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# Fostering Renewables and Recycling a Carbon Tax: Joint Aggregate and Intergenerational Redistributive Effects

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A rising share of renewables in the energy mix pushes up the average price of energy - and so does a carbon tax. However the former bolsters the accumulation of capital whereas the latter, if fully recycled, does not. Thus, in general equilibrium, the effects on growth and intertemporal welfare of these two environmental policies differ. The present article assesses and compares these effects. It relies on a computable general equilibrium model with overlapping generations, an energy module and a public finance module. The main result is that an increasing share of renewables in the energy mix and a fully recycled carbon tax have opposite (though limited) impacts on activity and individuals' intertemporal welfare in the long run. The recycling of a carbon tax fosters consumption and labour supply, and thus growth and welfare, whereas an increasing share of renewables does not. Results also suggest that a higher share of renewables and a recycled carbon tax trigger intergenerational redistributive effects, with the former being relatively detrimental for young generations and the latter being pro-youth. The policy implication is that a social planner seeking to modify the structure of the energy mix while achieving some neutrality as concerns the GDP and triggering some proyouth intergenerational equity, could usefully contemplate the joint implementation of higher quantitative targets for the future development of renewables and a carbon tax fully recycled through lower proportional taxes.

JEL classification: D58, D63, E62, L7, Q28, Q43

Keywords : Energy transition, intergenerational redistribution, overlapping generations, carbon tax, general equilibrium.

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# Fostering Renewables and Recycling a Carbon Tax: Joint Aggregate and Intergenerational Redistributive Effects

Frédéric Gonand*

April 25, 2014

**Abstract**

A rising share of renewables in the energy mix pushes up the average price of energy - and so does a carbon tax. However the former bolsters the accumulation of capital whereas the latter, if fully recycled, does not. Thus, in general equilibrium, the effects on growth and intertemporal welfare of these two environmental policies differ. The present article assesses and compares these effects. It relies on a computable general equilibrium model with overlapping generations, an energy module and a public finance module. The main result is that an increasing share of renewables in the energy mix and a fully recycled carbon tax have opposite (though limited) impacts on activity and individuals' intertemporal welfare in the long run. The recycling of a carbon tax fosters consumption and labour supply, and thus growth and welfare, whereas an increasing share of renewables does not. Results also suggest that a higher share of renewables and a recycled carbon tax trigger intergenerational redistributive effects, with the former being relatively detrimental for young generations and the latter being pro-youth. The policy implication is that a social planner seeking to modify the structure of the energy mix while achieving some neutrality as concerns the GDP and triggering some pro-youth intergenerational equity, could usefully contemplate the joint implementation of higher quantitative targets for the future development of renewables and a carbon tax fully recycled through lower proportional taxes.

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# 1 Introduction

A rising share of renewables in the energy mix pushes up the average price of energy - so does a carbon tax. However the former fosters the accumulation of capital while the latter, if fully recycled, does not. Thus the effects of these two environmental policies on growth and on intertemporal welfare for different cohorts policies differ. The present article assesses them.

General equilibrium (GE) analysis applied to energy issues has been developing since the 1970's. Sato (1967) and Solow (1978) popularized GE frameworks with CES production functions including energy as a third input. Energy-related computable GE models have been commonly used (*e.g.*, Perroni and Rutherford (1995), Böhringer and Rutherford (1997), Grepperud and Rasmussen (2004), Wissema and Dellink (2007)). Knopf et al. (2010) present different CGE models encapsulating an energy sector with a rising share of renewables in the energy mix, in order to assess empirically the long-run costs of meeting the 450ppm environmental objective. However, these models are not specifically designed to address issues such as the dynamics of the year-to-year effects on growth of environmental tax reforms and their implied intergenerational effects.

Some litterature focuses on the dynamics of environmental taxation in a general equilibrium setting and their intergenerational redistributive effects. It takes account of its impact on the intertemporal consumption/saving arbitrage and the capital intensity of the economy. To this end, John et al. (1995) rely on an overlapping generations (OLG) framework. OLG settings allow for modelling the interactions between the capital intensity of the economy, the environmental taxation and demographics. Bovenberg and Heijdra (1998) develop this approach to conclude that environmental taxes trigger pro-youth effects. Chiroleu-Assouline and Fodha (2006) also use an OLG model to argue that the favourable impact on growth of a recycled environmental tax ("second dividend") is closely related with the capital intensity of an economy and its dynamics over time. However, the above quoted OLG settings generally rely on a theoretical approach involving most of the time a limited number of generations (*e.g.*, two: a young and an old one). This bares the way to an empirical parameterisation that allows for a precise quantitative assessment of the mechanisms involved by a carbon tax with numerous cohorts, notably the consumption/saving arbitrage that drives the dynamics of the capital intensity.

This paper aims at assessing empirically the dynamic impacts on growth and on intertemporal welfare (and thus on intergenerational equity) of a rising share of renewables in the energy mix and of a fully recycled carbon tax. It relies on a GE setting incorporating an energy module as in some of the models presented by Knopf et al. (2010). However, our empirical computable GE model additionally encapsulates an empirical OLG framework with more than 60 cohorts each year and a public finance module, following here Auerbach and Kotlikoff (1987). In line with OECD (2005) and Brounen, Kok and Quigley (2012), the consumption of energy increases with age. Different policy scenarios are modeled as concerns the development of renewables in the energy mix and the implementation of an environmental tax. For illustrative purpose, it is parameterised on German data.

Results show that higher quantitative targets set by public authorities for the future development of renewables weigh on economic activity. Intuitively, the rise in the share of renewables in the energy mix fosters average energy prices for private agents, forcing them to buy at a higher price a good that is necessary for production and that has no perfect substitute. While lessening the demand for energy, it also fosters the stocks of capital and labour. In contrast, a carbon tax, if it is fully recycled, has a positive influence on GDP in the long run. This favourable influence on activity is related with the downward effect of the tax on the demand for energy in volume. Since the carbon tax weighs on the total demand for energy in volume, the rise in the total energy expenditures paid by private agents is less than the amount of the carbon tax collected and redistributed. Accordingly, the households' income, which encompasses energy expenditures and public spending, increases. This fosters consumption and growth and weighs on capital per unit of efficient labour. Eventually, recycling the revenue associated with the carbon tax with lower direct taxes entails slightly more favourable effects on growth than recycling the tax with a higher lump-sum public expenditures (*i.e.*, the second dividend is positive in the model). Intuitively, lessening distortionary taxes has a more favourable effect on activity than raising lump-sum public transfers. 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. In all results, the macroeconomic magnitude of the effects on growth remains subdued. In the long-run, around 2050, it is close to +/-0,5% of the level of the GDP. This is in line with the conventional wisdom of the "elephant and rabbit" tale in energy economics (Hogan and Manne, 1977) according to which the size of the energy sector in the economy bares it to entail very sizeable effects on growth under normal circumstances.

