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The Social Aversion to Intergenerational Inequality and the Recycling of a Carbon Tax

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Redistributing the income of a carbon tax impacts the economic activity and the intergenerational inequality, which both influence the intertemporal social welfare. Thus the way a social planner recycles a carbon tax is influenced by its degree of aversion to intergenerational inequality. This article analyses the effect of social aversion to intergenerational inequality on the social choice as concerns implementing and redistributing a carbon tax. It relies on a detailed computable general equilibrium model with overlapping generations and an energy module, with a parameterisation on empirical data. We use two types of social welfare functionals which both incorporate a variable parameter measuring the degree of aversion of the social planner to intergenerational inequality. Results suggest that the social planner recycles a carbon tax through higher public expenditures if its aversion to intergenerational inequity is relatively high. This holds even if recycling through lower income taxes increases activity.

JEL classification : D58 - D63 - E62 - L7 - Q28 - Q43.

Keywords : Energy transition - intergenerational redistribution - social choice - overlapping generations - carbon tax - general equilibrium.

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Frédéric Gonand*

July 17, 2014

Abstract

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1 Introduction

Redistributing a carbon tax impacts the economic activity and the intergenerational inequality. Higher economic activity or intergenerational inequality influence the intertemporal social welfare. Thus the way a social planner recycles a carbon tax is influenced by its degree of aversion to intergenerational inequality.

Recycling a carbon tax triggers direct and indirect positive effects on activity. The direct effect is related with the upward influence on the income of private agents. The indirect effect refers to the fact that recycled environmental taxes may lessen the distorsive influence of the whole tax system if they are substituted with income taxes, bringing about a "second dividend" (Pearce (1991), see Bovenberg and Goulder (2002) for a survey). Some debate arose in the 1990's about the existence of such a second dividend (Bovenberg and De Mooij, 1994). However, subsequent research tends globally to support the idea that environmental taxes indeed trigger favourable side-effects on activity (see Bento and Jacobsen (2007) for instance).

Analysing the impact on growth of recycled environmental taxes generally requires general equilibrium (GE) models. Following Solow (1978), GE frameworks with CES production functions including energy as a third input have been commonly used (*e.g.*, Böhringer and Rutherford (1997), Parry and Williams (1999) for relatively early examples), especially on issues related with environmental taxes (Bovenberg and Heijdra (1998), Wissema and Dellink (2007), Fullerton and Heutel (2010), Bretschger, Ramer and Schwark (2011)). Knopf et al. (2010) recently presented several CGE models assessing empirically the costs of abiding by the 450ppm environmental target.

However, these models are not usually designed specifically to analyse the dynamic effects on growth of environmental tax reforms and their implied intergenerational effects. Recycling a carbon tax indeed raises about intergenerational redistributive effects, as shown by a litterature analysing environmental taxes in GE models that take account of their influence on the intertemporal consumption/saving arbitrage and on capital intensity. Such settings generally encapsulate an overlapping generations (OLG) framework (see John et al. (1995)). Bovenberg and Heijdra (1998) use this approach to conclude that recycled environmental taxes trigger pro-youth effects. GE-OLG models with environmental taxes, however, generally develop a theoretical approach involving most of the time a limited number of generations (*e.g.*, two: a young and an old one; see Chiroleu-Assouline and Fodha (2006)), thus baring the way to empirical analysis.

Social welfare functionals aggregate the welfare of each individual to get a single index measuring social wellbeing that allows for ordering different policies and/or social situations (for a survey, see Blackorby, Bossert and Donaldson (2005)). The social welfare is intertemporal when the levels of welfare of the individuals are computed over their whole lifecycle. Social welfare functionals can encapsulate a variable degree of aversion of the social planner to inequality. This inequality is intergenerational when social welfare functionals aggregate the intertemporal welfare of the average individual of a cohort born the same year. Two types of social welfare functionals with a variable degree of aversion to intergenerational inequality can be distinguished. The first category ranks intertemporal utilities by decreasing order and then weights the utility of a cohort the more as it is lower ("Gini-generalised", see Donaldson and Weymark (1980) for instance). A second category applies an increasing and concave transformation when aggregating the intertemporal utilities of the cohorts (Kolm (1969), Pollack (1971)). Depending on the value of the parameter measuring the aversion to intergenerational inequality, social preferences tend to the utilitarianism of the mean, the rawlsian maximin or lie in-between.

This article models the social choice between different scenarios of implementing and recycling a carbon tax, based on levels of wellbeing of individuals obtained from a computable GE-OLG model and parameterised on empirical data. The OLG framework encapsulates more than 60 cohorts each year and a public finance module (as in Auerbach and Kotlikoff (1987)). The model assesses quantitatively the mechanisms involved by the recycling of a carbon tax with numerous cohorts, along with their effects on activity, intergenerational inequality and social welfare. The paper focuses on the influence on the social choice of the preferences of the social planner as concerns intergenerational inequality. We use two types of social welfare functionals which both incorporate a variable parameter measuring the degree of aversion of the social planner to intergenerational inequality. For illustrative purpose, the model is parameterised on German data.

Results show, first, that a fully-recycled carbon tax has a net positive influence on consumption and GDP. Recycling the revenue associated with the carbon tax with lower direct taxes entails more favourable effects on growth than recycling it with higher lump-sum public spendings. Implementing a carbon tax fully recycled through higher public lump-sum expenditures displays intergenerational redistributive effects that are relatively favourable to young and future generations, mainly because of a permanent income effect and a consumption effect that are relatively more favourable to these cohorts. Recycling a carbon tax through lower proportional taxes on income enhances these intergenerational redistributive impacts. It weighs on the intertemporal welfare of the baby-boomers (born in the 1950's and in the 1960's) and is significantly more favourable for young and future cohorts than a redistribution through higher public expenditures.

In general equilibrium, results suggest that the social planner decides to recycle a carbon tax through lower proportional income taxes if its aversion to intergenerational inequality is relatively low. However, it prefers recycling a carbon tax through higher public expenditures if its aversion to intergenerational inequity is relatively high - even if recycling through lower income taxes would have brought about a higher level of GDP. This social choice flows from an arbitrage of the social planner between efficiency and intergenerational inequality, given that recycling through lower proportional taxes triggers stronger intergenerational redistributive effects than increasing lump-sum public expenditures.

The remaining of this article is organised as follows. Section 2 introduces the model used in this paper. Section 3 presents the results obtained as concerns the social choice between recycling an environmental tax through higher public expenditures or lower proportional income taxes, depending on the social aversion to intergenerational inequality. Section 4 concludes and raises about some policy implications.

2 Assessing the impact of a carbon tax on the intergenerational social welfare in an empirical GE-OLG model

2.1 An overlapping generation framework

The dynamics of the model is mainly driven by tax policies, reforms in the sector of energy, world energy prices, demographics, and optimal responses of economic agents to price signals (*i.e.*, interest rate, wage, energy prices). Exogenous energy prices influence macroeconomic dynamics, which in turn affect the level of total energy demand and the future energy mix. One feature of this life-cycle framework is that it introduces a relationship between energy policy, fiscal policy, energy prices, private agents' income and capital accumulation. A technical annex presents the model in details.

2.1.1 The energy sector

The prices of energy are represented in the module for the energy sector by an intertemporal vector of average real price of energy for end-users. This end-use price of energy is a weighted average of end-use prices of electricity, oil products, natural gas, coal and renewables substitutes, where the weighs are the demand volumes.[1] The real end-use prices of *natural gas, oil products and coal* are weighted averages of end-use prices of different sub-categories of natural gas, oil or coal products[2] which take account of the costs of transport, distribution and/or refining, and also of taxes, including a carbon tax depending on the carbon content of each energy. The real end-use price of *electricity* is a weighted average of prices of electricity for households and industry, which take account of the costs of transport and distribution, differents taxes (including carbon quotas) and a market price of production of electricity. *Renewables substitutes* in the model are defined as a set of sources of energy whose price of production is not influenced in the long-run by an upward Hotelling-type trend, which does not contain carbon and thus is not affected by any carbon tax, and which do not raise about problems of waste management (as nuclear).[3] The real price of renewables substitutes in the model is assumed to remain constant over time.[4] See annex for details.

Energy demand in volume is broken down into demand for coal, oil products, natural gas, electricity and renewable substitutes. For future periods, a CES nest of functions allows for deriving the volume of each component of the total energy demand, depending on total demand, (relative) energy prices, and exogenous decisions of government (as in Leimbach et al. (2010)).

[1] This assumption is coherent with low levels of interfuel elasticities of substitution, implying that changes in relative prices of different energies does not alter immediately the structure of the energy mix. This is in line with investment cycles in the energy sector that last over several decades.

[2] *i.e.*, natural gas for households, natural gas for industry, automotive diesel fuel, light fuel oil, premium unleaded 95 RON, steam coal and coking coal.

[3] The demand for these renewables substitutes is approximated, over the recent past, by demands for biomass, biofuels, biogas and waste.

[4] This assumption of a stable real price of renewables in the long-run also avoids using unreliable (and sometimes non existing) time series for prices of renewables energies over past periods and in the future. This simplification relies on the implicit assumption that the stock of biomass is sufficient to meet the demand at any time, without tensions that could end up in temporarily rising prices.

2.1.2 Production function and households

The production function used in this article is a nested CES one (as in Perroni and Rutherford (1995) or Böhringer and Rutherford (1997)), with two levels: one linking the stock of physical capital and labour; the other relating the composite of the two latter with energy (see annex for details). The energy mix derives from total energy demand flowing from production in general equilibrium, and from changes in relative energy prices which trigger changes in the relative demands for oil, natural gas, coal, electricity and renewables. Accordingly, the model allows for a) energy prices to influence the total demand for energy, and b) the total energy demand, along with energy prices, to define in turn the demand for different energy vectors.

The model embodies around 60 cohorts each year[5], thus capturing in a detailed way changes in the population structure. Each cohort is represented by an average individual, with a standard, separable, time-additive, constant relative-risk aversion (CRRA) utility function and an intertemporal budget constraint. The instantaneous utility function has two arguments, consumption and leisure. Formally, the intertemporal utility function of the average working individual of a cohort of age a born in year t is:

$$U^*_{t,0} = \frac{1}{1-\sigma} \sum_{j=a}^{\Psi_{t,0}} \left[\frac{1}{(1+\rho)^j} \left[\left((c^*_{t+j,j})^{1-1/\xi} + \varkappa \left(H_j \left(1 - \ell^*_{t+j,j} \right) \right)^{1-1/\xi} \right)^{\frac{1}{1-1/\xi}} \right]^{1-\sigma} \right]$$

where $c^*_{t+j,j}$ is the consumption level of the average working individual of age j in year t, ρ is the subjective rate of time preference, σ is the relative-risk aversion coefficient, $V_{t,j} = \left((c^*_{t+j,j})^{1-1/\xi} + \eta \left(H_j \left(1 - \ell^*_{t+j,j} \right) \right)^{1-1/\xi} \right)^{\frac{1}{1-1/\xi}}$ is the CES instantaneous utility function at year t, $\varkappa$ is the preference for leisure relative to consumption, $1/\xi$ the elasticity of substitution between consumption and leisure in the instantaneous utility function, and H_j a parameter. Its value depends on the age j of an individual and its annual growth rate is equal to the annual TFP growth rate (with $H_0 = 1$). The intertemporal budget constraint for the working sub-cohort of age 20 (*i.e.*, $j = 0$) in year t is:

$$\ell^*_{t,0}\omega_{t,0} + \sum_{j=1}^{\Psi_{t,0}} \left[\ell^*_{t+j,j}\omega_{t+j,j} \prod_{i=1}^{j} \left(\frac{1}{1+r_{t+i}} \right) \right] = c^*_{t,0} + \sum_{j=1}^{\Psi_{t,0}} \left[c^*_{t+j,j} \prod_{i=1}^{j} \left(\frac{1}{1+r_{t+i}} \right) \right]$$

with $\omega_{t+j,j}$ the after-tax income of a working individual per hour worked. Households receive gross wage and pension income and pay proportional taxes on labour income to finance different public regimes. They benefit from lump-sum public spendings. They pay for energy expenditures. In line with OECD (2005) and Brounen, Kok and Quigley (2012), the consumption of energy increases with age. The annex provides with details.

[5] The exact number of cohorts living at a given year depends on the year and each cohort's life expectancy.

