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Dynamic Impacts on Growth and Intergenerational Effects of Energy Transition in a Time of Fiscal Consolidation

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Social planners in most western countries will be facing two long-lasting challenges in the next years: energy transition and fiscal consolidation. One problem is that governments might consider that implementing an energy transition could get in the way of achieving a fiscal consolidation. If so, interrupting the energy transition in a time of fiscal consolidation would involve significant aggregate impacts on activity and intergenerational redistributive effects. This article tries to assess them empirically. It relies on an overlapping-generations framework in a general equilibrium setting, with a detailed energy module. The model is parameterized on data provided by OECD/IEA for France. Different results emerge. Renouncing to the energy transition would slightly foster the level of GDP during the next 10 to 15 years - depending on the dynamics of the prices of fossil fuels on world markets - but weigh on it more significantly afterwards (up to -1% in 2050). If the prices of fossil fuels keep increasing in the future, implementing an energy transition could have broadly the same favourable effects on the GDP level in the long run as those of a fiscal consolidation diminishing significantly public spending instead of raising taxes. In the long-run, the GDP would be maximized by implementing an energy transition and simultaneously lessening the public deficit by lowering some public expenditure, a policy that would entail an overall gain of around 1,6% of GDP in 2050. Stopping the energy transition would also bring about intergenerational issues. It would be detrimental to the intertemporal wellbeing of almost all cohorts alive in 2010. A fiscal policy with lower public expenditures and frozen tax rates may be still more favourable to young and future generations than implementing an energy transition. However, renouncing to an energy transition would annihilate most of these pro-youth effects.

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

Keywords: Energy transition, intergenerational redistribution, overlapping generations, fiscal consolidation, general equilibrium

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Abstract

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Key words: Energy transition - intergenerational redistribution - overlapping generations - fiscal consolidation - general equilibrium.
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1 Introduction

Social planners in most western countries will be facing two long-lasting challenges in the next years: energy transition and fiscal consolidation. The former has been progressively implemented in most countries since the middle of the 2000's. The need for the latter is more recent and dates back only to the aftermaths of the financial crisis. One problem is that governments might consider that implementing an energy transition could get in the way of achieving a fiscal consolidation. If so, postponing or even stopping the energy transition in a time of fiscal consolidation would involve significant aggregate impacts on activity and intergenerational redistributive effects. This article tries to assess them empirically.

Energy transition aims at progressively shifting the main sources of energy from fossil fuels to renewables, along with increasing energy efficiency. Developed countries have been feeling the need for energy transition from the beginning of the 2000's onwards. Energy transition involves in most cases implementing feed-in tariffs for renewables, a carbon tax, and investments to foster energy efficiency.

Fiscal consolidation refers nowadays to balancing public finances in the aftermaths of the financial crisis, with ageing already weighing on public accounts. The financial crisis that has been developing since 2008 triggered massive fiscal expansions in the short run, with governements trying to avoid a global contraction. Since 2011 however, large public deficits have increasingly brought about the need for fiscal consolidation. The macroeconomic context now remains adverse because the negative supply-side effects of the crisis on GDP are still significant and hinder the economic recovery.

In this context, governments might consider that implementing an energy transition could get in the way of achieving the fiscal consolidation. Indeed, implementing a carbon tax with a significant rate can become uneasy for governements when tax rates and public deficits are already high. Increasing the prices of electricity through higher feed-in tariffs can bring about debates if aggregate demand remains sluggish and aggregate supply suffers from a lower profitability. Raising energy efficiency gains may require additional public spending and/or investment for which financing may no longer be easily available. In brief, an energy transition may push up taxes and public spending, while fiscal consolidation in countries with high tax rates requires at least some lower spending and not too many additional taxes. Implementing an energy transition could thus hinder achieving fiscal consolidation.

Postponing or even stopping the energy transition because of constraints on fiscal policy would involve significant aggregate effects, however. The influence of energy transition on economic growth flow through different channels. Energy transition can shelter the economy from the detrimental effects stemming from the increasing prices of fossil energy ressources on world markets. It impacts the volumes on the energy market by bolstering some technologies of production and fostering energy efficiency. It can modify the private agents' income for non-energy goods and services, and thus the dynamics of capital accumulation and growth.

The influence of energy transition on activity is interrelated with the impact of fiscal policy on growth. A carbon tax can alleviate pressures for increasing direct taxes by replacing them with less distorsive, indirect taxes, thus allowing for a "double dividend" and modifying the energy mix. It can contribute significantly to the reimbursement of the public debt accumulated after the financial crisis.

The influence of energy transition on activity may also depend on the time horizon considered. Energy transition can require more capital accumulation in the short run, new subsidizing schemes, temporarily higher prices in some cases. However, it normally fosters gains in energy efficiency in the long run, and alleviates tensions on the average price of energy if the future prices of fossil fuels keep increasing. Accordingly, energy transition might weigh on aggregate activity during some period in the short-run and, depending mainly on the dynamics of the prices of depleting ressources of energy in the long-run, favor GDP after some period.