As concerns the intergenerational effects, results suggest that higher quantitative targets set by public authorities for the future development of renewables trigger intergenerational redistributive effects. While they weigh on the future annual welfare of all cohorts, however, the detrimental effect in the short run is less pronounced for currently retired generations. This flows mainly from the joint influence of a permanent income effect and of an energy consumption effect. A carbon tax, if fully recycled, has pro-youth intergenerational redistributive properties. Eventually, recycling a carbon tax through lower direct, proportional taxes rather than higher lump-sum public expenditures conveys specific redistributive effects that also benefit to young and future generations.

Computing the intertemporal welfare of each cohort over its whole lifetime allows for precising and completing the above analysis of intergenerational redistributive effects. Result suggest that a higher share of renewables in the energy mix weigh relatively more on the intertemporal welfare of young and future generations. Fiscal policy implementing a fully recycled carbon tax more than offsets the detrimental effects of increasing renewables on private agent's intertemporal welfare, and display pro-youth redistributive features. This results holds especially if the carbon tax is recycled through lower proportional taxes on income rather than higher public lump-sum expenditures.

The remaining of this article is organised as follows. Section 2 introduces the model used in this article. Section 3 presents the results obtained as concerns the respective effects on growth and intertemporal welfare of a rising share of renewables in the energy mix and of a fully recycled carbon tax. Section 4 concludes by raising about some policy implications.

# 2 Assessing the aggregate and intergenerational impacts of developing renewables and recycling a carbon tax

## 2.1 An overlapping generation framework

The dynamics of the model is driven by reforms in the sector of energy, tax policies, 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. An important 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 main output of the module for the energy sector is an intertemporal vector of average weighted real price of energy for end-users ($q_{energy,t}$). This end-use price of energy is a weighted average of exogenous end-use prices of electricity, oil products, natural gas, coal and renewables substitutes ($q_{i,t}$), where the weighs are the demand volumes ($D_{i,t-1}$): $q_{energy,t} = \sum_{i=1}^{5} D_{i,t-1}q_{i,t}$.[1] The variable $q_{energy,t}$ stands for the average real weighted end-use price of energy at year $t$; $D_{i,t-1}$ stands for the demand in volume for natural gas ($i = 1$), oil products ($i = 2$), coal ($i = 3$), electricity ($i = 4$), renewables substitutes (biomass, biogas, biofuel, waste) ($i = 5$); $q_{i,t}$ is the price, at year $t$ , of natural gas ($i = 1$), oil products ($i = 2$), coal ($i = 3$), electricity ($i = 4$), and renewables substitutes (biomass, biogas, biofuel, waste) ($i = 5$)(see annex for further details).

The real end-use prices of *natural gas, oil products and coal* (resp. $q_{1,t}$, $q_{2,t}$,$q_{3,t}$) are weighted averages of end-use prices of different sub-categories of natural gas, oil or coal products.[2] The end-use prices of sub-categories of energy products are in turn computed by summing a real supply price with transport, distribution and/or refining costs, and taxes - including a carbon tax depending on the carbon content of each energy. The real supply price is a weighted average of the prices of domestic production and imports.

The real end-use price of *electricity* ($q_{4,t}$) is a weighted average of prices of electricity for households and industry. In each case, the end-use price is the sum of network costs of transport and distribution, differents taxes (including a carbon tax) and a market price of production of electricity. The latter derives from costs of producing electricity using 9 different technologies[3] weighted by the rates of marginality in the electric system of each technology.

[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 spread 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] *i.e.*, coal, natural gas, oil, nuclear, hydroelectricity, onshore wind, offshore wind, solar photovoltaïc, and biomass.

*Renewables substitutes* in the model are defined as a set of sources of energy whose price of production ($q_{5,t}$) is not influenced in the long-run by an upward Hotelling-type trend nor by a strongly downward learning-by-doing related trend, which does not contain carbon and/or is not affected by any carbon tax, and which do not raise about problems of waste management (as nuclear).[4] The *real price of renewables substitutes* in the model is assumed to remain constant over time.[5]

*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.

### 2.1.2 Production function

The production function used in this article is a nested CES one, with two levels: one linking the stock of productive capital and labour; the other relating the composite of the two latter with energy. The K-L module of the nested production function is $C_t = \left[\alpha K_t^{1-\frac{1}{\beta}} + (1-\alpha)\left[A_t \bar{\varepsilon}_t \Delta_t L_t\right]^{1-\frac{1}{\beta}}\right]^{\frac{1}{1-\frac{1}{\beta}}}$. The parameter $\alpha$ is a weighting parameter; $\beta$ is the elasticity of substitution between physical capital and labour; $K_t$ is the stock of physical capital of the private sector; $L_t$ is the total labour force; and $A_t$ stands for an index of total factor productivity gains which are assumed to be labour-augmenting (*i.e.*, Harrod-neutral)(cf. Uzawa (1961), Jones and Scrimgeour (2004)). The parameter $\bar{\varepsilon}_t$ links the aggregate productivity of labour force at year $t$ to the average age of active individuals at this year. $\Delta_t$ corresponds to the average optimal working time in $t$. Thus $\Delta_t L_t$ corresponds to the total number of hours worked, and $A_t \bar{\varepsilon}_t \Delta_t L_t$ is the labour supply expressed as the sum of efficient hours worked in $t$, or equivalently the optimal total stock of efficient labour in a year $t$ - i.e., the optimal total labour supply. The labour supply is endogenous since $\Delta_t$ is endogenous. Labour market policies modifying participation rates (as pension reform) are taken into account. 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.

