The "Second Dividend" and the Demographic Structure

Frédéric Gonand[1] and Pierre-André Jouvet[1]

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Abstract

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1   Introduction

The demographic structure of a country influences economic activity. The "second dividend" also modifies growth. Accordingly, in general equilibrium, the second dividend and the demographic structure are interrelated.

The notion of "second dividend" is related with the so-called double dividend hypothesis. Environmental taxes may not only curb down emissions of pollutants but also lessen the distorsive effects of the tax system if they are substituted with income taxes (Pearce, 1991). Environmental taxes fully recycled through lower standard income taxes could bolster employment, activity and welfare, and bring about a "second dividend" (for a survey, see Bovenberg and Goulder, 2002). Some debate arose in the 1990's about the existence of a "second dividend". In a few models, recycling the income of environmental taxes might exacerbate preexisting tax distortions (Bovenberg and De Mooij, 1994). One argument is that the tax interraction effect (through which a carbon tax raises the price of goods relative to leisure and thus fosters leisure and lessens working income *ceteris paribus*) might dominate the revenue recycling effect. However, subsequent research tends globally to support the idea that environmental taxes indeed trigger favourable side-effects on activity. Bento and Jacobsen (2007) show that a recycled environmental tax entails a second dividend in a model where the production function encapsulates a fixed factor - while Bovenberg and De Mooij (1994) rely on a rather simple linear production function with labour as the unique input. In a more specific setting, Parry (2000) also finds that, when some consumption spendings are tax-deductible, recycling environmental taxes through lower distorsive taxes can bring about a second dividend.

The litterature quoted above relies mainly on models that incorporate static general equilibrium mechanisms. A complementary litterature focuses on the dynamic dimension of environmental taxation in a general equilibrium setting. 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 second dividend 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 existence and the size of a second dividend can be closely related with the capital intensity of an economy and its dynamics over time. More recently, Habla and Roeder (2013) develop a majority voting framework in an OLG framework and confirm the existence of a second dividend.

However, the above quoted OLG settings generally develop 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 second dividend with numerous cohorts, notably the consumption/saving arbitrage that drives the dynamics of the capital intensity. On the aggregate scale, this consumption/saving arbitrage is related with the demographic structure of a country through a composition effect - at least if households' intertemporal arbitrage abides by the life-cycle theory. Overall, the aggregate, intertemporal and empirical effect of a fully recycled environmental tax in general equilibrium is related with the demographic structure of a country. To our knowledge, this link has not been analysed and assessed.

This paper aims at assessing empirically the second dividend of a recycled environmental tax in a dynamic, empirical and intertemporal setting that allows for measuring its relation with the demographic structure. The paper tries to fill some gap in the litterature by proposing a GE model incorporating an OLG framework with more than 60 cohorts each year, an energy module and a public finance module. The GE framework of the model relies on a CES production function including energy as a third input, in line with Sato (1967) and Solow (1978). Knopf et al. (2010) present a set of GE models encapsulating an energy sector that assess the physical feasibility of energy transition. Nevertheless these models are not designed to address the question of the dynamics of the year-to-year effects on growth of environmental tax reforms and their implied intergenerational effects. To our knowledge, no computable GE model has been developed to date that includes an overlapping-generations framework, an energy module and a public finance module.

Our model is parameterised with different policy scenarios as concerns the recycling of the environmental tax, and for different demographic structures (for illustrative purpose, younger France and older Germany).

Results show that the dynamic aggregate second dividend is higher in the model for relatively older country than for relatively younger ones, and that the difference mirrors mainly the influence of demographic factors. The intuition is that when the demographic structure is relatively more concentrated on cohorts with higher income and higher saving rate, a policy redistributing more income to these cohorts entails a relatively stronger effect on capital supply. The more concentrated the demographic structure on cohorts with a high saving rate (as in Germany), the higher the positive influence on long-run GDP of the second dividend related with an environmental tax reform. These results are reasonably robust to the parameterisation of the model (notably as concerns for instance the intertemporal elasticity of substitution or the dynamics of future energy prices on world markets).

In the model, recycling a carbon tax through lower proportional income taxes rather than higher lump-sum public expenditures indeed fosters GDP. This result flows mainly from the joint impact of the demographic structure and the consumption/saving arbitrage. The macroeconomic magnitude of the second dividend remains subdued in the model (around +0,1% of GDP in the long run) 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, under relatively normal circumstances, from entailing very sizeable effects on growth.

As concerns the intergenerational effects, results suggest that the second dividend displays pro-youth intergenerational redistributive features. It weighs on the welfare of currently relatively aged working cohorts whereas it fosters the wellbeing of currently relatively young working cohorts and of future generations. This result flows mainly from the joint influence of a distorsive effect (enshrined in the intratemporal arbitrage between work and leisure) and a capital deepening effect (stemming from the intertemporal arbitrages between consumption and saving). The latter weighs relatively more on the wellbeing of the aged working cohorts (*i.e.*, the baby-boomers) while the former bolsters relatively more the wellbeing of the youths (*i.e.*, the children of the baby-boomers).

The magnitude of the pro-youth intergenerational redistributive properties of the second dividend is influenced by the demographic structure. It is higher in a relatively older country than in a relatively younger one. The more concentrated the demographic structure on aged working cohorts, the higher the redistributive effects of a second dividend stemming from a carbon tax

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recycled through lower proportional income tax rather than higher lump-sum public expenditures. The (limited) net loss of wellbeing suffered by currently aged working cohorts, due to the recycling of the carbon tax with lower proportional income taxes, is higher in a relatively older country than in a relatively younger one. On the other hand, for young working cohorts and future generations, the wellbeing gains associated with the second dividend are also higher a relatively older country than in a relatively younger one.

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 effect of the "second dividend" of a carbon tax and its intergenerational redistributive empirical implications. Section 4 concludes by raising about some policy implications.

2 Assessing the aggregate, dynamic and intergenerational impact of a recycled environmental tax

2.1 An overlapping generation framework

The dynamics of the model is driven by demographics, reforms in the sector of energy, fiscal policies, world energy prices, 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 fiscal policy, savings and demographics. The aggregate saving rate is positively linked to the share of older employees in the total population, and negatively to the share of young working cohorts. 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 ($D_{i,t-1}$): $q_{energy,t} = \sum_{i=1}^{5} D_{i,t-1} q_{i,t}$. 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.[1] The end-

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[1] *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.

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[2] weighted by the rates of marginality in the electric system of each technology.

