will propagate through the system, or in a balancing loop through which there will be stronger pressure to counter change and reach equilibrium. It is therefore only through the simultaneous use of indicators and feedback loops, as shown by CLDs, that system performance can be assessed with confidence. This is especially the case for complex systems, in which multiple trends and policy packages affect performance and there is a high degree of connection across sectors, and hence indicators.

# 4. Computable general equilibrium model assumptions for GDynEP-AG for an ageing population, technical change and fiscal sustainability

## 4.1. Model description

### *4.1.1. General model settings*

The CGE model developed to carry out the analysis is called GDynEP-AG. It is based on GDynEP, the combination of the GDynE and the GTAP_Power, enriched with a specific module for modelling changes in consumption patterns driven by different demographic trends. Accordingly, it is a dynamic energy model that allows the representation of long-term policies and the capital accumulation function. It is based on the latest version of the GTAP-Database – GTAP-Database 9.1, updated to 2011. Since it is integrated with GTAP-Power, it also distinguishes between several energy-generating technologies and includes supply from different renewable energy sources. Combustion-based carbon dioxide emissions are also included at the sector level ([3]).

Nineteen regions and 22 sectors are considered. Six regions include rich economies – the EU, 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, Southeast Asia, African Energy Exporters, West Africa, East and South Africa, American Energy Exporters, South America, and Central America and Caribbean. The EU region corresponds to the EU-28 aggregate-current composition available in the EUROSTAT database.

The 22 sectors are agriculture; food, beverages and tobacco; textiles; wood; pulp and paper; chemical and petrochemical; non-metallic minerals; basic metals 1; basic metals 2 ([4]); machinery; 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, and electricity from renewable sources ([5]).

As for the temporal dimension (t), the period from 2011 to 2050 is considered, divided into eight steps of five years each, with the exception of the first step, which covers 2011–2015. In this way it is possible to fully calibrate data at 2015 with historical information, especially with respect to data provided by EUROSTAT for the EU.

### *4.1.2. The baseline scenario*

The baseline case corresponds to a business-as-usual (BAU) scenario, according to which no significant changes occur in terms of demographic composition, economics, technology, policies or people's attitudes. To this end, projections for macroeconomic variables are given by several sources. Gross domestic product projections are based on the average values of four sources: the GTAP Macro projections, the OECD Long-run Economic Outlook, the International Institute for Applied Systems Analysis (IIASA) projections used for the OECD EnvLink model, and the CEPII macroeconomic projections

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[3] 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.

[4] Basic metals 1 includes ferrous metals (iron and steel: basic production and casting) and non-ferrous metals (production and casting of copper, aluminium, zinc, lead, gold and silver); Basic metals 2 includes fabricated metal products (sheet metal products, but not machinery and equipment).

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

used in the GINFORS model ([6]). Population projections are taken from the United Nations Statistics (UNDESA) ([7]).
As for the BAU scenario, population is calibrated on the basis of data from UNDESA medium scenario ([8]). UNDESA data and projections for population are used in order to coherently calibrate the model for all regions at the global level ([9]) Consequently, some small differences arise with respect to data presented in the last report of EC on ageing population with respect to the distribution across age ranges of the total population up to 2050 (EC, 2018a) ([10]).

With respect to labour force, the model distinguishes between skilled and unskilled workers. In order to build projections of the labour force up to 2050, labour force projections provided by the International Labour Organization (ILO) (aggregate but recent); GTAP Macro projections, with a distinction between skilled and unskilled workers but calculated before 2011; and the United Nations Department of Economic and Social Affairs (UNDESA) projections on the active population defined as those aged 15–64 years (medium variation scenario) are combined.

In particular, starting from the ILO projections, for each region (*r*) in each temporal step (*t*) the share of labour force ($l_{r,t}$) with respect to active population is computed. The labour force (*L*) is then calculated as follows:

$$L_{r,t} = P(15-64)_{r,t} \cdot l_{r,t} \tag{1}$$

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

The distinction between skilled and unskilled labour is calculated starting from GTAP Macro projections: firstly, the share of skilled (*sk*) and unskilled (*unsk*) labour force with respect to total labour force in the BAU is computed; then the number of skilled (SKLAB) and unskilled (UNSKLAB) workers is obtained by applying the respective shares to labour force data:

$$SKLAB_{r,t} = L_{r,t} \cdot sk_{r,t} \tag{2}$$

$$UNSKLAB_{r,t} = L_{r,t} \cdot unsk_{r,t} \tag{3}$$

Consequently, the shares of skilled and unskilled labour change over time and across regions but do not change among different scenarios. Differences across scenarios are in fact due to changes in the total labour force according to changes in population aged 15-64 ([11]).

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[6] 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.10 in Appendix C for GDP projections in BAU for all regions.
[7] By taking 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) into account, it is worth noting that the GDP in the BAU scenario for the EU corresponds to SSP4 OECD-ENV Link, the scenario without mitigation policies. See OECD Env-Growth model (Dellink et al., 2017) from the SSP database, and Appendix A for further details on the concept of SSP.
[8] 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 at https://esa.un.org/unpd/wpp/Download/Standard/Population/ (last download on 28 January 2019).
[9] For full information on population trends in BAU and alternative scenarios for all regions, see Tables C.1, C.2. and C.3 in Appendix C.
[10] https://ec.europa.eu/info/publications/economy-finance/2018-ageing-report-economic-and-budgetary-projections-eu-member-states-2016-2070_en
[11] Within each scenario, an allocation of labour force over time was made 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.5–C.7 in Appendix C.

Following this approach, in the BAU scenario the EU labour force declines by 7.3 per cent between 2015 and 2050 (Table 4.1), in line with the results presented in the last European Commission report in 2018 ([12]).

Table 4.1 – Labour force in the EU (million) – 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.*

In order to calibrate carbon dioxide emissions with the BAU assumptions, 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.
Finally, several controls and adjustments have been made to calibrate GDynEP-AG data on fiscal sustainability and public budget with respect to the EU aggregate.

In particular, the labour tax rate in 2015 for the EU in GDynEP-AG is calculated as an average value between skilled and unskilled labour force (25 per cent), which is quite close to the 24 per cent EU average tax rate provided by EUROSTAT (2018) for the same year ([13]). The tax burden in the EU from historical data is consistent with the total tax revenue to GDP ratio resulting from the model – about 41 per cent in GTAP relative to 40 per cent in EUROSTAT ([14]).

Since results are all expressed at constant 2015 US dollar (USD) values, an exchange rate to convert all results expressed in monetary terms for all temporal steps has been applied. To this end, the exchange rate to convert USD in constant 2015 Euros (EUR) was calculated as the average of monthly values for 2011–2015 ([15]).

### 4.2. Alternative scenarios

Three groups of simulations were built. The first examines the impact of an ageing population, the second adds the role of automation in production processes, while the third group investigates the impact of carbon emissions mitigation policies as an example of the use of environmental policies as a potential remedy for pressure on fiscal sustainability.

It is worth noting that projections for GDP used in the BAU scenario, for population and the labour force adopted in the 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.

Furthermore, in the third simulation group, dealing with automation and mitigation policies, a unilateral shock valid only for the EU aggregate is assumed – the EU is the only region implementing mitigation

[12] EC (2018). The 2018 Ageing Report; Table III.1.28: Labour force 15,000–64,000.
[13] 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).
[14] 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).
[15] The applied exchange rate was USD 1 to EUR 0.7653, the average of maximum and minimum values for each month of 2011–2015. The statistical source is: https://www.x-rates.com.

actions while other regions have no constraints. Accordingly, given the structure of this CGE model, 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 and the indirect effects associated with international channels.

#### *4.2.1 Alternative scenarios of ageing*

The first set of scenarios simulates an increase in the dependency ratio through a reduction in the labour force up to 2050. In this respect, two alternative patterns were tested, resulting in two alternatives for labour force reduction: a 10 per cent and a 15 per cent reduction of the EU labour force, as follows:

1. **LF10:** a change in the labour force for world regions according to UNDESA, corresponding to a 10 per cent reduction of the EU labour force in 2050 relative to 2015 (also according to EC 2018a).

2. **LF15:** a change in the labour force for world regions according to UNDESA, corresponding to a 15 per cent reduction of the EU labour force in 2050 relative to 2015 (also according to EC 2018a).

To obtain the reduction in labour force, the steps described in the BAU case were applied to all regions. In this case the data on active population corresponded to the UNDESA no-change scenario (LF10) and low-variant scenario (LF15) ([16]). In these scenarios all regions face a change in the labour force trend according to UNDESA projections of the active population; for the EU in 2050 labour force decreases by 10 per cent and 15 per cent relative to 2015.

As illustrated in Figure 4.1 ([17]) the LF10 scenario registers a decrease in the EU population 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 aged 65+ decreases.

As for the LF15, a sharper labour force decrease is projected, although the overall population is only slightly lower compared to the LF10 scenario. The composition of population is, however, different from BAU: natality decreases, as in LF10, but life expectancy increases so that the number of 65+ people is higher than in LF10, quite in line with the BAU scenario. Additionally, the share of the inactive (65+) population increases relative to the total population. This demographic composition results in a substantially higher reduction in the labour force compared to BA: -15 per cent in 2050 relative to 2015 in LF15 as opposed to -7.3 per cent in the BAU case ([18]).

In terms of the old age dependency ratio, when comparing the three scenarios, an increase in BAU from 29 per cent in 2015 to 53 per cent in 2050 can be seen, while in LF10 there is still a positive trend with a lower increase reaching just 45 per cent by 2050, while LF15 shows the highest increase with a 57 per cent old age dependency ratio by 2050.

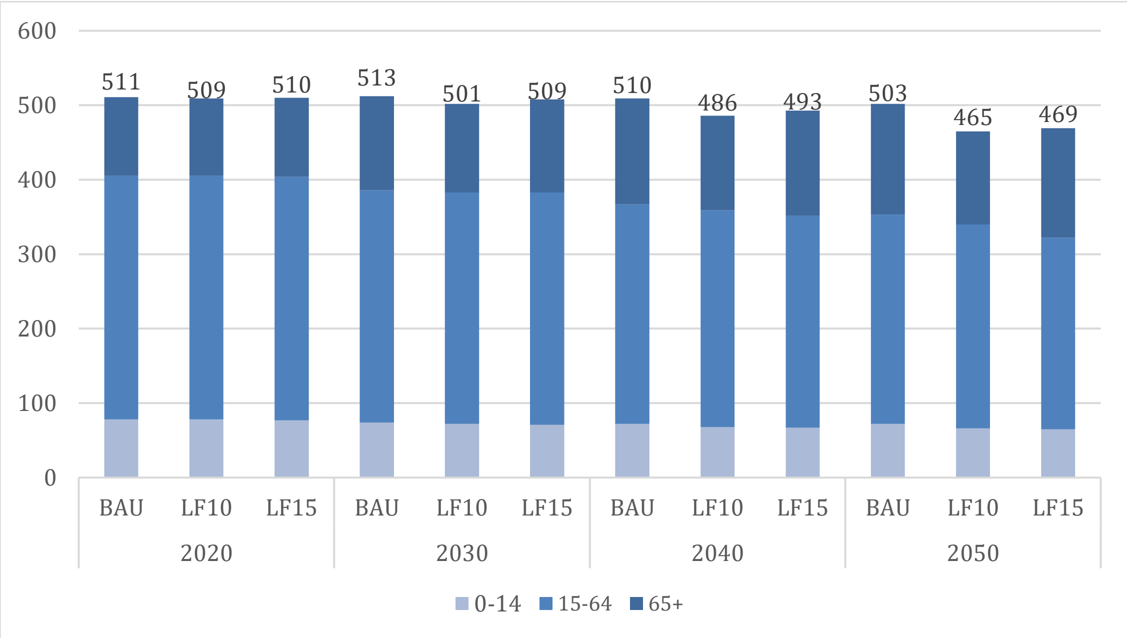
Accordingly, from this last scenario the impact of an ageing population on consumption patterns is examined by the development of an additional scenario only for the EU, in which a change in consumption propensity due to ageing population is projected.

[16] See Tables C.1–C.3 in Appendix C for full details on world population projections in alternative scenarios.
[17] See Table C.4 for further details.
[18] In Appendix C, demographic trends for all regions are reported at the general level (total population). Data on specific age groups for all regions adopted in different scenarios are available from the authors on request.

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

The LF15C scenario shows the overall effects of an ageing population for the EU with a 15 per cent reduction in the labour force and changes in the distribution of consumption quotas for households.

Figure 4.1 EU population by age groups (million people)




*Source: own elaborations on GDynEP-AG model results.*

The consumption propensity is adjusted on the basis of contributions from existing literature that analyse the effects of an ageing population on consumption in selected EU Member States ([19]). We introduce an increase in the propensity to consume coal; electricity from fossil fuel and renewable sources; gas, services and food sectors (Nagarajan et al., 2016; Maresova et al., 2015; Aigner-Walder and Doring, 2012). On the contrary, a reduction in the propensity to consume is introduced for transport, including transport equipment, and textiles. Such adjustments in consumption propensities are only applied to the EU, starting from 2020 when population trends begin to differ from BAU given that most of empirical studies are based on EU Member States.

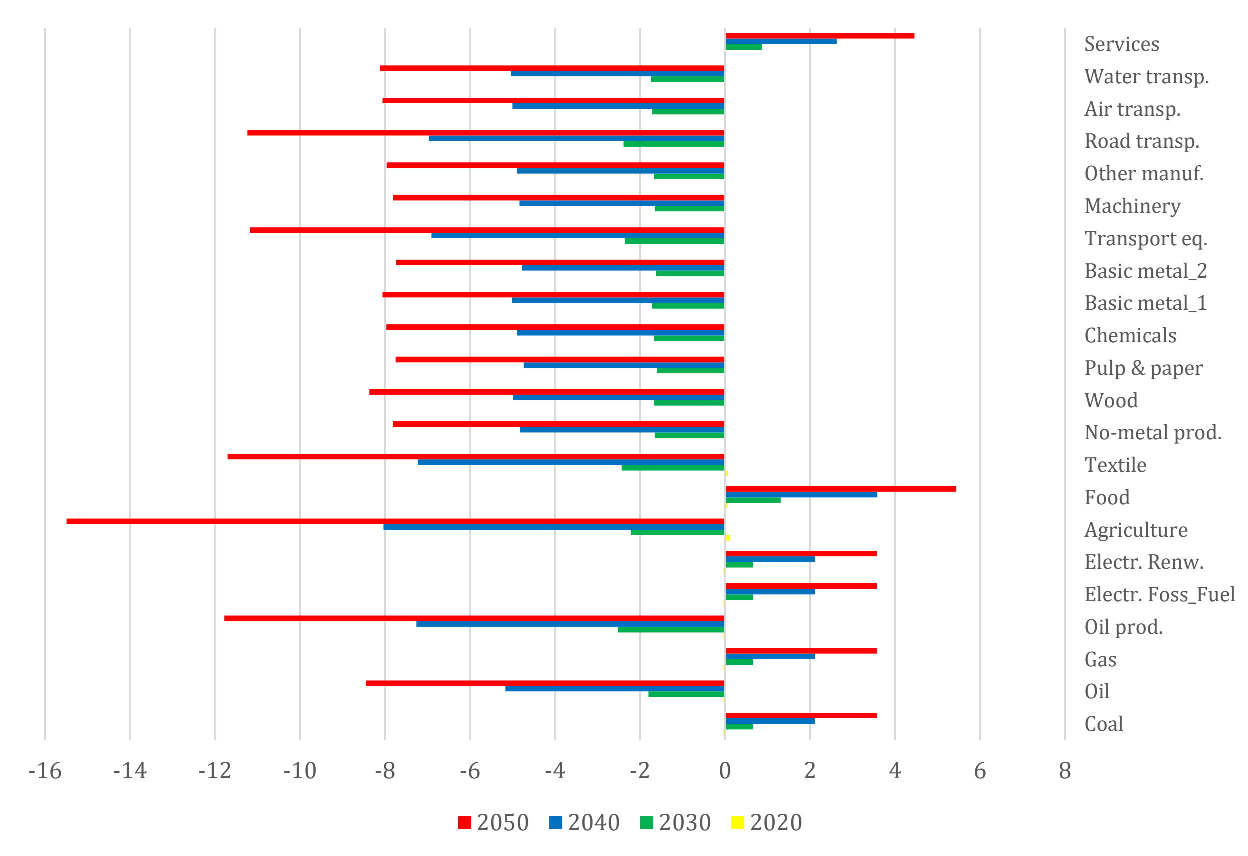
It is worth mentioning that changes in consumption shares in monetary terms depend on the combination of exogenous changes in consumption propensities at the quantitative levels and of endogenous changes in expenditure structure in monetary terms that are induced by the demographic shock. The sectors registering the highest variations are agriculture, transport and textiles, which show a reduction of 11-15 per cent as a consequence of ageing population, and food and services, for which the share of consumption increases (Figure 4.2). Indeed, older people tend to increase their need of services, such as health care or domestic assistance, while they reduce the use of transport. Moreover, in line with Engel's rule, the reduction in their income due to retirement entails a larger consumption quota for basic needs such as food, +5.44 per cent, and a smaller one for less necessary commodities including textiles, -11.71 per cent ([20]).