Introducing energy demand ($E_t$) in a CES function, as Solow (1974), yields the production function $Y_t$ such as: $Y_t = \left[a\left(B_t E_t\right)^{\gamma_{en}} + (1-\alpha)\left[C_t\right]^{\gamma_{en}}\right]^{\frac{1}{\gamma_{en}}}$ where $a$ is a weighting parameter; $\gamma_{en}$ is the elasticity of substitution between factors of production and energy; $E_t$ is the total demand of energy; and $B_t$ stands for an index of energy efficiency. Computing the cost function yields the optimal total energy demand $E_t$. In the model, one can check that when $C_t$ increases, the demand (in volume) for energy ($E_t$) rises. When the price of energy services ($q_t = B_t q_{energy,t}$) increases,

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

[5] Such an assumption mirrors two fundamental characteristics of renewables energies: a) they are renewables, hence their price do not follow a rising, Hotelling-type rule in the long-run; b) they are not fossil fuels: hence, the carbon tax does not apply. This assumption of a stable real price of renewables in the long-run also avoids using unreliable (or not publicly available) 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.

the demand for energy ($E_t$) diminishes. If energy efficiency ($B_t$) accelerates, the demand for energy ($E_t$) is lower.

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 modeling 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.

### 2.1.3 Households' maximisation

The model embodies around 60 cohorts each year[6], 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. 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. The technical annex provides with details.

The first-order condition for the intratemporal optimization problem for a working individual is $1-\ell^*_{t,a} = \left(\frac{\varkappa}{\omega_{t,a}}\right)^{\xi} \frac{c^*_{t,a}}{H_a} > 0$ where $\ell^*_{t,a}$ is the optimal fraction of time devoted to work by a working individual, $\varkappa$ the preference for leisure relative to consumption in his/her instantaneous CRRA utility function, $\omega_{t,a}$ the after-tax income of a working individual per hour worked, $1/\xi$ the elasticity of substitution between consumption and leisure in the utility function, $c^*_{t,a}$ the consumption level of a working individual of age $j$ in year $t$, and $H_j$ a parameter whose value depends on the age of an individual and of the total factor productivity growth rate. In this setting, a higher after-tax work income per hour worked ($\omega_{t,a}$) prompts less leisure ($1-\ell^*_{t,a}$) and more work ($\ell^*_{t,a}$). Thus the model captures the distorsive effect on labour supply of a tax on income.

The after-tax income of a working individual per hour worked ($\omega_{t+j,j}$) is such that $\omega_{t+j,j} = w_t \varepsilon_a (1-\tau_{t,P}-\tau_{t,H}-\tau_{t,NA}) + d_{t,NA} - d_{t,energy}$ where $w_t$ stands for the equilibrium gross wage per efficient unit of labour, $\varepsilon_a$ is a function relating the age of a cohort to its productivity, $\tau_{t,P}$ stands for the proportional tax rate financing the PAYG pension regime paid by households on their labour income, $\tau_{t,H}$ stands for the rate of a proportional tax on labour income, $\tau_{t,NA}$ stands for the rate of a proportional tax levied on labour income and pensions to finance public non ageing-related public expenditures $d_{t,NA}$. $d_{t,NA}$ stands for the non-ageing related public spending that one individual consumes irrespective of age and income. It is 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. In line with OECD (2005) and Brounen, Kok and Quigley (2012), the consumption of energy increases with age.

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

The first-order condition for intertemporal optimization is $\frac{c^*_{t,a}}{c^*_{t-1,a-1}} = \left(\frac{1+r_t}{1+\rho}\right)^{\kappa} \left(\frac{1+\varkappa^{\xi}\omega_{t,a}^{1-\xi}}{1+\varkappa^{\xi}\omega_{t-1,a-1}^{1-\xi}}\right)^{\frac{\kappa-\xi}{\xi-1}}$ with $\kappa = 1/\sigma$ and where $\sigma$ is the relative-risk aversion coefficient, $\rho$ the subjective rate of time preference, and $r_t$ the endogenous equilibrium interest rate. This life-cycle framework introduces a link between saving and demographics. 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.

### 2.1.4 Public finances

The public sector is modeled via a PAYG pension regime, a healthcare regime, a public debt to be partly reimbursed between 2010 and 2020; 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, 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.

### 2.1.5 Parameters common to all scenarios

In all scenarios, the fiscal consolidation is achieved mainly through lower public expenditures. Government implements from 2010 on a 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) lower non-ageing related public spendings from 2010 to 2020 so that the associated surplus is affected to reimburse part of the public debt[7]; d) a health regime remaining balanced thanks to higher social contributions. In all scenarios, the stock of public debt accumulated up to 2009 starts being partly paid back (service included) from 2010 onwards. In 2010, the level of public debt is close to 83% in Germany. The model assumes that fiscal consolidation yielding a debt below 60% of GDP is achieved in 2020. In line with historical evidence, the structural public deficit is assumed to be 0 in Germany.

All scenarios assume that future prices of fossil fuels on world markets will keep rising by 2% per annum in real terms until 2050, thus following a proxy of a Hotelling rule.[8] Accordingly, the price of a barel of Brent is $187\$_{2010}$ in 2040; the production price of natural gas is $18\$_{2010}$/MBTu in 2040. These prices remain constant after 2050 in the model. In all scenarios, annual gains of

[7] The decline in non-ageing related, lump-sum public expenditures paid by the governement to private agents in order to pay back part of the public debt amounts to 2,5% of gross income in 2010.

[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, checking that our results are not significantly dependant on this choice.

energy efficiency (*i.e.*, variations of parameter $B_t$) remain constant at +1,5% per annum in line with past evidence for Germany. These latest two assumptions as regards future fossil fuel prices and energy efficiency have no significant impact of the results (as checked with sensitivity analysis) because the results are presented as differences (of GDP, welfare...) between policy scenarios that rely on the same assumptions as regards future fossil fuel prices and energy efficiency.[9]

## 2.2 Policy scenarios

We define 4 policy scenarios. Scenario A is a no-reform scenario in the energy sector. The share of renewables in electricity is frozen in the future to its latest known level and no carbon tax is implemented. Scenario B introduces a rise of renewables[10] from the current levels to 35% of the production of electricity in 2020, 50% in 2030 and 65% in 2040. This corresponds to the target publicly set by German authorities. In the model, this weighs on wholesale electricity prices but bolsters network costs, feed-in tariffs and retail prices. Scenario C adds to scenario B the implementation of a carbon tax from 2015 onwards. In the model, the rate of the carbon tax begins at 32€/t in 2015, increases by 5% in real terms per year, until reaching a cap of 98€/t in 2038 and remains constant afterwards.[11] The income associated with the carbon tax is fully redistributed to private agents through higher lump-sum public expenditures. Eventually, scenario D differs from scenario C 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 assumed to be the baseline scenario. If governments decides any reform incoporated in scenarios B, C or D, this announcement modifies the informational set of all living agents in 2010. This triggers an optimal reoptimisation process at that year, yielding new future intertemporal paths for consumption, savings and capital supply.

| **No specific energy policy** | **Increasing share of renewables in the mix** with no carbon tax | **Increasing share of renewables in the mix** with a carbon tax redistributed through... | |
|---|---|---|---|
| | | *... higher lump-sum public expenditures* | *... lower proportional, direct income taxes financing lump-sum public expenditures* |
| Scenario A *(baseline)* | Scenario B | Scenario C | Scenario D |

Figure 1: Scenarios simulated in the model

[9] 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 Fulushima in 2011.