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).[3] The *real price of renewables substitutes* in the model is assumed to remain constant over time.[4]

Energy demand in volume is broken up 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 CES-nested 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 α is a weighting parameter; β 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. $N_{t,a}$ is the total number of individuals aged a at year t. Parameter $\nu_{t,a}$ is the fraction of a cohort of age a in t which is employed and receives a wage. Δ_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

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

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

[4] 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 (when not unavailable) 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.

total stock of efficient labour in a year t - i.e., the optimal total labour supply. The labour supply is endogenous since Δ_t is endogenous. Labour market policies modifying participation rates (as pension reform) can be taken into account through the $\nu_{t,a}N_{t,a}$'s which remain exogenous. 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: $Y_t = [a(B_tE_t)^{\gamma_{en}} + (1-\alpha)[C_t]^{\gamma_{en}}]^{\frac{1}{\gamma_{en}}}$ where a is a weighting parameter; γ_{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 (increasing) 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, the demand for energy (E_t) diminishes. When energy efficiency (B_t) accelerates, the demand for energy (E_t) is lower.

The energy mix derives from total energy demand flowing from activity 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[5], thus capturing in a detailed way changes in the population structure. Each cohort is represented by an average individual, with a standard, separable, time-additive, constant relative-risk aversion (CRRA) utility function and an intertemporal budget constraint. The instantaneous utility function has two arguments, consumption and leisure. 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 of a tax on labour supply.

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 gross wage per efficient

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

unit of labour, ε_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 expenditure $d_{t,NA}$. $d_{t,NA}$ 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.

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 σ is the relative-risk aversion coefficient, ρ 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 2030; 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. This is a proxy for public services. In all scenarios, governement announces in 2010 that the stock of public debt accumulated up to 2009 will start being partly paid back (service included) from 2010 onwards, through lower lump-sum public spendings.

2.1.5 Parameters common to all scenarios

In all scenarios, the fiscal consolidation is achieved mainly through lower public expenditures. Government announces in 2010 a reform, non anticipated by private agents, including: a) an anticipated pension reform implemented from 2010 onwards[6] increasing 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[7] ; c) lower non-ageing related public spendings from 2010 onwards so that the associated surplus is affected to reimburse part of the public debt; d) a health regime remaining

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[6] The year 2010 has been selected as the threshold year for simulation in the model mainly because some time series are not available after this date.

[7] From 62% in 2010 to 47% in 2030.

balanced thanks to higher social contributions. In 2010, the level of public debt is close to 95% of GDP in the early 2010's in France and close to 83% in Germany. For the sake of realism, the model assumes that fiscal consolidation yielding a debt below 60% of GDP is achieved in 2020 in Germany but no sooner than 2030 in France. In line with historical evidence, the structural public deficit is assumed to be 0 in Germany and 1% of GDP each year in the future for France.

All scenarios assume relatively high future prices for fossil fuels on world markets. In the model, the price of a barel of oil increases each year, from 2011 onwards, by 3% in real terms (corresponding approximately to the interest on public debt in the model) until 2050, thus following a proxy of a Hotelling rule. Prices for a ton of coal and a megawatthour of natural gas rise by 1,5% per year.[8] These prices remain constant after 2050 in the model. Alternative scenarios were run in the model assuming that the price of oil on world market would follow a path inferior to what a Hotelling rule would suggest (i.e. +1% per year in real terms instead of +3%). This entails an oil price 30% lower in 2025 than in the prévious scenarios.

All scenarios assume that the energy policy announced so far by the public authorities will be implemented in the future - unless that we additionnally model the implementation of a significant carbon tax from 2015 onwards in both countries. 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 remaining constant afterwards. For France, the future energy policy involves a) an increase in the percentage of hydroelectricity, wind and PV in electricity demand to 30% in 2020 with the associated impacts on feed-in tariffs and network costs, and b) a gradual increase in efficiency energy gains.[9] For Germany, it entails, in line with the *Energiewende* announced in 2010-2011, 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; increasing energy efficiency gains; and facilities producing electricity out of nuclear energy shut down during the 2010's.

The scenarios encapsulating a recycling of the carbon tax through higher lump-sum public expenditures are assumed to be baseline scenarios. If governements decide to recycle the carbon tax through lower proportional income taxes, this announcement modifies the informational set of all living agents in 2010. This triggers in turn an optimal reoptimisation process at that year, yielding new future intertemporal paths for consumption, savings and capital supply.

2.2 Policy scenarios

We define 4 policy scenarios: one in which the environmental tax is recycled through higher public lump-sum spending; one in which it is recycled through lower proportional income tax; with each scenario implemented for two countries with different demographic structures.

We select two different demographic structures existing in two countries with relatively comparable economic structures, namely, France and Germany. Figure 1 displays the dynamics over time of the fraction of the population that is aged 40-65 in France and in Germany. It shows that

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[8] Accordingly, the price of a barel of Brent is 157$_{2010}$ in 2025; the end-use price of natural gas for household reaches 75€_{2010}/MWh in 2025; the real supply price of a ton of coal is 99€_{2010}$ in 2025.

[9] This increase is linear from 1,0% per year in 2010 to 2,0% per year from 2020 on.

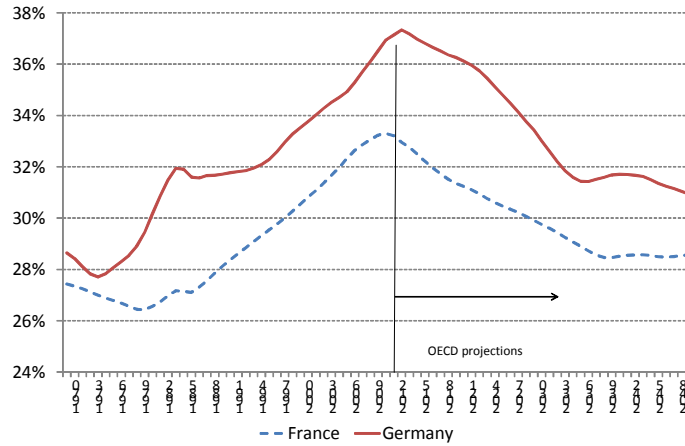[10] Defined here as encompassing hydroelectricity, wind and PV .

Figure 1: Percentage of the population that is aged between 40 and 65

the demographic structure has been different in France and Germany for decades, with Germany having on average an older population of working age. In the OECD projections, the fraction of the population that is aged 40-65 will remain higher in Germany than in France in the next decades.[11] In line with life-cycle theory, this group of cohorts saves more than other demographic groups in the model, in absolute as well as in relative terms.