Since the LF15C scenario provides a more comprehensive description than LF15, it is referred to when analysing the impacts of an ageing population entailing a 15 per cent labour force reduction.

[19] All scenarios, except LF10 and LF15, assume that only the EU faces the difference in projections while all the other regions move according to model functioning.
[20] See Appendix C, Table C.9 for further details.

Furthermore, it is used as a basis from which to build other groups of simulations, introducing the role of automation and environmental policies.

Figure 4.2 Change in consumption share in household expenditure in the EU (LF15C relative to BAU, per cent)




*Source: own elaborations on GDynEP-AG model results.*

### *4.2.2 Alternative scenarios of ageing and automation*

In addition to an ageing population, the second set of scenarios is characterised by an automation process taking place only in the EU.

In particular, it is assumed that the EU starts to invest in a massive introduction of automation and robotics in production processes in 2020, so that changes in the economic system occur in the next temporal step – 2025.

With respect to factor specific productivity, neutral technical change is assumed. This allows the simulation of two different ways in which investment in automation is transformed into increasing productivity: one acting on total factor productivity (TFP) at the national level (LF15CR scenario), and the other influencing multifactor productivity in a homogeneous way in respect of different factors but differently at the sector level (LF15CRS scenario).

Finally, the potential impact of massive automation on unemployment (LF25CRS scenario) is also tested by modelling a relatively higher increase in capital productivity relative to labour productivity (Doraszelski and Jaumandreu, 2018). Accordingly, three additional scenarios are defined:

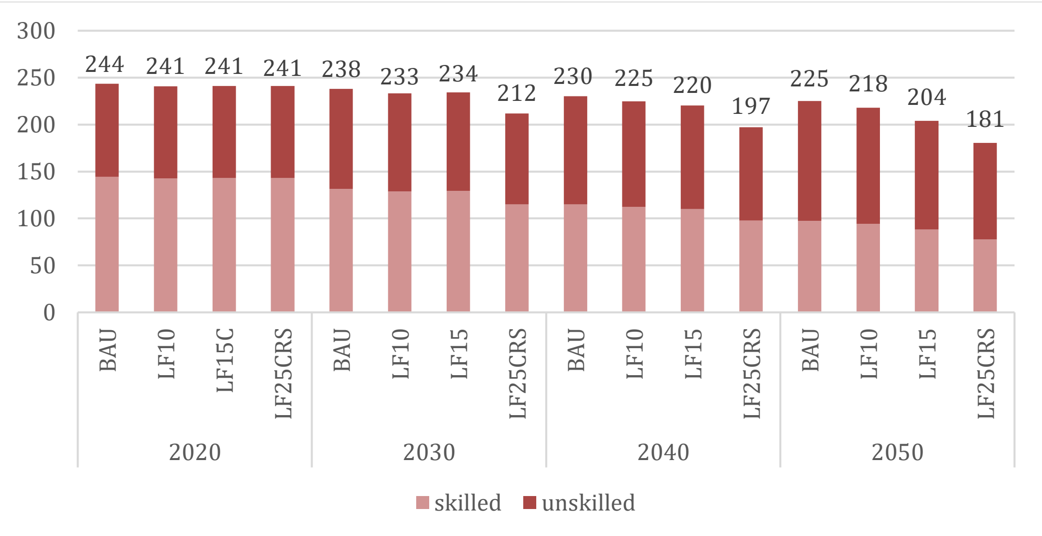
2. **LF15CR:** ageing plus automation: the same as LF15C plus technical change in production process through an increase of TFP. It is assumed, in line with the OECD (2018), that investment in automation will produce a 1 per cent annual increase in TFP according to ([21])

3. **LF15CRS:** ageing plus automation differentiated across sectors: the same as LF15CR with the productivity impacts of the automation process differentiated across sectors on the basis of their relative capital intensity. This scenario uses the share of capital intensity in each sector to allocate a 1 per cent annual increase in TFP among sectors to obtain a scenario fully comparable with LF15CR.

4. **LF25CRS:** ageing plus automation differentiated across sectors and unemployment: equal to LF15CRS in which the automation process acts as a biased technical change. A 10 per cent reduction of employment due to automation is assumed in addition to a reduction in the labour force due to ageing ([22]).

Figure 4.3 shows labour force trends for the EU in alternative scenarios resulting from the implementation of equations (1) to (3) in which the demographic structure changes and also when the automation process is responsible for unemployment.

Figure 4.3 EU labour force (million people)




*Source: own elaborations on GDynEP-AG model results.*

By computing the inverse of the support ratio that describes the number of pensioners to workers (Disney, 2007), 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, only precise data for pensioners and workers for the EU28 aggregate are available from EUROSTAT for 2015, namely around 122.56 million pensioners and 215.24 million employees. Given that in GTAP the active population is the same as total employment, the inverse of the support ratio is computed by using active population data from EUROSTAT in 2015. In 2015 it is about 51 per cent and looking at its projected values, it reaches 84 per cent by 2050 in BAU and 91 per cent in LF15.

[21] Given the structure of GDynEP-AG, to simulate the economic impacts of adopting automation technologies in the production system, it is necessary to include coefficients that allow transforming investments in automation into productivity improvements in the model. In this, we consider an average 1 per cent gain in TFP each year as a simple average improvement in productivity of all factors, relying on the calculation of the multifactor productivity by the OECD, which is in the range of 0–2 per cent 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).

[22] Given that there is no information on the impact of automation on two labour force types, skilled and unskilled, a homogeneous biased technical change is assumed.

### 4.2.3 Alternative scenarios for ageing, automation and environmental tax revenues

The following scenarios were developed to analyse the role of environmental policies. They are characterised by the implementation of a unilateral carbon mitigation policy in EU from 2020 onwards, while all other regions have no mitigation constraints. The abatement policy here consists of a carbon tax applied to combustion-based carbon dioxide emissions. The carbon tax unitary level per tonne of carbon dioxide emitted is exogenously modelled on the basis of the average the World Bank's carbon price (World Bank, 2017). Three main reasons explain this modelling choice. An exogenous carbon price, while emissions abatement is endogenous, allows the simulation of a policy design mechanism in a more realistic way, in which policy makers decide the unitary tax level. The adoption of a mitigation measure on carbon dioxide emissions allows covering the whole economy and hence ensuring the largest tax base, since each production sector, as well as households, is responsible for such emission types. Finally, an average carbon price value that results from the comparison of several different scenarios and models ensures remaining on track projections provided by bottom-up energy models.

Starting from the World Bank report (2017), two carbon price patterns that represent the upper and lower bound of carbon prices obtained as the mean of carbon tax values derived from the climate-economic models included in the report (Table 4.2) are considered. Each carbon price pattern is tested in two scenarios, the LF15C (without automation) and the LF25CR (with automation and unemployment).

5. **LF15CTXL:** ageing plus environmental policy: it starts from LF15C but adds carbon tax lower bound (World Bank, 2017);

6. **LF15CTXH:** ageing plus a more stringent environmental policy: it starts from LF15C and adds a carbon tax upper bound (World Bank, 2017);

7. **LF25CRSTXL:** ageing plus automation, unemployment and environmental policy: it starts from LF25CRS but adds a carbon tax lower bound (World Bank, 2017);

8. **LF25CRSTXH:** ageing plus automation, unemployment and a more stringent environmental policy: it starts from the LF25CRS and adds a carbon tax upper bound (World Bank, 2017).

Table 4.2 – Carbon tax applied in EU, EUR per tonne of carbon dioxide

| 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 |

*Source: World Bank (2017).*
*Note. Data are converted from USD to EUR by applying a constant 2015 exchange rate of USD 1: EUR 0.7653.*

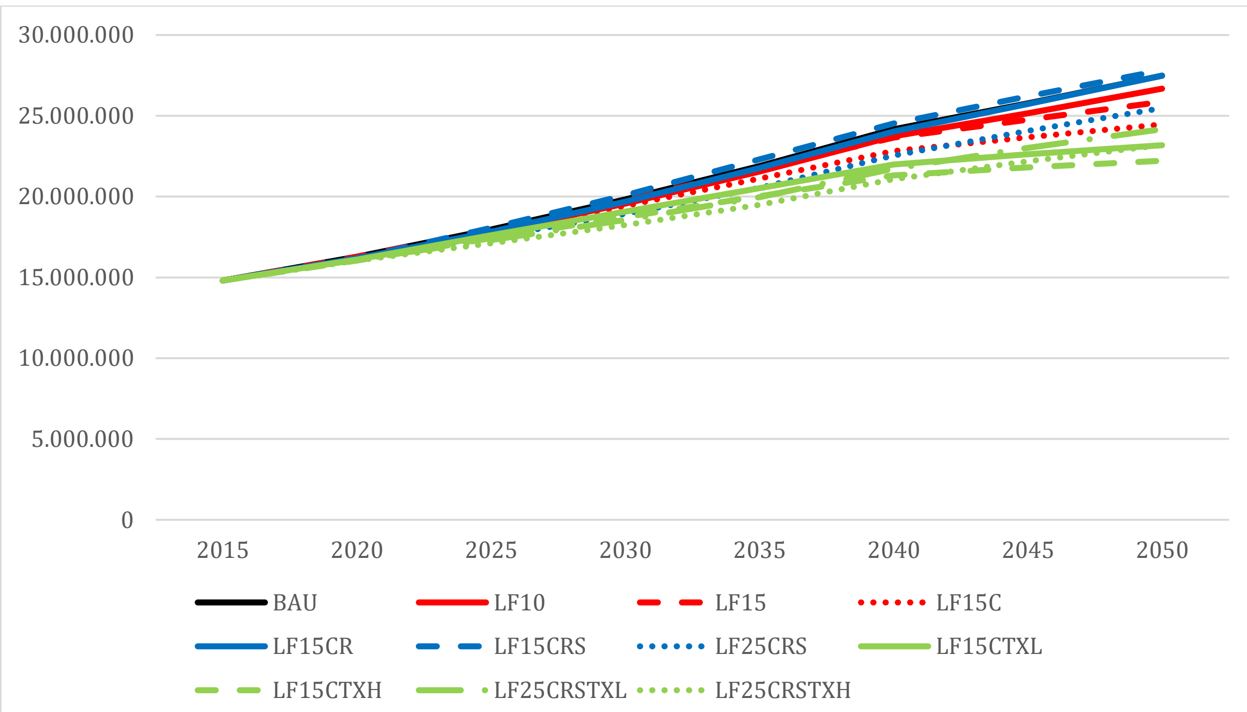
The carbon tax revenue is computed as the product of the marginal carbon tax rate and the amount of emissions, and it is modelled as a lump sum in welfare computation, meaning that the amount of fiscal revenue is directly used to compensate households in income equivalent terms for loss, and paid with a price increase due to the translation of taxes on final market prices.
The last two scenarios test all the challenges investigated in this work together, combining the ageing population, the introduction of robotics, technology-driven unemployment and the adoption of climate policies in line with the 2050 roadmap for a low carbon society (EC, 2011).

# 5. Results from the computable general equilibrium modelling

## 5.1. Impacts on economic growth

Results are presented by topic, starting with an analysis of the economic impacts in the EU. Accordingly, Figure 5.1 and Figure 5.2 show results in terms of the total level of GDP in the EU and GDP per person respectively. Not surprisingly, the decrease in the labour force generates a reduction in GDP. As for the effects of population ageing, the higher the labour force reduction (LF15C), the larger the economic impact. When automation is introduced, on the other hand, an increase in factor productivity is projected that contributes to increasing the level of GDP so that it reaches values close to the BAU case ([23]).

Figure 5.1 Gross domestic product in the EU (million constant 2015 EUR)



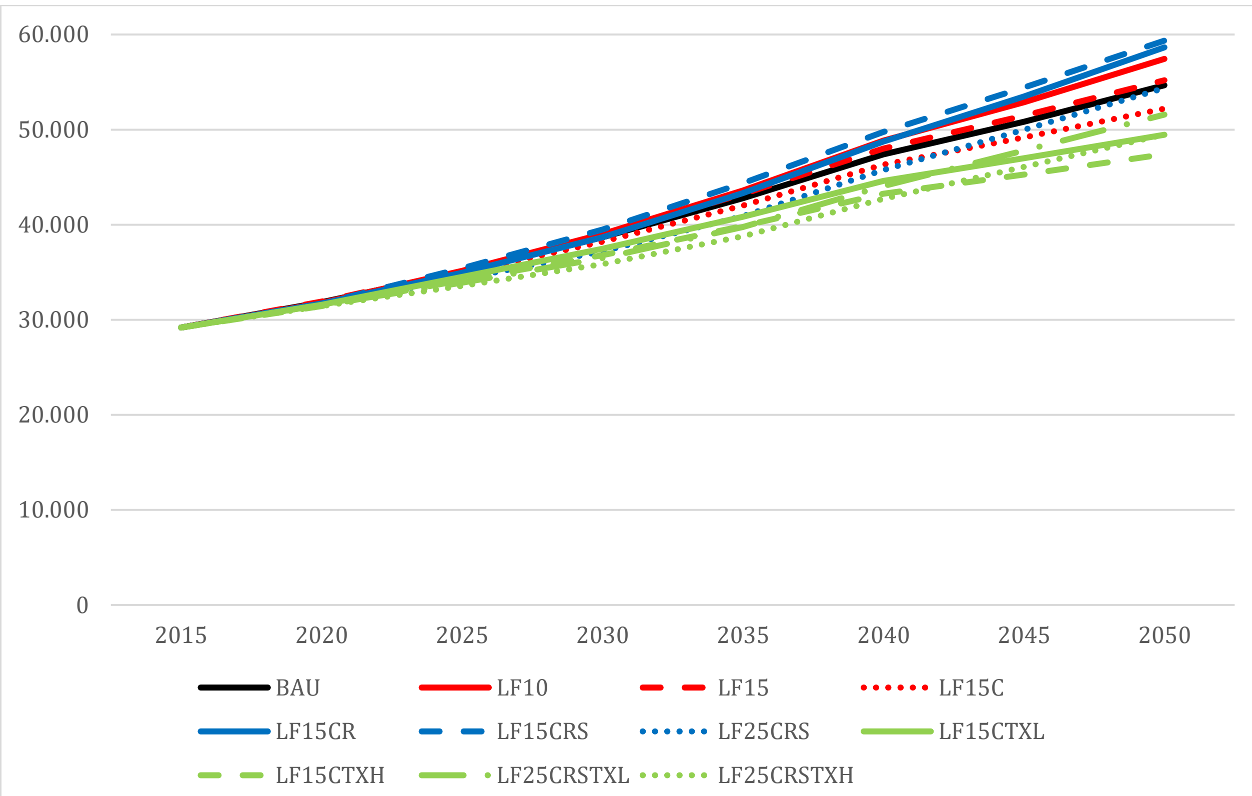

*Source: own elaborations on GDynEP-AG model results.*

When the introduction of automation generates a factor productivity improvement that is differentiated among sectors according to the relative capital intensity (LF15CRS), the economy reaches the highest level of GDP and an average growth rate higher than the BAU case. Nevertheless, in the LF25CRS scenario in which automation also generates unemployment, modelled here as a reduction in labour force, GDP decreases again reaching a value that is quite close to the GDP value associated with the case with the maximum ageing population without automation improvements (LF15C).

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

It is worth noting that it is assumed that the introduction of automation occurs in the EU only. In this way, the highest effect in terms of GDP growth, when neutral technical change is modelled, is obtained because in the rest of the world technology remains unchanged. Consequently, the technological pattern of the EU has two main effects. Firstly, it has a direct effect in terms of increasing multifactor productivity at the domestic level. Secondly, it has an indirect effect on trade, since the automation process generates higher factor efficiency compared to the rest of the world and hence an improvement in terms of revealed comparative advantage in trade patterns. Given this modelling choice, results related to the effects of technical change must be interpreted with care, while future research should include a comparison with scenarios where technological change related to automation is shaped for all regions at the world level.