2.1.3 Public finances

The public sector is modeled via a PAYG pension regime, a healthcare regime, and non-ageing related lump-sum public expenditures. The *PAYG pension regime* is financed by social contributions proportional to gross labour income. The full pension of an individual is proportional to its past labour income, and depends on the age of the individual and on the age at which he/she is entitled to obtain a full pension. The *health regime* is financed by a proportional tax on labour income and is always balanced through higher social contributions. The *non-ageing related public expenditures* are financed by a proportional tax levied on (gross) labour income and pensions. Each individual in turn receives in cash a non-ageing related public good which does not depend on his/her age. See annex.

In all scenarios, the fiscal consolidation is achieved mainly through lower public expenditures. Government implements from 2010 on a fully anticipated reform including: a) a rise in the average effective age of retirement of 1,25 year per decade; b) a lower replacement rate for new retirees to cover the residual deficit of the pension regime ; c) a health regime remaining balanced thanks to higher social contributions.

2.2 Policy scenarios

We define 3 policy scenarios. For illustrative purpose, the model is parameterised on German data.

- Scenario A is the no-reform scenario. No carbon tax is implemented.

- Scenario B adds to scenario A the implementation of a carbon tax from 2015 onwards. In the model, the rate of the carbon tax begins at 50€/t in 2015, increases by 5% in real terms per year, until reaching a cap of 146€/t in 2037 and remains constant afterwards.[6] The income associated with the carbon tax is fully redistributed to private agents through higher lump-sum public expenditures.

- Scenario C differs from scenario B only insofar as the income of the carbon tax is recycled through lowering the proportional, direct tax on income that finances lump-sum public expenditures, with the level of the latter remaining unchanged.

Scenario A is the baseline scenario. If government decides any reform incorporated in scenario B or C, it modifies the informational set of all living agents and triggers a reoptimisation process at that year, yielding new future intertemporal paths for consumption, savings and capital supply.

All scenarios assume that energy efficiency keeps increasing in the future by 1,5% per annum, in line with past evidence for Germany. The share of renewables in the production of electricity increases from the current levels to 35% in 2020, 50% in 2030 and 65% in 2040. This corresponds to the target publicly set by German authorities.[7] Scenarios A, B and C assume that future prices of

[6] The price of CO2 in the EU-ETS is supposed to be indexed to the rate of the carbon tax after a few years and increases accordingly in the next decades in this scenario.

[7] Additionnally, facilities producing electricity out of nuclear energy (which amount to one fourth of the electricity produced in Germany in the early 2010's) are shut down in the future in all scenarios - as publicly announced by the German government in the aftermath of the events in Fukushima in 2011.

fossil fuels on world markets will stabilise in the future at their current levels.[8] However, sensitivity analysis was carried out, notably with regularly increasing prices of fossil fuels on world markets.

By construction, in a dynamic GE model, all the variables interact with one another. The only way to isolate the influence of one variable (*e.g.*, a carbon tax) on another (*e.g.*, GDP, cohorts' welfare...) in the intertemporal, general equilibrium consists in running two scenarios where the only difference concerns one variable (*e.g.*, the carbon tax, or its recycling). With such a framework, the influence of implementing a carbon tax can be observed by a comparison between scenario B (or C) with scenario A, depending on the assumption as concerns the redistribution of the public income associated with the tax to households. The difference between scenario C and B mirrors the effect of recycling a carbon tax through lower proportional taxes rather than higher lump-sum public expenditures, namely, the so-called "second dividend" of an environmental taxation.

No carbon tax	**Carbon tax** redistributed through...	
	... higher lump-sum public expenditures	*... lower proportional, direct income taxes*
Scenario A	Scenario B	Scenario C

Figure 1: Main policy scenarios simulated in the model

2.3 Intertemporal social welfare

In order to measure social intertemporal welfare, we use social welfare functionals that encapsulate a variable degree of aversion to intergenerational inequality. In our intertemporal modelling with strictly positive technical progress[9], this raises about some specific problems as pinpointed by Arrow's critique of one aspect of Rawls' theory of justice (Rawls (1971), Arrow (1973)). Arrow focuses on the maximin and shows that applying this criterion in an intertemporal setting with strictly positive technical progress amounts to selecting the reform maximising the welfare of the oldest cohort alive. This is because the intertemporal welfare of the oldest cohort alive is mechanically the lowest among the living cohorts if technical progress is positive and thus increases over time.[10] Arrow's point can be extended to social welfare functionals that take account of the wellbeing of future generations. If the intertemporal wellbeing of future cohorts is not discounted by the social planner,[11]

[8] The International Energy Agency does not publish forecast of prices of energy. Most international organisations (IMF, OECD) usually assume that the prices of fossil fuels on world markets will remain constant in the short run (*i.e.*, over the next two years). Fishelson (1983) provides with a simple analytical model that allows for deriving long run trends in the prices of fossil fuels, depending on a limited set of parameters. In the end, we decided to make an assumption for future prices of fossil fuels and apply sensitivity analysis. Assuming that the price of energy may remain relatively stable over the next decades could be justified, for instance, by noting that the effects on prices of the abundance for natural gas and coal, of the foreseeable demographic-related deceleration of activity in Asia and of the increasing costs of extracting oil may offset each other for still a relatively long period.

[9] In the model, macroeconomic technical progress is measured by the TFP (total factor productivity). See annex.

[10] A positive trend on total factor productivity entails a positive trend in wages and consumption over the lifetime of a cohort. Accordingly, the intertemporal utility is an increasing function of the date of birth, *ceteris paribus*.

[11] Strict welfarism requires that social choice should depend only on information about well-being, disregarding all other information such as, for instance, the year of birth of a cohort. This implies *not* discounting the welfare

then Arrow's critique still holds. If it is discounted, Arrow's critique holds again in case the number of future generations taken into account by the social planner is infinite.[12] If the number of future generations whose wellbeing is discounted is finite, then applying the maximin in this intertemporal modelling environment amounts to selecting the reform maximizing the welfare of either the further cohort in time or the oldest currently living cohort (the latter case corresponding again exactly to Arrow's critique), depending on the values of the social discount rate and the number of future cohorts taken into account. To sum up, intertemporal social welfare functionals with a relatively high aversion to social inequality can often be biased towards the wellbeing of the oldest cohort alive (or towards a cohort born in a far future).

One way to overcome Arrow's critique in our intertemporal framework with positive technical progress consists in using social welfare functionals where the arguments are, for each cohort, the difference between the intertemporal utility in a given, reform scenario and the utility in a baseline no-reform scenario. This specification avoids the problems stemming from the positive correlation between the intertemporal utilities of the representative individual of a cohort and his/her year of birth. Computing the difference between two policy scenarios mechanically cancels out the trend that is common to both vectors of intertemporal utilities.[13]

We use two types of social welfare functionals which both incorporate a variable parameter measuring the degree of aversion of the social planner to intergenerational inequality. The Kolm-Pollack function (Kolm (1969), Pollack (1971), Blackorby, Bossert and Donaldson (2005)) applies a continuous, increasing, concave (logarithmic) transformation to its arguments[14] such that:

$$\Phi_{SCi}^{Kolm} = -\frac{1}{\gamma}\ln\left[\frac{\sum_t\left[N_t\left(1+\rho_s\right)^{-c(t)}\exp\left(-\gamma\left(W_{t,SCi}^{intertemp}-W_{t,SCbase}^{intertemp}\right)\right)\right]}{\sum_t N_t\left(1+\rho_s\right)^{-c(t)}}\right]$$

where Φ_{SCi}^{Kolm} stands for the Kolm-Pollack social welfare functional in a reform scenario SCi. N_t stands for the number of individuals in a cohort born in year t that is alive when the social planner announces its policy, or a cohort born before 2030.[15] The expression $\left(1+\rho_s\right)^{-c(t)}$ refers to the social rate discounting the welfare of future generations in the social welfare functional, with $\rho_s \in [0;1]$.[16] The parameter $\gamma > 0$ increases with the degree of aversion of the social planner to intergenerational inequality. For $\gamma \to 0$, social preferences tend to the utilitarism. For $\gamma \to +\infty$,

of future cohorts. Such a proposal usually may seem problematic at least from an empirical, applied point of view, since it can call for large sacrifices among current generations for the benefit of cohorts living in a far future.

[12] Indeed, applying the maximin in an intertemporal modelling environment does not allow for defining a solution because the further the cohorts in time, the lower their discounted intertemporal utility.

[13] Applying the maximin is specially meaningful with this specification. In case no scenario is Pareto-improving, the strictly rawlsian social planner always prefers the *statu quo* and chooses to implement baseline scenario in which the welfare of the most detrimentally affected cohort is maximised – indeed, it is nil by construction.

[14] Its arguments are the differentials of intertemporal utilities of the representative individual of each cohort born in year t ($W_{t,SCi}^{intertemp}-W_{t,SCbase}^{intertemp}$) where $SCbase$ refers to the baseline scenario A.

[15] From an applied, empirical point of view, it seems reasonable to take account of the welfare of a finite number of future generations. Determining this number is unavoidably arbitrary but the empirical implications are all the more limited as the value of the social discount rate is higher. In what follows, the analysis takes account of the welfare of the cohorts born up to 2030.

[16] We take account of the fact that children do not vote and are considered as future generations by the social planner by setting $c(t)$ such that $\{[t \leq 1996] \to [c(t) = 0]\,;[t \in (1996;2030]] \to [c(t){=}\ t-1996]\}$

they tend to the maximin.

The Gini generalised social welfare functional (see Donaldson and Weymark (1980)) sums its arguments and weights them all the more as their level is lower. A rank-ordered permutation is applied to the vector of the n intertemporal utilities of the cohorts. Differences of intertemporal utilities are ranked by decreasing order and associated with increasing values of ranking $[i]$:

$$\begin{aligned} & \left[W_{t,SCi}^{intertemp} - W_{t,SCbase}^{intertemp} \geq W_{t^*,SCi}^{intertemp} - W_{t^*,SCbase}^{intertemp}\right] \\ \rightarrow \quad & \left[\left[W_{t,SCi}^{intertemp} - W_{t,SCbase}^{intertemp}\right]_{[i]} \geq \left[W_{t^*,SCi}^{intertemp} - W_{t^*,SCbase}^{intertemp}\right]_{[i+1]}\right] \qquad \forall t, \forall t^* \neq t, \forall i \in [1, n-1] \end{aligned}$$

where $W_{t,SCi}^{intertemp}$ stands for the intertemporal utility of a cohort born in year t in the reform scenario SCi. In this context, the Gini generalised social welfare functional is:

$$\Phi_{SCi}^{Gini} = \frac{\sum_t \left(N_t \left(1+\rho_s\right)^{-c(t)} \left[i^{\vartheta} - (i-1)^{\vartheta}\right] \left[W_{t,SCi}^{intertemp} - W_{t,SCbase}^{intertemp}\right]_{[i]}\right)}{\left(\sum_t N_t \left(1+\rho_s\right)^{-c(t)}\right)^{\vartheta}}$$

The parameter $\vartheta \geq 1$ stands for the degree of aversion of the social planner to intergenerational inequality. If $\vartheta = 1$, then Φ_{SCi}^{Gini} corresponds to the utilitarism of the mean. For $\vartheta \rightarrow 0$, Φ_{SCi}^{Gini} tends to the maximin because the weight of the lowest intertemporal utility is increasingly higher that the other weights. Between these two polar cases, the degree of aversion of the social planner to inter-generational inequality can vary in a continuous fashion.[17]

3 Results

3.1 Aggregate effects

3.1.1 Effects on growth dynamics

Figure 2 displays some numerical results obtained in the model, notably as concerns the prices of energy, the carbon tax, the demand for energy, the accumulation of capital and the GDP growth.

In the baseline scenario A where no carbon tax is implemented, the capital per unit of efficient labour rises gradually over the future decade in this model parameterised on German data. Indeed, German demography is ageing relatively quickly and will keep weighing on the labour force.

[17] Such a specification assumes cardinal comparability of the preferences since the utilities are weighted by the number of individuals in each cohort (i.e., by N_t). Incidentally, it avoids Parfit's (1982 and 1984) so-called "repugnant conclusion" by taking account of the size of the total population - as it clearly appears, for instance, when $\vartheta = 1$.

In scenario B where a carbon tax is implemented, retail prices of electricity for industry rise by 77% in 2040 in real terms as compared to their level in 2009.[18] The total weighted end-use price of energy displays a strong upward trend (+51% in real terms from 2009 to 2040). In this context, the future total demand for energy in volume remains broadly stable.[19] As concerns public finances, the revenue associated with the carbon tax in the model (close to 50bn€$_{2010}$ in 2040) is redistributed to the households each year through higher lump-sum public expenditures. In 2040, these lump-sum public expenditures are 1,7 point of percentage (of private agents' income) higher than in scenario A with no carbon tax.