	Carbon tax redistributed through…	
	… higher lump-sum public expenditures	… lower proportional, direct income taxes
Germany	Scenario DEU EXP	Scenario DEU TAX
France	Scenario FRA EXP	Scenario FRA TAX

Figure 2: Main scenarios simulated in the model

Such a setting allows for measuring the link between the demographic structure and the magnitude of the second dividend. By construction, in a dynamic GE model, all the variables interact with one another. The only way to isolate the influence of one variable (*e.g.*, the demographic structure) on another (*e.g.*, the second dividend) in the intertemporal, general equilibrium consists in running two scenarios where the only difference is the first variable (*i.e.*, demographic structure).

By definition, the second dividend on German data is measured by computing each year the difference between the level of GDP in scenario DEU TAX and scenario DEU EXP. This difference

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[11] Over the recent past, the median age was 46 years in Germany, significantly higher than in France (41 years).

is not directly related with the effect of the demographic structure on the GDP level.[12] Indeed, it is computed from the results of two scenarios that rely on the same demographic structure. Let's call this difference A. In order to measure the influence of the demographic structure on the size of the second dividend, an intermediary step is necessary. We run two additional scenarios consisting in computing scenario DEU EXP and scenario DEU TAX but using French demographic data, instead of German demographic data as in the previous step. The difference each year between the level of GDP in scenario DEU TAX with French demographic data and the level of GDP in scenario DEU EXP with French demographic data is the second dividend in Germany with a different (*i.e.*, non German) demographic structure. This difference is not directly related with the effect of the demographic structure on the GDP level because it is computed from the results of two scenarios that rely on the same demographic structure (in this case, a French one). Let's call this difference B.

The difference between A and B as defined above is the effect of the demographic structure on the second dividend. It is still not directly related with the effect of the demographic structure on the GDP level since it is computed as a difference of two differences that are not directly related with the effect of the demographic structure on the GDP level since each is computed from the results of two scenarios that rely on the same demographic structure.[13]

This method can also be presented intuitively. The dynamics of the model is driven by a) demographics, b) reforms in the sector of energy, c) fiscal policies, d) world energy prices, and e) optimal responses of economic agents to price signals (*i.e.*, interest rate, wage, energy prices). The modelling of factors d) and e) is identical in all scenarios for both countries. The modelling of factor c) is almost identical here in Germany and France. Factor b) is somewhat different whether the model is parameterised on French or German data. Factor a) - *e.g.*, demographics - is different between the two countries. Accordingly, the difference between the magnitude of the second dividend in Germany and in France should mainly stem in the model either from demographic differences, or from differences between energy policies, with an intuition that the former effect dominates the latter. In this context, if the difference between DEU EXP with French demographics and DEU TAX with French demographics is close to the second dividend in France (*i.e.*, FRA EXP - FRA TAX), then most of the difference between Germany and France as concerns the magnitude of the second dividend mirrors demographic factors. On the other hand, if the difference between

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[12] By "directly", we mean before macroeconomic feedback effects.

[13] Another equivalent method could have been used, yielding the same results. As a first step, let's compute the difference between the level of GDP in scenario DEU EXP and scenario FRA EXP. This difference measures the effect on the level of GDP of changing the demographic structure (in scenarios where the environmental tax is recycled through higher lump-sum spending). This difference *is* directly related with the effect of the demographic structure on the GDP level because it is computed from the results of two scenarios that rely on two different demographic structures. Let's call this difference C. Second step: compute the difference between the level of GDP in scenario DEU TAX and scenario FRA TAX. This difference measures the effect on the level of GDP of changing the demographic structure, in scenarios where the environmental tax is recycled through lower distorsive taxes). This difference *is* directly related with the effect of the demographic structure on the GDP level because it is computed from the results of two scenarios that rely on two different demographic structures. Let's call this difference D. The difference between C and D measures the effect of the demographic structure on the second dividend. Indeed, it is still *not* directly related with the effect of the demographic structure on the GDP level since it is computed as a difference of two differences, each of them being computed from the results of two scenarios incorporating the same change in the demographic structure.

In this empirical model, the effect of the demographic structure on the level of GDP and the effect of the demographic structure on the second dividend are easily distinguishable: the former is quantitatively significantily larger than the latter.

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DEU EXP with French demographics and DEU TAX with French demographics is close to the second dividend in Germany (*i.e.*, DEU EXP - FRA DEU), then the conclusion would be that the effects of demographic factors on the magnitude of the second dividend remain subdued.

3   Results

We present some aggregate results of the scenarios before going directly and in more detail to the implications on GDP growth.

3.1   Aggregate effects

- *in the scenarios on German data,* the energy transition policy triggers a rise of renewables as a share in the production of electricity from the current levels to 35% in 2020, 50% in 2030 and 65% in 2040. PV, onshore and offshore wind produce overall 155TWh in 2020 in the model. This is close to the official target of 146TWh, which does not take account of GE effects (whereas the model does). The downward effect on wholesale prices in the model amounts to -29€/MWh in 2030. The associated consequences are sizeable for feed-in tariffs (from 40€/MWh in 2013 in the model to 70€/MWh in 2030) as well as for electric network costs (from 17€/MWh in 2013 to 55€/MWh in 2030). Overall, average retail prices of electricity rise by 76% in 2030 in real terms as compared to their level in 2008. The total weighted end-use price of energy surges from 2008 to 2030 (+55% in real terms), mirroring partly the effect of the implementation of the carbon tax from 2015 onwards. The share of total renewables in the total final consumption of energy is 27% in 2025 in the model. German publicly announced targets imply a rise in efficiency gains from 1,5% per year over the recent past to around 2,2% per year in the future.[14] The total demand for energy declines over the next decades (by close to -20% up to 2030). As concerns public finances, in case the carbon tax is recycled through higher public lump-sum expenditures, these spendings increase from 18,0% of gross disposable income to 18,6%, *ceteris paribus* and in the short-run. When the carbon is recycled through a lower proportional income tax financing the lump sum public expenditures regime, the rate of the tax declines from 18% to 17,4% *ceteris paribus* and in the short-run. Eventually, since German demography is ageing relatively quickly, the capital per unit of efficient labour rises gradually in the next decades.