[10] Defined here as encompassing hydroelectricity, wind and PV; along with renewables substitutes (*i.e.*, biomass, biogas, biofuel, waste).

[11] 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 the model.

Such a framework allows for measuring the dynamic impacts on growth and intertemporal welfare of each cohorts of a rising share of renewables in the energy mix and a fully recycled carbon tax. By construction, in a dynamic GE model, all the variables interact with one another. The only way to isolate the influence of one variable (*i.e.*, increasing renewables, environmental taxation) on another (*i.e.*, GDP, cohorts' welfare...) in the intertemporal, general equilibrium consists in running two scenarios where the only difference is the first variable (*i.e.*, increasing renewables, environmental taxation). With this setting, the effects of increasing the share of renewables in the energy mix can be assessed by computing the differences between the results of scenario B and scenario A. The influence of implementing a carbon tax stems from the comparison between scenario C (or D) with scenario B, depending on the assumption as concerns the redistribution of the public income associated with the tax to households. The difference between scenario D and C 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" on an environmental taxation.

# 3 Results

Some aggregate results of the scenarios are presented before going in more details to the implications on GDP growth and intergenerational equity.

## 3.1 Aggregate effects

- *in the baseline scenario A* where no specific energy policy is implemented, the prices of fossil fuels keep increasing over the next decades by assumption. No specific policy bolsters the development of the production of electricity out of renewables from 2012 on. Accordingly, the amount of the tax financing feed-in tariffs declines gradually in the future to reach 21€/MWh in 2040 (in line with declining costs of production for wind and PV stemming from learning-by-doing productivity effects). Coal firing remains the main peaker on the electricity market in the future (in part because the price of CO2 in the EU-ETS is assumed to remain depressed in this scenario). The rise in the prices of fossil fuels on world markets triggers an upward trend in the total weighted end-use price of energy (+58% in real terms from 2009 to 2040). In this context, the total demand for energy almost stabilises while the activity keeps growing. The rise of total renewables[12] in the energy mix (from 14% of total demand of energy in 2009 to 21% in 2040) mirrors the consequences on the energy mix of the surge in the prices of fossil fuels. The capital per unit of efficient labour in Germany rises gradually over the future decade since German demography is ageing relatively quickly and will keep weighing on the labour force. Accordingly, the future cost of productive capital declines in the model.

- *in scenario B (which differs from scenario A only insofar as public authorities set higher quantitative targets for the future development of renewables)*, the energy policy implies a rise of renewables[13] as a share in the production of electricity from the current levels to 35% in 2020, 50%

[12] Total renewables are defined here as encompassing hydroelectricity, wind, PV, biomass, biofuels, biogas, waste.
[13] Renewables in the electricity sector are defined here as encompassing hydroelectricity, wind and PV .

in 2030 and 65% in 2040 - as publicly announced by German authorities. PV, onshore and offshore wind produce overall 157TWh in 2020 in the model[14], entailing a downward effect on wholesale prices of -27€/MWh in 2040. The associated consequences are sizeable for feed-in tariffs (surging from 37€/MWh in 2013 to 114€/MWh in 2040) as well as for electric network costs (with an upcard specific effect of 10€/MWh in 2009 and 61€/MWh in 2040). The average retail price of electricity for industry rises by 59% in 2040 in real terms as compared to its level in 2009 (corresponding to 180% rise in nominal terms over the same period)[15]. The total weighted end-use price of energy surges from 2009 to 2040 (+67% in real terms). The share of total renewables (*i.e.*, biomass, biofuels, biogas, hydro, wind and PV) in the total final consumption of energy reaches 37% in 2040. The total demand for energy is lower in scenario B than in scenario A because prices of energy are higher.

- *Scenario C differs from scenario B only insofar as public authorities implement a carbon tax from 2015 on, fully recycling it with higher lump-sum public expenditures.* Retail prices of electricity for industry rise by 78% in 2040 in real terms as compared to their level in 2009. The total weighted end-use price of energy displays a strong upward trend (+88% in real terms from 2009 to 2040). In this context, the total demand for energy declines by -6% in volume over the next decades.[16] Taxation of carbon magnifies the effects on energy demand stemming from high prices of fossil fuels on markets, along with the impact of the development of renewables. However, the share of total renewables[17] in the total final consumption of energy is 38% in 2040: this result, compared to its counterpart in scenario B (*i.e.*, 37%) suggests that the impact on the energy mix of this carbon tax remains limited in the model. Sensitivity analysis indeed confirms that the prices of fossil fuels on world markets or centralised development of renewables with quantitative targets set by policy planners have more influence on the energy mix than implementing a carbon tax with a rate less than 100€/t. As concerns public finances, the revenue associated with the carbon tax modeled here (23bn€$_{2010}$ in 2030 and 34bn€$_{2010}$ in 2040) is redistributed to the households each year from 2015 on, through higher lump-sum public expenditures. In 2040, these lump-sum public expenditures are 1,1 point of percentage (of private agents' income) higher than in scenarios A and B with no carbon tax.

- *Scenario D differs from scenario C only insofar as the revenue of the carbon tax is fully redistributed to the private agents by lowering the proportional, direct tax financing the lump-sum public expenditures regime* (with unchanged non-ageing public spending). In 2040, this proportional income tax is 1,1 point of percentage (of private agents' income) lower than in scenarios A, B and C.

[14] This is close to the German official target of 146TWh, which does not take account of GE effects (whereas the model does).

[15] Assuming an annual rate of inflation of 1,5%.

[16] 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 of the results as the results are presented as differences between policy scenarios that rely on the same assumptions as regards energy efficiency.