If the carbon tax had not been recycled (a scenario not presented here), it would have weighed on economic activity[20] in line with its detrimental impact on the income of private agents. The private agents would have increased their saving rate so as to partly offset the downward effect of the tax on their future consumption. On the aggregate level, this would have entailed some substitution between physical capital and energy.

In scenario B, the carbon tax is fully-recycled and triggers a net (slightly) positive influence on GDP. This stems from a direct comparison between the results of scenario B and scenario A. The favourable influence on activity in the long run of fully recycling a carbon tax in scenario B is related to its downward effect on the demand for energy in volume. Indeed, since the carbon tax weighs on the total demand for energy in volume, the rise in the total energy expenditures paid by private agents - which mirrors volume and real price effects altogether - is less than the amount of the carbon tax collected and fully redistributed. Accordingly, the households' net income, which encompasses energy expenditures and public transfers, rises in the model. This fosters consumption. Capital supply is lower in scenario B than in scenario A. Labour supply increases slightly.[21] Overall, compared to the no-reform scenario A, a carbon tax fully recycled through higher public lump-sum spendings weighs on the capital per unit of efficient labour and on the demand for energy, and fosters aggregate consumption.

Scenario C incorporates a carbon tax which is fully redistributed by lowering the proportional direct income tax that finances the lump-sum public, non-ageing related, expenditures regime. In 2040, this proportional income tax is 1,7 point of percentage (of private agents' income) lower than in scenarios A or B. Recycling the revenue associated with the carbon tax with lower direct taxes on income entails more favourable effects on growth than recycling it with higher lump-sum public spendings. In other words, the second dividend is positive in the model. This stems from a direct comparison between the results of scenario C and scenario B. Intuitively, lessening taxes that have distortionary effects on the labour supply in the model[22] has a more favourable effect on private agents' gross income and on overall economic activity than raising lump-sum public transfers. This is in line with the litterature on optimal environmental taxation (Nichols (1984), Terkla (1984), Pearce

[18] This corresponds, for instance, with a cumulated increase in nominal terms of 181%, assuming an inflation rate of 1,5% per annum in the future.

[19] By assumption, energy efficiency gains are constant in the model. Had they accelerated, the decline of energy demand would have been stronger. The assumption of stable annual energy gains has no significant impact on the results since the results are presented as differences between policy scenarios that rely on the same assumptions as regards energy efficiency.

[20] By close to -0,05% per year of GDP during the 2030's in the model.

[21] Analysing the first order intratemporal condition for a working individual here would suggest that increasing prices of energy, in line with the creation of a carbon tax, bolsters the amount of expenditures in energy ($d_{t,energy}$) and thus tends to increase optimal working time *ceteris paribus*.

[22] See annex, first order intratemporal condition in the household's optimisation program.

All currencies (€,$) are in constant value 2010		Assumptions common to scenarios A, B and C				
		2012			**2040**	
Production price of natural gas ($/MBTu)		10			10	
Production price of oil ($/barel)		108			108	
Production price of coal (€/t)		78			78	
Rate of the social contribution to the pension regime (%)		10%			10%	
Average effective age of retirement (years)		61			65	
Rate of the social contribution to the health regime (%)		7%			9%	
	Scenario A		**Scenario B**		**Scenario C**	
	2009	**2040**	**2009**	**2040**	**2009**	**2040**
Rate of the carbon tax on oil and natural gas (€/t)		0		146		146
Price of the CO2 quotas in the EU-ETS (€/t)	13	0	13	146	13	146
Production market price of electricity (€/MWh)(ind. effect of renewables)	53	38	53	66	53	66
Tax financing feed-in tariffs for wind and PV (€/MWh, € constant 2010)	28	119	28	95	28	95
Fraction of renewables in the energy mix (ind.hydro, wind, PV)(%)	14%	31%	14%	33%	14%	33%
Price of electricity - retail - households (€/MWh)	231	341	231	386	231	386
Price of electricity - industry (€/MWh)	107	165	107	190	107	190
Price of natural gas - households (€/MWh)	71	74	71	103	71	103
Price of natural gas - industry (€/MWh)	35	39	35	68	35	68
Price of automotive diesel fuel (€/l)	1,1	1,5	1,1	1,9	1,1	1,9
Price of fuel oil (€/l)	0,5	0,9	0,5	1,3	0,5	1,3
Price of premium unleaded RON 95 (€/l)	1,3	1,6	1,3	2,1	1,3	2,1
Total weighted end-use price of energy in the model (1989=100)	151	178	151	228	151	228
Demand for energy (1989=100)(volume)	89	103	89	93	89	93
Tax financing non-ageing related public spendings (% of gross income)	18%	18%	18%	18%	18%	16%
Non-ageing related public spendings (% of gross income)	18%	18%	18%	20%	18%	18%
	Scenario A		**Scenario B**		**Scenario C**	
	2009	**2040**	**2009**	**2040**	**2009**	**2040**
Capital per unit of efficient labour (1989=100)	132,3	145,4	132,3	145,1	132,3	145,6
Average cost of productive capital (real)(1989=100)	78,1	71,7	78,1	71,9	78,1	71,7
Real GDP level (1989=100)		197,7		198,5		198,8

Figure 2: Some aggregate results in the model

(1991) and Poterba (1991)) which suggests that substituting environmental taxes with other, direct taxes may reduce the distortionary cost of the tax system and thus enhance economic activity. As far as the households' accounts are concerned, this result mirrors a joint influence of fiscal policy on the households' income and their life-cycle consumption/saving behaviour, entailing some additional capital deepening when taxes are lowered. Lessening the proportional tax amounts, in absolute terms, to distributing more revenues to cohorts receiving higher wages. These cohorts receiving on average a higher gross labour income are relatively older working cohorts, which are more productive in the model than the younger working cohorts. In line with the life-cycle theory, the saving rate of aged working cohorts is also higher than the one of younger working cohorts. Overall, capital supply (and capital per unit of efficient labour[23]) is higher in scenario C than in scenario B.[24]

[23] The optimal labour supply in scenario C is not sizeably different than in scenario B because, along with positive distorsive effects associated with lower taxes on income, other effects take place in general equilibrium that offset most of this impact.

[24] These results are reasonably robust to different parameterisations of the model. For instance, sensivity analysis was carried out with increasing prices of fossil fuels on world markets in the next decades. Results presented in the paper remain qualitatively valid, with orders of magnitude varying within reasonable bounds. When prices of fossil fuels are higher, the capital supply is higher (because private agents save more in order to partially offset the detrimental effect on their consumption of higher energy prices), GDP growth is lower (because private agents have to pay more for getting the same amount of energy services) and the demand of energy is lower (because private

3.1.2 Intergenerational redistributive effects

Figure 3 displays the current annual welfare, at each year and for each cohort in the model, in scenario B as compared to scenario A.[25] Accordingly it materializes the intergenerational effects of implementing a carbon tax fully recycled through higher lump-sum, non-ageing related, public expenditures. Two intergenerational redistributive mechanisms are involved here, and both favor younger and future cohorts. First, a permanent income effect: the shorter the period of life remaining before death, the smaller the effects on optimal behaviours, defined intertemporally, of a permanent rise in lump-sum public expenditures. Thus the currently older the cohort, the smaller the positive influence on permanent income associated with the recycling of the carbon tax. Second, an energy consumption effect: since the energy consumption increases with age in the model, the magnifying effect of a carbon tax on energy prices weighs relatively more on older households. The net effect of recycling a carbon tax is thus relatively lower for the current older generations, as shown in Figure 3, because the detrimental energy consumption effect (which is relatively stronger for them) offsets the favourable permanent effect (which is relatively smaller for these generations). For young and future cohorts, the detrimental energy consumption effect (which is relatively subdued as far as they are concerned) is dominated by the favourable permanent effect (which is relatively stronger for these generations).

If the carbon tax had not been recycled, its impact on the future annual welfare would have been detrimental for all cohorts. As concerns currently living cohorts, the detrimental impact would have been relatively more concentrated on the baby-boomers (*i.e.*, cohorts currently aged around 45-65) because these cohorts are not sufficiently young - so as to benefit from a relatively lower detrimental consumption effect - nor sufficiently old - so as to benefit from a relatively lower, detrimental permanent income effect. As concerns future cohorts, a non-recycled carbon tax would have been more detrimental for them than for current cohorts, firstly because the carbon tax would apply to their whole lifecycle, and secondly because the rate of the carbon tax increases over time by assumption in the model.

Figure 4 displays the current annual welfare in scenario C as compared to scenario B. It materializes the intergenerational effects of the second dividend associated with the carbon tax. It may be useful to remind here that annual welfare in the model depends on the optimal consumption and leisure paths defined by perfectly anticipating households over their whole life-cycle, and not only on their current income. The impact on future welfare of recycling a carbon tax through lower direct taxes rather than higher lump-sum spendings mirrors mainly two differents effects in the model: a wage-profile effect and a discounting effect. As concerns the wage-profile effect, replacing higher lump-sum spendings with lower proportional taxes on income mechanically benefits to cohorts with higher income - basically, the older, active cohorts aged 45-65 - while being detrimental to cohorts with relatively lower income - *i.e.*, the young cohorts and the retired ones at any given year. In this context, recycling the tax with lower proportional taxes on income rather than higher lump-sum spendings triggers detrimental impacts on the permanent income of the relatively older cohorts over their remaining life-cycle. This impact is all the more significant as the cohort is not too old and has two or three decades of life remaining. The other intergenerational redistributive effect involved by

agents substitute some physical capital to energy in the model).

[25] Before the announcement of a reform package, annual current welfare of one cohort is by assumption equal between the baseline scenario A and any of the reform scenarios B and C. Graphically, this involves a flat portion of the surface, at value 0.

lowering direct proportional taxes rather than raising lump-sum public spendings is the discounting effect. It is relatively more beneficial to young cohorts. For young cohorts, recycling the tax with lower proportional taxes rather than higher lump-sum spendings bolsters their permanent income and future annual welfare. Indeed, such policy successively weighs on income during the youth, bolsters income between 40 and 65, and weighs again on income when retired. However, this latter effect is strongly discounted when computing the permanent income of a young cohort. The net effect on the permanent income of a young cohort is positive in the model, and so is, accordingly, its effect on the future annual welfare of young cohorts, as displayed on Figure 4.[26][27]

Overall, a carbon tax recycled through lower direct taxes rather than higher lump-sum spendings displays intergenerational effects that are beneficial to young and future cohorts, but detrimental to current baby-boomers.

Figure 5 displays the effects on *the intertemporal welfare of each cohort*, and for each scenario of reform compared to scenario A.[28] These results complete those obtained with the future annual current welfare. In scenario B, the fiscal policy implementing a carbon tax fully recycled through higher public lump-sum expenditures displays intergenerational redistributive effects that are relatively favourable to young and future generations. Additionnally, in this empirical model parameterised on real data, it is close to be a Pareto-improving policy as compared to the no-reform scenario A. Results obtained for scenario C confirm that recycling a carbon tax through lower proportional taxes on income rather than higher lump-sum public spendings triggers stronger intergenerational redistributive impacts. It weighs on the intertemporal welfare of the currently relatively aged cohorts, and notably of the baby-boomers (born during the 1950's and the 1960's). However, compared to scenarios A and B, it is significantly more favourable for young and future cohorts than scenarios A and B.

3.2 Effects of the social aversion to intergenerational inequality on the recycling of the carbon tax

Figure 6 and 7 show the social choice between scenarios A, B and C depending on the value of two parameters in the social welfare functional: the social aversion to intergenerational inequality and the discount rate applied by the social planner to the intertemporal wellbeing of future cohorts. Social welfare is computed with the Kolm-Pollack social welfare functional in Figure 6, and with the Gini generalised function in Figure 7. The social planner chooses to implement the decision

[26] Additionnally, the capital per unit of efficient labour is higher when the carbon tax is recycled through lower proportional taxes (as in scenario C) rather than through higher public lump-sum expenditures (as in scenario B)(see preceeding subsection). This weighs on the yield of the saving of these cohorts which have accumulated significantly more capital than younger cohorts when the carbon tax is implemented in the model. This lessens relatively more the optimal consumption path of older cohorts in the model, and thus their future annual welfare. This is a capital-yield effect, which stems from the general equilibrium in the model.