- *in the scenarios on French data*, a carbon tax is implemented from 2015 onwards in the model, with the same characteristics as in the model on German data. The associated annual public income reaches 17bn€$_{2010}$ in 2030. The price of CO2 in the EU-ETS is supposed to be indexed to the rate of the carbon tax and increases thus sizeably. The main peaker on the electricity market remains coal up to the late 2020's. The end-use price of electricity for households increases by 80% in real terms between 2010 and 2030, mainly as a consequence of the impact of the development of renewables on taxes and network costs, and the implementation of the carbon tax. The total weighted end-use price of energy displays a very strong upward trend (+70% in real terms from 2010 to 2030). In this context, the total demand for energy remains sluggish over the next decades.

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[14]This increase is linear in the model, up to 2020.

€ constant 2010	Assumptions common to all scenarios	
	2012	2040
Production price of natural gas ($/MBTu)	10	15
Production price of oil ($/barel)	108	246
Production price of coal (€/t)	80	123
Rate of the carbon tax on oil products and natural gas (€/t)	0	98

	Germany		France	
	2012	2040	2012	2040
Amount of the carbon tax if created in 2015 (bn€)	0	34	0	25
Impact of wind and PV on average market price (€/MWh)	-7	-40	-2	-18
Production market price of electricity (€/MWh)(ind. effect of renewables)(*)	55	64	53	101
Impact of wind and PV on grid-level system costs (€/MWh)	15	61	8	23
Price of electricity - retail - households (€/MWh)	253	383	131	235
Price of electricity - industry (€/MWh)	119	188	96	157
Total weighted end-use price of energy in the model (1989=100)	184	292	144	247
Demand for energy (1989=100)	96	77	115	102
Fraction of renewables in the energy mix (ind.hydro, wind, PV)(%)	16%	39%	15%	25%
Rate of the social contribution to the pension regime (%)	9%	9%	11%	11%
Replacement rate of the pension regime (%)	57%	44%	61%	45%
Average effective age of retirement (years)	61	65	61	65
Rate of the social contribution to the health regime (%)	7%	9%	11%	13%
Public debt (% GDP)	78%		95%	

	DEU EXP		DEU TAX		FRA EXP		FRA TAX	
	2009	2040	2009	2040	2009	2040	2009	2040
Tax financing non-ageing related public spendings (% of gross income)	18,0%	18,0%	18,0%	16,9%	20,0%	20,0%	20,0%	19,2%
Non-ageing related public spendings (% of gross income)	18,0%	19,1%	18,0%	18,0%	20,0%	20,8%	20,0%	20,0%
Capital per unit of efficient labour (1989=100)	139,03	146,18	139,03	146,65	120,13	114,78	120,13	114,90
Average cost of productive capital (real)(1989=100)	74,69	71,40	74,69	71,20	85,08	88,58	85,08	88,50
GDP level (1989=100)	138,91	177,78	138,91	177,82	154,75	224,17	154,75	224,24

(*) In the model, the dynamics of the future market price of production of electricity diverges between Germany and France because a) France will keep using nuclear energy for producing electricity, the cost of which will increase for safety reasons, whereas Germany will shut down its nuclear facilities in the next decade; b) the strong development of renewables will weigh far more significantly of the market production price of electricity in Germany than in France. However, German private agent face much higher future retail prices of electricity than in France in the model, in line with rising system costs and feed-in tariffs related with renewables.

Figure 3: Aggregate results

Taxation of carbon magnifies the effects on energy demand stemming from high prices of fossil fuels on world markets, along with the impact of accelerating gains in energy efficiency. The energy mix displays a rise of the renewable sources of energy[15], from 12% of total demand in 2010 to 23% in 2025. Capital per unit of efficient labour unit declines slowly over the next decades, mirroring among other factors the effects of demographics that is relatively more favourable in France than in Germany.

3.2   Implications on growth dynamics

Figure 4 displays the results obtained in the model as concerns growth dynamics. Several results emerge.[16]

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[15] This increase mirrors both the effects of the energy transition policy and the increase of the prices of fossil fuels.

[16] In Figure 3, the GDP appears somewhat lower in the early 2010's in the scenarios with a recycling of the carbon tax through lower taxes than in the scenarios with a recycling of the carbon tax through higher lump-sum public expenditures. This mirrors different modelling assumptions that do not have far reaching economic implications nor significance. The reform consisting in recycling the carbon tax through lower taxes rather than higher lump-sum public expenditures is announced in 2010 and implemented in 2015 in the model (by assumption). This triggers
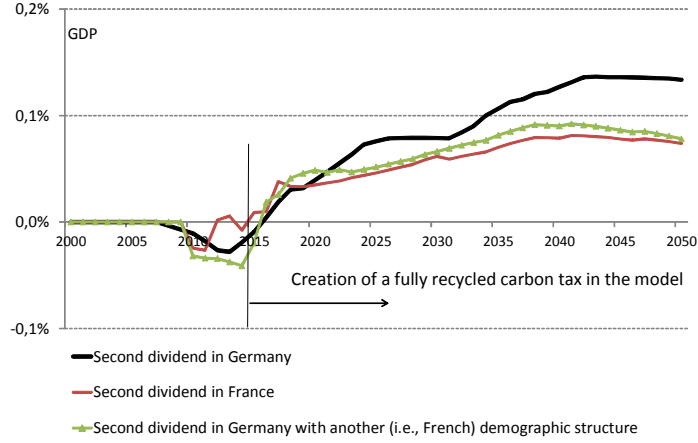
Figure 4: Impact on the GDP level of a second dividend

Result 1: The second dividend is positive in the model since GDP is fostered when the carbon tax is recycled through lower proportional income taxes instead of higher lump-sum public expenditures.

In our model this is mainly because lessening the proportional tax amounts, in absolute terms, to distributing more revenues to cohorts receiving higher wages. These cohorts receiving on average a higher gross labour income are relatively older working cohorts, which are more productive in the model than the younger ones. 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 DEU TAX than in scenario DEU EXP (with the same result appying also on French data) and this stems from demographic factors.