[17] incl. hydro, wind, PV, biomass, biofuels and biogas.

| *All currencies (€,$) are in constant value 2010* | Assumptions common to all scenarios | |
|---|---|---|
| | **2012** | **2040** |
| Production price of natural gas ($/MBTu) | *10* | *18* |
| Production price of oil ($/barel) | *108* | *187* |
| Production price of coal (€/t) | *81* | *141* |
| Rate of the social contribution to the pension regime (%) | *9%* | *9%* |
| 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** | | **Scenario D** | |
|---|---|---|---|---|---|---|---|---|
| | **2009** | **2040** | **2009** | **2040** | **2009** | **2040** | **2009** | **2040** |
| Amount of the carbon tax if created in 2015 (bn€) | | *0* | | *0* | | *34* | | *34* |
| Rate of the carbon tax on oil and natural gas (€/t) | | *0* | | *0* | | *98* | | *98* |
| Price of the CO2 quotas in the EU-ETS (€/t) | *13* | *0* | *13* | *0* | *13* | *98* | *13* | *98* |
| Production market price of electricity (€/MWh)(ind. effect of renewables) | *53* | *62* | *53* | *43* | *53* | *67* | *53* | *67* |
| Impact of wind and PV on grid-level system costs (€/MWh) | *10* | *16* | *10* | *61* | *10* | *61* | *10* | *61* |
| Share of wind, PV and hydro in demand of electricity (%) | *14%* | *18%* | *14%* | *65%* | *14%* | *65%* | *14%* | *65%* |
| Tax financing feed-in tariffs for wind and PV (€/MWh, € constant 2010) | *28* | *21* | *28* | *114* | *28* | *93* | *28* | *93* |
| Fraction of renewables in the energy mix (ind.hydro, wind, PV)(%) | *14%* | *21%* | *14%* | *37%* | *14%* | *38%* | *14%* | *38%* |
| Price of electricity - retail - households (€/MWh) | *231* | *262* | *231* | *351* | *231* | *388* | *231* | *388* |
| Price of electricity - industry (€/MWh) | *107* | *126* | *107* | *170* | *107* | *191* | *107* | *191* |
| Price of natural gas - households (€/MWh) | *71* | *128* | *71* | *128* | *71* | *147* | *71* | *147* |
| Price of natural gas - industry (€/MWh) | *35* | *67* | *35* | *67* | *35* | *87* | *35* | *87* |
| Price of automotive diesel fuel (€/l) | *1,1* | *2,3* | *1,1* | *2,3* | *1,1* | *2,6* | *1,1* | *2,6* |
| Price of fuel oil (€/l) | *0,5* | *1,5* | *0,5* | *1,5* | *0,5* | *1,8* | *0,5* | *1,8* |
| Price of premium unleaded RON 95 (€/l) | *1,3* | *2,4* | *1,3* | *2,4* | *1,3* | *2,7* | *1,3* | *2,7* |
| Total weighted end-use price of energy in the model (1989=100) | *151* | *238* | *151* | *253* | *151* | *285* | *151* | *285* |
| Demand for energy (1989=100)(volume) | *89* | *91* | *89* | *88* | *89* | *84* | *89* | *84* |
| Tax financing non-ageing related public spendings (% of gross income) | *18%* | *18%* | *18%* | *18%* | *18%* | *18%* | *18%* | *17%* |
| Non-ageing related public spendings (% of gross income) | *18%* | *18%* | *18%* | *18%* | *18%* | *19%* | *18%* | *18%* |
| Energy expenditures of private agents (ind.industry)(% of gross income) | *9,2%* | *9,8%* | *9,2%* | *10,1%* | *9,2%* | *10,8%* | *9,2%* | *10,8%* |

| | **Scenario A** | **Scenario B** | **Scenario C** | **Scenario D** |
|---|---|---|---|---|
| | *average 2010-2029* | *average 2010-2029* | *average 2010-2029* | *average 2010-2029* |
| Saving rate (100=scenario A) | *100* | *102,7* | *100,9* | *102,4* |
| Stock of physical capital (100=scenario A) | *100* | *100,4* | *100,3* | *100,4* |
| Private agents' income (100=scenario A)(after energy expenditures) | *100* | *99,88* | *99,91* | *99,94* |

| | **Scenario A** | | **Scenario B** | | **Scenario C** | | **Scenario D** | |
|---|---|---|---|---|---|---|---|---|
| | **2009** | **2040** | **2009** | **2040** | **2009** | **2040** | **2009** | **2040** |
| Capital per unit of efficient labour (1989=100) | *137,99* | *147,26* | *137,99* | *147,97* | *137,99* | *147,31* | *137,99* | *147,48* |
| Average cost of productive capital (real)(1989=100) | *75,2* | *70,9* | *75,2* | *70,6* | *75,2* | *70,9* | *75,2* | *70,8* |
| Real GDP level (1989=100) | | *195,05* | | *194,54* | | *195,16* | | *195,32* |

Figure 2: Some results

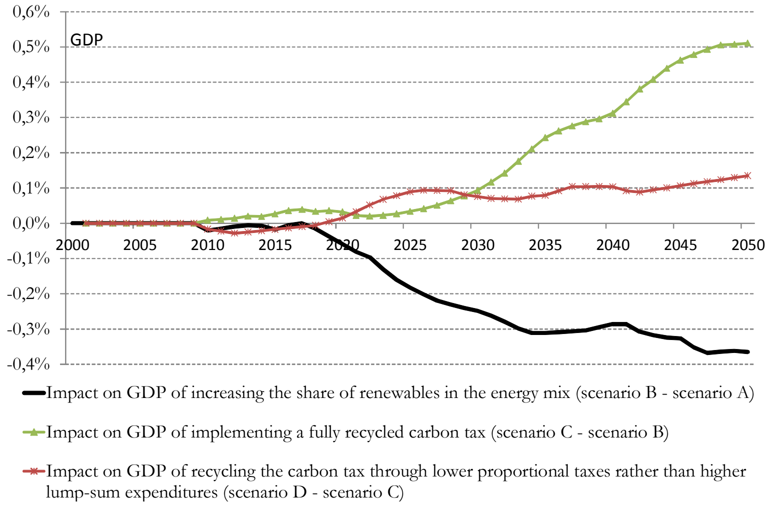


Figure 3: Impact on the level of GDP in the long run of the scenarios simulated in the model

## 3.2 Implications on growth dynamics

Figure 3 displays the results obtained in the model as concerns growth dynamics. Several results emerge.[18]

*Result 1: Higher quantitative targets set by public authorities for the future development of renewables weigh on economic growth in the long run.* This stems from a direct comparison between the results of scenario B and scenario A. Intuitively, the rise in the share of renewables in the energy mix fosters average energy prices for private agents, forcing them to buy at a higher price a good that is necessary for production and has no perfect substitute.