[27] The intergenerational redistributive effects are qualitatively relatively robust to different assumptions as concerns future prices of fossil fuels on world markets: the graphs obtained in scenarios with increasing prices of fossil fuels on world markets display the same patterns as those presented here.

[28] Thus, the $W_{t,SCB}^{intertemp} - W_{t,SCbase}^{intertemp}$'s and the $W_{t,SCC}^{intertemp} - W_{t,SCbase}^{intertemp}$'s.

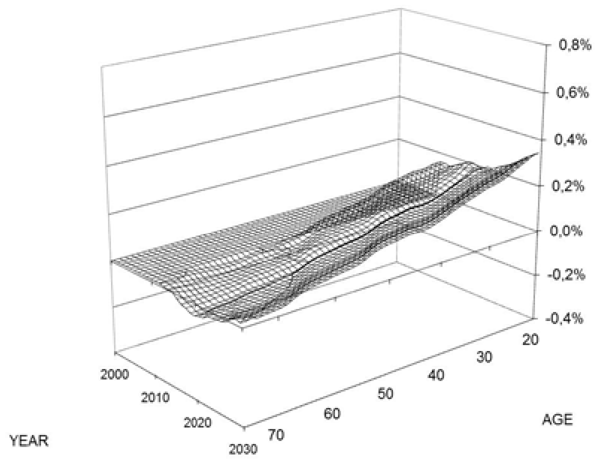

Figure 3: Effect on the annual welfare of the cohorts associated with implementing a carbon tax fully recycled through higher lump-sum public expenditures (scenario B - scenario A)

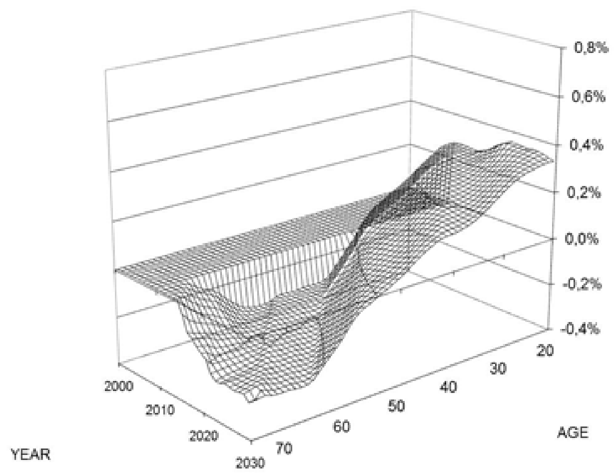

Figure 4: Effect on the annual welfare of the cohorts associated with implementing a carbon tax fully recycled through lower proportional taxes on income rather than higher lump-sum public expenditures (scenario C - scenario B)

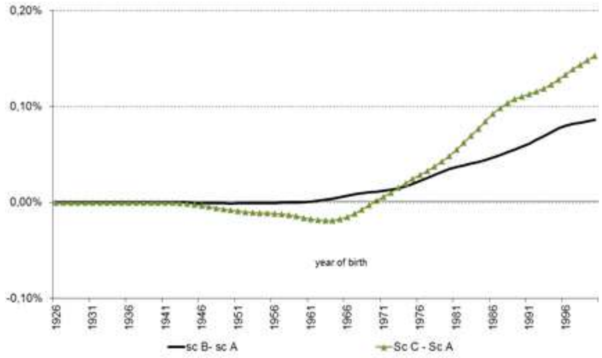

Figure 5: Effect of recycling a carbon tax on the intertemporal welfare of the cohorts

that maximises the intertemporal social welfare as assessed by the two social welfare functionals.[29]

Results suggest that, in general equilibrium, the social planner decides to recycle a carbon tax through lower proportional income taxes if its aversion to intergenerational inequity is relatively low.[30] Graphically, these characteristics of social preferences correspond to the left handside of the (γ, ρ_s) (or (ϑ, ρ_s)) plans in Figures 6 and 7, respectively. However, the social planner decides to recycle a carbon tax through higher public expenditures if its aversion to intergenerational inequity is relatively high. Graphically, these characteristics of social preferences correspond to the right handside of the (γ, ρ_s) (or (ϑ, ρ_s)) plans in Figure 6 and 7, respectively.[31] These results hold even if recycling through lower income taxes increases the GDP in all cases, as shown above. They mirror an arbitrage of the social planner between efficiency and intergenerational equality, given that recycling through lower proportional taxes triggers stronger intergenerational redistributive effects than increasing lump-sum public expenditures and favours relatively more the future generations. As far as social preferences are concerned, this may more than offset the favourable effect on GDP of the "second dividend" when social aversion to intergenerational inequality is high.

4 Conclusion and policy implications

This paper analyses the effect of social aversion to intergenerational inequality on the social choice as concerns implementing and redistributing a carbon tax. It relies on a detailed computable general equilibrium model with overlapping generations and an energy module, with a parameterisation on

[29] Sensitivity analysis suggests that these results are reasonably robust to different parameterisation of the model, for instance as concerns the future dynamics of fossil fuel prices on world markets.

[30] and/or, in the case of the Kolm-Pollack function, if the weight assigned to the wellbeing of future generations is relatively high, implying a relatively low social discount rate of their wellbeing.

[31] The decision of *not* implementing a carbon tax at all would characterise a social planner with (quasi)rawlsian preferences, with a degree of aversion to intergenerational inequity that tends to $+\infty$. Intuitively, if the social planner refuses to lessen the welfare of any cohort, it prefers the *status quo*.

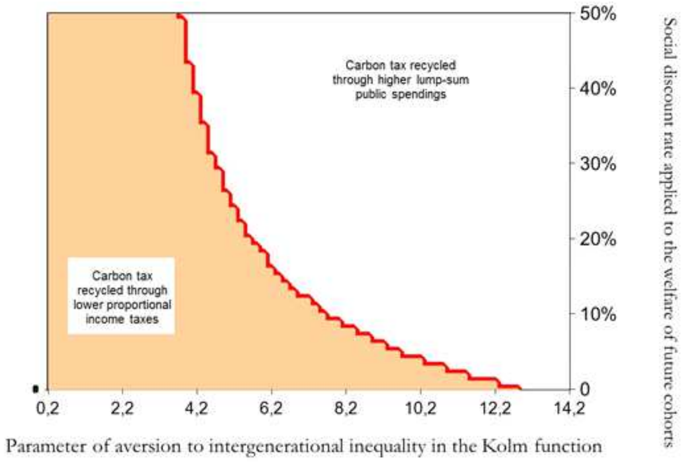

Figure 6: Social choice using the Kolm-Pollack social welfare functional

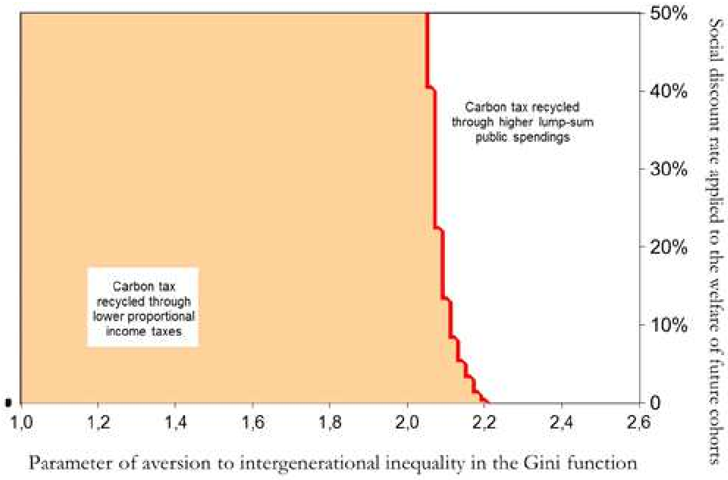

Figure 7: Social choice using the Gini-generalised social welfare functional

empirical data. Results suggests that the social planner recycles a carbon tax through higher public expenditures (*resp.* lower proportional income taxes) if its aversion to intergenerational inequity is relatively high (*resp.* low). This holds even if fully recycling through lower income taxes is always more favourable to the level of GDP.

The policy implications of this paper are twofold. First, due to intergenerational redistributive effects, implementing a fully recycled carbon tax is not necessarily Pareto-improving. In a polar case where the social planner refuses that its decision lessens the intertemporal welfare of any cohort, it will prefer the status quo - *i.e.*, not implementing a carbon tax. Second, if public authorities have a relatively high aversion to intergenerational inequality - a situation that is not unrealistic in current democracies - then they will prefer fully recycling the carbon tax with higher public spendings rather than lowering proportional, distorsive taxes, even if the latter would have delivered better results as concerns the level of GDP. Accordingly, even if the "second dividend" is positive, the social planner may still prefer, in some cases, recycling a carbon tax with higher public spendings rather than lower income taxes.

A Description of the GE-OLG model

This CGE model displays an endogenously generated GDP with exogenous energy prices influencing macroeconomic dynamics, which in turn affect the level of total energy demand and the future energy mix. GE-OLG models combine in a single framework the main features of GE models (Arrow and Debreu, 1954), Solow-type growth models (Solow, 1956), life-cycle models (Modigliani and Brumberg, 1964) and OLG models (Samuelson, 1958). The development of applied GE-OLG models, using empirical data, owes much to Auerbach and Kotlikoff (1987). This GE model includes a detailed overlapping generations framework so as to analyse, in a dynamic setting, the intergenerational redistributive effects of energy and fiscal reforms, and to take account of demographic dynamics on the economic equilibrium.[32]

A.1 The Energy sector

A.1.1 Energy prices

End-use prices of natural gas, oil products and coal ($q_{1,t}$, $q_{2,t}$, $q_{3,t}$) The end-use prices of natural gas, oil products and coal ($q_{i,t}$, $i \in \{1;2;3\}$) are computed as weighted averages of prices of different sub-categories of energy products: $\forall i \in \{1;2;3\}$, $q_{i,t} = \sum_{j=1}^{n} a_{i,j,t} q_{i,j,t}$. $q_{i,j,t}$ stands for the real price of the product j of energy i at year t. For natural gas ($i = 1$), two sub-categories j are modeled: the end-use price of natural gas for households ($j = 1$) and the end-use price of natural gas for industry ($j = 2$). For oil products ($i = 2$), three sub-categories j are modeled: the end-use price of automotive diesel fuel ($j = 1$), the end-use price of light fuel oil ($j = 2$) and the end-use price of premium unleaded 95 RON ($j = 3$). For coal ($i = 3$), two sub-categories j are modeled: the end-use price of steam coal ($j = 1$) and the end-use price of coking coal ($j = 2$). This hierarchy of energy products covers a great part of the energy demand for fossil fuels. The $a_{i,j,t}$'s weighting coefficients are computed using observable data of demand for past periods. For future periods, they are frozen to their level in the latest published data available: whereas the model takes account of interfuel substitution effects (cf. *infra*), it does not model possible substitution effects between sub-categories of energy products (for which data about elasticities are not easily available).

The end-use prices of sub-categories of natural gas, oil or coal products ($q_{i,j,t}$) are in turn computed by summing a real supply price with transport/distribution/refining costs and taxes:

$$\forall i \in \{1;2;3\},\ \forall j,\ q_{i,j,t} = q_{i,j,t,s} + q_{i,j,t,c} + q_{i,j,t,\tau}$$

[32] In line with most of the literature on dynamic GE-OLG models, the model used here does not account explicitly for effects stemming from the external side of the economy. First, the question that is adressed here is: what optimal choice should the social planner do as concerns energy and fiscal transition so as to maximize long-run growth and minimize intergenerational redistributive effects? Accounting for external linkages would not modify substantially the answer to this question. It would smooth the dynamics of the variables but only to a limited extent. Home bias (the "Feldstein-Horioka puzzle"), exchange rate risks, financial systemic risk and the fact that many countries in the world are also ageing and thus competing for the same limited pool of capital all suggest that the possible overestimation of the impact of ageing on capital markets due to the closed economy assumption is small.

- $q_{i,j,t,s}$ stands for the real supply price at year t of the product j of energy i. This real price is computed as a weighted average of real import costs and real production prices: $\forall i \in \{1;2;3\}$, $\forall j$, $q_{i,j,t,s} = [M_{i,j,t}m_{i,j,t} + P_{i,j,t}p_{i,j,t}] / [M_{i,j,t} + P_{i,j,t}]$ where $M_{i,j,t}$ stands for imports in volume of the product j of energy i at year t ; $m_{i,j,t}$ stands for imports costs of the product j of energy i at year t ; $P_{i,j,t}$ stands for national production, in volume, of the product j of energy i at year t ; $p_{i,j,t}$ stands for production costs of national production of the product j of energy i at year t. The weights $M_{i,j,t}$ and $P_{i,j,t}$ are computed using OECD/IEA databases for past periods, and frozen to their latest known level for future periods.