The dynamics of the labour supply and of the optimal average working time is more complex in the model and mirrors different effects (a direct demographic effect, a capital-deepening effect, a structural productivity effect, a tax distorsive effect, a public spending effect and a direct carbon tax effect) of which the net effect is close to zero in the model. These effects stem from the first order intratemporal condition for a working individual, which 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 $\xi > 0$). A *direct demographic effect* fosters the gross wage (w_t) because labour is scarcier in an ageing society, thus its relative price increases. Accordingly, leisure diminishes, *ceteris paribus*. A *capital deepening effect* weighs on consumption in the model ($c_{t,a}^*$) because it lessens the interest rate and the first order intertemporal condition shows that this has a decelerating effect on consumption, thus on optimal leisure, *ceteris paribus*. A *structural productivity effect* is related with the positive impact of ageing on ε_a: since the average working individual ages in the model, its productivity increases over time and this lessens, *ceteris paribus*, the optimal level of leisure. A *distorsive effect of taxes* on labour supply ($(1 - \tau_{t,P} - \tau_{t,H} - \tau_{t,NA})^\xi$ with $\xi > 0$) captures the positive influence on leisure

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higher saving which lessens somewhat the GDP level in the short run but, through stronger future capital deepening, enhances growth after some years.

of a rise in tax rates (or, equivalently, the positive influence on working time of lower tax rates). A *public lump-sum spending effect* flows through parameter $(d_{t,NA})$. Eventually, a *direct carbon tax effect* appears through the amount of expenditures in energy $(d_{t,energy})$ which is influenced by the introduction of a carbon tax (with an upward price effect partially offset by a downward volume effect, the net effect being positive on optimal leisure). In scenarios where the carbon tax is recycled through higher lump-sum public expenditures $(d_{t,NA})$, there is no distorsive effect of a change in the tax rates, but a favourable public spending effect on optimal leisure as well as on the level of consumption (the latter lessening the above quoted capital deepening effect).

Overall, since capital supply is higher in scenario DEU TAX than in scenario DEU EXP, and since labour supply remains practically identical in both scenarios, then growth in scenario DEU TAX is slightly higher than growth in scenario DEU EXP. The same features qualitatively apply to the model parameterized on French data. *Qed.*

Result 2: the macroeconomic magnitude of the second dividend remains subdued in the model.

In the long-run, around 2050, the macroeconomic magnitude of the second dividend is expected to be around +0,1%. 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. We only remind here that what was accurate when Hogan and Manne wrote their article, might be less so in our post-financial crises era characterized by very limited growth.

Result 3 (main result): the dynamic aggregate second dividend is relatively higher in a country with a relatively older working population.

This can be directly observed on Figure 4. As said above, the difference between the magnitude of the second dividend in Germany and in France can stem in the model either from demographic differences, or from differences between energy policies. Figure 4 displays the macroeconomic effect of the second dividend in scenarios paramterised on Germand data except for demographics where French data have been used. It shows that the difference between the dynamics of GDP in the DEU EXP scenario with French demographics and in the DEU TAX scenario with French demographics is close to the macroeconomic influence of the second dividend measured on French data (*i.e.*, FRA EXP - FRA TAX). Accordingly, most of the difference between Germany and France as concerns the magnitude of the second dividend mirrors demographic factors.

Intuitively, when the demographic structure is relatively more concentrated on cohorts with higher saving rate, a policy distributing more income to these cohorts entail a relatively stronger effect on capital supply. The model suggests that the impact on labour supply remains limited (see above). Thus, the more concentrated the demographic structure on cohorts with a high saving rate, the higher the macroeconomic influence of the second dividend related with an environmental tax reform.

Result 4: the magnitude of the second dividend remains practically unaffected by alternative assumptions as concerns the dynamics of future energy prices on world markets.

Even with an oil price 30% lower in 2025 than in the scenarios presented above, the size of the second dividend would not be sizeably modified.

3.3 Intergenerational redistributive effects of a dynamic aggregate second dividend

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 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 in both scenarios. 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 second dividend, as measured by its influence on current welfare.

Result 5: the second dividend displays pro-youth intergenerational redistributive features in the model.

Figure 5 and 6 display the Lexis surface for current welfare at each year for each cohort in the model on German (resp., French) data, in the 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. Thus it materializes the intergenerational effects of the second dividend in Germany (resp., France) in the model.

As shown in Figures 5 and 6, it weighs on the future annual welfare of currently relatively aged working cohorts. It simultaneously fosters the future annual wellbeing of currently relatively young working cohorts, and of future generations. Before explaining the two main mechanisms involved for this result, 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 on their current income.

In this context, result 5 flows mainly from the joint influence of a distorsive effect (enshrined in the intratemporal arbitrage between work and leisure) and a capital deepening effect (stemming from the intertemporal arbitrages between consumption and saving):

- the distorsive effect refers to the positive influence due to lower income taxes on optimal working time, thus on income and wellbeing. This effect does not exist for higher lump-sum public spending. The younger the cohort, the longer the effect over its whole life-cycle, the stronger the positive impact on income and wellbeing.

- the capital deepening effect flows from the conditions of the consumption/saving arbitrage. Recycling the revenue of the carbon tax through lower direct taxes increases relatively more the income of the relatively numerous aged working cohorts, in absolute terms, and their savings as well (as seen in result 1 above). On the aggregate scale, this entails a higher capital deepening than
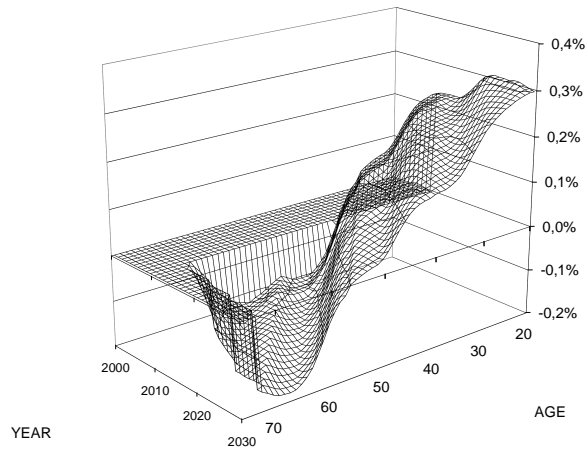
Figure 5: Effect on annual welfare of recycling a carbon tax through lower proportional income taxes instead of higher lump-sum public spending (in Germany, in %)
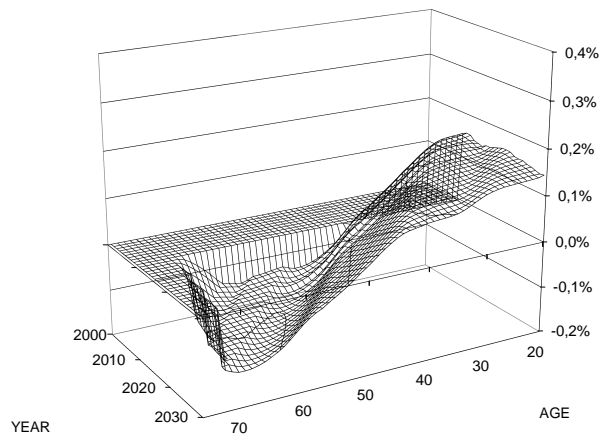