While lessening the demand for energy, the rise of renewables in the energy mix also fosters the stocks of capital and labour. In the private agents' accounts, higher energy prices stemming from a development of renewables weigh on disposable income. Life-cycle optimizing behaviour imply a rise in the saving rate, entailing an upward effect on the supply of capital. The dynamics of the labour supply and of the optimal average working time is also influenced by the rise in renewables. The first order intratemporal condition for a working individual can be written as $1-\ell^*_{t,a} = \frac{c^*_{t,a}(\varkappa^\xi H_a^{-1})}{[w_t\varepsilon_a(1-\tau_{t,D}-\tau_{t,P}-\tau_{t,H}-\tau_{t,NA})+d_{t,NA}-d_{t,energy}]^\xi}$ (where $1-\ell^*_{t,a}$ is optimal leisure and $\xi > 0$). Increasing prices of energy bolsters the amount of expenditures in energy ($d_{t,energy}$) and thus tend to increase optimal working time. This latter effect remains quantitatively subdued, however. In

[18] In Figure 3, the GDP appears somewhat different in the early 2010's in the scenarios with a recycling of the carbon tax than in the baseline scenario A, while the carbon tax is assumed to be implemented in 2015 in the model. This mirrors different modelling assumptions that do not have far reaching economic significance nor implications. By assumption, the reform consisting in implementing a carbon tax is announced in 2010 and implemented in 2015 in the model. This triggers reoptimisation in 2010 by forward-looking agents, which account for some small effects right from the beginning of the 2010's.

the end, higher energy prices stemming from a development of renewables increase the capital per unit of efficient labour. This rise in the stock of capital *per capita* flows from the private agents' optimal responses to a negative supply shock that lessens economic output because of increasing prices of energy.[19] The existence of retired cohorts which consume relatively more energy, feeds the downward effect on average income after energy expenditures and the impact on saving. Accordingly, the older the population, the stronger the capital deepening associated with a rise in renewables in the energy mix.

*Result 2: a carbon tax, if it is fully recycled, has a positive influence on GDP in the long run.* This stems from a direct comparison between the results of scenario C (or D) and scenario B.

This favourable influence on activity in the long run of a fully recycled carbon tax 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' income, which encompasses energy expenditures and public spending, rises in the model. This fosters consumption. Such an effect dominates the upward influence on savings that flows from higher energy prices *ceteris paribus*. Accordingly, capital supply is lower in scenario C than in scenario B. Labour supply remains quantitatively little affected. Overall, capital per unit of efficient labour is lower when a fully recycled carbon tax is implemented.

The existence of retired cohorts consuming relatively more energy lessens the upward effect on income after energy expenditures and the downward impact on saving. Accordingly, the older the population, the smaller the upward impact on growth (as shown in Figure 3 during the 2010's and the 2020's for scenario C) and the smaller the downward impact on the stock of capital associated with the implementation of a fully recycled carbon tax.[20]

*Result 3: Recycling the revenue associated with the carbon tax with lower direct taxes entails more favourable effects on growth than recycling the tax with a rise in lump-sum public spending* (*i.e.*, the second dividend is positive in the model). This stems from a direct comparison between the results of scenario D and scenario C. Intuitively, lessening distortionary taxes has a more favourable effect on activity than raising lump-sum public transfers. This is in line with the theoretical litterature on optimal environmental taxation (Nichols (1984), Terkla (1984), Pearce (1991) and Poterba (1991)) which suggests that substituting environmental taxes with other, direct taxes may reduce the distortionary cost of the tax system.

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. In scenario D, 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

[19] Only skyrocketting prices for fossil fuels on world markets might influence significantly this result. It could then happen that a higher share of renewables in the energy mix would alleviate tensions on the dynamics of the average prices of energy. This provides with a rationale for a possible positive effect on GDP of the development of renewables - however, only in the very long run, given the amount of remaining reserves of fossil fuels (natural gas, coal).

[20] This can be checked for instance with sensitivity analysis where there is no relation between the level of consumption of energy and the age of the private agents.

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 is higher in scenario D than in scenario C.

*Result 4: the macroeconomic magnitude of the effects on growth obtained in results 1, 2 and 3 remain subdued in the long run.*

Around 2050, the macroeconomic magnitude of these effects are close to +/-0,5% of the level of the GDP. This is in line with the "elephant and rabbit" tale in energy economics (Hogan and Manne, 1977) according to which the size of the energy sector in the economy bares it to entail very sizeable effects on growth. This is also globally in line with Knopf et al. (2010) who suggest that meeting environmental objectives so as to mitigate the climate change would trigger only limited macroeconomic long-run costs.

## 3.3 Intergenerational redistributive effects

### 3.3.1 Effects on future annual welfare of each cohort

A first detailed analysis of the cohorts loosing or gaining in different scenarios is possible using Lexis surfaces (Figures 4, 5 and 6). A Lexis surface represents in 3 dimensions the level of a variable associated with a cohort of a given age at a given year. The variable considered here is the gain (or loss) of annual welfare of a cohort aged $a$ in a given year $t$ and in a scenario where the carbon tax is recycled through lower proportional income tax compared to the baseline scenario where the carbon tax is recycled through higher lump-sum public spending. Annual welfare refers here to the instantaneous utility function of a private agent in the model, and thus depends on the level of consumption and optimal leisure. Before the announcement of a reform package in 2010, annual current welfare of one cohort is by assumption equal between the vaseline scenario A and any of the reform scenarios considered here. Graphically, this involves a flat portion in the Lexis surface, at value 0. From 2010 onwards, the deformations of the Lexis surfaces mirror the influence of mechanisms of intergenerational redistribution of the reform scenario, as measured by its influence on current welfare.

*Result 5: Higher quantitative targets set by public authorities for the future development of renewables trigger intergenerational redistributive effects in the population.*

Figure 5 displays the Lexis surface for current annual welfare, at each year and for each cohort in the model, in scenario B as compared to scenario A. Accordingly it materializes the intergenerational effects of setting higher quantitative targets for the future development of renewables. 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.

As shown in Figure 5, higher quantitative targets set by public authorities for the development of renewables weighs on the future annual welfare of all cohorts. However, the detrimental effect in the short run is slightly less pronounced for currently retired generations. This flows mainly from the joint influence of a permanent income effect and of an energy consumption effect:

- the permanent income effect is intuitive. The shorter the period of remaining life, the smaller the effect on optimal behaviours, defined on an intertemporal basis, stemming from a permanent rise in energy prices and the development of renewables. Thus the currently older the cohort, the smaller the detrimental effect on its permanent income associated with a rise of renewables.