- $q_{i,j,t,c}$ stands for the cost of transport and distribution and/or refinery for the different energy products for natural gas, oil and coal. More precisely, $q_{1,1,t,c}$ stands for the cost of transport and distribution of natural gas for households in year t; $q_{1,2,t,c}$ stands for the cost of transport of natural gas for industry in year t; $q_{2,1,t,c}$, $q_{2,2,t,c}$ and $q_{2,3,t,c}$ stand respectively for the cost of refining and distribution for automotive diesel fuel, light fuel oil and premium unleaded 95 RON in year t; $q_{3,1,t,c}$ and $q_{3,2,t,c}$ stand respectively for the transport cost of steam coal and coking in year t. The $q_{i,j,t,c}$'s are calculated as the difference between the observed end-use prices excluding taxes by category of products (as provided by OECD/IEA databases) and the supply prices (the $q_{i,j,t,s}$'s) as computed above. For future periods, each $q_{i,j,t,c}$'s is computed as a moving average over the 10 preceding years before year t.

- $q_{i,j,t,\tau}$ stands for the amount, in real terms, of taxes paid by an end-user of a product j of energy i at year t. For past periods, these data are provided by OECD/IEA databases. They include VAT, excise taxes, and other taxes: $q_{i,j,t,\tau} = VAT_{i,j,t} + Excis_{i,j,t} + others_{i,j,t} + carbon\ tax_{i,j,t}$. For future periods, the rate of $VAT_{i,j,t}$ and $others_{i,j,t}$ are computed as a moving average over the latest 10 years before year t, and the absolute real level of $Excis_{i,j,t}$ is computed as a moving average over the latest 10 years before year t. For future periods, depending on the reform scenario considered, $q_{i,j,t,\tau}$ can also include a carbon tax ($carbon\ tax_{i,j,t}$) which is computed by applying a tax rate to the carbon contained in one unit of volume of product j of energy i.

Prices of electricity ($q_{4,t}$) The real end-use price of electricity is computed as a weighted average of prices of electricity for households and industry ($i = 4$); $q_{4,t} = \sum_{j=1}^{2} a_{4,j,t}q_{4,j,t}$. $q_{4,j,t}$ stands for the end-use real price, at year t , of the product j of electricity. Two sub-categories j are modeled: the end-use price of electricity for households ($j = 1$) and the end-use price of electricity for industry ($j = 2$). The $a_{4,j,t}$'s weighting coefficients are computed using observable data of demand for past periods, and frozen to their level in the latest published data available for future periods. Real end-use prices of electricity are computed by adding network costs of transport and distribution ($q_{4,j,t,c}$) and differents taxes (VAT, excise, tax financing feed-in tariffs for renewables, carbon tax...)($q_{4,j,t,\tau}$) to an endogenously generated (structural) wholesale market price of production of electricity ($q_{4,t,s}$): ($i = 4$); $\forall j$, $q_{4,j,t} = q_{4,t,s} + q_{4,j,t,c} + q_{4,j,t,\tau}$

Wholesale structural market price of production of electricity ($q_{4,t,s}$) The wholesale market price of production of electricity ($q_{4,t,s}$) is computed from an endogenous average peak price of electricity and a peak/offpeak spread: $\forall j$, $q_{4,t,s} = \frac{(q_{el,peak,t} + spread_{peak,t} * q_{el,peak,t})}{2}$. The parameter $spread_{peak,t}$ is constant for future periods and set at 75% (corresponding to a spread of 25%).

The peak market price of production of electricity ($q_{el,peak,t}$) derives from costs of production of electricity among different technologies, weighted by the rates of marginality in the electric system of each production technology: $q_{el,peak,t} = \frac{\left[\sum_{x=1}^{9} \xi_{el,x,t} \varrho_{el,x,t,prod}\right](1+\xi_{el,import,t})}{\left[\sum_{x=1}^{9} \xi_{el,x,t}\right]+\xi_{el,import,t}+\varpi_{fatal,t}}$. The costs of producing electricity ($\varrho_{el,x,t,prod}$) are computed for 9 different technologies x: coal ($x = 1$), natural gas ($x = 2$), oil ($x = 3$), nuclear ($x = 4$), hydroelectricity ($x = 5$), onshore wind ($x = 6$), offshore wind ($x = 7$), solar photovoltaïc ($x = 8$), and biomass ($x = 9$). The $\xi_{el,x,t}$'s stand for the rates of marginality in the electric system of the producer of electricity using technology x

Cost of production of electricity among different technologies ($\varrho_{el,x,t,prod}$) Following, for instance, Magné, Kypreos and Turton (2010), each $\varrho_{el,x,t,prod}$ is computed as the sum of variable costs (*i.e.*, fuel costs and operational costs) and fixed (*i.e.*, investment) costs of producing electricity: $\forall x,\ \varrho_{el,x,t,prod} = \left[\frac{\varrho_{el,x,t,fuel}+\varrho_{co2\ price,t}*\varrho_{el,x,t,co2em}}{\varrho_{el,x,t,therm}} + \varrho_{el,x,t,ops}\right]+\varrho_{el,x,t,fixed}$ where $\varrho_{el,x,t,fuel}$ stands for the fuel costs for technology x (either coal, oil, natural gas, uranium, water, biomass for costly fuel, or wind and sun for costless fuels) measured in €/MWh; $\varrho_{el,x,t,therm}$ stands for thermal efficiency (in %). CO2 costs are measured by the exogenous price of CO2 on the market for quotas (EU ETS) ($\varrho_{co2\ price,t}$, in €/ton), as applied to technology x characterised by an emission factor $\varrho_{el,x,t,co2em}$ expressed in t/MWh; $\varrho_{el,x,t,ops}$ stands for operational and maintenance variable costs (in €/MWh). Fixed costs $\varrho_{el,x,t,fixed}$ are expressed in €/MWh and computed according to the following annuity formula: $\forall x,\ \varrho_{el,x,t,fixed} = \frac{\varrho_{el,x,t,inv}\frac{1+\varrho_{el,x,t,prodloss}}{1+\varrho_{el,x,t,learning}}\varrho_{el,x,t,cap\ c}}{\left(1-(1+\varrho_{el,x,t,cap\ c})^{-\varrho_{el,x,t,life}}\right)\varrho_{el,x,t,util}}$. $\varrho_{el,x,t,inv}$ corresponds to overnight cost of investment (expressed in €/MW); $\varrho_{el,4,t,prodloss}$ is the rate of productivity loss due to increased safety in the nuclear industry ; $\varrho_{el,x,t,learning}$ is the learning rate for renewables; $\varrho_{el,x,t,cap\ c}$ stands for the cost of capital ($\varrho_{el,x,t,cap\ c} = 10\%$); $\varrho_{el,x,t,life}$ the average lifetime of the facility (in years) depending of the technology used; $\varrho_{el,x,t,util}$ the utilisation rate of the facility (in hours). All these parameters are exogenous and found mainly in IEA and/or NEA databases.

Rates of marginality ($\xi_{el,x,t}$) and main peaker between coal firing and natural gas firing ($\xi_{el,1,t}$ and $\xi_{el,2,t}$) The rates of marginality are the fraction of the year during which a producer of electricity is the marginal producer, thus determining the market price during this period. These rates are exogenous in the model. They are computed by the Energy Regulation Authority and/or by operators in the electric sector. For future periods, the model uses the 2010 values which are frozen onwards.[33]

The computation of the future values for $\xi_{el,1,t}$ and $\xi_{el,2,t}$ in the model stems from an endogenous determination of the main peaker, either coal firing or natural gas firing. The model computes, for each year $t > 2012$, the clean dark spread and the clean dark spread. These are mainly influenced by CO2 prices ($\varrho_{co2\ price,t}$), respective emission factors ($\varrho_{co2\ price,t}$ and $\varrho_{el,2,t,co2em}$) and fuel costs ($\varrho_{el,x,1,fuel}$ and $\varrho_{el,x,2,fuel}$). Each year $t > 2012$, if the difference between the clean spark spread

[33] Accordingly, the formula used for computing ($q_{elec,peak,t}$) assumes that the energy mix of imports is the same as the domestic energy mix.

and the clean dark spread is negative, and if the clean dark spread alone is positive, then the main peaker is coal. The reverse holds if signs are opposite (the natural gas become main peaker).

Simulated market peak price of production of electricity ($q_{el,peak,t}$) The development of fatal producers of electricity (onshore wind, offshore wind and solar PV) weighs down on market prices by moving rightward the supply curve. We take account of this phenomenon by introducing a parameter $\varpi_{fatal,t}$ [34] in the denominator of the expression of $q_{el,peak,t}$ which allows for capturing some characteristics of fatal producers of electricity. Their marginal cost is nil and they are not marginal producers: hence $\xi_{el,6,t} = \xi_{el,7,t} = \xi_{el,8,t} = 0\%$ in the numerator. They shift the supply curve of the wholesale market rightward: hence the more they produce, the less the market price. This is taken into account in the model by introducing $\varpi_{fatal,t}$ at the denominator of $q_{el,peak,t}$. We assume that the mark-up of market price of electricity over the average weighted cost of production is zero. A parameter $markup_{el,t}$ could have been included. Including such a parameter would have brought about the question of the modelling of the associated surplus between economic agents. Since this parameter would have remained constant, its first order effect on the dynamics of the model would have been zero.

Network costs of electricity ($q_{4,j,t,c}$) $q_{4,j,t,c}$ stands for the cost of transport and/or distribution of electricity. More precisely, $q_{4,1,t,c}$ stands for the cost of transport and distribution of electricity for households in year t; $q_{4,2,t,c}$ stands for the cost of transport (only) of electricity for industry in year t. The $q_{4,j,t,c}$'s are calculated as the difference between the observed end-use prices excluding taxes of electricity for households or industry (as provided by OECD/IEA databases) and the supply price ($q_{4,t,s}$) as computed above. For future periods, each $q_{4,j,t,c}$'s is computed as a moving average over the 10 preceding years before year t. In scenarios of reforms involving a rise in the fraction of electricity produced out of fatal producers (i.e., onshore and offshore wind and solar PV), supplementary network costs are incorporated in the model following NEA (2012) orders of magnitude.[35]

Taxes on electricity ($q_{4,j,t,\tau}$): VAT, excise tax, tax financing feed-in tariffs for renewables $q_{4,j,t,\tau}$ stands for the amount, in real terms, of taxes paid by an end-user of electricity (either households ($j = 1$) or industry ($j = 2$)) at year t: $\forall j \in \{1;2\}$, $q_{4,j,t,\tau} = VAT_{4,j,t} + Excis_{4,j,t} + others_{4,j,t} + TafFTAR_{4,t}$. For past periods, these data are provided by OECD/IEA databases. They include VAT, excise taxes and other taxes. For future periods, the rates of $VAT_{4,j,t}$ and $others_{4,j,t}$ are computed as a moving average over the latest 10 years before year t, and the absolute real level of $Excis_{4,j,t}$ (if any) is computed as a moving average over the latest 10 years before year t. For future periods, depending on scenario reforms, $q_{4,j,t,\tau}$ can also include a tax financing feed-in tariffs for fatal producers of electricity ($TafFTAR_{4,t}$, in €/MWh). Indeed, government in the model is assumed, when it decides to implement an energy transition, to create a scheme compensating the difference between the market price of electricity ($q_{4,j,t,s}$) and

[34] $\varpi_{fatal,t}$ assesses the penetration level of fatal producers of electricity at year t and is computed as the ratio between production of electricity out of wind and solar PV ($x \in \{6;7;8\}$, in GWh) in year t divided by total demand of electricity in year $t-1$.

[35] NEA (2012) computes the supplementary network cost (in €/MWh) of a given rise in the penetration rate of intermittent sources of electricity.

the costs of production for onshore and offshore wind and solar PV ($q_{el,6,t,prod}$, $q_{el,7,t,prod}$, $q_{el,8,t,prod}$ respectively) by levying an indirect tax on end-use prices excluding taxes. The aim of such a scheme is to allow fatal producers of electricity avoiding operational losses, since their costs of production are most of the time much higher than the wholesale prices on the market, and to develop. Given the modeling framework, one can check that the rate of $TafFTAR_{4,t}$ depends on market price of electricity ($q_{4,t,s}$), costs of production of fatal producers ($q_{el,6,t,prod}$, $q_{el,7,t,prod}$ and $q_{el,8,t,prod}$) and, notably, their learning rate ($\varrho_{el,6,t,learning}$, $\varrho_{el,7,t,learning}$ and $\varrho_{el,8,t,learning}$).