Eventually, the influence of energy transition lasts over a long period - a few decades. Accordingly, implementing or interrupting it may raise intergenerational issues in both cases.

While the litterature about the effects of energy transition on growth is relatively abundant, fewer studies deal with the effects of energy transition in a time of fiscal consolidation. The current relative lack of litterature on this question may stem from the rise of both issues on the political agenda of western countries which is recent and rapid. Up to now, most studies linking energy and public finances have focused on energy-producing countries and the implications of oil revenues on their public accounts.

The litterature is even smaller as concerns the intergenerational redistributive effects of implementing or interrupting an energy transition. Back in the 1970's, though, Solow (1974) adressed the relationship between energy transition and intergenerational equity, in a rather theoretical framework analysing the relevance of Rawls' (1971) maximin criterion. More recently, Stern (2006) revived concerns for the preservation of the wellbeing of future generations through accurate climate policies. Yet, his study focused mainly of discount rate issues.

The present article simulates the empirical effects on potential (*i.e.*, long-run) growth of scenarios incorporating either a comprehensive policy of energy transition, or stopping it from 2010 onwards, in a context of fiscal consolidation. It also assesses their intergenerational redistributive effects. It relies on a general equilibrium model which encapsulates an overlapping-generations framework and a module representing the energy sector. To our knowledge, no EG model with an OLG framework has been developped to date in order to assess the long run impact of energy transition in a time of fiscal consolidation. A general equilibrium setting seems fitting for analysing long-run growth dynamics of interrelated transitions. The overlapping-generations module involves around 60 cohorts each year and allows for a detailed analysis of intergenerational redistributive effects. The model is parameterized on OECD/IEA data for France, a country with sizeable needs of fiscal consolidation and currently involved in some lively energy transition debates.

In the scenarios modeled, two polar options are considered as concerns energy policy: whether the social planner implements an energy transition or renounces to it from 2010 on. Fiscal consolidation is either mainly tax-based or incorporates significantly lower public expenditures. The simulations assume that the future prices of fossil fuels on world markets will keep increasing in the future. Sensitivity analysis is carried out in case the prices of fossil fuels on world energy markets experience a significant downward trend in the next decade.

An energy transition policy is defined here on French data as implying the creation of a carbon tax, an increase in the percentage of renewables in electricity production to 30% in 2020 (with associated impacts on feed-in tariffs and network costs) and an increase in efficiency energy gains from 1,0% per year to 2,0% per year.

As concerns fiscal policy, all scenarios include an anticipated pension reform from 2010 onwards, increasing the average effective age of retirement of 1,25 year per decade - which, *per se*, strongly moderates the dynamics of public spending in the future. Tax-based consolidations involves mainly that a) the remaining deficit of the pension regime is covered by increases in the social contribution rate, b) non-ageing related public spendings do not decline, c) a specific tax is levied from 2010 on to 2030 to reimburse part of a public debt, and d) if a carbon tax is implemented, the associated income is used mainly to reimburse public debt up to 2030, but can also be partially redistributed to households through lump-sum public expenditures. The second type of fiscal consolidation contemplated here involves lower public spending, including a) a lower replacement rate for new retirees to cover the remaining deficit of the pension regime, b) a decline in non-ageing related public spendings so that the associated public surplus is affected to reimburse part of the public debt, c) if a carbon tax is implemented, the associated income is mainly used to reimburse public debt up to 2030.

The results show that renouncing to the energy transition would slightly foster the level of GDP during 10 to 15 years - depending on the dynamics of the prices of fossil fuels on world markets - but weigh on it more significantly afterwards (up to -1% of GDP in 2050). Simulations also suggest that, if the prices of fossil fuels keep increasing in the future, implementing an energy transition could have broadly the same favorable medium-run effects on the GDP level in the long run as those of a fiscal consolidation diminishing significantly public spending instead of raising taxes. Overall, these results suggest that stopping the energy transition in a time of fiscal consolidation would have detrimental effects on growth from the 2025-2030 onwards, at least on French data. In the long-run, the GDP would be maximized by implementing an energy transition and simultaneously lessening the public deficit by lowering some public expenditures, a policy that would entail an overall gain of around 1,6% of GDP in 2050.

Stopping the energy transition would also bring about intergenerational issues. The OLG module of the model allows for analysing these effects with precision. First, results suggest that stopping the energy transition would be detrimental to the intertemporal wellbeing of almost all cohorts alive in 2010. Accordingly, implementing an energy transition may be close to be a Pareto-improving policy, at least as far as intertemporal wellbeing is concerned.

On the other hand, fiscal policy with lower public expenditures may be more favorable to young and future generations than implementing an energy transition. Lower public spending allows for freezing the levels of taxes in a period when ageing puts Social Security under financial pressure. This effect is especially favourable to young workers who, otherwise, would have paid higher taxes and contributions rates during their whole remaining working life. However, renouncing to implement an energy transition would annihilate most of these favourable, pro-youth effects of a fiscal consolidation with lower spending. These results shed some new light on the possible arbitrage looming between implementing an energy transition and achieving a fiscal consolidation: by renouncing to the former, social planners would undermine most of the pro-youth effects of the latter.