Figure 5.2 Gross domestic product per capita in the EU (million constant 2015 EUR)




*Source: own elaborations on GDynEP-AG model results.*

The introduction of a carbon mitigation policy entails additional costs for the economy, which is detrimental to GDP growth that falls to its lowest level when the upper bound carbon tax level is introduced with no productivity gain embedded due to automation investments. The negative impact on GDP is also driven by the assumption that mitigation policies are implemented with the adoption of a unilateral carbon tax by the EU only. This brings an overestimation of abatement costs for the EU and a corresponding lower bound GDP reduction, as the literature defines within the carbon leakage concept (Antimiani et al., 2016; 2013; Böhringer et al., 2012). This fully explains why scenarios with an ageing population and carbon price, but without investment in automaton, register a EU GDP level that is lower while in the other regions it grows slightly.

In terms of GDP per person, among alternative scenarios without automation, the lowest level is associated with LF15C. Indeed, in this scenario the reduction of the total population is mainly due to a decrease in the active population, thus reducing the level of production relative to LF10, in which the total EU population is approximately the same but there is a reduction in the 65+ population.

When mitigation is also added to this scenario (LF15CTXL and LF15CTXH), a further contraction of the economy is registered with the GDP per person falling to its lowest level. Conversely, the introduction of automation (LF15CR) generates an increase of the GDP per person thanks to the positive effects on productivity and overtaking the LF10 scenario. Nevertheless, when unemployment impacts are also taken into account (LF25CRS), there is a reduction of GDP per person, which is further lowered by the introduction of abatement policies (LF25CRSTXL and LF25CRSTXH) ([24]).

### 5.2. Tax revenue, public expenditure, environmental and fiscal sustainability

This section shows how both an ageing population and automation affect fiscal dynamics, as illustrated in the following tables. In this respect, Table 5.1 compares revenue arising from different sources of taxation in alternative scenarios in terms of direct (labour) and indirect taxation ([25]).

First, it is worth mentioning that the starting point of the simulations (2015) registers a level of total revenue that is in line with data provided by the EC (EC, 2018b), corresponding to 41 per cent of GDP ([26]).
As for future dynamics, scenarios with lower labour forces show a reduction of direct taxation and hence register lower revenues compared to BAU. Moreover, in all cases taxation on skilled labour generates higher revenues than on unskilled labour, although the highest growth over the whole period is always from unskilled workers. Two reasons lie behind this effect. Firstly, in GDynEP-AG the tax rate is not differentiated between skilled and unskilled workers – it is the same for the skilled and unskilled labour force – but the total amount of tax revenue is also dependent on unitary wage values that in turn changes across different scenarios due to the labour market mechanism of demand and supply equilibrium. Secondly, the reduction of the unskilled workers' share brings a changing equilibrium price to the labour market, with a resulting increase in wage levels. Given that total wages are the base for direct taxation, even though the number of workers decreases over time, the increase in the monetary wage value partly compensates for it.

The aggregate of revenues from other taxation, that in the GTAP computation includes VAT, is strongly influenced by ageing dynamics, especially as a consequence of the changes in consumption structure due to population ageing. Indeed, by comparing values of other taxation in BAU, LF15 and LF15C the sharpest decrease occurs when changes in the consumption structure are included (LF15C).

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[24] For further details on GDP trends in the EU, see Appendix Tables C.10–C.12.
[25] In GDynEP-AG direct taxation corresponds to labour taxation. More precisely, it corresponds to the difference between the gross labour cost payed by a firm and the net salary received 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) 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. The tax rate is fixed over time. The tax base is determined on value added and consumption.
[26] EC (2018b). Graph 2.28, page 62: Government expenditure and tax revenues, 2016.

Things change with the introduction of automation (Table 5.2). The total revenue increases as a consequence of a rise in revenue from both direct and indirect taxation, especially when automation results in an increase of productivity differentiated among sectors. Conversely, if automation also entails unemployment (LF25CRS), the reduction in labour force brings a collapse of revenue from direct and other taxation aggregates that in turn generates a sharp decrease of total revenue, below the BAU case. It is worth noting that, since the other taxation component includes revenues from VAT, it is the one that contributes the most to total revenue due to a reduction on aggregated demand associated with consumers' lower disposable income.

Table 5.3 shows what happens when mitigation policies are also taken into account. The carbon tax revenue, provided by a unitary carbon price applied to the total amount of carbon dioxide emissions at every temporal step, is introduced as an additional component of the public budget. Carbon dioxide emissions are endogenously determined and are different across scenarios according to the carbon price adopted and the other model assumptions.

Revenues from carbon taxation are higher in those scenarios with higher per unit carbon tax levels (LF15CTXH and LF25CRSTXH). These two scenarios also correspond to an almost complete achievement of the EU's abatement targets by 2050 in line with the EU's commitment to the Paris Agreement (Figure 5.3).

Nevertheless, the total revenue in these scenarios is lower than that registered for cases with a low carbon price. This can be explained by the sharp economic contraction characterised in these scenarios (Figures 5.1 and 5.2) that leads to lower revenue from other forms of taxation. For the same reason, in most cases the total revenue associated with scenarios with mitigation policies is lower than that observed in the corresponding scenarios without abatement action. Furthermore, carbon tax revenues are higher in the case of LF25CRSTXL and LF25CRSTXH relative to the corresponding LF15CTXL and LF15CTXH scenarios given the same carbon price as in Table 5.3. This is due to differences in carbon dioxide emissions (Figure 5.3) that are higher in scenarios with automation that also include technology-driven unemployment ([27]).

This means that the amount of revenue is strictly dependent on the economic structure under scrutiny. If population ageing is considered, carbon dioxide emissions are lower than in the BAU case and hence the total carbon tax revenue will be reduced for a given carbon price. Two reasons lie behind this specific result. Firstly, the reduction in the labour force due to population ageing generates a decrease in both production and consumption that in turn leads to a strong contraction of the EU economy. This results in decreasing energy consumption and consequently a reduction in carbon dioxide emissions. Secondly, a progressively ageing society impacts energy consumption both through a reduction in consumption across all commodities at the household level, and by changing the energy consumption share in the commodity basket (Kim and Seo, 2012). Conversely, the productivity gains observed when automation is also included raise carbon dioxide emissions and consequently also the total revenue from carbon taxes ([28]). Trends in emissions suggest that if environmental sustainability is the only policy

[27] For further details on combustion-based carbon dioxide emissions, see Appendix C Table C.13.

[28] In this modelling exercise BAU is the only case in which emissions are exogenously given according to International Energy Agency (IEA) projections. Conversely, in all scenarios the level of emissions is endogenous. In addition, in the case of introducing automation, neutrality is assumed in terms of input augmenting technical change and no specific investment in green energy technologies. This means that energy efficiency improves together with all other inputs' efficiency and that there are no changes regarding convenience in producing energy from renewable sources relative to to traditional fossil fuel due to specific investment in renewables.

target under consideration, an ageing population plays a positive role while technological innovation is detrimental, the opposite conclusions compared to 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.

### Table 5.1 – Tax revenues with ageing in the EU (million constant 2015 EUR)

| Scenario | | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|
| BAU | Total revenue | 6,845,631 | 8,247,565 | 9,685,353 | 10,416,398 |
| | Revenue from direct tax | 1,858,443 | 2,214,796 | 2,621,965 | 2,845,058 |
| | *Direct skilled* | *1,116,401* | *1,349,603* | *1,620,590* | *1,785,817* |
| | *Direct unskilled* | *742,042* | *865,193* | *1,001,375* | *1,059,241* |
| | Revenue from indirect tax | 828,296 | 965,711 | 1,117,522 | 1,194,135 |
| | Revenue from other tax | 4,158,892 | 5,067,059 | 5,945,866 | 6,377,205 |
| LF10 | Total revenue | 6,791,852 | 8,010,888 | 9,168,347 | 9,570,795 |
| | Revenue from direct tax | 1,844,958 | 2,184,663 | 2,574,080 | 2,759,724 |
| | *Direct skilled* | *1,108,175* | *1,331,100* | *1,590,497* | *1,730,498* |
| | *Direct unskilled* | *736,783* | *853,563* | *983,583* | *1,029,226* |
| | Revenue from indirect tax | 822,391 | 951,627 | 1,096,764 | 1,161,819 |
| | Revenue from other tax | 4,124,502 | 4,874,598 | 5,497,503 | 5,649,253 |
| LF15 | Total revenue | 6,845,804 | 8,214,209 | 9,573,013 | 10,103,930 |
| | Revenue from direct tax | 1,858,943 | 2,216,731 | 2,566,272 | 2,673,729 |
| | *Direct skilled* | *1,118,352* | *1,353,948* | *1,588,150* | *1,677,605* |
| | *Direct unskilled* | *740,591* | *862,782* | *978,123* | *996,124* |
| | Revenue from indirect tax | 828,127 | 966,085 | 1,092,910 | 1,118,819 |
| | Revenue from other tax | 4,158,734 | 5,031,394 | 5,913,831 | 6,311,383 |
| LF15C | Total revenue | 6,804,170 | 8,030,446 | 9,143,840 | 9,506,389 |
| | Revenue from direct tax | 1,846,201 | 2,170,228 | 2,471,681 | 2,529,776 |
| | *Direct skilled* | *1,108,925* | *1,323,147* | *1,529,695* | *1,589,785* |
| | *Direct unskilled* | *737,276* | *847,081* | *941,986* | *939,991* |
| | Revenue from indirect tax | 822,960 | 958,068 | 1,091,504 | 1,128,112 |
| | Revenue from other tax | 4,135,009 | 4,902,151 | 5,580,656 | 5,848,501 |

*Source: own elaborations on GDynEP-AG model results.*

### Table 5.2 – Tax revenues with ageing and automation in the EU (million constant 2015 EUR)

| Scenario | | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|
| LF15CR | Total revenue | 6,824,845 | 8,192,232 | 9,663,904 | 10,542,314 |
| | Revenue from direct tax | 1,846,201 | 2,202,385 | 2,616,546 | 2,876,840 |
| | *Direct skilled* | *1,108,925* | *1,343,192* | *1,620,725* | *1,811,067* |
| | *Direct unskilled* | *737,276* | *859,193* | *995,821* | *1,065,773* |
| | Revenue from indirect tax | 822,960 | 969,906 | 1,144,734 | 1,257,658 |
| | Revenue from other tax | 4,155,685 | 5,019,941 | 5,902,625 | 6,407,816 |
| LF15CRS | Total revenue | 6,824,845 | 8,335,156 | 9,810,325 | 10,618,812 |
| | Revenue from direct tax | 1,846,201 | 2,240,540 | 2,643,797 | 2,855,734 |
| | *Direct skilled* | *1,108,925* | *1,366,801* | *1,636,853* | *1,796,225* |
| | *Direct unskilled* | *737,276* | *873,738* | *1,006,945* | *1,059,509* |
| | Revenue from indirect tax | 822,960 | 984,437 | 1,156,812 | 1,254,407 |
| | Revenue from other tax | 4,155,685 | 5,110,179 | 6,009,716 | 6,508,670 |
| LF25CRS | Total revenue | 6,822,778 | 8,029,273 | 9,191,739 | 9,786,424 |
| | Revenue from direct tax | 1,846,201 | 2,099,860 | 2,422,863 | 2,608,205 |
| | *Direct skilled* | *1,108,925* | *1,279,235* | *1,498,880* | *1,639,355* |
| | *Direct unskilled* | *737,276* | *820,626* | *923,982* | *968,851* |
| | Revenue from indirect tax | 822,960 | 931,065 | 1,069,745 | 1,149,176 |
| | Revenue from other tax | 4,153,617 | 4,998,348 | 5,699,131 | 6,029,043 |

*Source: own elaborations on GDynEP-AG model results.*

A further aspect to be addressed is fiscal sustainability. Indeed, changes in production processes and population structure also bring changes in revenues from direct and indirect taxation together with a simultaneous increase in public expenditure, such as higher health and pension expenditure, to sustain the inactive segment of the population.
Since the model does not include a detailed representation of public expenditure, *ex-post* calculations were performed on selected expenditure lines in the public budget system starting from model results, starting from the variable derived from the model that describes government expenditure (*G*). Its value in the BAU case in 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. To obtain the total EU government expenditure (*G_Exp*), a coefficient ($\varphi$) is applied describing the share of *G* relative to total government expenditure, which is equal to 0.49 for the EU aggregate according to EUROSTAT data ([29]).

Table 5.3 – Tax revenues with carbon pricing in the EU (million constant 2015 EUR)

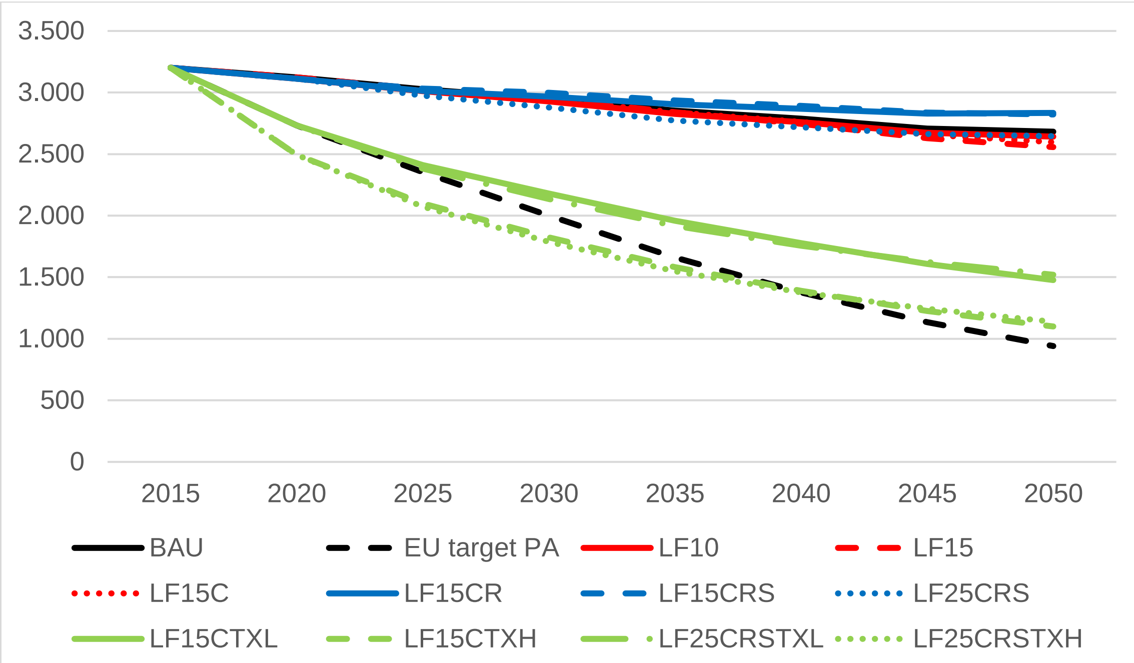
| **Scenario** | | **2020** | **2030** | **2040** | **2050** |
|---|---|---|---|---|---|
| | Total revenues | 6,808,445 | 8,040,418 | 9,158,492 | 9,515,828 |
| | Revenue from direct tax | 1,834,409 | 2,122,589 | 2,378,125 | 2,397,351 |
| | *Direct skilled* | *1,101,691* | *1,293,868* | *1,471,712* | *1,506,742* |
| **LF15CTXL** | *Direct unskilled* | *732,719* | *828,721* | *906,412* | *890,609* |
| | Revenue from indirect tax | 831,475 | 977,435 | 1,116,793 | 1,151,378 |
| | Revenue from carbon tax | 83,674 | 83,391 | 85,701 | 88,154 |
| | Revenue from other tax | 4,058,888 | 4,857,002 | 5,577,874 | 5,878,945 |
| | Total revenues | 6,790,299 | 7,955,549 | 8,944,450 | 9,202,929 |
| | Revenue from direct tax | 1,823,592 | 2,083,609 | 2,307,889 | 2,304,562 |
| | *Direct skilled* | *1,095,003* | *1,269,835* | *1,428,173* | *1,448,600* |
| **LF15CTXH** | *Direct unskilled* | *728,589* | *813,774* | *879,716* | *855,962* |
| | Revenue from indirect tax | 838,285 | 988,673 | 1,125,980 | 1,153,446 |
| | Revenue from carbon tax | 152,754 | 139,490 | 132,995 | 131,384 |
| | Revenue from other tax | 3,975,669 | 4,743,777 | 5,377,587 | 5,613,537 |
| | Total revenues | 6,808,445 | 7,916,331 | 9,047,964 | 9,562,641 |
| | Revenue from direct tax | 1,834,409 | 2,053,570 | 2,331,715 | 2,474,397 |
| | *Direct skilled* | *1,101,691* | *1,250,805* | *1,442,409* | *1,555,306* |
| **LF25CRSTXL** | *Direct unskilled* | *732,719* | *802,764* | *889,306* | *919,091* |
| | Revenue from indirect tax | 831,475 | 949,841 | 1,094,366 | 1,173,569 |
| | Revenue from carbon tax | 83,674 | 81,739 | 84,708 | 90,720 |
| | Revenue from other tax | 4,058,888 | 4,831,181 | 5,537,176 | 5,823,955 |
| | Total revenues | 6,790,299 | 7,864,104 | 8,923,677 | 9,413,777 |
| | Revenue from direct tax | 1,823,592 | 2,015,697 | 2,263,116 | 2,379,847 |
| | *Direct skilled* | *1,095,003* | *1,227,475* | *1,399,893* | *1,495,934* |
| **LF25CRSTXH** | *Direct unskilled* | *728,589* | *788,222* | *863,222* | *883,913* |
| | Revenue from indirect tax | 838,285 | 960,760 | 1,103,485 | 1,176,551 |
| | Revenue from carbon tax | 152,754 | 136,781 | 131,718 | 135,828 |
| | Revenue from other tax | 3,975,669 | 4,750,866 | 5,425,359 | 5,721,550 |

*Source: own elaborations on GDynEP-AG model results.*

[29] Data for government expenditure in the EU are taken from the 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.