Prices of renewables substitutes ($q_{5,t}$) "Renewables substitutes" in the model are defined as a set of sources of renewable energy whose price of production is not influenced in the long-run by an upward Hotelling-type trend; nor by a strongly downward learning-by-doing related trend; and which, eventually, does not contain (much) carbon and/or is not affected by any carbon tax. The demand for these renewables substitutes is approximated, over the recent past, by demands for biomass, biofuels, biogas and waste.[36] Given this definition, the real price of renewables substitutes is set at 1 and remains constant through time. In other words, it is assumed that the price of renewable substitutes (excluding wind and PV in the electric sector) rises in the long run as inflation. Since inflation is zero in this model where all prices are expressed in real terms, then $\forall t,\ q_{5,t} = 1$.

In this framework, the dynamics of the energy mix depends on those of oil, natural gas and coal. The more the prices of the latter increase, the more the demand of the former rises.

A.1.2 Energy demand in volume

Energy demand over past periods Energy demand in volume over the past is broken up into demand for coal ($D_{coal,t}$), demand for oil ($D_{oil,t}$), demand for natural gas ($D_{natgas,t}$), demand for electricity ($D_{el,t}$) and demand for renewable substitutes ($D_{renew,t}$, which covers, over the recent past, demand and supply for biomass, biofuels, biogas and waste). Data can be found in OECD/IEA databases. In this model, they are used mainly to compute the average weighted real energy price for end-users ($q_{energy,t}$) in the past, following the above mentioned formula $q_{energy,t} = \sum_{i=1}^{5} D_{i,t-1} q_{i,t}$.

Structure of the energy demand in the future The modeling framework used here follows the litterature (see for instance Leimbach et al. (2010)) which usually computes future energy mix using a nest of interrelated CES functions. This nest allows for the relative importance in the future of each component of the energy mix - i.e., $D_{coal,t}$, $D_{oil,t}$, $D_{natgas,t}$, $D_{elec,t}$ and $D_{renew,t}$ - to vary over time according to changes in their relative prices (i.e. $q_{1,t}$, $q_{2,t}$, $q_{3,t}$, $q_{4,t}$ and $q_{5,t}$) and according to exogenous decisions of public policy.

In the production function (see below), total demand of energy at year t is designed as E_t. The dynamics of E_t mirrors, among other factors, the macroeconomic dynamics of the GE model, and the dynamics of energy efficiency gains. E_t is the primary input for the module computing

[36] In the model, wind and solar PV are defined as fatal producers of electricity. The dynamics of their prices is specific and has been presented above, in the section presenting prices of electricity.

the future energy mix. We define $E_t^{'}$ as the total demand of energy E_t less the production of electricity out of wind, solar PV, hydroelectricity and nuclear[37], and split it up into two components: $D_{non\ elec,t}$ and $D^{'}_{elec,t}$. The latter corresponds to the demand for electricity less wind, solar PV and hydro. Using a CES function with $D_{non\ elec,t}$ and $D^{'}_{elec,t}$ as arguments and the weighted prices of these two aggregates (using the prices $q_{i,t}$'s and the volumes $D_{x,t-1}$'s), one can derive relations at the optimum between the exogenous elasticity of substitution between $D_{non\ elec,t}$ and $D^{'}_{elec,t}$, their endogenous relative prices, the endogenous $\Delta E_t^{'}$ and the unknowns ($\Delta D^{'}_{elec,t}$, $\Delta D_{non\ elec,t}$). Knowing $D_{non\ elec,t-1}$ and $D^{'}_{elec,t-1}$, the optimal values of $D_{non\ elec,t}$ and $D^{'}_{elec,t}$ follow immediately. This operation is iterated over the whole period of simulation of the model, and duplicated to compute, in turn, $D_{oil\ natgas\ coal,t}$ and $D_{renew,t}$, then $D_{oil\ natgas,t}$ and $D_{coal,t}$, and eventually $D_{oil,t}$ and $D_{natgas,t}$.

A.2 Demographics

The model embodies around 60 cohorts each year (depending on the average life expectancy), thus capturing in a detailed way changes in the population structure. Each cohort is characterised by its age at year t, has $N_{t,a}$ members and is represented by one average individual. The average individual's economic life begins at 20 ($a = 0$) and ends with certain death at $\Psi_{t,0}$ ($a = \Psi_{t,0} - 20$), where $\Psi_{t,0}$ stands for the average life expectancy at birth of a cohort born in year t. In each cohort, a proportion $\nu_{t,a}$ of individuals are working while $\mu_{t,a}$ are unemployed and receive no income. The inactive population is divided into two components. A first component corresponds to individuals who never receive any contributory pension during their lifetime.[38] The proportion $\pi_{t,a}$ of pensioners in a cohort is then computed as a residual. Future paths for the labour force and the working population over the simulation period are in line with a rise in the average *effective* age of retirement of 1.25 year per decade from 2010 on, following a reform of the PAYG pension regime implemented by the goverment from 2010 on. Accordingly, future age-specific participation and employment rates of workers above 50 years of age increase in line with the changes in the age of retirement.

[37] Public policy may foster the development of some energy technologies whatever the costs of production and the market prices. This might for instance be the case for renewable sources of electricity such as onshore wind, offshore wind and solar PV. Since the dynamics of production of fatal producers of electricity does not abide by price signals, we define $E_t^{'} = E_{less\ wind\ PV\ hydro,t} = E_t - D_{hydro,t} - D_{nuclear,t} - D_{onshore,t} - D_{offshore,t} - D_{solar\ PV,t}$ as the aggregate demand whose components do change according to price signals. Hydroelectricity is excluded from this aggregate since no new significant hydroelectric capacities of production are foreseen in the future. Nuclear electricity is also be substracted to E_t when computing $E_t^{'}$, given the fact that the amount of nuclear energy in a national energy mix is more related to political factors than to market price signals. This is the assumption made in the model on German data, in line with the German energy policy aiming at closing all nuclear facilities in the 2010's.

[38] A proxy for the share of the inactive population that never receives a contributory pension is found in the ratio of inactive people aged 40-44 to inactive people aged 65-69 (in 2000). Distinguishing between pensioners and inactive people who never receive any pension is not only realistic but also important to get reasonable levels for the contribution rate balancing the PAYG regime.

A.3 The Production function

In the production function module, the nested CES pruduction function has two levels: one linking the stock of productive capital and labour; the other relating the composite of the two latter with energy. The vector ($q_{energy,t}$) computed in the energy module of the model, allows for computing - along with vectors of physical capital, labour force, wage and interest rate - an intertemporal vector of total energy demand (E_t). The energy mix ($D_{i,t}$) then derives from total energy demand (E_t) through changes in relative energy prices ($q_{i,t}$), which trigger changes in the relative demands for oil, natural gas, coal, electricity and renewables (see above, presentation of the module for the energy sector). Accordingly, the modeling allows for a) energy prices defining the total demand for energy, and b) the total energy demand, along with energy prices, defining in turn the demand for different energy vectors.

A.3.1 The CES production sub-function linking physical capital and labour

The K-L module of the nested production function is $C_t = \left[\alpha K_t^{1-\frac{1}{\beta}} + (1-\alpha)\left[A_t\bar{\varepsilon}_t\Delta_t L_t\right]^{1-\frac{1}{\beta}}\right]^{\frac{1}{1-\frac{1}{\beta}}}$ where the variables are defined in the main text. Some additional details may be helpful. The parameter $\bar{\varepsilon}_t = \sum_a^{\max(a,t)} \varepsilon_a \frac{\nu_{t,a}N_{t,a}}{L_t}$ links the aggregate productivity of labour force at year t to the average age of active individuals at this year. $\max(a,t)$ stands for the age of the older cohort in total population at year t. Parameter ε_a is the productivity of an individual as function of his/her age a. Following Miles (1999), it is defined using a quadratic form: $\varepsilon_a = e^{0.05(a+20)-0.0006(a+20)^2}$ which yields its maximum at 42 years of age when individual productivity is 32% higher than its level for age 20. $N_{t,a}$ is the total number of individuals aged a at year t.[39] The variable $\Delta_t = \sum_a \ell^*_{t,a}\frac{\nu_{t,a}N_{t,a}}{L_t}$ is the aggregate parameter corresponding to the average working time across working sub-cohorts in t (where $\ell^*_{t,a}$ is the optimal fraction of time devoted to work by the working sub-cohort, see below, section about private agents' maximizing behaviour). Thus $A_t\bar{\varepsilon}_t\Delta_t L_t$ is the optimal total labour supply. This labour supply is endogenous since the $\ell^*_{t,a}$'s (and thus Δ_t) are endogenous in the model. Profit maximization of the production function in its intensive form yields optimal factor prices, namely, the equilibrium cost of physical capital and the equilibrium gross wage per unit of efficient labour. The long-run equilibrium of the model is characterised by a constant capital per unit of efficient labour k_t and a growth of real wage equalising annual labour productivity gains. The model is built on real data exclusively: the price of the good produced out of physical capital and labour p_{c_t} is constant and normalized to 1.

A.3.2 The CES production sub-function incorporating energy

In the previous CES production function, C_t stands for an aggregate of production in volume. However, since intermediate consumptions do not appear in its expression, they are implicitly neglected

[39] Remember that each cohort is a group of individuals born the same year, and is represented in the model by a representative individual whose economic life begins at 20 ($a = 0$) and ends up with certainty at $\Psi_{t,0}$ years (thus $a = \Psi_{t,0} - 20$), where $\Psi_{t,0}$ is the average life expectancy at birth for cohort born in t.

and C_t equivalently stands for the GDP in volume. Introducing energy demand (E_t) in a CES function, as Solow (1974), yields a more realistic production function Y_t , again in volume, associated with the value-added which remunerates labour and capital: $Y_t = \left[a\,(B_t E_t)^{\gamma_{en}} + (1-\alpha)\,[C_t]^{\gamma_{en}}\right]^{\frac{1}{\gamma_{en}}}$ where a is a weighting parameter; γ_{en} is the elasticity of substitution between factors of production and energy (with γ_{en}=1-1/elasticity); E_t is the total demand of energy; and B_t stands for an index of (increasing) energy efficiency. The cost function is the solution of $\min_{E_t,C_t} q_t B_t E_t + p_{C_t} C_t$ SC $Y_t^{\gamma_{en}} = a\,(B_t E_t)^{\gamma_{en}} + (1-a)\,[C_t]^{\gamma_{en}}$. It is worth noting that in the latter expression, q_t refers to the price of energy services, these services being measured by $(B_t E_t)$. The price of energy services (q_t) is related to the price of energy computed in the energy module ($q_{energy,t}$) by the relation: $q_t = B_t q_{energy,t}$.

Solving with the Lagrangian, and given that the stock of capital, the labour supply, the cost of capital, the wage per unit of efficient labour, the GDP deflator (p_{c_t}) and the real price of energy ($q_{energy,t}$) are all known, and that B_t is exogenous, one can derive the optimal total energy demand E_t after some manipulations: $E_t = \frac{q_t^{\frac{1}{\gamma_{en}-1}} a^{\frac{-1}{\gamma_{en}-1}} C_t}{p_{C_t}^{\frac{1}{\gamma_{en}-1}} (1-a)^{\frac{-1}{\gamma_{en}-1}}}$.

As mentioned in the presentation of the energy module of the model, the variable E_t is the main input for a nest of CES functions allowing for computing the relative importance in the future of each component of the energy mix - i.e., $D_{coal,t}$, $D_{oil,t}$, $D_{natgas,t}$, $D_{elec,t}$ and $D_{renew,t}$, depending on changes in their relative prices (computing using the $q_{x,t}$'s) and exogenous public policy for some renewables.

A.4 The private agents's maximizing behaviour

The household sector is modelled by a standard, separable, time-additive, constant relative-risk aversion (CRRA) utility function and an inter-temporal budget constraint. This utility function has two arguments, consumption and leisure.