Another result is that in the less probable case with prices of fossil fuels declining strongly in the next 10-15 years, postponing the energy transition may foster somewhat the GDP level during around 15 years without entailing strong intergenerational effects. This does not downplay the need for an energy transition but suggest that the dynamics of its implementation should take account of the dynamics of the prices of fossil fuels on world markets in the future.

These results are relatively robust to alternative assumptions as concerns prices of fossil fuels on world markets. They are not significantly related, either, with the specificities of the energy-mix in France and its relatively prominent role of nuclear in electricity generation. They stem from a model parameterized on OECD/IEA data for a country (i.e., France) which is experiencing fiscal imbalances that are comparable in intensity to those of many other developed countries nowadays - with Germany being a notable exception.

The remaining of this article is organised as follows. Section II reminds of some important results in the litterature focusing on the aggregate effects on activity of energy transition. Section III introduces the model used in this article, which combines an OLG framework with an EG setting. Section IV presents the results obtained as concerns the dynamic impacts on growth of energy transition in a time of fiscal consolidation, and expands on their intergenerational redistributive effects with some possible policy implications they bring about. Section V concludes.

2 Assessing the aggregate impact on activity of energy transition: brief insights from the litterature

A brief overview of some past debates in energy economics is useful for the modeler contributing to the current debates about energy transition. The oil crisis in the 1970's prompted a rapid surge in the economic litterature trying to understand and assess the aggregate impact on activity of a hike in energy prices. To simplify, three mains areas of interest of the litterature emerged at that time.

The first concerned studies about the "energy intensity", its determinants, its heterogeneity among different countries and its historical - mainly downward - trends (Schurr, 1984). Accounting methods disintangled different channels of energy intensity broken down by industry branches (Criqui, 1982). Input-output matrices were used to analyse the dynamics of prices involved by an oil shock across different industries through energy intensity coefficients by industry (OECD-IEA, 1979). While interesting, this is not the part of the litterature this article will mainly rely on.

The second area of research focused on the demand of energy, using mainly econometrics to assess, for instance, income-elasticities or price elasticities, in the short run as well as in the long-run; or interfuels substitution of elasticities. It is not the scope either of this article to expand on this issue; though the litterature on energy demand may be helpful when parameterizing the general equilibrium, analytical, model used in this article.

Thirdly, a vast litterature emerged in the 1970's with production functions enshrining energy as an additional input along with physical capital and labour. Cobb-Douglas production functions with energy, assuming ex-ante and ex-post substituability between labour, physical capital and energy, proved easy to manage - but unsufficiently realistic. In order to simulate more precisely the gradual diffusion of technological progress and higher energy efficiency to the stock of physical capital, models with generations of capital were developped. However, they were unsufficiently manageable for empirical studies. By contrast, constant elasticity of substitution (CES) functions including energy have been extensively used in the empirical litterature. They were considered as an acceptable compromise between the Cobb Douglas function (which assumes full substituability) and the Leontieff function (which assumes full complementarity) (see, for instance, Solow (1978)). They owed much to Sato (1967) who generalized CES functions incorporating more than two inputs. Hogan and Manne (1977) additionally suggested that the (hard-to-measure) 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.[1]

All these results have been paving the way for numerous empirical studies relying on EG models with CES production functions including energy as a third input. Energy CGE models have been commonly used, for example in the energy efficiency and rebound literature (Grepperud and Rasmussen, 2004; Wissema and Dellink, 2007), and have relied routinely on nested CES functions (e.g., Perroni and Rutherford (1995), Böhringer and Rutherford (1997)).

In 2010, the *Energy Journal* published a special issue presenting a set of models assessing the long-run costs of meeting the 450ppm objective (Knopf et al., 2010), with models such a POLES (Kitous, Criqui, Bellevrat and Chateau, 2010) where GDP remains exogenous; MERGE (Magné, Kypreos and Turton (2010) where GDP is endogenous and technological change includes learning-by-doing effects), E3MG (Barket and Serban Scrieciu (2010) who use a neo-keynesian setting) and REMIND-R (Leimbach, Bauer, Baumstark, Lüken, Edenhofer (2010)).

REMIND-R is a GE-model with a standard nested CES production function including energy and an energy module distinguishing fuels costs, investment costs and operational costs for each energy. The model maximises aggregate consumption over time on a 5-years to 5-years basis. REMIND-R has thus common features with many standard CGE models applied to energy models (see also Cassen et al. (2010) for the Imaclim model).