Then we calculate the amount of government expenditure allocated to different purposes only for the EU aggregate ([30]). We first obtain the expenditures for health (H), education (E) and pensions (P) in 2015 in absolute values starting from the total government expenditure obtained applying three coefficients taken from EUROSTAT data that describe the share of total government expenditure that EU directs towards health (0.15), education (0.10) and pensions (0.22), respectively ([31]).

Figure 5.3 Combustion-based carbon dioxide emissions in the EU (million tonnes of carbon dioxide)




*Source: own elaborations on GDynEP-AG model results.*

In order to approximate how expenditure flows evolve over time, two different methods were used, one for pensions, and a different one for health and education.

For pensions, we first compute the unitary cost of pensions for the EU (*Ppc*) in 2015, as the ratio between the amount of public budget directed to pensions provided by EUROSTAT and the number of people aged 65+.

The evolution of the unitary cost of pensions over time depends on wage rises. In a defined contribution pension scheme, an increase of wages leads to a rise in pensions, even if not proportionally. Since EU Member States have different pension schemes, simplifying assumptions are required. Starting from the current average cost of pension systems for the EU as an aggregate, no reforms in terms of funding systems and age retirement rules were assumed. Given that the employment rate for people aged 65–69 is very low in most EU Member States, an average retirement age of 64 is assumed. This allows considering 65+ people as automatically retired across the EU, providing full comparability between

[30] Given the focus on the EU, in what follows *ex-post* calculations referred to the EU only, but they can be applied to each region forming the model if appropriate information on the composition of public budget is available.
[31] 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).

demographic and retirement trends. The evolution of the unitary pension is thus associated to the rate of increase in average wages, 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, the unitary cost of pensions is adjusted according to change in the level of wages starting from a unitary value at 2015 that is calculated using EU data. Finally, the total public expenditure for pensions is computed (*P*) over time taking account of the unitary cost and the demographic evolution ([32]).

For health, we start with the computation of two aggregates of public health expenditure: the 0–64 age group, the sum of all age groups under 64, and the 65+ age group alone. The shares of health expenditure for these two macro age aggregates for 2015 correspond to $\psi$=58.9 per cent and $\omega$=41.1 per cent, respectively ([33]):

$$H(0-64)_{2015} = H_{2015} \cdot \psi \quad (1)$$

$$H(65+)_{2015} = H_{2015} \cdot \omega \quad (2)$$

The per person public expenditure (*Hpc*) in 2015 for the 0–64 age group and the 65+ age group are computed as:

$$Hpc(0-64)_{2015} = \frac{H(0-64)_{2015}}{POP(0-64)_{2015}} \quad (3)$$

$$Hpc(65+)_{2015} = \frac{H(65+)_{2015}}{POP(65+)_{2015}} \quad (4)$$

Then for each scenario (*s*), we compute how *Hpc* evolves over time. The per person health expenditure grows over time in proportion to the increase in the population share of people aged 65+. The per person expenditure for health increases similarly with the ageing population (Sanz and Velázquez, 2007). The total public expenditure on health (*H*) over time, taking account of the increase in the unitary cost due to the composition of the population, is computed for each temporal step by multiplying the *Hpc* of each age group by the total number of people within it.

The total expenditure for health is indexed at +1 per cent per year to take account of changes in the cost of health care services due to, for instance, the adoption of new technologies or the replacement of medical equipment.

For education, starting from the aggregate expenditure, we also compute the per person public expenditure (*Epc*) in 2015 as for the 0-64 age group. Then, we project the total expenditure for education up to 2050 by considering different evolutions of the demographic structure suggested by the

[32] On the basis of OECD data (OECD, 2017), the unitary cost of pensions across OECD countries (net of inflation) on average increases by a 1.25 per cent per year due to the effect of the increasing value of wages and salaries. In this exercise the yearly growth rate is assumed to be on average 0.8 per cent for the period 2015–2050 for the BAU case representing the lower bound value, while the upper bound is a yearly average growth rate by 1.22 per cent for the LF15CRS scenario corresponding to the highest projected increase in wage values.
[33] Data on expenditure by disease, age and gender are extracted from the OECD database on the System of Health Accounts (SHA) Framework available online at https://stats.oecd.org/index.aspx?DatasetCode=EBDAG.

scenarios and, as for health expenditure, indexing it with a +1 per cent increase per year to take account of changes in the cost of education function ([34]).
The remaining government expenditure for 2015 is classified as a residual term that complements total government expenditure, adding to health, education and pensions expenditures that are singled out. Then, starting from the 2015 value, which is the same in all scenarios, the evolution over time of other government expenditure for all scenarios is proxied by the variation rate of variable *G* in the model results for each temporal 5-year step, defined as $g_{s,t-(t-1)}$, that is endogenously determined by the model as:

$$Oth\_Exp_{s,t} = Oth\_Exp_{s,t-1} \cdot \left(1 + g_{s,t-(t-1)}\right) \quad (5)$$

The evolution of total government expenditure over time is the simple sum of all expenditure lines and varies in each scenario.

Once the value and composition government expenditure has been defined, the current deficit is computed as the difference between government expenditure and the sum of revenues arising from all forms of taxation that is endogenously calculated in GDynEP-AG for all scenarios directly by the model optimisation procedure. The deficit to GDP ratio is then available for all scenarios over the temporal 2015–2050 horizon. Tables 5.4, 5.5 and 5.6 summarise these results for ageing, automation and carbon policy related scenarios, respectively.

The first and most straightforward consequence of an ageing population is that it reduces the labour force and this leads to a contraction of the economic system and hence a decrease in revenues arising from direct taxation and a reduction in GDP. Government expenditure is also higher when there is a more pronounced level of ageing population with a 15 per cent reduction of the labour force, due to the rise of expenditure on health and pensions. This study found pension expenditure in 2050, expressed in terms of GDP, to be similar to the projections provided by the EC – 10.8 per cent of GDP shown in GDynEP-AG compared to 9.5 per cent projected by the EC (2018a). In addition, our results show a 5.7per cent of GDP directed to health expenditure in 2050, against a 7.8 per cent projected by the EC (2018a). Nevertheless, it is worth noting that our results are strongly influenced by the assumptions made in building the scenarios and calculating *ex-post* variables. Consequently, they must not be interpreted as projections, but rather 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 5.4 shows that when a process of ageing population is taken into account (LF15C), the EU will not be able to respect its SGP target of holding the deficit to GDP ratio below 3 per cent from 2035. Turning to the impact of automation, this generally improves fiscal sustainability. This is mainly driven by the likely higher GDP as a consequence

[34] For the sake of simplicity, per person 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 education expenditures from pre-primary to continuous training for workers. In this, we are not interested in analysing different structures of allocation of public expenditure according to different bargaining outcomes between voters from different age groups when choosing allocation of government expenditure to different functions –typically health and pensions versus education. Accordingly, the evolution of total expenditure for health, education and pensions only depends on demographic structure changes across scenarios. This assumption is consistent with Sanz and Velàzquez's results (2007) since the negative influence on education expenditure brought about by elderly people seems to be confined to the short term while in our analysis a long term perspective is adopted.

of automation (Figure 5.1). In particular, we found it led to a lower deficit to GDP ratio, especially in the LF15CRS scenario.

Table 5.4 – Fiscal sustainability with ageing in the EU (million constant 2015 EUR)

| Scenario | | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|
| **BAU** | Total revenue | 6,845,631 | 8,247,565 | 9,685,353 | 10,416,398 |
| | Total government expenditure | 7,199,500 | 8,653,511 | 10,171,871 | 10,959,151 |
| | *Health* | *1,116,786* | *1,328,333* | *1,505,574* | *1,578,590* |
| | *Health 65+* | *457,882* | *601,596* | *753,206* | *872,357* |
| | *Education* | *688,566* | *725,972* | *761,283* | *809,246* |
| | *Pensions* | *1,624,399* | *2,138,725* | *2,689,159* | *2,973,989* |
| | *Other government expenditure* | *3,769,748* | *4,460,480* | *5,215,855* | *5,597,326* |
| | Deficit | -353,869 | -405,945 | -486,518 | -542,754 |
| | Deficit/GDP % | -2.17 | -2.05 | -2.01 | -1.97 |
| **LF10** | Total revenue | 6,791,852 | 8,010,888 | 9,168,347 | 9,570,795 |
| | Total government expenditure | 7,139,957 | 8,398,668 | 9,621,197 | 10,048,773 |
| | *Health* | *1,102,939* | *1,254,906* | *1,343,708* | *1,321,157* |
| | *Health 65+* | *452,205* | *568,341* | *672,227* | *730,095* |
| | *Education* | *687,122* | *718,109* | *743,807* | *777,509* |
| | *Pensions* | *1,606,796* | *2,026,328* | *2,405,919* | *2,489,687* |
| | *Other government expenditure* | *3,743,100* | *4,399,325* | *5,127,763* | *5,460,420* |
| | Deficit | -348,105 | -387,780 | -452,851 | -477,978 |
| | Deficit/GDP % | -2.15 | -1.98 | -1.91 | -1.79 |
| **LF15** | Total revenue | 6,845,804 | 8,214,209 | 9,573,013 | 10,103,930 |
| | Total government expenditure | 7,201,959 | 8,673,747 | 10,154,175 | 10,762,205 |
| | *Health* | *1,115,819* | *1,324,172* | *1,494,102* | *1,550,112* |
| | *Health 65+* | *457,486* | *599,711* | *747,466* | *856,620* |
| | *Education* | *687,287* | *719,976* | *729,010* | *737,395* |
| | *Pensions* | *1,637,834* | *2,181,700* | *2,789,123* | *3,149,785* |
| | *Other government expenditure* | *3,761,018* | *4,447,899* | *5,141,939* | *5,324,914* |
| | Deficit | -356,155 | -459,539 | -581,161 | -658,275 |
| | Deficit/GDP % | -2.20 | -2.36 | -2.55 | -2.69 |
| **LF15C** | Total revenue | 6,804,170 | 8,030,446 | 9,143,840 | 9,506,389 |
| | Total government expenditure | 7,181,153 | 8,571,732 | 9,851,572 | 10,281,263 |
| | *Health* | *1,115,819* | *1,324,172* | *1,494,102* | *1,550,112* |
| | *Health 65+* | *457,486* | *599,711* | *747,466* | *856,620* |
| | *Education* | *687,287* | *719,976* | *729,010* | *737,395* |
| | *Pensions* | *1,632,619* | *2,160,601* | *2,741,748* | *3,069,977* |
| | *Other government expenditure* | *3,745,428* | *4,366,982* | *4,886,712* | *4,923,779* |
| | Deficit | -376,983 | -541,286 | -707,732 | -774,874 |
| | Deficit/GDP % | -2.33 | -2.78 | -3.10 | -3.17 |

*Source: own elaborations on GDynEP-AG model results.*

It is worth mentioning that the expenditure on pensions increases when automation is included, especially when improvements in factor productivity are assigned to more capital-intensive sectors. If, on one hand, this brings to the highest impact in terms of GDP growth, it also leads to increasing demand for the labour factor, Since the labour supply is constrained by an ageing population (and no migration), the market reacts by increasing wage levels. At the same time, given that direct taxation is a positive function of wages in monetary terms, the increase in workforce remuneration raises revenue from labour taxation, positively impacting fiscal sustainability. However, a non-neutral technical change negatively impacts employment, as in the LF25CRS scenario due to additional government expenditures for transfers to unemployed workers.

In this respect, using EUROSTAT data on total EU expenditure for unemployment, EUR 194.38 million ([35]) and on the number of unemployed in 2015, 22.99 thousand ([36]), we compute the government expenditure per unemployed person per year, about EUR 8,490, with an evolution over time as for health expenditure and apply the number of projected unemployed workers.

Table 5.5 summarises this *ex-post* computation through an additional row in the LF25CRS scenario describing the social transfer provided by the government to support technology-driven unemployed people.

### Table 5.5 – Fiscal sustainability with ageing and automation in the EU (million constant 2015 EUR)

| **Scenario** | | **2020** | **2030** | **2040** | **2050** |
|---|---|---|---|---|---|
| | Total revenue | 6,824,845 | 8,192,232 | 9,663,904 | 10,542,314 |
| | Total government expenditure | 7,181,153 | 8,643,302 | 10,175,589 | 11,066,956 |
| | *Health* | *1,115,819* | *1,324,172* | *1,494,102* | *1,550,112* |
| | *Health 65+* | *457,486* | *599,711* | *747,466* | *856,620* |
| **LF15CR** | *Education* | *687,287* | *719,976* | *729,010* | *737,395* |
| | *Pensions* | *1,632,619* | *2,175,633* | *2,820,391* | *3,274,464* |
| | *Other government expenditure* | *3,745,428* | *4,423,521* | *5,132,085* | *5,504,985* |
| | Deficit | -356,308 | -451,070 | -511,684 | -524,642 |
| | Deficit/GDP % | -2.20 | -2.29 | -2.13 | -1.91 |
| | Total revenue | 6,824,845 | 8,335,156 | 9,810,325 | 10,618,812 |
| | Total government expenditure | 7,181,153 | 8,744,252 | 10,272,917 | 11,095,233 |
| | *Health* | *1,115,819* | *1,324,172* | *1,494,102* | *1,550,112* |
| | *Health 65+* | *457,486* | *599,711* | *747,466* | *856,620* |
| **LF15CRS** | *Education* | *687,287* | *719,976* | *729,010* | *737,395* |
| | *Pensions* | *1,632,619* | *2,204,180* | *2,861,759* | *3,315,773* |
| | *Other government expenditure* | *3,745,428* | *4,495,923* | *5,188,046* | *5,491,953* |
| | Deficit | -356,308 | -409,096 | -462,592 | -476,421 |
| | Deficit/GDP % | -2.20 | -2.04 | -1.89 | -1.71 |
| | Total revenue | 6,822,778 | 8,029,273 | 9,191,739 | 9,786,424 |
| | Total government expenditure | 7,178,118 | 8,587,571 | 9,863,539 | 10,536,135 |
| | *Health* | *1,115,819* | *1,324,172* | *1,494,102* | *1,550,112* |
| | *Health 65+* | *457,486* | *599,711* | *747,466* | *856,620* |
| | *Education* | *687,287* | *719,976* | *729,010* | *737,395* |
| **LF25CRS** | *Pensions* | *1,629,583* | *2,072,914* | *2,581,584* | *2,918,365* |
| | *Other government expenditure* | *0* | *223,105* | *251,721* | *280,514* |
| | Deficit | *3,745,428* | *4,247,404* | *4,807,122* | *5,049,749* |
| | Deficit/GDP % | -355,340 | -558,299 | -671,800 | -749,711 |
| | Total revenue | -2.20 | -2.95 | -2.98 | -2.94 |

*Source: own elaborations on GDynEP-AG model results.*

[35] Data for government expenditure on unemployment correspond with the EUROSTAT code COFOG GF1005 (Unemployment) http://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do. [accessed September 2019]
[36] 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 . [accessed September 2019]

Table 5.5 shows that despite this additional expense, the total amount of government expenditure remains low as a consequence of the general contraction of the economy in this scenario, as also indicated by the low level of GDP (Figure 5.1). Nevertheless, in addition to a low GDP, this scenario also shows a reduction in revenues from labour taxation. Consequently, this is the case in which the EU might face deep fiscal sustainability problems from 2025 onwards, with the deficit to GDP ratio rising beyond the 3 per cent threshold.
Table 5.6 shows the same fiscal sustainability issues when mitigation policies are implemented. Accordingly, an additional revenue line related to carbon taxation adds to total revenues.