Introducing an endogenous labour market in general equilibrium models with OLG raises several challenges. Among others, many models compute the households' optimal behaviour using shadow wages during the retirement period (see for instance Auerbach and Kotlikoff, 1987; Broer et al. , 1994). The use of numerically computed shadow wages allows for meeting a temporal constraint during the retirement period, *i.e.*, when the fraction of time devoted to leisure is equal to 1. These shadow wages are proxies for Kuhn-Tucker multipliers. While in principle mathematically correct, this method may not be very intuitive from an economic point of view since it assumes that agents keep optimising between work and leisure even during the retirement period. One practical issue with the shadow wage approach as implemented in this literature is that the method chosen to derive the shadow wages has an impact on the overall general equilibrium and therefore on all variables via the intra-temporal first-order condition. Furthermore, this approach makes it practically impossible to derive an analytical solution to the model and complicates its numerical solution.

These problems can be overcome by specifying the model in a way where the households' maximisation problem can be solved in two steps. The specification separates each cohort into working individuals, who decide on their optimal consumption and labour supply, and non-working individuals, whose labour supply is zero by definition.

The labour supply of the representative individual of a whole cohort ($\ell_{t,a} \in [0;1]$) is such that $1-\ell_{t,a} = \nu_{t,a}(1-\ell^*_{t,a})+(1-\nu_{t,a}) = 1-\nu_{t,a}\ell^*_{t,a} \leq 1$ where $\nu_{t,a}$ is the fraction of working individuals in a cohort aged a in year t and $\ell^*_{t,a}$ is the optimal fraction of time devoted to work by the working sub-cohort.[40] The objective function over the lifetime of the average *working* individual of a cohort of age a born in year t is:

$$U^*_{t,0} = \frac{1}{1-\sigma}\sum_{j=a}^{\Psi_{t,0}}\left[\frac{1}{(1+\rho)^j}\left[\left((c^*_{t+j,j})^{1-1/\xi} + \varkappa\left(H_j\left(1-\ell^*_{t+j,j}\right)\right)^{1-1/\xi}\right)^{\frac{1}{1-1/\xi}}\right]^{1-\sigma}\right]$$

where $c^*_{t+j,j}$ is the consumption level of the average individual of the working sub-cohort of age j in year t, ρ is the subjective rate of time preference, σ is the relative-risk aversion coefficient,[41] $V_{t,j} = \left((c^*_{t+j,j})^{1-1/\xi} + \eta\left(H_j\left(1-\ell^*_{t+j,j}\right)\right)^{1-1/\xi}\right)^{\frac{1}{1-1/\xi}}$ is the CES instantaneous utility function at year t, $\varkappa$ is the preference for leisure relative to consumption, $1/\xi$ the elasticity of substitution between consumption and leisure in the instantaneous utility function, and H_j a parameter whose value depends on the age of an individual and whose annual growth rate is equal to the annual TFP growth rate (with $H_0 = 1$).[42] The intertemporal budget constraint for the working sub-cohort of age 20 (*i.e.*, a=0) in year t is:

$$\ell^*_{t,0}\omega_{t,0} + \sum_{j=1}^{\Psi_{t,0}}\left[\ell^*_{t+j,j}\omega_{t+j,j}\prod_{i=1}^{j}\left(\frac{1}{1+r_{t+i}}\right)\right] = c^*_{t,0} + \sum_{j=1}^{\Psi_{t,0}}\left[c^*_{t+j,j}\prod_{i=1}^{j}\left(\frac{1}{1+r_{t+i}}\right)\right]$$

Parameter $\omega_{t+j,j}$ is the after-tax income of a working individual per hour worked such that $\omega_{t+j,j} = w_t\varepsilon_a(1-\tau_{t,P}-\tau_{t,H}-\tau_{t,NA}) + d_{t,NA} - d_{t,energy}$. w_t stands for the gross wage per efficient unit of labour. The parameter ε_a links the age of a cohort to its productivity. Following Miles (1999), a quadratic function is used: $\varepsilon_a(a) = e^{0.05(a+20)-0.0006(a+20)^2}$. Parameter $\tau_{t,P}$ stands for the proportional tax rate financing the PAYG pension regime (see infra) paid by households on their labour income. $\tau_{t,H}$ stands for the rate of a proportional tax on labour income, which finances an always balanced health care regime (see infra). $\tau_{t,NA}$ stands for the rate of a proportional tax levied on labour income and pensions to finance public non ageing-related public expenditure $d_{t,NA}$. $d_{t,NA}$ stands for the non-ageing related public spending that one individual consumes irrespective of age and income. This variable is used as a monetary proxy for goods and services in kind bought by the public sector and consumed by households. $d_{t,energy}$ stands for the energy expenditures paid by one individual to the energy sector (see below).

[40] For instance, if $\nu_{t,a}$=70% of a cohort age a at a year $t$are working and devote $\ell^*_{t,a}$ of their available time to labour, then the average individual of the same cohort devotes $\ell_{t,a}$=35% of its available time to labour, and 65% to leisure.

[41] For a CRRA function, this coefficient is equal to the inverse of the intertemporal substitution coefficient.

[42] Introducing this parameter stabilises the ratio of the contributions of consumption and leisure to utility when technical progress is strictly positive. The Euler equation (infra) suggests that the annual growth rate of consumption is equal, at the steady-state, to the difference between the interest rate and the discount rate, which in turn is equal to annual TFP growth. See Broer et al., 1994.

In such a specification, the working sub-cohort always chooses a strictly positive optimal working time throughout its life. In other terms, the representative individual associated with the working sub-cohort never retires. This property of the model does not lead to unrealistic results because each entire cohort is made of a working sub-cohort and a non-working sub-cohorts, with weights that vary with the age of the cohort. De facto, for the representative individual associated with the whole cohort, the retirement age is defined exogenously through the $\nu_{t,a}$'s which become equal to zero between 65 and 75 years. Since $1-\ell_{t,a} = 1-\nu_{t,a}\ell^*_{t,a}$, the representative individual associated with the whole cohort retires in the model when the exogenous parameter $\nu_{t,a}$ reaches zero.[43]

The first-order condition for the intratemporal optimization problem derives from equalizing the ratio between the marginal utilities of consumption and leisure with the ratio of consumption and leisure prices. In the model, the price of the goods produced is 1. The price of leisure (*i.e.,* its opportunity cost) is equal to the net wage per unit of efficient labour for cohort (*a*,*t*) – *i.e.*, $\omega_{t,a}$. Some algebra yields the optimal relation between $c^*_{t,a}$ and $\ell^*_{t,a} > 0$: $1-\ell^*_{t,a} = \left(\frac{\varkappa}{\omega_{t,a}}\right)^{\xi} \frac{c^*_{t,a}}{H_a} > 0$. A higher after-taw work income per hour worked ($\omega_{t,a}$) prompts less leisure ($1-\ell^*_{t,a}$) and more work ($\ell^*_{t,a}$). Thus it captures the distorsive effect of a tax on labour supply.

The first-order condition for the inter-temporal optimization problem derives from maximizing the inter-temporal utility function under the budget constraint. Solving with a Lagrangian and after some algebra, the following Euler equation is obtained (where $\kappa = 1/\sigma$): $\frac{c^*_{t,a}}{c^*_{t-1,a-1}} = \left(\frac{1+r_t}{1+\rho}\right)^{\kappa} \left(\frac{1+\varkappa^{\xi}\omega^{1-\xi}_{t,a}}{1+\varkappa^{\xi}\omega^{1-\xi}_{t-1,a-1}}\right)^{\frac{\kappa-\xi}{\xi-1}}$. If after-tax income per hour worked ($\omega_{t,a}$) is steady and the real rate of return (r_t) is higher than the psychological discount rate (ρ), consumption will rise over time. If after-tax work income per hour worked ($\omega_{t,a}$) rises over time and the real rate of return (r_t) is steady and not lower than the psychological discount rate (ρ), consumption ($c^*_{t,a}$) will rise over time. Lower risk aversion (lower σ hence higher κ) implies larger inter-temporal changes in consumption (in the natural case where the real rate of return r_t is higher than the psychological discount rate ρ).

Plugging this expression back into the budget constraint yields the initial level of consumption for the working cohort aged a at year t ($c^*_{t,0}$). The optimal consumption path for each working sub-cohort is derived from the optimal value of $c^*_{t,0}$ and the Euler equation. The paths of the labour supplies of the working cohorts ($\ell^*_{t,a}$) are then derived from the values ($c^*_{t,a}$) using the intra-temporal first-order condition. Eventually, one can derive the optimal labour supply of the average individual of a whole cohort (*i.e.*, $\ell_{t,a}$ such that $1-\ell_{t,a} = 1-\nu_{t,a}\ell^*_{t,a}$). Knowing the optimal paths ($\ell_{t,a}$) simplifies the computation of the optimal level of consumption of the average individual representative of a *whole* cohort. The values ($c_{t,a}$) are obtained by maximising the utility function of the average individual of a whole cohort, where the labour supply $1 > \ell_{t,a} = \nu_{t,a}\ell^*_{t,a} \geq 0$ is already known, *i.e.*,

[43] Endogenising the retirement decision with the $\ell^*_{t,a}$ would bring about serious problems. The year when $\ell^*_{t,a}$ becomes equal to zero is closely related to the function $\varepsilon_a(a) = e^{0.05(a+20)-0.0006(a+20)^2}$ linking the age and individual productivity and its decline after some threshold year. Indeed, the first-order condition suggests that $\ell^*_{t,a} = 0$ only if ε_a declines sufficiently so that $1-\ell^*_{t,a} = (\eta/\omega_{t,a})^{\xi}\, c^*_{t,a}$ equals 1. The associated retirement age can be very high with such a specification (more than 90). Moreover, there is a debate about the form of the function $\varepsilon_a(a)$, which may not decline after some threshold-year. For these reasons, endogenising the retirement decision using the $\ell^*_{t,a}$'s brings about significant problem at least in this dynamic, general equilibrium context. Noteworthingly, Auerbach and Kotlikoff (1987), for instance, impose an exogenous retirement age of 66 in their model.

$U_{t,0} = \frac{1}{1-\sigma} \sum_{j=0}^{\Psi_{t,0}} \left[\frac{1}{(1+\rho)^j} \left[\left((c_{t+j,j})^{1-\frac{1}{\xi}} + \varkappa \left(H_j (1 - \ell_{t+j,j}) \right)^{1-\frac{1}{\xi}} \right)^{\frac{1}{1-\frac{1}{\xi}}} \right]^{1-\sigma} \right]$ under the inter-temporal budget constraint $y_{t,0} + \sum_{j=1}^{\Psi_{t,0}} \left[y_{t+j,j} \prod_{i=1}^{j} \left(\frac{1}{1+r_{t+i}} \right) \right] = c_{t,0} + \sum_{j=1}^{\Psi_{t,0}} \left[c_{t+j,j} \prod_{i=1}^{j} \left(\frac{1}{1+r_{t+i}} \right) \right]$, where $y_{t+j,j}$ stands for the total income net of taxes of the average individual representative of a whole cohort, such that $y_{t,a} = \ell_{t,a} w_t \varepsilon_j (1 - \tau_{t,P} - \tau_{t,H} - \tau_{t,NA}) + d_{t,NA} - d_{t,energy} + \Phi_{t,a}$. In this expression, $\Phi_{t,a}$ stands for the pension income received by the retirees of a cohort (see below, pension system, for more details).

Parameter $d_{t,energy}$ stands for the energy expenditures paid by households, such that $d_{t,energy} = C_{age} C_{en} \frac{\sum_a [w_t \varepsilon_a \upsilon_{t,a} N_{t,a} + \Phi_{t,a} \pi_{t,a} N_{t,a}]}{\sum_a N_{t,a}} \frac{q_{energy,t} E_t}{A_t}$ where $[w_t \varepsilon_a \upsilon_{t,a} N_{t,a} + \Phi_{t,a} \pi_{t,a} N_{t,a}]$ is the aggregate tax base, C_{en} is a constant of calibration and $\frac{q_{energy,t} E_t}{A_t}$ measures the dynamics of energy expenditures as a share of income. C_{age} is a constant depending on age that capture the rising share of energy in income when age increases. Its value, depending on age, is in line with OECD (2005) which suggests that the share of energy in income is close to 6,2% for German households under 30; 6,5% for households between 30 and 44; 7% for households between 45 and 59; and 8% for households over 60.