Overall, these GE models suggest that meeting with the 450ppm aim may be technologically feasible and would entail a loss of a few percentage points of discounted GDP in the long run (i.e., 2050) (Knopf et al., 2010). Such an order of magnitude at this horizon seems relatively benign to not a small number of analysts. However, it amounts to loosing around -0,1% or -0,2% of GDP growth per year, something which would nowadays seem hardly bearable for not a small number of European decision makers, given the sluggish growth rate in their countries and the deteriorated situation of their fiscal balances. Moreover, to our knowledge, no CGE model with an energy module has been developed to date that includes an overlapping-generations framework, which seems a necessary input for analysing precisely, on the aggregate scale, the intergenerational redistributive effects of policies implemented over a long period of time.

[1] The use - and even validity - of aggregate production functions has been criticized by some prominent economists (see Cohen and Harcourt (2003) for an account), raising problems about measurement of capital or factor shares. Other no less prominent economists (as Solow, Stiglitz, Samuelson and Hahn) have been advocating in favor of using aggregate production functions, though. Partially related debates nowadays have arisen concerning the accuracy of using production functions with constant elasticity of substitution when simulating energy transition in the very long-run (for instance, when CO2 prices rise in very important proportions).

Accordingly, some further detailed analysis seems required as concerns the impact of energy transition on the annual GDP dynamics in the next decades and its intergenerational redistributive effects. This is all the more required as, as explained in the introduction, governements might nowadays consider that implementing an energy transition could get in the way of achieving fiscal consolidation. The above quoted GE models, while accurate for assessing the long-run impact and feasibility of energy transition, are not specifically designed to answer the question of the dynamics of the year-to-year effects on growth of implementing - or interrupting - an energy transition in a time of fiscal consolidation, nor the question of the implied possible intergenerational effects. Accordingly, this model benefits from the experience accumulated by GE modelers in energy economics but applies it to somewhat new issues. It adopts more closely the viewpoint of a national policy maker concerned primarily with growth and intergenerational equity at the national level. The aim here is not to minimize the quantity of CO2 produced by the world economy. The objective of the domestic social planner consist in trying to preserve potential GDP growth and intergenerational equity as much as possible.[2] Both rank among the main principles guiding economic policy decisions in practice. Accordingly, the paper introduces some applied normative economic analysis along with EG modeling, a characteristic that may justify the use of a GE model with an OLG framework, which is introduced in the next section.

3 Energy transition in a time of fiscal consolidation: the model

3.1 An overlapping generation framework in a general equilibrium setting, with a detailed energy sector

The model used in this article is a dynamic general equilibrium model with an overlapping generations framework, a module for energy prices and volumes, a relatively detailed public sector, and private agents belonging to around 60 cohorts of diffent age, optimizing over their life-cycle. It simulates both energy transition in a context of fiscal consolidation so as to compute its impact on GDP growth and its intergenerational redistributive effects. Exogenous energy prices influence macroeconomic dynamics, which in turn affect the level of total energy demand and the future energy mix (as, for instance, in REMIND (Leimbach et al., 2010)).

More precisely, the model encompasses a two-level nested CES production function, a demographic module, different public regimes, an energy module with fossil fuels, electricity and renewables, and an OLG framework simulating each year the optimal behaviour of around 60 cohorts of different age. The dynamics of the model is driven by demographics, reforms in the sector of

[2] 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.