## Table 5.6 – Fiscal sustainability with carbon pricing in the EU (million constant 2015 EUR)

| Scenario | | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|
| | Total revenue | 6,808,445 | 8,040,418 | 9,158,492 | 9,515,828 |
| | Total government expenditure | 7,162,492 | 8,478,047 | 9,646,056 | 10,019,437 |
| | *Health* | *1,115,819* | *1,324,172* | *1,494,102* | *1,550,112* |
| | *Health 65+* | *457,486* | *599,711* | *747,466* | *856,620* |
| **LF15CTXL** | *Education* | *687,287* | *719,976* | *729,010* | *737,395* |
| | *Pensions* | *1,623,452* | *2,121,791* | *2,659,124* | *2,944,044* |
| | *Other government expenditure* | *3,735,933* | *4,312,107* | *4,763,820* | *4,787,886* |
| | Deficit | -354,047 | -437,629 | -487,564 | -503,608 |
| | Deficit/GDP % | -2.20 | -2.30 | -2.22 | -2.17 |
| | Total revenue | 6,787,767 | 7,978,644 | 8,999,972 | 9,310,301 |
| | Total government expenditure | 7,143,487 | 8,394,384 | 9,479,246 | 9,830,377 |
| | *Health* | *1,115,819* | *1,324,172* | *1,494,102* | *1,550,112* |
| | *Health 65+* | *457,486* | *599,711* | *747,466* | *856,620* |
| **LF15CTXH** | *Education* | *687,287* | *719,976* | *729,010* | *737,395* |
| | *Pensions* | *1,615,066* | *2,090,145* | *2,597,037* | *2,854,993* |
| | *Other government expenditure* | *3,725,315* | *4,260,091* | *4,659,097* | *4,687,877* |
| | Deficit | -351,713 | -387,997 | -418,225 | -429,355 |
| | Deficit/GDP % | -2.19 | -2.07 | -1.96 | -1.93 |
| | Total revenue | 6,808,445 | 7,916,331 | 9,047,964 | 9,562,641 |
| | Total government expenditure | 7,159,985 | 8,505,080 | 9,685,501 | 10,265,160 |
| | *Health* | *1,115,819* | *1,324,172* | *1,494,102* | *1,550,112* |
| | *Health 65+* | *457,486* | *599,711* | *747,466* | *856,620* |
| **LF25CRSTXL** | *Education* | *687,287* | *719,976* | *729,010* | *737,395* |
| | *Pensions* | *1,620,945* | *2,043,769* | *2,523,486* | *2,831,861* |
| | *Social transfer* | *0* | *223,105* | *251,721* | *280,514* |
| | *Other government expenditure* | *3,735,933* | *4,194,059* | *4,687,182* | *4,865,278* |
| | Deficit | -351,539 | -588,750 | -637,537 | -702,519 |
| | Deficit/GDP % | -2.18 | -3.17 | -2.93 | -2.91 |
| | Total revenue | 6,790,299 | 7,864,104 | 8,923,677 | 9,413,777 |
| | Total government expenditure | 7,141,641 | 8,430,711 | 9,538,925 | 10,055,003 |
| | *Health* | *1,115,819* | *1,324,172* | *1,494,102* | *1,550,112* |
| | *Health 65+* | *457,486* | *599,711* | *747,466* | *856,620* |
| **LF25CRSTXH** | *Education* | *687,287* | *719,976* | *729,010* | *737,395* |
| | *Pensions* | *1,613,219* | *2,019,951* | *2,479,244* | *2,769,329* |
| | *Social transfer* | *0* | *223,105* | *251,721* | *280,514* |
| | *Other government expenditure* | *3,725,315* | *4,143,507* | *4,584,848* | *4,717,653* |
| | Deficit | -351,342 | -566,608 | -615,248 | -641,227 |
| | Deficit/GDP % | -2.19 | -3.11 | -2.92 | -2.77 |

*Source: own elaborations on GDynEP-AG model results.*

The most evident result is that if an Environmental Tax Reform (ETR) is applied through the introduction of a carbon tax, as suggested by Speck (2017), all other things being equal, fiscal sustainability improves. In fact, if mitigation scenarios are compared with the corresponding ones without mitigation, it can be seen that the level of deficit is always lower when abatement measures are introduced. Indeed, even if mitigation entails a general contraction of the economy and hence a reduction in revenue, public expenditure also decreases. Consequently, deficit targets are always respected, especially in LF15CTXH, where a 15 per cent labour force reduction is included due to population ageing, the absence of automation and the implementation of a high carbon price.

With the introduction of automation, the level of emissions increases due to economic recovery. Nevertheless, in LF25CRS, the total level of emissions decreases compared to the other scenarios with technical change due to the impact of unemployment, thus reaching a level close to that in BAU. This can be explained by both a more pronounced economic contraction as a consequence of a lower labour force and the development of more efficient production systems thanks to automation.

### 5.3. Emissions

This last section provides results in terms of emissions. Since the GDynEP-AG model only takes carbon dioxide emissions into account, in order to have a more comprehensive picture, EUROSTAT data, which provide information on sectoral direct emissions on the basis of NAMEA classification, is also considered. Accordingly, we first combine this classification with the GDynEP-AG aggregation to have uniform and comparable information.

Then we obtain the level of emissions from both production and household consumption on the basis of an emission coefficient (e) given by the ratio between the level of emission (E) associated to each type of emission (i) and the level of production in each sector and household consumption (j), as follows:

$$e_{ij} = (\frac{E_i}{Y_j})_{2015} \tag{6}$$

The emission coefficient is calculated for 2015 and we suppose that it does not change over time. Accordingly, the level of emissions is then calculated combining the coefficient with the level of production and household consumption (Y) in different scenarios:

$$E_{i,j,st} = e_{ij} \cdot Y_{j,s,t} \tag{7}$$

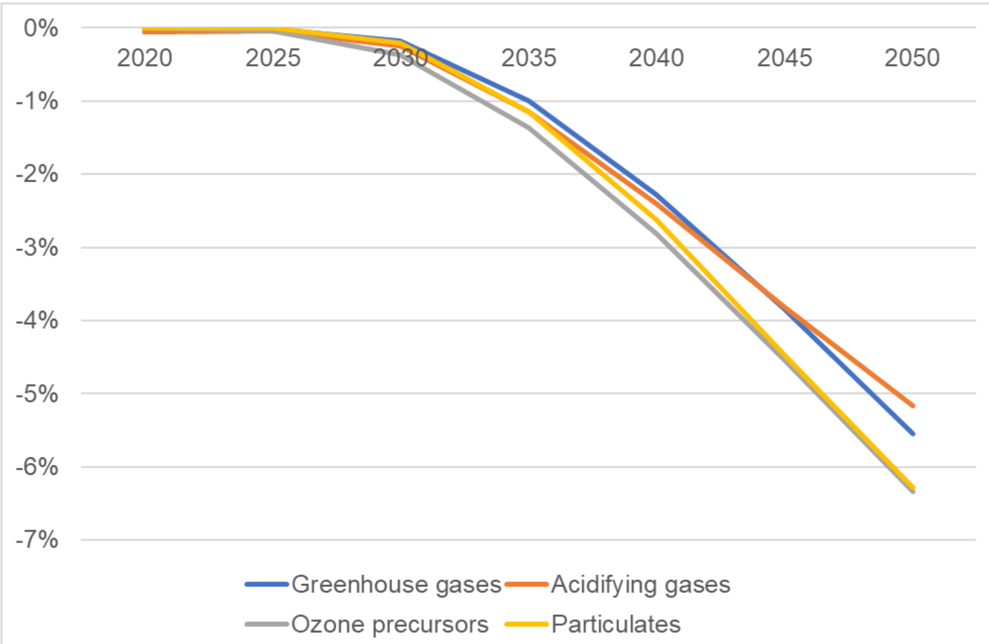
The emission types (i) considered are those arising from greenhouse gases (GHGs), acidifying gases, ozone precursors and particulates ([37]). Tables 5.7-5.14 illustrate results for each of these groups of emissions in BAU and LF15C, in order to compute the direct impact of ageing on polluting emissions ([38]).

[37] GHGs include carbon dioxide ($CO_2$), nitrous oxide ($N_2O$) and methane ($CH_4$); Acidifying gases include sulphur dioxide ($SO_2$), nitrogen oxides ($NO_X$) and ammonia ($NH_3$); ozone precursors include non-methane volatile organic compounds (NMVOC), $NO_X$, carbon monoxide (CO), and CH); finally, we consider Particulate matter less than 10 µm ($PM_{10}$), meaning inhalable particles with diameters of 10 micrometres or less.

[38] We do not show emissions associated with the automation scenarios since we can not know how technological change affects the emission intensity coefficient.

By comparing emissions at the aggregate level for the whole economic system, including manufacturing and service sectors and households, in Figure 5.4, we show percentage changes of different pollutants in LF15C relative to BAU for the whole time horizon, highlighting a substantial reduction in all four pollutants of between -5 and -6.5 per cent by 2050. This reveals a strong impact of an ageing population in reducing emissions, although reductions are quite differentiated across sectors.

Figure 5.4 Change in emission levels for selected pollutants (LF15C relative to BAU, per cent)

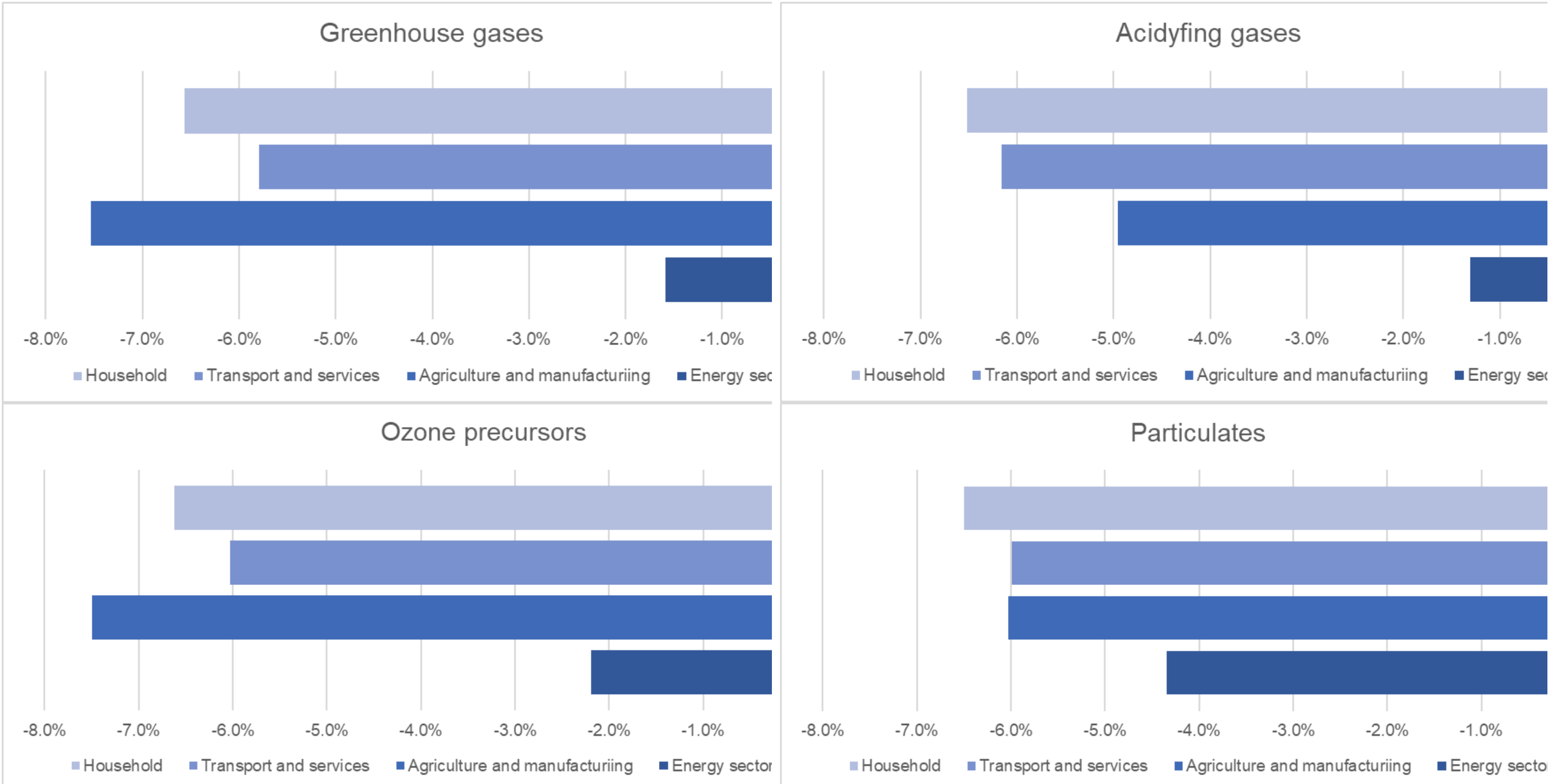



*Source: our elaboration on GDynEP results and Eurostat.*

Figure 5.5 shows changes by 2050 in emission levels for the four polluting aggregates computed for four macro sectors – energy production, agriculture and manufacturing, transport and services, and households.

Many differences emerge in the contributions from four sectors of the four pollutants. For instance, the largest contribution of GHG is associated with the agriculture and manufacturing sector, while in the case of the acidification process and particulate matter, the major contribution in relative emissions reduction is associated with changes in the consumption behaviour of households.

Figure 5.5 Change in emission levels by 2050 for aggregated sectors (LF15C relative to BAU, per cent)




*Source: our elaboration on GDynEP results and Eurostat.*

# 6. The advantage of soft-linking inputs from system dynamics analysis into a dynamic computable general equilibrium model

Several methodological frameworks and tools are available to support policy makers analyse trends and policy options. Most of these are, however, designed for and focus on specific areas of analysis, performing economic, social, environmental or governance assessments.

A few approaches can be used to create nested models, an incremental approach in which the strengths of two or more methodologies and models are retained, as well as their levels of detail. This is the case when CGE models are linked with other sectoral models, such as SD ones, or systems engineering models for the energy sector.

A second option is to create new and integrated models that can capture change across dimensions of development more dynamically and endogenously. This allows taking a more systemic approach because integration is done by design, but in the vast majority of cases leads to a loss of detail. Among the available methodologies are SD and agent-based modelling (ABM). The former aims to explore interaction across indicators and sectors, generally from a macro perspective; the latter focuses on understanding the causes of emergent behaviour, considering agents as primary drivers of change.

Given the long-term focus, macro perspective and interest in capturing connections between social, economic and environmental drivers of change and indicators of performance, we explore the potential of linking CGEs with integrated SD models, building on the work done with CLDs. A first step in this regard is represented by the creation of a soft link between models – the results of one model used as an input by the other one, and vice versa.

Given the structure of the two model types, while CGE models provide reliable results in a long-term perspective, they are affected by a strong rigidity in modelling assumptions, as for instance fixed technical coefficients, homogeneous agents and no feedback loops that can change behavioural parameters, such as demand elasticity to price and income, substitution elasticity across inputs in the production function, or substitution elasticity in consumer (households) basket expenditure.