Figure 6: Effect on annual welfare of recycling a carbon tax through lower proportional income taxes instead of higher lump-sum public spending (in France, in %)

if the carbon tax had been recycled through higher lump-sum public expenditures. This weighs relatively more on the optimal consumption path of older cohorts in the model because it depresses the yield of the saving of these relatively numerous cohorts which have accumulated (much) more capital than younger cohorts when the public policy is announced in the model. Younger cohorts suffers relatively less from this effect since their accumulated capital is lower (and even negative at the beginning of the life-cycle) and since its influence will materialize for them in 2 or 3 decades in the future and will be discounted accordingly in the definition of their optimal consumption and leisure paths.[17]

- overall, the capital-deepening effect of the second dividend weighs relatively more on the wellbeing of the aged working cohorts (*i.e.*, the baby-boomers) and the distorsive effect of the second dividend bolsters relatively more the wellbeing of the youths (*i.e.*, the children of the baby-boomers).

What the model additionnally suggests is that the distorsive effect dominates the capital-deepening effect for the young working cohorts (since the effect of the second dividend is positive for them as shown in Figures 5 and 6), and vice-versa for the aged working cohorts (since the effect of the second dividend is negative for them as shown in Figures 5 and 6).

Result 6: the magnitude of the pro-youth intergenerational redistributive properties of the second dividend is influenced by the demographic structure.

As shown in Figures 5 and 6, it is higher in Germany than in France. Result 3 suggests that this stems mainly from demographic factors. The demographic structure does not directly influence the intratemporal arbitrage of the households and hence the distorsive effect of the second dividend. However, it does impact directly the capital intensity of the economy, the capital yield and hence the intertemporal arbitrage of the cohorts.

Germany will experience (and is already currently experiencing) more capital deepening than France because of less favourable demographics and a relatively scarcier labour input in its production function. This involves a slightly increasing capital intensity over the next decades in Germany while the capital per efficient unit of labour may stabilise or even slightly decline in the future for France. These dynamics in turn account for a capital yield that decline in Germany up to the late 2020's in the model, before starting to increase again; while the capital yield would remain broadly stable in France over the same period. Consequently, the capital deepening effect of the second dividend will be stronger for German aged working cohorts (*i.e.*, baby-boomers) than for their French counterparts in the model. This explains that the wellbeing loss related with the second dividend for aged working cohorts is higher in Germany than in France, as displayed in Figure 5 and 6.

By contrast, the younger working cohorts and the future generations will benefit from the rise in the capital long-run equilibrium yield in Germany from the 2030's onwards. Accordingly, the capital deepening effect of the second dividend will be lower for German young working cohorts (*i.e.*, baby-boomers) and future generations than for their French counterparts in the model. This explains that the wellbeing gains related with the second dividend for young working cohorts and future generations is higher in Germany than in France, as shown in Figure 4 and 5.

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[17]These intergenerational redistributive effects are robust to different assumptions as concerns future prices of fossil fuels on world market.
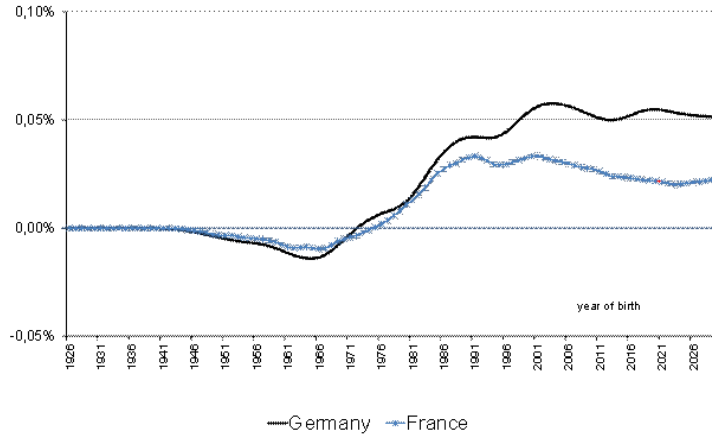
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Figure 7: Effects on the intertemporal welfare of recycling a carbon tax through lower proportional income tax instead of higher lump-sum public spending

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, on German and French data, the effects on intertemporal welfare of each cohort of 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.

Result 7: The second dividend fosters the intertemporal wellbeing of young active cohorts and future generations, while weighing slightly on the intertemporal wellbeing of currently aged working cohorts.

This result is in line with result 5; however it additionnally provides with a quantitative assessment, from an intertemporal point of view, of the magnitude of the redistributive mechanisms involved by the second dividend.

Result 8: The magnitude of the intertemporal redistributive effect of the second dividend is related with the demographic structure.

This appears directly on Figure 6 and provides a quantitative assessment, from an intertemporal perspective, of the mechanisms involved in result 5. The more concentrated the demographic structure on aged working cohorts, the higher the redistributive effects of a second dividend stemming from recycling a carbon tax with lower proportional income tax rather than higher lump-sum public expenditures.

Result 9: As far as the intertemporal wellbeing of the cohorts is concerned, the second dividend of recycling a carbon tax through lower proportional income tax rather than lump-sum public expenditures is not far from being a Pareto-improving policy.

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Again, this appears in Figure 7 which shows that the negative effect of the second dividend on the intertemporal wellbeing of aged working cohorts remains subdued, whereas its favourable effects on the intertemporal wellfare of younger working cohorts and future generations is relatively more sizeable.

4 Conclusion and policy implications

This paper assesses the empirical, aggregate, intertemporal impact of the demographic structure on the magnitude of the "second dividend" associated with an environmental tax. The main result is that the older the working population, the higher the second dividend. The intuition is that when the demographic structure is relatively more concentrated on cohorts with higher income and saving rate, then a policy redistributing more income to these cohorts entails a relatively stronger effect on capital supply. Results also suggest that the second dividend displays pro-youth intergenerational redistributive features. This result flows mainly from the joint influence of a distorsive effect and a capital deepening effect. The latter weighs relatively more on the wellbeing of the aged working cohorts while the former bolsters relatively more the wellbeing of the young cohorts. The more concentrated the demographic structure on aged working cohorts, the higher the redistributive, pro-young effect of a second dividend.

These results have direct policy implications. If some government seeks to increase the second dividend of an environmental tax and its pro-youth redistributive properties, then the magnitude of this tax reform should be relatively more important in countries with relatively younger working populations.