The optimal path for consumption stems from the Euler equation using a Lagrangian: $\frac{c_{t,a}}{c_{t-1,a-1}} = \left(\frac{1+r_t}{1+\rho} \right)^{\kappa}$ where the intertemporal substitution coefficient is equal to the inverse of the risk aversion ($\kappa = \sigma^{-1}$) parameter. The initial level of consumption $c_{t,0}$ (*i.e.*, the level of consumption of a cohort of age 20 at year t) is obtained by plugging the Euler equation into the budget constraint.

All the modifications of the information set of private agents (cf. public finance module) involve a reoptimisation process in 2010, defining new intertemporal paths for consumption, savings and capital supply. Before 2010, the informational set corresponds to the baseline scenario. Consumption of any cohort is thus the same before 2010 in all scenarios. From 2010 onwards, a new intertemporal path of consumption is defined by the private agents with perfect foresight. This path takes account of the previously accumulated capital (*i.e.*, $(1 + r_{2010})\Omega^*_{2009,a-1}$). Having computed the optimal path of consumption for all the cohorts of the model, average individual saving ($s_{t,a} = y_{t,a} - c_{t,a}$) and individual wealth ($\Omega_{t,a} = (1 + r_t)\Omega_{t-1,a-1} + s_{t,a}$) can be computed. The annual saving is invested in the capital market, yielding the interest rate r_t. The interest payments are capitalised into individual wealth.

This life-cycle framework introduces a link between saving and demographics. In such a setting, the aggregate saving rate is positively correlated with the fraction of older employees in total population, and negatively with the fraction of retirees. When baby-boom cohorts get older but remain active, ageing increases the saving rate. When these large cohorts retire, the saving rate declines.

A.5 The public sector and the scenarios of fiscal consolidation

A.5.1 The PAYG pension regime

The PAYG pension regime is financed by social contributions ($\tau_{t,P}$) which are proportional to gross labour income ($w_t\varepsilon_j$). The full pension ($\Phi_{t+j,j}$) is proportional to past labour income, depends on the age of the individual and on the age ψ_t at which an individual is entitled to obtain a full pension. Three cases may occur in the model. a) No pension can be received before the age of 50: $[a + 20 < 50] \rightarrow [\Phi_{t+j,j} = 0]$. b) If an individual is above 50 but below the full-right retirement age ζ_t, he or she can receive a pension reduced by a penalty. This penalty was assumed to be equal to 6% per year,[44] which corresponds approximately to actuarial neutrality for current PAYG regimes. c) an individual will obtain a full pension if his or her age is above or equal to ζ_t. The pension of the average representative individual is flat over time (i.e. not wage-indexed), but is adjusted each year by the change in the number of pensioners in each cohort. In scenarios with tax-based consolidations, the residual imbalances of the PAYG regime are covered by increases in the tax rate ($\tau_{t,P}$) so as to balance the system each year. In consolidations with lower public spendings, the residual imbalances of the PAYG regime are covered by decreases of the replacement rate (p_t) with the taxe rate frozen from 2010 onwards ($\bar{\tau}_{t,P}$). This public choice is announced in 2010, modifies the information set of private agents, which reoptimize accordingly their intertemporal path of consumption and labour supply. The annual replacement rate (p_t) is then computed using a recursive formula.

A.5.2 The healthcare system

The health regime is financed by a proportional tax ($\tau_{t,H}$) on labour income and is always balanced, such that $\tau_{t,H} = \frac{\sum_a C_H h_{a,H} A_t N_{t,a}}{\sum_a \ell_{t,a} w_t \varepsilon_a \nu_{t,a} N_{t,a}}$ $\forall t$ where $h_{a,H}$ stands for a relative level of health spending depending on age a of a cohort (OECD, 2006), A_t is the level of multifactor productivity, C_H is a constant of calibration. In all scenarios, the health regime is balanced through higher social contributions. This is because this entitlement programme is presumably one where keeping spending stable as a ratio to GDP is most difficult in the face of ageing.[45] Health spendings are not modeled as in-cash transfers. They influence favorable the private agents' utility, however, by contributing to the rise in their life-expectancy in the module for demographics. In other words, the utility associated with the health system is not related with a higher income, but with a longer life.

A.5.3 Non-ageing related and lump-sum public expenditures

The non-ageing related public expenditures are financed by a proportional tax levied on (gross) labour income and pensions. Each individual in turn receives in cash a non-ageing related public

[44] This benchmark corresponds roughly to an actuarially fair penalty rate.

[45] It is well known that healthcare spendings are also,if not mainly, influenced by medical technical progress, and aggregate income. However, the model focuses on fiscal consolidation, not healthcare dynamics, and the hypothesis are the same for the healthcare regime in all scenarios. Accordingly, the comparisons between scenarios are not affected by hypothesis as concerns the health regime.

good ($d_{t,NA}$) which does not depend on his/her age and verifies:[46]

$$d_{t,NA} = \frac{\tau_{t,NA} \sum_a \left[\ell_{t,a} w_t \varepsilon_a \upsilon_{t,a} N_{t,a} + \Phi_{t,a} \pi_{t,a} N_{t,a}\right]}{\sum_a N_{t,a}} \qquad \forall t$$

A.6 Aggregation and convergence of the model

In the aggregation block, capital supplied by households is $W_t = \sum_a \Omega_{t,a} N_{t,a}$. Total efficient labour supply $A_t \bar{\varepsilon}_t \Delta_t L_t$ is aggregated in the same way, taking account of the number of working individuals in each cohort at a given year, and is also normalised to 1 in 1989. The intertemporal equilibrium of the model is dynamic: modifying the equilibrium variable (i.e. the endogenous interest rate or wage) in a given year changes the supply and demand of capital in that year and in any other year in the model, after as well as before the change. Numerical convergence applies to both $(\Xi_t)_d = K_t / A_t \bar{\varepsilon}_t \Delta_t L_t$ and $(\Xi_t)_s = W_t / A_t \bar{\varepsilon}_t \Delta_t L_t$, *i.e.*, the demand and supply of capital per unit of efficient labour respectively.

A.7 Parameterization of the model

As concerns demographic data, for the period 2000 to 2050, we use OECD data and projections. After 2050, population level and structure by age groups are assumed to be constant. The average life expectancies at birth for the cohorts ($\Psi_{t,0}$'s) are assumed to have increased by 2 years per decade during the 20th century. After 2050, average life expectancy remains stable.

In the production function, K_t, L_t, A_t are normalized to 1 in the base year of the model (1989). As in Miles (1999), there is no depreciation of capital, an assumption which has no consequence for the dynamics of the model and the equilibrium interest rate in a model with perfect competition. The annual growth rate of A_t associated with TFP gains incorporated in labour productivity in the long-run (Acemoglu, 2002) is set to 1.5% per year from 1975 to 2000, and from 2020 onwards. It is set to 1,0% per year from 2000 to 2020.[47] The model does not attempt to trace effects of ageing on TFP and possible endogenous growth effects. The model is back to its economic long-run steady-state in 2080.

The weighting parameter α in the production function is set at 0,3. In models incorporating a depreciation rate (Börsch-Supan et al., 2003), the value for this parameter is usually higher (e.g. 0.4) corresponding approximately to the ratio (gross operating surplus/value added including depreciation) in the business sector. Assuming this figure of 0.4 and a standard depreciation rate

[46] This specification ensures that the amount of non-ageing related public expenditures follows the same temporal trend as GDP which is related in the long run to annual TFP gains. Accordingly, non-ageing related public expenditures remain more or less constant as a fraction of GDP, *ceteris paribus*.

The existence of such a public regime of redistribution with proportional taxes financing lump-sum expenditures involves some intergenerational redistribution among living cohorts. Indeed, the absolute amount of taxes paid is influenced by age (since $\tau_{t,NA}$ is a proportional rate that applies to a level of income which is linked to the number of units of efficient labour provided by households, which is related with age), while the absolute level of the lump-sum expenditure $d_{t,NA}$, by definition, is not related with age a nor with the level of income of a household.

[47] This takes account of recent observed data and the probable effect of the financial crisis on TFP.

as a per cent of added value of 15% yields a net profit ratio of around 0.3. This is close to Miles (1999) who uses 0.25.

The elasticity of substitution between capital and labour is set at 0,8. A wide but still inconclusive empirical literature has attempted to estimate the elasticity of substitution between capital and labour in the CES production function. On average these studies suggest a value close to 1. Sensitivity analysis suggests that choosing an elasticity of 0.8 would have changed the results only marginally.

The households' psychological discount rate is set at 2% per annum, in line with much of the empirical literature (Gourinchas and Parker (2002). Parameter $\varkappa$ - the preference for leisure relative to consumption - is set to 0,25, in line with empirical literature. The elasticity of substitution between consumption and leisure in the instantaneous utility function ($1/\xi$) is equal to 1 (so as to avoid a temporal trend in the conditions for the optimal working time, cf. Auerbach et Kotlikoff, 1987, p.35).

The variable ζ_t is used in the model as a proxy for the length of the average working life and is approximated here by the average retirement age in each country at year t . The average effective age of retirement increases in the model from 61 to 65 over the next decades. The level of the average replacement rate (p_t) is computed as the ratio of pensions received per capita over gross wages received per capita. It is around 57% in the model.

The risk-aversion parameter σ in the CRRA utility function is assumed to be equal to 1.33 (implying an intertemporal substitution elasticity of 0.75). A standard result in financial and behavioural economics is to consider this parameter as greater than 1 (cf. Kotlikoff and Spivak, 1981). Kotlikoff and Spivak (1981) use 1.33. Epstein and Zin (1991) suggest values between 0.8 and 1.3 while Normandin and Saint-Amour (1998) use 1.5.

The model is calibrated on a real average rate of cost of capital of 6,0% in the base year. It incorporates - as suggested by the life-cycle theory - TFP gains, discount rate and a spread mirroring risk on capital markets. Contrary to other studies, the model is not calibrated on some technical parameters (e.g. the relative aversion to risk) so as to reproduce broadly observed variations in the stock of capital around the base year. This procedure can indeed bias the results.

The values of $\tau_{t,P}$ (the tax rate financing the balanced pension regime), $\tau_{t,H}$ (the tax rate financing the balanced health care system) and $\tau_{t,NA}$ (the tax rate financing the non ageing-related public expenditures system) are chosen in 2009 - the year preceding the implementation of the reforms in the model - so that total taxes amount to around 40% on German data. The breaking up between the three types of public spending (financed by $\tau_{t,P}$, $\tau_{t,H}$ and $\tau_{t,NA}$) is in line with the national accounts. For example, $\tau_{2009,NA}$ is 18% on German data.

The elasticity of substitution between energy and capital (defining γ_{en}) is set at 0,4. Hogan and Manne (1977) suggested that the elasticity of substitution between energy and capital in a CES function could be proxied by the price-elasticity of the energy demand. The weighting parameter (a) in the CES production function with energy is set at 0,1. This value is obtained through the input-output matrix in national accounts. In the CES nest, C_t refers to GDP (i.e., added value) in volume, whereas Y_t refers to aggregate production in volume, and thus takes account of intermediate consumption (here, B_t). Accordingly, the weighting parameter (a) should not be computed as the share of the value added of the energy sector in GDP but, preferably, as the share of intermediate consumption in energy items as a fraction of GDP.

The litterature about interfuel elasticities is not clearly conclusive and provides generally with price-elasticities, whereas the parameterization of the model here requires elasticities of substitution in a CES function. We calibrate the values of these elasticities mainly so as to reproduce observed evolutions of the energy sector. The elasticity of substitution between oil and gas is set at 0,3. Coal is assumed not to be substituable to oil and gas. The elasticity of substitution between electricity and renewables is set at 0,15. Eventually, the elasticity of substitution of renewables substitutes to fossil fuels is set at 0,1. In a version of the model parameterized on French data, these values allows for reproducing in the simulations of the model well-known characteristics of the energy sector in this country (*e.g.*, the aim of 23% of energy demand from renewables in 2020 would not be reached if no additional policy effort are implemented). Sensitivity analysis shows that the dynamics of the energy mix in the model is relatively robust to these values.

As concerns the gains or losses of productivity for different technology, we use $\varrho_{el,4,t,prodloss} = 5\%$ per year from 2013 to 2025 for nuclear (with a negative sign); for onshore wind: $\varrho_{el,6,t,learning} = 2\%$ per year up to 2025; for offshore wind: $\varrho_{el,7,t,learning} = 1\%$ per year up to 2025; for solar photovoltaïc: $\varrho_{el,8,t,learning} = 10\%$ per year up to 2025; for biomass: $\varrho_{el,9,t,learning} = 4\%$ per year up to 2020.

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