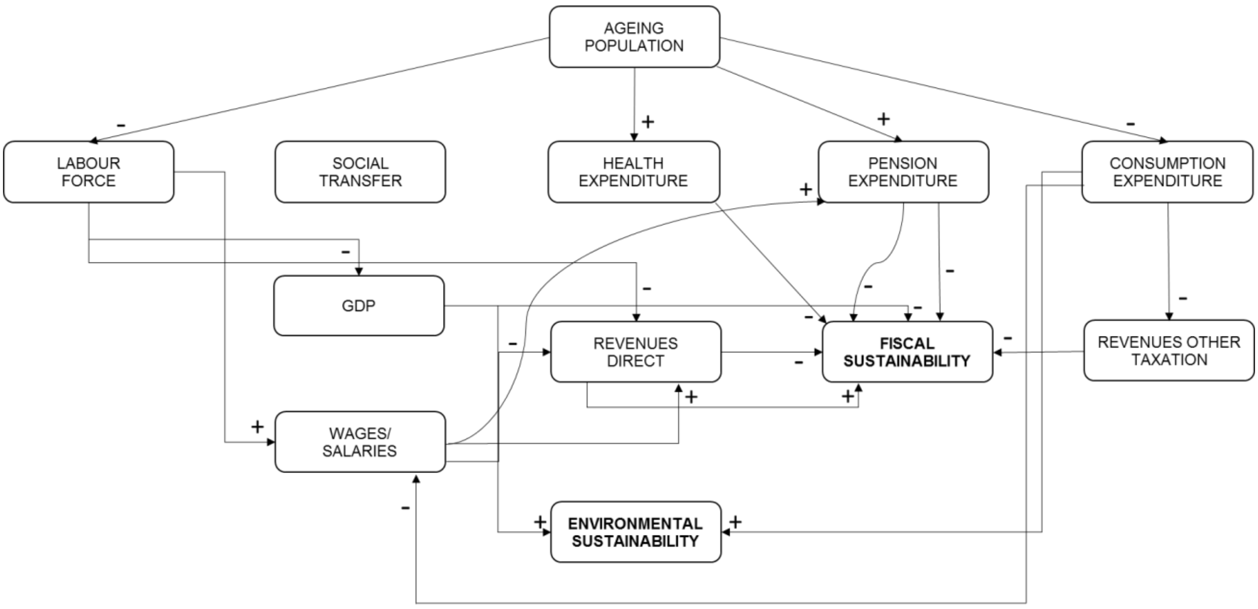
All these sources of rigidity might be smoothed by first running an SD model and assessing changes in selected parameters derived from the evolution of complex systems due to ageing, robotisation and environmental policies. Such changes in parameters can be used as inputs for additional simulation design in a CGE by introducing them as exogenous shocks, directly driven by behavioural changes in the SD framework.

To highlight the most relevant links and relationships in the CGE mechanisms that might be affected by exogenous shocks obtained as outputs from the SD exercise, it is necessary to open the black box of the CGE, at least in selected branches.
To capture main mechanisms simultaneously influencing both environmental and fiscal sustainability the following figures groups the most relevant ones operating in the GDynEP-AG. For the sake of simplicity, comments divided on the basis of the three dynamics under investigation – the impact of ageing population, automation and environmental policies on fiscal and environmental sustainability.

The first and most straightforward implication of an ageing population (Figure 6.1) is its direct role in increasing government expenditure on health and pensions. It also has an indirect impact on revenue due to a reduction in consumption expenditure that leads to lower revenue from other taxation.

The reduction in total labour force has two opposite effects on the revenue side: a negative effect, namely a reduction in the tax base due to the fall in the number of workers; simultaneously, the reduction in labour supply leads to higher wages and salaries, thus increasing the amount of direct taxation payed by each employee.

Figure 6.1 – Ageing population




When simulating these mechanisms in a dynamic CGE, the net effect in LF15C is negative, since the reduction in tax base overwhelms the increase in unitary tax. At the same time, higher wages bring a further increase in unitary pensions as these are direct function of salary levels, aggravating the pressure on government expenditure. When considering the SGP rules in the EU, the lower GDP levels due to ageing add pressure on fiscal sustainability, here measured as the deficit to GDP ratio.

When automation in productive processes is introduced (Figure 6.2), the first impact is an increase in multifactor productivity. This influences GDP growth positively thus reducing, all other things being equal, the deficit to GDP ratio. Furthermore, higher multifactor productivity, given a fixed labour supply, drives an increase in wages that in turn has three effects:

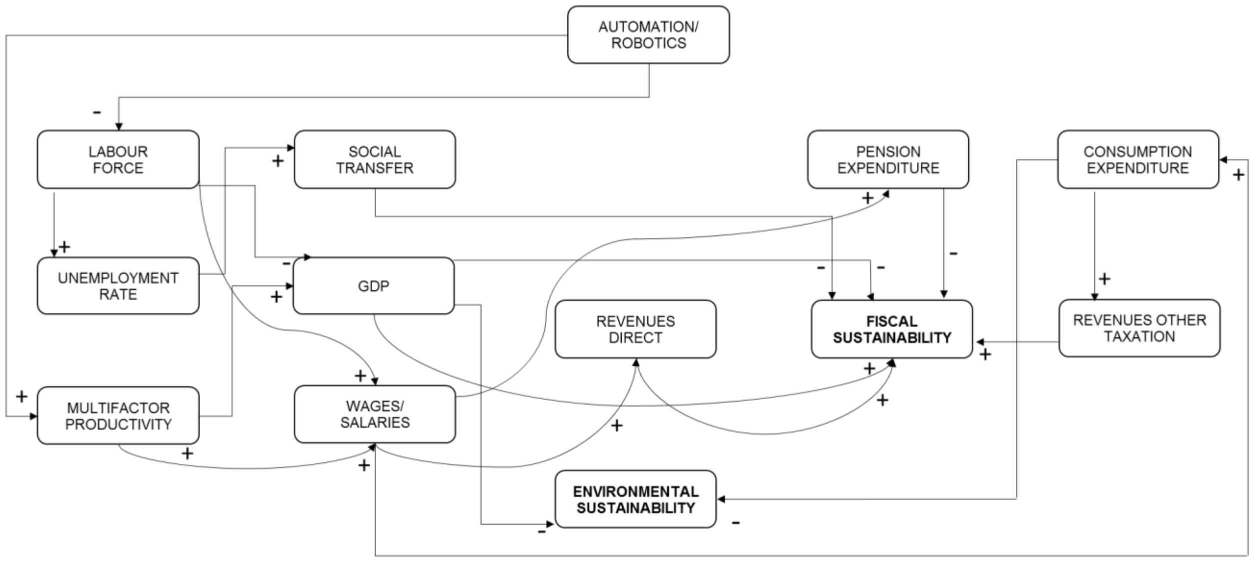
i) an increase in direct taxation revenue;
ii) an increase in household consumption that increases other tax revenue;
iii) an increase in the unitary cost of pensions.

All three effects influence fiscal sustainability in different ways: while higher consumption and revenue from direct taxation contribute to improving the European performance in terms of fiscal sustainability, the increase of the unitary cost for pensions adds pressure on government expenditure and hence on fiscal sustainability.

When technological innovation is employment neutral (LF15CR and LF15CRS), the net impact in terms of fiscal sustainability is positive compared to scenarios without automation, but not sufficient to completely make up for the impact of an ageing population.

If the introduction of automation causes a rise in unemployment (LF25CRS), other mechanisms come into play. The reduction in number of employees further increases wage levels, reinforcing the positive impact on direct and other tax revenues already described. At the same time. however, it also affects fiscal sustainability, since it leads to higher expenditure on pensions and for social transfers. In addition, the reduction in the labour force lowers GDP, thus negatively affecting the deficit to GDP ratio. It is worth mentioning that in this modelling framework the labour force is exogenous. Accordingly, when automation induces unemployment, there is no feedback loop in to pushing down salaries and reabsorbing unemployed workers. Although this is a strong assumption, the literature suggests that most negative effects on the labour market brought about by automation are on unskilled workers, partly justifying the growth in unitary wage levels that is mainly correlated with a growing scarcity of skilled employees.

Figure 6.2 – Automation




Finally, Figure 6.3 examines the mechanisms arising from the introduction of environmental policies. Focusing on carbon taxation on carbon dioxide emissions from combustion, we have direct control on its multiple effects thanks to the direct impact on energy consumption of this fiscal instrument.

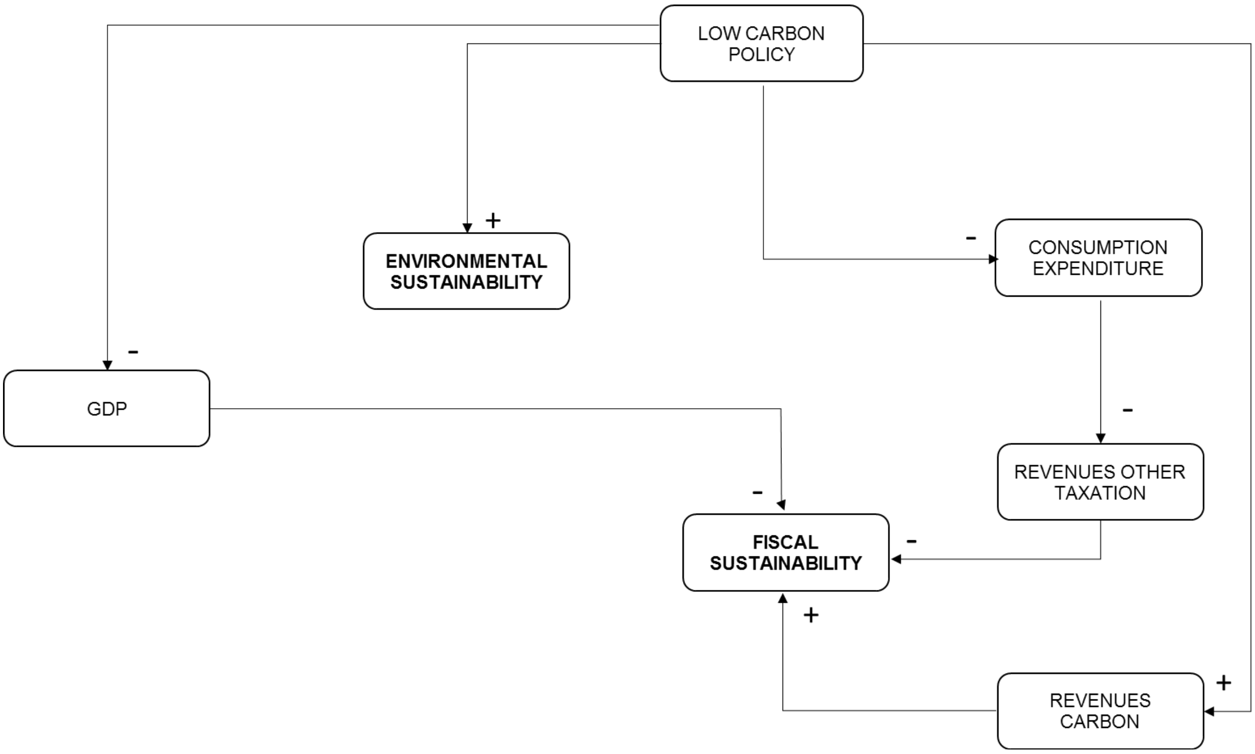
The first positive impact is a growth in revenue from carbon taxation that increases the overall public budget and, all other things being equal, reduces the deficit. Conversely, the contraction in consumption expenditure at the household level reduces revenue from other taxation, with an opposite effect on fiscal sustainability. The increase in the cost of the energy inputs also negatively affects GDP growth, reinforcing pressure on fiscal sustainability.

Accordingly, if environmental sustainability is the only goal in a policy impact evaluation, then a carbon tax is certainly successful in mitigating emissions. If, on the other hand, environmental policies are considered as an instrument to counter the negative impacts of ageing on fiscal sustainability, the net outcome in terms of fiscal sustainability under the SGP rules is uncertain. In particular, when the effects of automation are ignored, then the answer is that an ETR could help face the challenges of fiscal sustainability due to ageing. In a more complex framework, however, accounting for non-employment-neutral technological change, the positive effect of an ETR is not sufficient to ensure that the EU economic system will be fully sustainable from a public budget point of view. At the same time, if population ageing is responsible for a reduction in carbon dioxide emissions, partly reducing the cost of achieving mitigation targets relative to the BAU case, when the automation process is simulated, carbon dioxide emissions increase more than in the BAU case. This reveals that, in this case, a carbon tax policy is not only required to reduce the effects of ageing on fiscal sustainability but also for ensuring the environmental sustainability of a highly automated production system.

These dynamics, and the figures presented above, highlight how the economic analysis provided by a CGE model can be strengthened by the use of an SD model that primarily focuses on physical indicators. These may include the number of jobs created in the economy, energy consumption and emissions, based, for example, on a bottom-up approach that considers technologies for energy efficiency as well as assessing fuel switching, resulting in energy consumption measured in joules, and the estimation of health costs in relation to health facilities and the demand for health services and treatment, as a result, for example, of air pollution. The availability of a model that can forecast these indicators dynamically can provide inputs for a CGE in terms of parameters for the calibration of baseline conditions, as well as for the formulation of realistic medium- to longer-term scenarios. The latter is facilitated by the capability of SD models to explicitly capture feedback loops, delays and non-linearity across social, economic and environmental dimensions.

Practically, the soft coupling of these two approaches allows retention of the strengths of each – primarily the depth of economic analysis of the CGE and the breadth, cross-sectoral and cross-dimensional, of the SD model – and the creation of new synergies for the simulation of more reliable scenarios.

Figure 6.3 Low carbon policies



# 7. Conclusions and policy implications

This report addresses three key emerging challenges that the EU will soon have to face: an ageing population, increasing speed of technological development and adoption, and growing concerns over fiscal sustainability.

The peculiarity of these issues is their strong interdependency, which requires taking account of feedback loops, delays and non-linear effects. The original contribution of this analysis lies in the joint modelling of the multiple impacts and potential reinforcing or balancing mechanisms of an ageing population, automation and environmental taxes in (i) a qualitative systems approach and (ii) in an *ad hoc* quantitative dynamic CGE GTAP-based model.

The links between these macro trends and social, economic and environmental performance were evaluated under the lens of two policy objectives on which the EU is increasingly focusing:

i) the fulfilment of the SGP rule related to respect for the fiscal sustainability of the public budget with a deficit to GDP ratio below the threshold of 3 per cent;

ii) the achievement of environmental sustainability in the long term, specifically looking at the decarbonisation trend required by 2050.

Both modelling approaches employ a systemic approach, but to different extents. The CLDs created, based on ST and SD are qualitative, and hence neither bounded by data availability nor by formal methodological constraints. The result is a very comprehensive assessment of the main drivers of change in the system, and how these are impacted by macro trends and selected policy interventions. The CGE also uses a systemic approach, in that it estimates economy-wide impacts across a variety of economic sectors, as well as extending the analysis to the global economy, with dynamics across countries, specifically with inter-country flows of commodities and investments.

The results of the analysis performed with these two approaches indicates that:

a) when accounting for demographic trends in an ageing society scenario, the deep reduction in the active population might impact the EU's capacity to respect the fiscal sustainability criteria under SGP rules;
b) if an ETR policy designed to tax carbon emissions were adopted, although it has the largest tax base available for the entire EU economic system, the positive impulse to reduce the deficit to GDP ratio is not sufficient to be fully compliant with SGP rules; and conversely,
c) when the role of automation is considered, fiscal constraints seem to relax but only in the case of labour-neutral technological change. If input-biased technical change induces an additional outflow of workers from the job market, increasing unemployment would produce an additional cost to the public budget for social transfers and a simultaneous reduction in production activity, again undermining the capacity to comply with the SGP rules.

This work is a first attempt to identify and quantify the mechanisms driving selected objectives, such as environmental and fiscal sustainability, under various scenarios. It shows that mixed-method and multidisciplinary knowledge are required to support the formulation of effective policy packages in light of growing complexity.

This analysis and the results obtained are far from perfect. Nevertheless, it does show how the synergies emerge from using two systemic methods. The CLDs, despite being qualitative, create a shared understanding of the dynamics of the system and can serve both as a blueprint for model and scenario formulation as well as for the interpretation of results. Specifically, being more comprehensive than a CGE model, CLDs allow the determination of how the results of a model may change when considering the potential addition of factors and dynamics that could not be quantified. Further, the CGE model provides much needed quantification of the outcomes of macro trends and policies. This is crucial in prioritising efforts and delivering value for money. As a result, although this work a small initial step, it is one that can stimulate further efforts in developing complex, systems models.

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# 9. Appendix

### 9.1. Appendix A - Shared socioeconomic pathways (SSP)

**SSP1: Sustainability – taking the green road.** Low challenges for mitigation (resource efficiency) and adaptation (rapid development).
**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-fuelled development – taking the highway.** High challenges for mitigation (resource/fossil fuel intensive) and low for adaptation (rapid development).