- the energy consumption effect is mechanical. Since the energy consumption increases with age, the detrimental impact of rising energy prices concentrates relatively more on older households. The energy consumption effect thus partially offsets the permanent income effect. Figure 5 provides with the net influence of both mechanisms on future current welfare.

*Result 6: A carbon tax, if fully recycled, has pro-youth intergenerational redistributive properties.*

Figure 6 displays the Lexis surface for current annual welfare, at each year and for each cohort in the model, in scenario C as compared to scenario B. Accordingly it materializes the intergenerational effects of implementing a fully recycled carbon tax. Two mechanisms are involved. Both favor younger and future cohorts:

- a permanent income effect: the shorter the period of remaining life, the smaller the favourable effect 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.

- an energy consumption effect: since the energy consumption increases with age, the magnifying effect of a carbon tax on energy prices weighs more on older households.

The net effect of recycling a carbon tax is thus negative for the older generations, as shown in Figure 6, because the detrimental energy consumption effect (which is relatively stronger for them) dominates 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).

*Result 7: Recycling a carbon tax through lower direct, proportional taxes rather than higher lump-sum public expenditures conveys specific redistributive effects that benefit to young and future generations.*

Figure 7 displays the Lexis surface for current annual welfare, at each year and for each cohort in the model, in scenario D as compared to scenario C. Accordingly it materializes the intergenerational effects of the second dividend associated with the carbon tax. One main mechanism is involved here and it relatively favours young and/or active generations. The capital per unit of efficient labour is higher when the carbon tax is recycled through lower proportional taxes (as in scenario D) rather than through higher public lump-sum expenditures (as in scenario C) - as seen in table 2 and explained in result 3. 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 weighs relatively more on the optimal consumption path of older cohorts in the

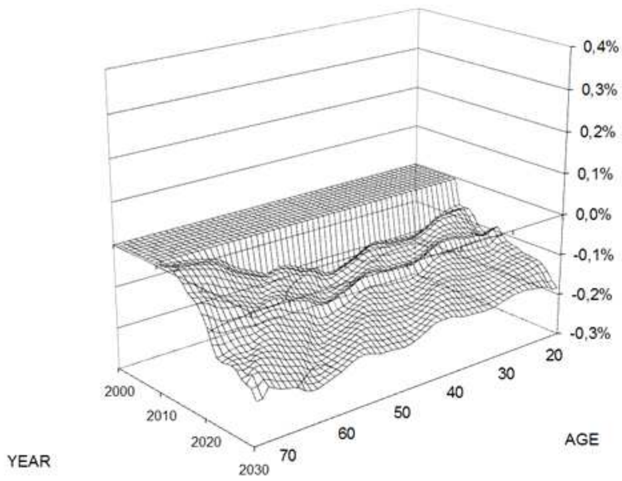


Figure 4: Effect on annual welfare of increasing the share of renewables in the energy mix (%, Germany) (scenario B - scenario A)

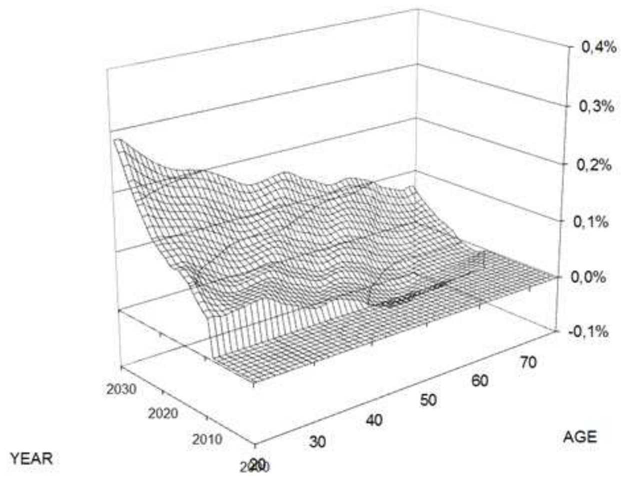


Figure 5: Effect on annual welfare of implementing a carbon tax fully recycled through higher lump-sum public expenditures (%, Germany) (scenario C - scenario B)

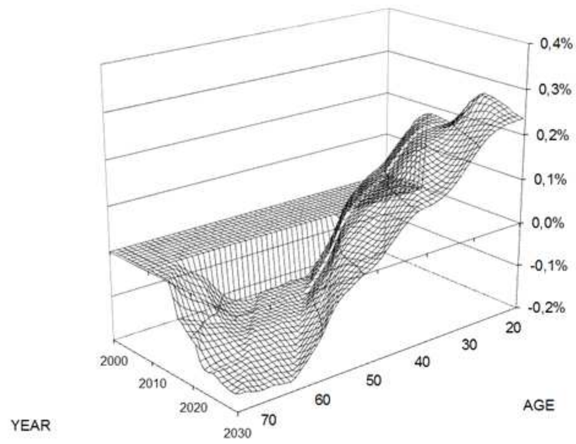


Figure 6: Effect on annual welfare of implementing a carbon tax fully recycled through lower proportional taxes on income rather than higher lump-sum public expenditures (%, Germany) (scenario D - scenario C)

model.[21]

### 3.3.2 Effects on intertemporal welfare of private agents

Computing the *intertemporal welfare of each cohort over its whole lifetime* allows for precising and completing the above analysis of intergenerational redistributive effects. Figure 7 displays the effects on intertemporal welfare for each scenario of reform.

*Result 8: a higher share of renewables in the energy mix weighs relatively more on the intertemporal welfare of young and future generations.* As long as intertemporal welfare is defined as depending only on consumption and leisure, all cohorts would suffer a loss of wellbeing in case of a rising share of renewables in the energy mix. However, the younger a cohort today, the longer it will bear the cost of higher energy prices associated with the development of renewables in the mix, *ceteris paribus*, the higher the detrimental influence on its intertemporal welfare. This result is relatively robust to realistic hypothesis about future world energy prices.

*Result 9: A fiscal policy implementing a fully recycled carbon tax may more than offset the detrimental effects of increasing renewables on private agent's intertemporal welfare, and would display pro-youth redistributive features.* This result holds especially if the carbon tax is recycled through lower proportional taxes on income rather than higher public lump-sum expenditures.

[21] These intergenerational redistributive effects are robust to different assumptions as concerns future prices of fossil fuels on world market. The Lexis surfaces obtained in scenarios with low prices of fossil fuels on world markets display the same patterns as those presented in the text.