This analysis shows that demographic structures can play a significant role in energy economics and policies. Overlapping generation frameworks enshrined in EG modeling are well suited for studying such issues.

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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.[18]

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:

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

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[18] 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 main 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: $\forall x, \quad \varrho_{el,x,t,prod} = \left[\frac{\varrho_{el,x,t,fuel}+\varrho_{co2\ price,t}*\varrho_{el,x,t,co2em}}{\varrho_{el,x,t,therm}} + \varrho_{el,x,t,ops}\right]+\varrho_{el,x,t,fixed}$ 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: $\forall x, \quad \varrho_{el,x,t,fixed} = \frac{\varrho_{el,x,t,inv}\frac{1+\varrho_{el,x,t,prodloss}}{1+\varrho_{el,x,t,learning}}\varrho_{el,x,t,cap\ c}}{(1-(1+\varrho_{el,x,t,cap\ c})^{-\varrho_{el,x,t,life}})\varrho_{el,x,t,util}}$. $\varrho_{el,x,t,inv}$ 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.[19]

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

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[19] 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 $\varpi_{fatal,t}$ [20] 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 $q_{el,peak,t}$. For a peak price of around 70€/MWh, such a specification yields a downward effect of a 10% rise in the penetration rate of fatal producers on the market prices comprised between 6€/MWh and 8€/MWh. 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 effect on the dynamics of the model would have been very small.

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.[21]

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).

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

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

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 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.[22] 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 $\forall t$, $q_{5,t} = 1$.

Such an assumption takes account of two fundamental characteristics of renewables energies. They are renewables: hence their price may not follow a Hotelling rule in the long-run. They are decarbonated: hence, the carbon tax does not apply. This assumption also avoids using unreliable (if not unavailable) time series for prices of renewables energies over past period and in the future. This simplification doubtless introduces some contraints when building reform scenarios. For instance, it 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.

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 $q_{energy,t} = \sum_{i=1}^{5} D_{i,t-1} q_{i,t}$.

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[22] 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.

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 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 and hydroelectricity[23], 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.[24] The proportion $\pi_{t,a}$ of pensioners in a cohort is then computed as a residual. Future paths for the labour force and

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[23] 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 $E_t' = E_{less\ wind\ PV\ hydro,t} = E_t - D_{hydro,t} - D_{onshore,t} - D_{offshore,t} - D_{solar\ PV,t}$ as the aggregate demand whose components do change according to price signals. Hydroelectricity is excluded from this aggregate since, in France, the installed capacity of hydroelectricity has remained constant for more than 20 years. Accordingly, no new hydroelectric capacities of production on a large scale are foreseeable in France today, even taking account of the development of small hydroelectric facilities. It could be argued that nuclear electricity could 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. In fact, 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.

[24] 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) (cf. Cournède and Gonand, 2006). 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.

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.

A.3 The Production function

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

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

The K-L module of the nested production function is $C_t = \left[\alpha K_t^{1-\frac{1}{\beta}} + (1-\alpha)\left[A_t \bar{\varepsilon}_t \Delta_t L_t\right]^{1-\frac{1}{\beta}}\right]^{\frac{1}{1-\frac{1}{\beta}}}$ where the variables are defined in the main text. Some additional details may be helpful. The parameter $\bar{\varepsilon}_t = \sum_{a}^{\max(a,t)} \varepsilon_a \frac{\nu_{t,a} N_{t,a}}{L_t}$ links the aggregate productivity of labour force at year t to the average age of active individuals at this year. $\max(a,t)$ stands for the age of the older cohort in total population at year t. Parameter ε_a is the productivity of an individual as function of his/her age a. Following Miles (1999) and Ingénue (2001), 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.[25] The variable $\Delta_t = \sum_{a} \ell_{t,a}^* \frac{\nu_{t,a} N_{t,a}}{L_t}$ is the aggregate parameter corresponding to the average working time across working sub-cohorts in t (where $\ell_{t,a}^*$ is the optimal fraction of time devoted to work by the working sub-cohort, see below, section about private agents' maximizing behaviour). Thus $A_t \bar{\varepsilon}_t \Delta_t L_t$ is the optimal total labour supply. This labour supply is endogenous since the $\ell_{t,a}^*$'s (and thus Δ_t) are endogenous in the model. Profit maximization of the production function in its intensive form yields optimal factor prices, namely, the equilibrium cost of physical capital and the equilibrium gross wage per unit of efficient labour. The long-run equilibrium of the model is characterised by a constant capital per unit of efficient labour k_t and a growth of real wage

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[25] 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.

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 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; γ_{en} is the elasticity of substitution between factors of production and energy (with γ_{en}=1-1/elasticity); E_t is the total demand of energy; and B_t stands for an index of (increasing) energy efficiency. The cost function is the solution of $\min_{E_t, C_t} q_t B_t E_t + p_{C_t} C_t$ SC $Y_t^{\gamma_{en}} = a \, (B_t E_t)^{\gamma_{en}} + (1 - a) \, [C_t]^{\gamma_{en}}$. It is worth noting that in the latter expression, q_t refers to the price of energy services, these services being measured by $(B_t E_t)$. The price of energy services (q_t) is related to the price of energy computed in the energy module ($q_{energy,t}$) by the relation: $q_t = B_t q_{energy,t}$.

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

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

A.4 The private agents's maximizing behaviour

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

Introducing an endogenous labour market in general equilibrium models with OLG raises several challenges. Among others, many models compute the households' optimal behaviour using shadow wages during the retirement period (see for instance Auerbach and Kotlikoff, 1987; Broer et al. , 1994; Chauveau and Loufir, 1997). 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.[26] The objective function over the lifetime of the average *working* individual of a cohort of age a born in year t is:

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

where $c^*_{t+j,j}$ is the consumption level of the average individual of the working sub-cohort of age j in year t, ρ is the subjective rate of time preference, σ is the relative-risk aversion coefficient,[27] $V_{t,j} = \left((c^*_{t+j,j})^{1-1/\xi} + \eta \left(H_j \left(1 - \ell^*_{t+j,j} \right) \right)^{1-1/\xi} \right)^{\frac{1}{1-1/\xi}}$ 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 $H_0 = 1$).[28] The intertemporal budget constraint for the working sub-cohort of age 20 (*i.e.*, a=0) in year t is:

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

Parameter $\omega_{t+j,j}$ is the after-tax income of a working individual per hour worked such that $\omega_{t+j,j} = w_t\varepsilon_a(1 - \tau_{t,P} - \tau_{t,H} - \tau_{t,NA}) + d_{t,NA} - d_{t,energy}$. w_t stands for the gross wage per efficient unit of labour. The parameter ε_a links the age of a cohort to its productivity. Following Miles (1999), a quadratic function is used: $\varepsilon_a(a) = e^{0.05(a+20)-0.0006(a+20)^2}$. Parameter $\tau_{t,P}$ stands for

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[26] 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.