Figure A.1 Shared Socio-economic Pathways (SSP)


*Source: O'Neill et al., 2017*

## 9.2. 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 | Southeast 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 | Ferrous metals |
| 15 | basicmet2 | Metals products |
| 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 Former Soviet Union | AF2 | civ | Côte d'Ivoire |
| EU28 | cze | Czechia | 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 | Kyrgyzstan | AF3 | uga | Uganda |
| 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 | Rep of South Africa |
| EU28 | esp | Spain | AS3 | xoc | Rest of Oceania | AF3 | xsc | Rest 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 Republic | LAM1 | ven | Venezuela |
| EU28 | rou | Romania | AS3 | phl | Philippines | LAM2 | bol | Bolivia |
| USA | usa | Un 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 South America |
| 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 Centr. Am. |
| CHN | hkg | Hong Kong | AF1 | xnf | Rest of North Africa | LAM3 | dom | Dom 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 and Tob |
| 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 fibres | 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 distribution |
| 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, distribritution |
| 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 administration |
| nometal | nmm | mineral products nec | services | dwe | ownership of dwellings |

## 9.3. Appendix C – Exogenous projections for scenario setting

### Table C.1 – Population in BAU Scenario (million)

| 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 (million)

| 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 (million)

| 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 |
| **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 – Population in the EU by age group (million)

| 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 C.5 – Labour force in BAU Scenario (million)

| 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.6 – Labour force in LF10 Scenario (million

| 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 |
| | 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.7 – Labour force in LF15 Scenario (million)

| 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 (2018) projections on labour force.*

### Table C.8 – Labour force in the EU(million)

| | 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 C.9 – Change in consumption share on household expenditure in EU (LF15C relative to BAU, per cent)

| Sectors* | 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 |
| Electricity, fossil fuel | -0.04 | -0.07 | 0.66 | 1.39 | 2.12 | 2.85 | 3.58 |
| Electricity, renewables | -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 products | -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 and 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 |
| Ferrous metals | -0.01 | -0.02 | -1.72 | -3.38 | -5.01 | -6.55 | -8.06 |
| Metals products | 0.00 | 0.01 | -1.62 | -3.21 | -4.78 | -6.27 | -7.74 |
| Transport equipment | 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 manufactures | -0.01 | 0.00 | -1.67 | -3.30 | -4.89 | -6.43 | -7.96 |
| Road transport | -0.01 | -0.01 | -2.39 | -4.70 | -6.97 | -9.13 | -11.24 |
| Air transport | -0.01 | -0.02 | -1.72 | -3.38 | -5.00 | -6.54 | -8.06 |
| Water transport | -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 |

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

## Table C.10 – GDP in BAU (USD million)

| | 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.*

## Table C.11 – GDP in the EU (million constant 2015 EUR)

| | 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 | 16,169,938 | 17,782,566 | 19,563,490 | 21,549,575 | 23,731,255 | 25,161,775 | 26,681,294 | 1.68% |
| **LF15** | 14,808,018 | 16,274,062 | 17,956,150 | 19,817,664 | 21,715,403 | 23,661,103 | 24,770,336 | 25,865,680 | 1.59% |
| **LF15C** | 14,808,018 | 16,179,566 | 17,810,466 | 19,440,836 | 21,114,886 | 22,828,993 | 23,681,427 | 24,467,651 | 1.43% |
| **LF15CR** | 14,808,018 | 16,179,566 | 17,827,292 | 19,688,818 | 21,769,336 | 24,027,904 | 25,742,055 | 27,488,911 | 1.77% |
| **LF15CRS** | 14,808,018 | 16,179,566 | 18,063,352 | 20,087,351 | 22,298,968 | 24,521,060 | 26,209,090 | 27,819,901 | 1.80% |
| **LF25CRS** | 14,808,018 | 16,179,566 | 17,497,391 | 18,935,502 | 20,543,126 | 22,547,519 | 24,070,829 | 25,480,657 | 1.55% |
| **LF15CTXL** | 14,808,018 | 16,111,137 | 17,612,050 | 19,064,692 | 20,522,569 | 21,992,395 | 22,621,158 | 23,180,806 | 1.28% |
| **LF15CTXH** | 14,808,018 | 16,041,227 | 17,425,424 | 18,730,937 | 20,023,184 | 21,319,685 | 21,801,084 | 22,219,011 | 1.16% |
| **LF25CRSTXL** | 14,808,018 | 16,111,137 | 17,301,911 | 18,567,892 | 19,966,797 | 21,727,868 | 23,012,637 | 24,173,855 | 1.40% |
| **LF25CRSTXH** | 14,808,018 | 16,041,227 | 17,118,074 | 18,241,876 | 19,480,864 | 21,067,775 | 22,191,109 | 23,190,375 | 1.28% |

*Source: own elaboration on GDynEP-AG results.*

### Table C.12 – GDP per person in the EU (constant 2015 EUR)

| | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|
| **BAU** | 29,179 | 31,852 | 35,054 | 38,670 | 42,770 | 47,408 | 50,841 | 54,662 |
| **LF10** | 29,179 | 31,782 | 35,128 | 39,020 | 43,579 | 48,836 | 52,875 | 57,436 |
| **LF15** | 29,179 | 31,904 | 35,191 | 38,940 | 43,217 | 47,991 | 51,451 | 55,187 |
| **LF15C** | 29,179 | 31,718 | 34,906 | 38,200 | 42,022 | 46,303 | 49,189 | 52,204 |
| **LF15CR** | 29,179 | 31,718 | 34,939 | 38,687 | 43,324 | 48,735 | 53,469 | 58,650 |
| **LF15CRS** | 29,179 | 31,718 | 35,402 | 39,470 | 44,378 | 49,735 | 54,439 | 59,356 |
| **LF25CRS** | 29,179 | 31,718 | 34,292 | 37,207 | 40,884 | 45,732 | 49,998 | 54,365 |
| **LF15CTXL** | 29,179 | 31,584 | 34,517 | 37,461 | 40,843 | 44,606 | 46,987 | 49,458 |
| **LF15CTXH** | 29,179 | 31,447 | 34,151 | 36,805 | 39,849 | 43,242 | 45,283 | 47,406 |
| **LF25CRSTXL** | 29,179 | 31,584 | 33,909 | 36,484 | 39,737 | 44,070 | 47,800 | 51,577 |
| **LF25CRSTXH** | 29,179 | 31,447 | 33,549 | 35,844 | 38,770 | 42,731 | 46,093 | 49,479 |

*Source: own elaboration on GDynEP-AG results.*

### Table C.13 – Combustion-based carbon dioxide emissions in the EU (million tonnes of oil equivalent)

| Scenario | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|
| **BAU** | 3,201 | 3,123 | 3,027 | 2,950 | 2,853 | 2,789 | 2,708 | 2,682 |
| **EU target** | 3,201 | 2,732 | 2,353 | 1,999 | 1,660 | 1,376 | 1,135 | 941 |
| **LF10** | 3,201 | 3,112 | 3,011 | 2,929 | 2,828 | 2,760 | 2,674 | 2,642 |
| **LF15** | 3,201 | 3,122 | 3,027 | 2,950 | 2,839 | 2,747 | 2,629 | 2,557 |
| **LF15C** | 3,201 | 3,112 | 3,013 | 2,942 | 2,841 | 2,762 | 2,658 | 2,597 |
| **LF15CR** | 3,201 | 3,112 | 3,015 | 2,968 | 2,904 | 2,869 | 2,829 | 2,834 |
| **LF15CRS** | 3,201 | 3,112 | 3,033 | 2,997 | 2,937 | 2,892 | 2,837 | 2,822 |
| **LF25CRS** | 3,201 | 3,112 | 2,976 | 2,880 | 2,771 | 2,717 | 2,663 | 2,646 |
| **LF15CTXL** | 3,201 | 2,733 | 2,411 | 2,179 | 1,959 | 1,777 | 1,608 | 1,477 |
| **LF15CTXH** | 3,201 | 2,495 | 2,099 | 1,823 | 1,581 | 1,390 | 1,227 | 1,100 |
| **LF25CRSTXL** | 3,201 | 2,733 | 2,382 | 2,136 | 1,916 | 1,757 | 1,624 | 1,520 |
| **LF25CRSTXH** | 3,201 | 2,495 | 2,074 | 1,787 | 1,549 | 1,377 | 1,243 | 1,138 |

*Source: own elaboration on GDynEP-AG results and Corradini et al. (2018) for the EU target PA calculation.*

## 9.4. Appendix D – Emissions projections

### Table D.1 – Total greenhouse gas emissions (million tonnes, carbon dioxide equivalent) – BAU

| Sector | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|
| Coal | 6.54 | 5.91 | 5.51 | 4.95 | 4.35 | 3.78 | 3.48 | 3.27 |
| Oil | 72.97 | 69.75 | 67.67 | 62.94 | 56.99 | 49.71 | 51.04 | 51.72 |
| Gas | 17.24 | 15.88 | 15.01 | 14.13 | 13.38 | 12.74 | 11.84 | 11.18 |
| Petroleum, coal products | 145.70 | 144.85 | 141.19 | 138.24 | 133.95 | 130.73 | 126.74 | 125.02 |
| Electricity, fossil fuels and nuclear | 1121.38 | 1109.17 | 1122.11 | 1144.03 | 1166.29 | 1194.75 | 1244.18 | 1311.63 |
| Electricity, renewables | 8.01 | 8.49 | 9.17 | 10.13 | 11.36 | 12.79 | 14.40 | 16.32 |
| Agriculture | 531.59 | 593.90 | 674.57 | 751.97 | 828.21 | 903.60 | 944.54 | 973.79 |
| Food | 58.60 | 63.61 | 69.43 | 75.35 | 81.62 | 88.43 | 92.61 | 96.71 |
| Textile | 8.47 | 8.33 | 8.32 | 8.48 | 8.84 | 9.35 | 9.71 | 10.22 |
| Non-metallic mineral products | 195.06 | 212.21 | 230.76 | 253.65 | 281.99 | 315.68 | 336.00 | 362.23 |
| Wood | 6.23 | 6.52 | 6.96 | 7.54 | 8.24 | 9.06 | 9.63 | 10.28 |
| Pulp and paper | 35.51 | 38.64 | 42.13 | 46.10 | 50.68 | 55.89 | 59.54 | 63.65 |
| Chemical and petrochemical | 168.37 | 178.57 | 187.56 | 200.46 | 217.99 | 238.64 | 251.43 | 268.75 |
| Ferrous metals | 175.30 | 178.92 | 177.95 | 181.56 | 189.65 | 200.06 | 192.83 | 191.51 |
| Metals products | 14.99 | 15.82 | 16.68 | 17.94 | 19.55 | 21.37 | 22.00 | 23.05 |
| Transport equipment | 12.40 | 13.68 | 15.01 | 16.61 | 18.45 | 20.54 | 21.71 | 23.09 |
| Machinery and equipment | 17.07 | 17.72 | 18.10 | 19.18 | 20.75 | 22.55 | 22.44 | 22.94 |
| Other manufacturing industries | 14.24 | 14.71 | 15.07 | 15.87 | 17.01 | 18.37 | 18.59 | 19.33 |
| Transport | 229.98 | 253.03 | 275.98 | 302.69 | 333.54 | 369.20 | 393.02 | 420.02 |
| Water transport | 142.90 | 160.46 | 175.47 | 193.45 | 214.64 | 239.38 | 256.47 | 275.43 |
| Air transport | 120.01 | 139.24 | 156.65 | 178.14 | 204.33 | 236.25 | 260.03 | 287.85 |
| Services | 490.09 | 539.27 | 601.52 | 668.88 | 741.90 | 822.45 | 889.19 | 958.69 |
| Household | 871.68 | 960.41 | 1052.61 | 1143.64 | 1238.15 | 1342.31 | 1395.13 | 1450.54 |
| **Total** | 4464.34 | 4749.09 | 5085.43 | 5455.91 | 5861.86 | 6317.66 | 6626.53 | 6977.24 |

*Source: our elaboration on GDynEP results and Eurostat.*

### Table D.2 – Acidifying gases: sulphur oxides, nitrogen oxides, ammonia (million tonnes, sulphur dioxide equivalent) – BAU

| Sector | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|
| Coal | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 |
| Oil | 0.10 | 0.09 | 0.09 | 0.08 | 0.08 | 0.07 | 0.07 | 0.07 |
| Gas | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.02 | 0.02 |
| Petroleum, coal products | 0.41 | 0.41 | 0.40 | 0.39 | 0.37 | 0.37 | 0.35 | 0.35 |
| Electricity, fossil fuels and nuclear | 2.21 | 2.19 | 2.21 | 2.25 | 2.30 | 2.35 | 2.45 | 2.58 |
| Electricity, renewables | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.03 | 0.03 | 0.03 |
| Agriculture | 8.00 | 8.94 | 10.16 | 11.32 | 12.47 | 13.60 | 14.22 | 14.66 |
| Food | 0.11 | 0.12 | 0.13 | 0.14 | 0.16 | 0.17 | 0.18 | 0.18 |
| Textile | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 |
| Non-metallic mineral products | 0.45 | 0.49 | 0.54 | 0.59 | 0.66 | 0.73 | 0.78 | 0.84 |
| Wood | 0.04 | 0.04 | 0.04 | 0.04 | 0.05 | 0.05 | 0.06 | 0.06 |
| Pulp and paper | 0.13 | 0.15 | 0.16 | 0.17 | 0.19 | 0.21 | 0.22 | 0.24 |
| Chemical and petrochemical | 0.38 | 0.40 | 0.42 | 0.45 | 0.49 | 0.54 | 0.56 | 0.60 |
| Ferrous metals | 0.34 | 0.35 | 0.35 | 0.36 | 0.37 | 0.39 | 0.38 | 0.38 |
| Metals products | 0.03 | 0.03 | 0.04 | 0.04 | 0.04 | 0.05 | 0.05 | 0.05 |
| Transport equipment | 0.02 | 0.03 | 0.03 | 0.03 | 0.03 | 0.04 | 0.04 | 0.04 |
| Machinery and equipment | 0.03 | 0.03 | 0.03 | 0.03 | 0.04 | 0.04 | 0.04 | 0.04 |
| Other manufacturing industries | 0.04 | 0.04 | 0.04 | 0.04 | 0.05 | 0.05 | 0.05 | 0.05 |
| Transport | 0.80 | 0.88 | 0.96 | 1.06 | 1.16 | 1.29 | 1.37 | 1.47 |
| Water transport | 0.34 | 0.38 | 0.41 | 0.45 | 0.50 | 0.56 | 0.60 | 0.65 |
| Air transport | 2.49 | 2.89 | 3.25 | 3.69 | 4.24 | 4.90 | 5.39 | 5.97 |
| Services | 0.93 | 1.02 | 1.14 | 1.27 | 1.40 | 1.56 | 1.68 | 1.81 |
| Household | 1.66 | 1.82 | 2.00 | 2.17 | 2.35 | 2.55 | 2.65 | 2.76 |
| **Total** | 18.58 | 20.37 | 22.46 | 24.66 | 27.02 | 29.58 | 31.22 | 32.88 |