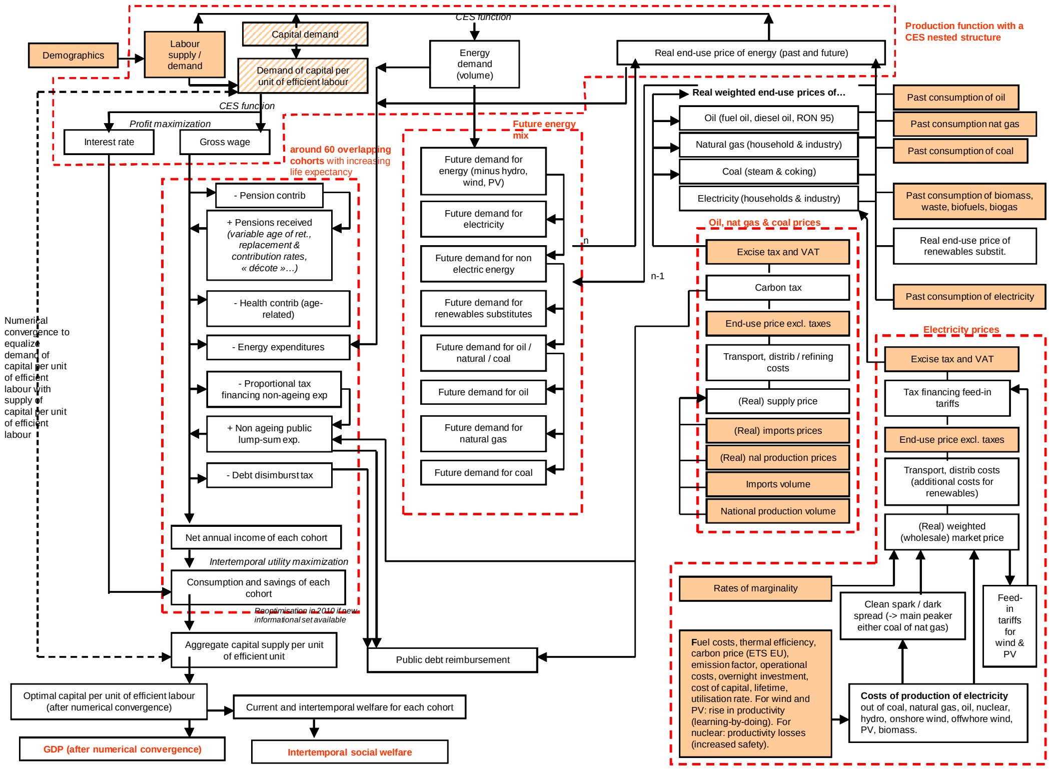

Figure 1: Summarized structure of the OLG-GE model

energy, reforms of public finances, world energy prices, and optimal responses of economic agents to price signals (*i.e.*, interest rate, wage, energy prices). The final outputs of the model are, for each scenario of reform, annual domestic GDP growth rate and welfare for each cohort, which the national social planner seeks to maximize.

A technical annex presents the model in details. The following paragraphs give the basic insights. Figure 1 delivers a graphic summary of the structure of the EG-OLG model.

3.1.1 The energy sector

The main output of the *energy module* is an intertemporal vector of average weighted real price of energy for end-users, computed as a weighted average of exogenous end-use prices of electricity, oil products, natural gas, coal and renewables substitutes, where the weighs are the volumes of demand.

The real end-use price of *electricity* 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 and an endogenously generated (structural) wholesale market price of production of electricity. This wholesale market price of production of electricity stems from an endogenous average peak price of electricity and a peak/offpeak spread. The peak market price of production of electricity in turn derives from costs of producing electricity using 9 different technologies[3] weighted by the rates of marginality in the electric system of each technology. Costs of production are the sum of fixed and variables costs. The model computes endogenously the main peaker of the electric system (either coal firing or natural gas firing), depending on CO2 prices, emission factors and fuel costs. It takes account of the impact of the development of fatal producers of electricity[4] on market prices of electricity. Network costs of electricity stem from observed data and take account of supplementary network costs associated with the rise of renewables (IEA, 2012). Taxes on electricity involve VAT, excises, carbon tax and a tax financing feed-in tariffs for renewables. Data for France stem from IEA/OECD databases. This modeling of prices of electricity in the model allows for simulating in a realistic way future end-use prices by making assumptions over a limited set of exogenous variables.[5]

The real end-use prices of *natural gas, oil products and coal* are weighted averages of end-use prices of different sub-categories of natural gas, oil or coal products.[6] The end-use prices of sub-categories of energy products are in turn computed by summing a real supply price with transport, distribution and/or refining costs, and taxes. The real supply price is a weighted average the prices of domestic production and imports.

Renewables substitutes in the model are defined as a set of sources of energy whose price of production is not influenced in the long-run by an upward Hotelling-type trend; 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.[7] The *real price of renewables substitutes* in the model is assumed to remain constant over time. 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,[8] without tensions that could end up in temporarily rising prices.

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

[4] Defined as onshore wind, offshore wind and solar PV.

[5] *i.e.*, mainly, the annual variation of the real prices of fossil inputs; an objective of development for wind and solar PV in the sector of electricity set by public authorities which in turn requires a tax financing feed-in tariffs and implies rising network costs; rising productivity through learning rate for renewables and productivity loss for nuclear; CO2 prices.

[6] *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.

[7] 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 paragraph presenting the prices of electricity.

[8] On other terms, it is assumed that production of energy out of bioenergies does not trigger any tension on the stock of available biomass, biofuels or biogas.

Overall, the modeling of prices of natural gas, oil and coal products in the model allows for simulating in a realistic way future end-use prices of energy by making assumptions over a limited set of exogenous variables.[9]

Energy demand in volume is broken up into demand for coal, oil products, natural gas, electricity and renewable substitutes.[10] For future periods, following the litterature (as, for instance, for the models REMIND or IMACLIM), 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.

3.1.2 Production function and private agents

The production function is a nested CES one. Caution is required when using constant elasticities of substitution in a GE model with energy. This constancy may bias the results if extreme and/or very long-run scenarios are simulated. For the sake of comparability with most other models existing in the litterature, we abide by the conventional use of nested CES functions. However, we bear in mind that the design of the scenarios should avoid extreme hypothesis as regards, for instance, the rate of the carbon tax or the price of fossil fuels on world markets. Moreover, the results will be commented over a relatively short period (up to 2040-2050 at the maximum) while most GE model with an energy sector comment their results up to 2100.

The nested CES production 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 energy mix derives from total energy demand through 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 define 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.