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

[28] 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.

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).

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.[29]

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

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

Plugging this expression back into the budget constraint yields the initial level of consumption

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

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.,

$$U_{t,0} = \frac{1}{1-\sigma} \sum_{j=0}^{\Psi_{t,0}} \left[\frac{1}{(1+\rho)^j} \left[\left((c_{t+j,j})^{1-\frac{1}{\xi}} + \varkappa \left(H_j(1 - \ell_{t+j,j}) \right)^{1-\frac{1}{\xi}} \right)^{\frac{1}{1-\frac{1}{\xi}}} \right]^{1-\sigma} \right]$$ 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 $d_{t,energy} = C_{en} \frac{\sum_a [w_t \varepsilon_a \nu_{t,a} N_{t,a} + \Phi_{t,a} \pi_{t,a} N_{t,a}]}{\sum_a N_{t,a}} \frac{q_{energy,t} E_t}{A_t}$ where $[w_t \varepsilon_a \nu_{t,a} N_{t,a} + \Phi_{t,a} \pi_{t,a} N_{t,a}]$ 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.

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

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

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

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

A.5.1 The PAYG pension regime

The PAYG pension regime is financed by social contributions ($\tau_{t,P}$) which are proportional to gross labour income ($w_t \varepsilon_j$). The full pension ($\Phi_{t+j,j}$) is proportional to past labour income, depends on the age of the individual and on the age ψ_t at which an individual is entitled to obtain a full pension. Three cases may occur in the model. a) No pension can be received before the age of 50: $[a + 20 < 50] \rightarrow [\Phi_{t+j,j} = 0]$. b) If an individual is above 50 but below the full-right retirement age ζ_t, he or she can receive a pension reduced by a penalty. This penalty was assumed to be equal to 6% per year,[30] which corresponds approximately to actuarial neutrality for current PAYG regimes. c) an individual will obtain a full pension if his or her age is above or equal to ζ_t. The pension of the average representative individual is flat over time (i.e. not wage-indexed), but is adjusted each year by the change in the number of pensioners in each cohort. In scenarios with tax-based consolidations, the residual imbalances of the PAYG regime are covered by increases in the tax rate ($\tau_{t,P}$) so as to balance the system each year. In consolidations with lower public spendings, the residual imbalances of the PAYG regime are covered by decreases of the replacement rate (p_t) with the taxe rate frozen from 2010 onwards ($\bar{\tau}_{t,P}$). This public choice is announced in 2010, modifies the information set of private agents, which reoptimize accordingly their intertemporal path of consumption and labour supply. The annual replacement rate (p_t) is then computed using a recursive formula.

A.5.2 The healthcare system

The health regime is financed by a proportional tax ($\tau_{t,H}$) on labour income and is always balanced, such that $\tau_{t,H} = \frac{\sum_a C_H h_{a,H} A_t N_{t,a}}{\sum_a \ell_{t,a} w_t \varepsilon_a \nu_{t,a} N_{t,a}}$ $\forall t$ where $h_{a,H}$ stands for a relative level of health spending depending on age a of a cohort (OECD, 2006), A_t is the level of multifactor productivity, C_H is a constant of calibration. In all scenarios, the health regime is balanced through higher social contributions. This is because this entitlement programme is presumably one where keeping spending stable as a ratio to GDP is most difficult in the face of ageing.[31] 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

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[30] This benchmark corresponds roughly to an actuarially fair penalty rate (see for instance Casey et al., 2003).

[31] 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:[32]

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

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 2030 on French data (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 1% in France in the future decades, and 0% for Germany). In all scenarios, the level of public debt, expressed in % of GDP, reaches some unique threshold value in 2030 in France (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 $W_t = \sum_a \Omega_{t,a} N_{t,a}$. In other words, the representative stock of capital of every cohort is weighted by the size of each cohort in total population. 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.

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[32] 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.[33] The model does not attempt to trace effects of ageing on TFP and possible endogenous growth effects.

The weighting parameter α in the production function is set at 0,3. In models incorporating a depreciation rate (Börsch-Supan et al., 2003), the value for this parameter is usually higher (e.g. 0.4) corresponding approximately to the ratio (gross operating surplus/value added including depreciation) in the business sector. Assuming this figure of 0.4 and a standard depreciation rate 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 model is back to its long-run steady-state in 2080.

The households' psychological discount rate is set at 2% per annum, in line with much of the empirical literature (Gallon and Masse (2004); Gourinchas and Parker (2002)). Parameter $\varkappa$ - the preference for leisure relative to consumption - is set to 0,25, in line with empirical literature. The elasticity of substitution between consumption and leisure in the instantaneous utility function ($1/\xi$) is equal to 1 (so as to avoid a temporal trend in the conditions for the optimal working time, cf. Auerbach et Kotlikoff, 1987, p.35).

The variable ζ_t is used in the model as a proxy for the length of the average working life and is approximated here by the average retirement age in each country at year t . The average effective age of retirement in France is currently close to 61 years. 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 62%.

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

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[33] 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 46% of GDP (on French data) and 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 20% on French data and 18% on German data.

The elasticity of substitution between energy and capital (defining γ_{en}) is set at 0,4. Hogan and Manne (1977) suggested that the elasticity of substitution between energy and capital in a CES function could be proxied by the price-elasticity of the energy demand, which is easier to assess. Following a debate between Berndt and Wood (1975) and Griffin and Gregory (1976), it is generally agreed nowadays that physical capital and labour are partial substitutes, especially in the long-run.

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. On French data, this yields around 10%, a figure relatively stable over time.

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 set the values of these elasticities mainly so as to reproduce observed evolutions of the French energy sector. The elasticity of substitution between oil and gas is set at 0,3. Coal (whose demand in France is very small) is assumed not to be substituable to oil and gas in France. 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. This value allows for reproducing in the simulations of the model well-known characteristics of the French energy sector (e.g., the aim of 23% of energy demand from renewables in 2020 would not be reached if no additional policy effort are implemented (Cour des Comptes, 2013).

As concerns the gains or losses of productivity for different technology, we use on Franch data $\varrho_{el,4,t,prodloss} = 5\%$ 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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