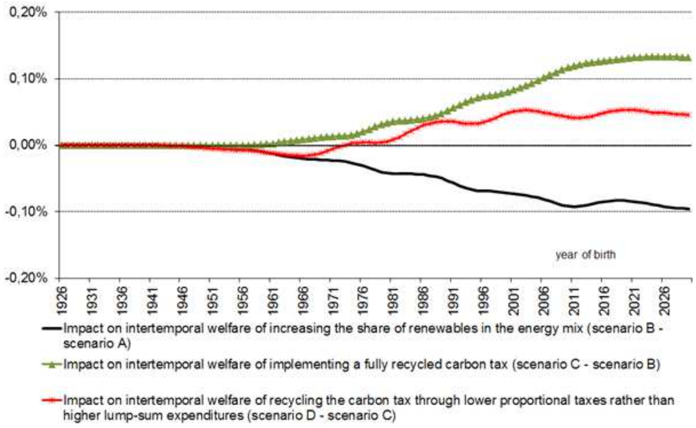


Figure 7: Effects on the intertemporal welfare of scenarios simulated in the model (%)

# 4 Conclusion and policy implications

This paper assesses the respective effects on growth and intertemporal welfare of a rising share of renewables in the energy mix and of a fully recycled carbon tax. The main result is that while both policies foster the average price of energy, they entail opposite (though limited) impacts on growth and intertemporal welfare of the cohorts. The intuition is that the recycling of a carbon tax fosters consumption and labour supply, and thus growth and welfare, whereas an increasing share of renewables does not. Results also suggest that a higher share of renewables and a recycled carbon tax trigger intergenerational redistributive effects, with the former being relatively detrimental to young generations and the latter being more pro-youth.

The policy implication of this article is not that implementing a fully recycled carbon tax should be preferred to setting higher quantitative targets for renewables in the future energy mix. Rather, it implies that significant economic gains arise when both are implemented. The model shows that the price-signal associated with a carbon tax (with a rate less than 100€/t) triggers relatively contained effects on the structure of the energy mix. In this context, a policy aiming at modifying the energy mix while simultaneaoulsy achieving some form of neutrality as concerns the GDP and triggering some pro-youth intergenerational equity could usefully contemplate implementing simultaneously higher quantitative targets for the future development of renewables and a carbon tax fully recycled through lower proportional 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.[22]

## 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:

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

[22] 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: $\forall x,\quad \varrho_{el,x,t,fixed} = \frac{\varrho_{el,x,t,inv}\frac{1+\varrho_{el,x,t,prodloss}}{1+\varrho_{el,x,t,learning}}\varrho_{el,x,t,cap\ c}}{\left(1-(1+\varrho_{el,x,t,cap\ c})^{-\varrho_{el,x,t,life}}\right)\varrho_{el,x,t,util}}$. $\varrho_{el,x,t,inv}$ 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 in France by the French Energy Regulation Authority and/or by operators in the electric sector in France and Germany. For future periods, the model uses the 2010 values which are frozen onwards.[23]

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

[23] 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 $\varpi_{fatal,t}$ [24] 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.[25]

**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

[24] $\varpi_{fatal,t}$ 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 $t-1$.

[25] 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.[26] 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

[26] 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[27], 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.[28] 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.

[27] 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.

[28] 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 $\varepsilon_a$ 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 $t$.[29] 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 $\Delta_t$) 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

[29] 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: $Y_t = [a\,(B_t E_t)^{\gamma_{en}} + (1-\alpha)\,[C_t]^{\gamma_{en}}]^{\frac{1}{\gamma_{en}}}$ where $a$ is a weighting parameter; $\gamma_{en}$ is the elasticity of substitution between factors of production and energy (with $\gamma_{en}$=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 $\min\limits_{E_t,C_t} q_t B_t E_t + p_{C_t} C_t$ 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.[30] 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 $t$, $\rho$ is the subjective rate of time preference, $\sigma$ is the relative-risk aversion coefficient,[31] $V_{t,j} = \left((c^*_{t+j,j})^{1-1/\xi} + \eta\left(H_j\left(1-\ell^*_{t+j,j}\right)\right)^{1-1/\xi}\right)^{\frac{1}{1-1/\xi}}$ 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 $H_0 = 1$).[32] 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 $\varepsilon_a$ 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).

[30] 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.

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

[32] 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; Chauveau and Loufir, 1995; Docquier et al., 2002.

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.[33]

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 $\kappa = 1/\sigma$): $\frac{c^*_{t,a}}{c^*_{t-1,a-1}} = \left(\frac{1+r_t}{1+\rho}\right)^{\kappa} \left(\frac{1+\varkappa^{\xi}\omega_{t,a}^{1-\xi}}{1+\varkappa^{\xi}\omega_{t-1,a-1}^{1-\xi}}\right)^{\frac{\kappa-\xi}{\xi-1}}$. 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 ($\rho$), 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 ($\rho$), consumption ($c^*_{t,a}$) will rise over time. Lower risk aversion (lower $\sigma$ hence higher $\kappa$) 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 $\rho$).

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.*,

[33] 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 $\varepsilon_a$ 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 $\psi_t$ 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 $\zeta_t$, he or she can receive a pension reduced by a penalty. This penalty was assumed to be equal to 6% per year,[34] 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 $\zeta_t$. 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.[35] 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

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

[35] 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:[36]

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

### A.5.4 Reimbursement of a fraction of the public debt after 2010

The governement announces in 2010 that the stock of public debt accumulated up to 2009 will start being partly paid back (service included) from 2010 until 2020 on German data. The rate on the public debt is assumed to be equal to the long-run cost of productive capital ($r_t$) minus 3%. The reimbursement of the public debt accumulated up to 2009 is financed by lowering non-ageing related public expenditures. Thus $d_{t,NA}$ becomes solution of :

$$d_{t,NA} = \frac{\tau_{t,NA} \sum_a \left[\ell_{t,a} w_t \varepsilon_a \upsilon_{t,a} N_{t,a} + \Phi_{t,a} \pi_{t,a} N_{t,a}\right] - Debt_{2009}/41 - (r_{t-1} - 3\%) Debt_{t-1} - structdef_t}{\sum_a N_{t,a}}$$

The dynamics of the stock of public debt ($Debt_t$) is also influenced by an annual structural public deficit $structdef_t$ (assumed to remain constant at 0% for Germany in the future). In all scenarios, the level of public debt, expressed in % of GDP, reaches some unique threshold value in 2020 in Germany that is assumed to be slightly below 60%.

## 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.

[36] 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.

## 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, 2000) 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.[37] 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 $\alpha$ 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 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 $\zeta_t$ 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 $\sigma$ 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

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

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 $\gamma_{en}$) 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. 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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