As concerns private agents, the model embodies around 60 working or retired cohorts each year[11], thus capturing in a detailed way changes in the population structure. Demographic projections flow from a specific simulation model (Gonand, 2005) and rely on official demographic assumptions. Participation rates by age-groups are increasing in line with rising retirement ages (see below, presentation of scenarios). Each cohort is represented by an average individual, with a standard, separable, time-additive utility function and an intertemporal budget constraint. Each average individual of a given cohort decides how much to consume and save so as to maximise the discounted value of his/her lifetime utility subject to his/her intertemporal budget constraint. Households receive gross wage and pension income and pay proportional taxes on labour income to finance a) the PAYG pension regime, b) a health-insurance regime, c) non-ageing related, lump-sum public spendings, and d) in some scenarios, a special tax implemented from 2010 to 2030 in order to reimburse part of a stock of accumulated public debt. Households also pay for energy expenditures, whose amount depends mainly on energy prices, the level of aggregate production and energy efficiency gains.

[9] *i.e.*, the annual variation of the real import cost of natural gas, the annual variation of the real price of a barel of Brent, the annual variation of the real import cost of coal, and the implementation, in some scenarios, of a carbon tax.

[10] *i.e.*, mainly, biomass, biofuels, biogas and waste.

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

3.1.3 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. In all scenarios, the legal effective age at which an individual can receive a full pension is raised by 1.25 years every 10 years, from 2010 onwards and until 2050.[12] This contributes to lessen sizeably the imbalances of the PAYG regime in the future. In scenarios with tax-based consolidations, the residual imbalances of the PAYG regime are covered by increases in the tax rate 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 for future retirees with the taxe rate frozen from 2010 onwards.

The *health regime* is financed by a proportional tax on labour income and is always balanced through higher social contributions. Health spendings are not modeled as in-cash transfers. They influence favorably 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.

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 until 2030.[13] In tax-based consolidations, the public debt is paid back thanks to a special, additional proportional tax levied on labour income and pensions between 2010 and 2030. In consolidations with lower public spendings, the reimbursement of the public debt accumulated up to 2009 is financed by lowering non-ageing related public expenditures up to 2030.

3.2 Policy scenarios

This article focuses on simulating the empirical combined effects on potential (*i.e.*, medium-run) growth of different scenarios of energy transition in a context of different possible fiscal consolidations, and assesses their intergenerational redistributive effects. In the scenarios modeled, two options are considered as concerns energy policy - whether the social planner implements an energy policy or renounces to it - along with two possible types of fiscal consolidation - whether the consolidation is mainly tax-based or implements mainly tax restraints -. Sensitivity analysis is carried out in order to assess whether relatively low future prices of fossil fuels on world energy markets in

[12] It is assumed that age-specific participation rates of workers above 50 years of age increase in line with the changes in the age of retirement. For example, individuals work five years more in 2050 than in 2010.

[13] In the model on French data, the dynamics of the stock of public debt is also influenced by an annual structural public deficit (assumed to remain constant at 1% in the future decades).

the 2010's would modify sizeably the results of the model in each scenario (see annex).

In all scenarios, an anticipated pension reform is implemented from 2010 onwards[14], with a rise of the average effective age of retirement of 1,25 year per decade, starting from 61 years in 2010. The health regime remains balanced thanks to increasing social contributions. The public income of a carbon tax (implemented in scenarios 3 and 4 as in Figure 2) increases non-ageing related, lump-sum public expenditures after 2030.

The scenarios simulated with the model are defined as follows:

	Pension reform + tax hikes	Pension reform + lower public spending
No energy transition	Scenario 1	Scenario 2
Energy transition	Scenario 3	Scenario 4

Figure 2: Scenarios of reforms simulated in the model

As concerns the two types of energy policy considered:

- Scenarios 1 and 2 assume that the energy transition is interrupted from 2010 onwards. This implies no carbon tax; a percentage of hydroelectricity, wind and PV in electricity demand frozen to its 2011 level[15]; and no increase in efficiency energy annual gains.[16]

- Otherwise, in scenarios 3 and 4, the social planner announces in 2010 a reform, non anticipated by private agents, including: a) a carbon tax from 2015 onwards[17]; b) an increase in the percentage of hydroelectricity, wind and PV in electricity demand to 30% in 2020[18], c) a gradual increase in efficiency energy gains.[19]

Two types of fiscal consolidation are considered: tax-based consolidations or consolidations relying mainly on lower public spendings:

- first option: a tax-based consolidation involves here: a) the remaining deficit of the pension regime is financed by supplementary increases in the social contribution rate[20]; b) non-ageing related public spendings do not decline and remain financed by proportional taxes of gross income[21]; c) a specific tax is levied from 2010 to 2030 in order to reimburse part of a public debt that amounts

[14] 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.

[15] Latest data available.

[16] which remains at 1% per year accordingly.

[17] In the model, the rate of the carbon tax begins at 16€/t in 2015, increases by 5% in real terms per year, until reaching a cap of 76€/t in 2047 and remaining constant afterwards. The rate of 16€/t stems from a law passed by the French Parliament in late 2013.

[18] With the associated impacts on feed-in tariffs and network costs.

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

[20] On French data, from around 11% in 2010 to close to 15% in 2030.