*Source: our elaboration on GDynEP results and Eurostat.*

Table D.3 – Ozone precursors: Non-methane volatile organic compounds, nitrogen oxides, carbon monoxide, methane (million tonnes, non-methane volatile organic compound equivalent) – BAU

| Sector | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|
| Coal | 0.03 | 0.03 | 0.02 | 0.02 | 0.02 | 0.02 | 0.01 | 0.01 |
| Oil | 0.31 | 0.30 | 0.29 | 0.27 | 0.25 | 0.21 | 0.22 | 0.22 |
| Gas | 0.03 | 0.03 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| Petroleum, coal products | 0.45 | 0.44 | 0.43 | 0.42 | 0.41 | 0.40 | 0.39 | 0.38 |
| Electricity, fossil fuels and nuclear | 1.78 | 1.76 | 1.78 | 1.81 | 1.85 | 1.89 | 1.97 | 2.08 |
| Electricity, renewables | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.02 | 0.02 | 0.03 |
| Agriculture | 2.92 | 3.26 | 3.70 | 4.13 | 4.55 | 4.96 | 5.19 | 5.35 |
| Food | 0.46 | 0.50 | 0.55 | 0.60 | 0.65 | 0.70 | 0.73 | 0.77 |
| Textile | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.08 | 0.08 | 0.08 |
| Non-metallic mineral products | 0.55 | 0.60 | 0.65 | 0.72 | 0.80 | 0.89 | 0.95 | 1.02 |
| Wood | 0.14 | 0.15 | 0.16 | 0.17 | 0.19 | 0.21 | 0.22 | 0.24 |
| Pulp and paper | 0.38 | 0.41 | 0.45 | 0.49 | 0.54 | 0.59 | 0.63 | 0.67 |
| Chemical and petrochemical | 0.72 | 0.77 | 0.81 | 0.86 | 0.94 | 1.03 | 1.08 | 1.16 |
| Ferrous metals | 0.65 | 0.66 | 0.66 | 0.67 | 0.70 | 0.74 | 0.71 | 0.71 |
| Metals products | 0.22 | 0.24 | 0.25 | 0.27 | 0.29 | 0.32 | 0.33 | 0.34 |
| Transport equipment | 0.32 | 0.36 | 0.39 | 0.43 | 0.48 | 0.53 | 0.56 | 0.60 |
| Machinery and equipment | 0.13 | 0.14 | 0.14 | 0.15 | 0.16 | 0.17 | 0.17 | 0.18 |
| Other manufacturing industries | 0.27 | 0.27 | 0.28 | 0.30 | 0.32 | 0.34 | 0.35 | 0.36 |
| Transport | 1.59 | 1.75 | 1.91 | 2.09 | 2.31 | 2.55 | 2.72 | 2.90 |
| Water transport | 0.57 | 0.64 | 0.70 | 0.78 | 0.86 | 0.96 | 1.03 | 1.11 |
| Air transport | 3.16 | 3.66 | 4.12 | 4.69 | 5.37 | 6.21 | 6.84 | 7.57 |
| Services | 2.13 | 2.34 | 2.62 | 2.91 | 3.23 | 3.58 | 3.87 | 4.17 |
| Household | 5.71 | 6.30 | 6.90 | 7.50 | 8.12 | 8.80 | 9.15 | 9.51 |
| **Total** | 22.61 | 24.68 | 26.92 | 29.38 | 32.12 | 35.23 | 37.24 | 39.47 |

*Source: our elaboration on GDynEP results and Eurostat.*

## Table D.4 – Particulates (million tonnes) – BAU

| Sector | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|
| Coal | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 |
| Oil | 0.08 | 0.08 | 0.08 | 0.07 | 0.07 | 0.06 | 0.06 | 0.06 |
| Gas | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Petroleum, coal products | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| Electricity, fossil fuels and nuclear | 0.13 | 0.13 | 0.13 | 0.13 | 0.14 | 0.14 | 0.15 | 0.15 |
| Electricity, renewables | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Agriculture | 0.56 | 0.62 | 0.71 | 0.79 | 0.87 | 0.95 | 0.99 | 1.02 |
| Food | 0.03 | 0.03 | 0.03 | 0.04 | 0.04 | 0.04 | 0.05 | 0.05 |
| Textile | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Non-metallic mineral products | 0.11 | 0.12 | 0.13 | 0.14 | 0.16 | 0.17 | 0.18 | 0.20 |
| Wood | 0.06 | 0.07 | 0.07 | 0.08 | 0.08 | 0.09 | 0.10 | 0.10 |
| Pulp and paper | 0.05 | 0.05 | 0.06 | 0.06 | 0.07 | 0.07 | 0.08 | 0.08 |
| Chemical and petrochemical | 0.04 | 0.05 | 0.05 | 0.05 | 0.06 | 0.06 | 0.07 | 0.07 |
| Ferrous metals | 0.08 | 0.08 | 0.08 | 0.08 | 0.09 | 0.09 | 0.09 | 0.09 |
| Metals products | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Transport equipment | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Machinery and equipment | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Other manufacturing industries | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.02 |
| Transport | 0.14 | 0.16 | 0.17 | 0.19 | 0.21 | 0.23 | 0.25 | 0.26 |
| Water transport | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.03 | 0.03 | 0.03 |
| Air transport | 0.37 | 0.43 | 0.48 | 0.55 | 0.63 | 0.73 | 0.80 | 0.89 |
| Services | 0.25 | 0.28 | 0.31 | 0.34 | 0.38 | 0.42 | 0.46 | 0.49 |
| Household | 1.67 | 1.84 | 2.01 | 2.19 | 2.37 | 2.57 | 2.67 | 2.77 |
| **Total** | 3.67 | 4.02 | 4.41 | 4.81 | 5.25 | 5.74 | 6.04 | 6.36 |

*Source: our elaboration on GDynEP results and Eurostat.*

## Table D.5 – Total greenhouse gas emissions (million tonnes, carbon dioxide equivalent) – LF15C

| Sector | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|
| Coal | 6.54 | 5.91 | 5.51 | 4.94 | 4.30 | 3.69 | 3.32 | 3.06 |
| Oil | 72.97 | 69.75 | 67.67 | 61.95 | 54.92 | 46.58 | 46.74 | 46.33 |
| Gas | 17.24 | 15.88 | 15.00 | 14.08 | 13.32 | 12.67 | 11.73 | 11.00 |
| Petroleum, coal products | 145.70 | 144.85 | 141.19 | 137.50 | 131.90 | 126.84 | 120.89 | 117.04 |
| Electricity, fossil fuels and nuclear | 1121.38 | 1109.17 | 1122.11 | 1151.47 | 1177.60 | 1206.00 | 1247.87 | 1301.79 |
| Electricity, renewables | 8.01 | 8.49 | 9.17 | 10.13 | 11.34 | 12.70 | 14.15 | 15.80 |
| Agriculture | 531.59 | 593.75 | 674.20 | 751.20 | 820.12 | 884.03 | 913.57 | 934.10 |
| Food | 58.60 | 63.59 | 69.40 | 76.40 | 83.18 | 90.04 | 93.73 | 97.24 |
| Textile | 8.47 | 8.33 | 8.32 | 8.25 | 8.30 | 8.44 | 8.33 | 8.31 |
| Non-metallic mineral products | 195.06 | 212.21 | 230.75 | 251.20 | 275.15 | 302.42 | 315.05 | 331.99 |
| Wood | 6.23 | 6.52 | 6.96 | 7.41 | 7.92 | 8.48 | 8.72 | 9.01 |
| Pulp and paper | 35.51 | 38.64 | 42.13 | 45.86 | 49.77 | 53.90 | 56.07 | 58.39 |
| Chemical and petrochemical | 168.37 | 178.56 | 187.55 | 195.97 | 207.40 | 220.46 | 224.16 | 231.05 |
| Ferrous metals | 175.30 | 178.92 | 177.94 | 175.30 | 176.93 | 180.81 | 168.91 | 162.98 |
| Metals products | 14.99 | 15.82 | 16.68 | 17.61 | 18.77 | 20.03 | 20.05 | 20.39 |
| Transport equipment | 12.40 | 13.68 | 15.01 | 16.27 | 17.63 | 19.08 | 19.50 | 20.04 |
| Machinery and equipment | 17.07 | 17.72 | 18.10 | 18.58 | 19.47 | 20.49 | 19.72 | 19.49 |
| Other manufacturing industries | 14.24 | 14.71 | 15.07 | 15.62 | 16.38 | 17.24 | 16.89 | 16.97 |
| Transport | 229.98 | 253.02 | 275.97 | 300.82 | 327.37 | 356.27 | 371.63 | 388.67 |
| Water transport | 142.90 | 160.46 | 175.46 | 191.73 | 209.62 | 229.49 | 240.56 | 252.73 |
| Air transport | 120.01 | 139.24 | 156.65 | 176.96 | 200.72 | 228.83 | 247.80 | 269.91 |
| Services | 490.09 | 539.28 | 601.56 | 672.37 | 743.46 | 816.13 | 868.55 | 918.21 |
| Household | 871.68 | 960.39 | 1052.59 | 1144.40 | 1227.66 | 1309.52 | 1333.63 | 1355.37 |
| **Total** | 4464.34 | 4748.91 | 5084.99 | 5446.03 | 5803.25 | 6174.14 | 6371.58 | 6589.86 |

*Source: our elaboration on GDynEP results and Eurostat.*

Table D.6 – Acidifying gases: sulphur oxides, nitrogen oxides, ammonia (million tonnes, sulphur dioxide equivalent) – LF15C

| **Sector** | **2015** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
|---|---|---|---|---|---|---|---|---|
| Coal | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 |
| Oil | 0.10 | 0.09 | 0.09 | 0.08 | 0.07 | 0.06 | 0.06 | 0.06 |
| Gas | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.02 | 0.02 | 0.02 |
| Petroleum, coal products | 0.41 | 0.41 | 0.39 | 0.38 | 0.37 | 0.35 | 0.34 | 0.33 |
| Electricity, fossil fuels and nuclear | 2.21 | 2.19 | 2.21 | 2.27 | 2.32 | 2.38 | 2.46 | 2.57 |
| Electricity, renewables | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.03 | 0.03 | 0.03 |
| Agriculture | 8.00 | 8.94 | 10.15 | 11.31 | 12.35 | 13.31 | 13.75 | 14.06 |
| Food | 0.11 | 0.12 | 0.13 | 0.15 | 0.16 | 0.17 | 0.18 | 0.19 |
| Textile | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Non-metallic mineral products | 0.45 | 0.49 | 0.54 | 0.58 | 0.64 | 0.70 | 0.73 | 0.77 |
| Wood | 0.04 | 0.04 | 0.04 | 0.04 | 0.05 | 0.05 | 0.05 | 0.05 |
| Pulp and paper | 0.13 | 0.15 | 0.16 | 0.17 | 0.19 | 0.20 | 0.21 | 0.22 |
| Chemical and petrochemical | 0.38 | 0.40 | 0.42 | 0.44 | 0.47 | 0.50 | 0.50 | 0.52 |
| Ferrous metals | 0.34 | 0.35 | 0.35 | 0.34 | 0.35 | 0.35 | 0.33 | 0.32 |
| Metals products | 0.03 | 0.03 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 |
| Transport equipment | 0.02 | 0.03 | 0.03 | 0.03 | 0.03 | 0.04 | 0.04 | 0.04 |
| Machinery and equipment | 0.03 | 0.03 | 0.03 | 0.03 | 0.04 | 0.04 | 0.04 | 0.04 |
| Other manufacturing industries | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.05 | 0.05 | 0.05 |
| Transport | 0.80 | 0.88 | 0.96 | 1.05 | 1.14 | 1.24 | 1.30 | 1.36 |
| Water transport | 0.34 | 0.38 | 0.41 | 0.45 | 0.49 | 0.54 | 0.56 | 0.59 |
| Air transport | 2.49 | 2.89 | 3.25 | 3.67 | 4.16 | 4.75 | 5.14 | 5.60 |
| Services | 0.93 | 1.02 | 1.14 | 1.27 | 1.41 | 1.54 | 1.64 | 1.74 |
| Household | 1.66 | 1.82 | 2.00 | 2.17 | 2.33 | 2.49 | 2.53 | 2.58 |
| **Total** | 18.58 | 20.36 | 22.45 | 24.60 | 26.71 | 28.87 | 30.03 | 31.18 |

*Source: our elaboration on GDynEP results and Eurostat.*

Table D.7 – Ozone precursors: Non-methane volatile organic compounds, nitrogen oxides, carbon monoxide, methane (million tonnes, non-methane volatile organic compound equivalent) – LF15C

| Sector | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|
| Coal | 0.03 | 0.03 | 0.02 | 0.02 | 0.02 | 0.02 | 0.01 | 0.01 |
| Oil | 0.31 | 0.30 | 0.29 | 0.27 | 0.24 | 0.20 | 0.20 | 0.20 |
| Gas | 0.03 | 0.03 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| Petroleum, coal products | 0.45 | 0.44 | 0.43 | 0.42 | 0.40 | 0.39 | 0.37 | 0.36 |
| Electricity, fossil fuels and nuclear | 1.78 | 1.76 | 1.78 | 1.82 | 1.87 | 1.91 | 1.98 | 2.06 |
| Electricity, renewables | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.02 | 0.02 | 0.03 |
| Agriculture | 2.92 | 3.26 | 3.70 | 4.13 | 4.50 | 4.85 | 5.02 | 5.13 |
| Food | 0.46 | 0.50 | 0.55 | 0.61 | 0.66 | 0.71 | 0.74 | 0.77 |
| Textile | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 |
| Non-metallic mineral products | 0.55 | 0.60 | 0.65 | 0.71 | 0.78 | 0.85 | 0.89 | 0.94 |
| Wood | 0.14 | 0.15 | 0.16 | 0.17 | 0.18 | 0.19 | 0.20 | 0.21 |
| Pulp and paper | 0.38 | 0.41 | 0.45 | 0.48 | 0.53 | 0.57 | 0.59 | 0.62 |
| Chemical and petrochemical | 0.72 | 0.77 | 0.81 | 0.84 | 0.89 | 0.95 | 0.96 | 0.99 |
| Ferrous metals | 0.65 | 0.66 | 0.66 | 0.65 | 0.65 | 0.67 | 0.62 | 0.60 |
| Metals products | 0.22 | 0.24 | 0.25 | 0.26 | 0.28 | 0.30 | 0.30 | 0.30 |
| Transport equipment | 0.32 | 0.36 | 0.39 | 0.42 | 0.46 | 0.50 | 0.51 | 0.52 |
| Machinery and equipment | 0.13 | 0.14 | 0.14 | 0.14 | 0.15 | 0.16 | 0.15 | 0.15 |
| Other manufacturing industries | 0.27 | 0.27 | 0.28 | 0.29 | 0.30 | 0.32 | 0.31 | 0.32 |
| Transport | 1.59 | 1.75 | 1.91 | 2.08 | 2.26 | 2.46 | 2.57 | 2.69 |
| Water transport | 0.57 | 0.64 | 0.70 | 0.77 | 0.84 | 0.92 | 0.97 | 1.02 |
| Air transport | 3.16 | 3.66 | 4.12 | 4.65 | 5.28 | 6.02 | 6.52 | 7.10 |
| Services | 2.13 | 2.34 | 2.62 | 2.92 | 3.23 | 3.55 | 3.78 | 3.99 |
| Household | 5.71 | 6.30 | 6.90 | 7.50 | 8.05 | 8.58 | 8.74 | 8.88 |
| **Total** | 22.61 | 24.68 | 26.91 | 29.27 | 31.68 | 34.24 | 35.55 | 36.97 |

*Source: our elaboration on GDynEP results and Eurostat.*

## Table D.8 – Particulates (million tonnes) – LF15C

| Sector | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|
| Coal | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 |
| Oil | 0.08 | 0.08 | 0.08 | 0.07 | 0.06 | 0.05 | 0.05 | 0.05 |
| Gas | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Petroleum, coal products | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| Electricity, fossil fuels and nuclear | 0.13 | 0.13 | 0.13 | 0.13 | 0.14 | 0.14 | 0.15 | 0.15 |
| Electricity, renewables | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Agriculture | 0.56 | 0.62 | 0.71 | 0.79 | 0.86 | 0.93 | 0.96 | 0.98 |
| Food | 0.03 | 0.03 | 0.03 | 0.04 | 0.04 | 0.04 | 0.05 | 0.05 |
| Textile | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Non-metallic mineral products | 0.11 | 0.12 | 0.13 | 0.14 | 0.15 | 0.17 | 0.17 | 0.18 |
| Wood | 0.06 | 0.07 | 0.07 | 0.08 | 0.08 | 0.09 | 0.09 | 0.09 |
| Pulp and paper | 0.05 | 0.05 | 0.06 | 0.06 | 0.07 | 0.07 | 0.07 | 0.08 |
| Chemical and petrochemical | 0.04 | 0.05 | 0.05 | 0.05 | 0.05 | 0.06 | 0.06 | 0.06 |
| Ferrous metals | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 |
| Metals products | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Transport equipment | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Machinery and equipment | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Other manufacturing industries | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.01 | 0.01 |
| Transport | 0.14 | 0.16 | 0.17 | 0.19 | 0.20 | 0.22 | 0.23 | 0.24 |
| Water transport | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.03 | 0.03 |
| Air transport | 0.37 | 0.43 | 0.48 | 0.54 | 0.62 | 0.70 | 0.76 | 0.83 |
| Services | 0.25 | 0.28 | 0.31 | 0.34 | 0.38 | 0.42 | 0.45 | 0.47 |
| Household | 1.67 | 1.84 | 2.01 | 2.19 | 2.35 | 2.51 | 2.55 | 2.59 |
| **Total** | 3.67 | 4.02 | 4.41 | 4.80 | 5.19 | 5.59 | 5.77 | 5.96 |

*Source: our elaboration on GDynEP results and Eurostat.*

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