[21] The rate of this tax is 20% in the model on French data.

to around 94% of GDP in 2010 on French data[22] and diminishes to 55% of GDP in 2030. Overall, the total tax rate in the corresponding scenarios rises from 42% in 2009 to 50% in 2029.

- second option: the fiscal consolidation is achieved mainly through significantly lower public expenditures. Government announces in 2010 a reform, non anticipated by private agents, including: a) a lower replacement rate for new retirees to cover the remaining deficit of the pension regime[23] ; b) non-ageing related public spendings declining by more than 3% of gross income in 2010 so that the associated surplus is affected to reimburse part of the public debt.

Scenarios 3 and 4 involve the creation of a carbon tax in 2015. After 2030, when fiscal consolidation is achieved, the associated income is entirely redistributed to the households through higher lump-sum public expenditures. Before 2030, when fiscal consolidation is still under way, the income of the carbon tax is shared the between the households and the reimbursement of the public debt, such as the level of public debt reached in 2030 is the same as in the scenarios without carbon tax (*i.e.*, 56% of GDP).[24]

The four scenarios are simulated assuming 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, though 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.[25] These prices remain constant after 2050 in the model. Sensitivity analysis is carried out with low future prices of fossil fuels on world markets (see annex).

All the modifications of the informational set of private agents involve a reoptimisation process in 2010, defining new intertemporal paths for consumption, savings and capital supply. The baseline, no-reform scenario is defined as scenario 1. All scenarios rely on an assumption of a total factor productivity (TFP) of 1,5% per year up to 1999, slowing down to 1,0% per year from 2000 to 2020, before going back to 1,5% per year.[26] Since the results are expressed as differences between scenarios, such an assumption does not have any significant influence on the policy implications of the model.

[22] Each year, the interest rate on the debt and 1/41th of the stock are reimbursed. Public deficit before interest payments is assumed to equal zero. Interest on public debt is 3% lower than the average cost of capital for private agent (i.e., around 3% in the model, in real terms).

The rate of the tax is close to 3%, on average, of gross income (wage and pensions) between 2010 and 2030.

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

[24] This ensures comparability among the 4 scenarios modeled here: the intensity of the fiscal consolidation is the same in all scenarios. This criterion of comparability between the scenarios entails that a) in scenario 3, 100% of the income associated with the carbon tax is affected to the reimbursement of the public debt between 2015 and 2030; b) in scenario 4, around one half of the tax on average over 2015-2030 is affected to the reimbursement of the public debt, the other half being redistributed to households through slightly higher lump-sum public expenditures - especially during the late 2020's. The difference between both scenarios mirrors the relatively more detrimental impact on tax bases of the tax hikes implemented in scenario 3 (see the presentation of the results, further in this article), which requires that a higher fraction of the income of the carbon tax has to be devoted to the reimbursement of the public debt so as to maintain the same path of the public debt until 2030 as in scenario 4. Had 100% of the carbon tax been affected to the reimbursement of the debt in scenario 4, the debt in 2030 would have been 4 GDP percentage points lower.

The aggregate impact of these hypothesis in the model remains subdued since the level of the carbon tax voted by the French parliament in late 2013 is relatively small (*i.e.*, 16€/t).

[25] 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.

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

With this setting, the effects of stopping an energy transition can for instance be assessed by computing the differences between the results of scenario 2 and scenario 4 (if governement chooses to implement a fiscal consolidation restraining public spending), or by computing the differences between the results of scenario 1 and scenario 3 (if governement chooses to implement a fiscal consolidation increasing taxes).

4 Results: effects of interrupting or implementing an energy transition in a time of fiscal consolidation

4.1 Aggregate effects

(The technical annex provides with some additional graphs illustrating the main aggregate effects obtained in the model for some scenarios.)

- *in the no-reform, baseline scenario 1*, the prices of fossil fuels keep increasing over the next decades, by assumption. No specific policy in the 2010's bolsters the development of the production of electricity out of wind and PV. Accordingly, the amount of the tax financing feed-in tariffs remains subdued - around 4€-5€/MWh. The price of CO2 in the EU-ETS is assumed to remain depressed (at 7€/tCO2). Consequently, coal firing remains the main peaker on the electricity market in the future. The end-use price of electricity for households increases by 26% in real terms between 2010 and 2030. The total weighted end-use price of energy displays an strong upward trend (+44% in real terms from 2010 to 2030). In this context, the total demand for energy does not increase, notably because high prices of fossil fuels weigh on its level. The energy mix displays a rise of the renewable sources of energy mainly because of this surge in the prices of fossil fuels. Since there is no energy policy in favor of energy transition in this scenario, the rise in the percentage of renewables[27] in the mix is subdued, from 12% of total demand in 2010 to 19% in 2025. As concerns public finances, total tax rate increases from 42% of gross income in 2009 to 50% in 2029[28], which depresses net income and private capital accumulation. Since the reform of the PAYG pension regime bolsters labour force over the period, the capital per unit of efficient labour unit declines gradually, by 11% between 2009 and 2030.

- *in scenario 2 (no energy transition, lower public spending)*, the energy module displays the same results as in scenario 1, by assumption: high prices fossil fuels, some substitution of renewables, coal remaining as the main peaker on the electricity market. As regards public finances, on the contrary, total tax rate remains broadly stable around 43%-44% of gross income over the next decades - instead of increasing to close to 50% as in scenario 1. Contrary to scenario 1, the capital per unit of efficient labour unit remains almost stable over the next decades.

- *in scenario 4 (energy transition implemented, fiscal consolidation with lower public expenditures)*, an energy transition policy is implemented that bolsters the development of renewables

[27] Here defined as encompassing hydroelectricity, wind, PV, biomass, biofuels, biogas.

[28] The year 2029 corresponds to the latest year in the model where a the special tax financing the reimbursement of the public debt is levied.

thanks notably to a carbon tax imposed on fossil fuels. This policy fosters the production of electricity out of wind and PV. By assumption, it doubles the gains of energy efficiency.[29] The amount of the tax financing feed-in tariffs (for wind and PV only) almost doubles from the late 2000's to 2020, reaching around 15€/MWh. The carbon tax is implemented from 2015 onwards, with a rate of 16€/t. It then increases by 5% in real terms per year and stabilises to 76€/t in 2047. The associated public income increases from around 5bn€ per year to 10bn€. It is shared between the reimbursement of the public debt and the households (through higher public lump-sum expenditures) on a 50-50 basis, which ensures to meet a level of public debt of 55% of GDP 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 (mainly because the rate of the carbon tax remains low here)[30]. The end-use price of electricity for households increases by 70% 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 (+60% in real terms from 2010 to 2030). In this context, the total demand for energy remains sluggish over the next decades. Taxation of carbon magnifies the effects on energy demand stemming from high prices of fossil fuels on markets, along with the impact of accelerating gains in energy efficiency. The energy mix displays a rise of the renewable sources of energy[31], from 12% of total demand in 2010 to 23% in 2025. As concerns public finances, results are the same as in scenario 2 (i.e., no tax hikes). Capital per unit of efficient labour unit is almost stable over the next decades.

- *in scenario 3 (energy transition implemented, fiscal consolidation mainly with tax hikes)*, the results obtained in the public finance module are very comparable to those presented in scenario 1. The total tax rate increases to 50% of GDP in 2029. In the energy module, results are close to those obtained in scenario 4. The end-use price of electricity displays a very strong upward trend (around +73% in real terms from 2010 to 2030). The energy mix displays a rise of the use of renewables sources of energy[32], from 12% of total demand of energy in 2012 to 23% in 2025. Capital per unit of efficient labour declines significantly over the next decades (-6% between 2009 and 2030). This contrasts with scenario 4 where the capital per unit of efficient labour does not decline in the future decades.[33]

4.2 Implications on growth dynamics

As suggested in the introduction, the influence of energy transition on activity depends on the time-horizon considered. Energy transition can require new subsidizing schemes, temporarily higher prices in some cases, and more capital accumulation in the short run. In the long-run however, it should foster energy efficiency and allow for lower prices of energy relative to prices of fossil (thus

[29] In the model, efficiency gains in energy increase gradually from +1,0% per year in 2010 to +2,0% per year from 2020 on, by assumption (see *supra*).

[30] However, 16€/t is the rate of the carbon tax passed by the French Parliament in late 2013.

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

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

[33] This less favourable macroeconomic environment in scenario 3 as compared to scenario 4 explains that the public income associated with the carbon tax is fully used for reimbursing the public debt in scenario 3, in order for fiscal policy to meet the 55% of GDP target in 2030. In scenario 4, the income associated with the carbon tax is shared between the government (to reimburse the debt) and households (trhough higher lump-sum public expenditures) and the debt target of 55% of GDP in 2030 is still met.

depleting) ressources. Accordingly, energy transition may weigh on aggregate activity during some period on the short-run and favor GDP after some years.

These mechanisms can be quantitatively assessed in the model by comparing the growth rate between different scenarios.[34] Results can be summarised as follows: (cf. Figures 3 and 4).

Result 1: the model confirms that stopping the energy transition involves some short-run macroeconomic gains but long-run pains, and the higher the market prices of fossil fuels, the lower the macroeconomic gains of interrupting the energy transition. If the prices of fossil fuels keep increasing in the future, the defavorable influence of energy transition on GDP could last a little bit more than a decade. The energy transition, as defined in the model on French data, would lessen the GDP level by -0,2% in 2020, before fostering it from 2030 onwards. In 2050, the level of GDP would be 1,0% higher than if energy transition had not been implemented from 2010 on. Would the prices of fossil fuels diminish significantly up to 2020 before rising up again afterwards, then the pain of energy transition would be higher (reaching -0,4% on the GDP level in 2020) and lasts 15 years. This result is intutive. The more expensive fossil energies will be, the more accurate an energy transition would be for future growth, by accelerating the rise of renewables substitutes to fossil fuels. Overall, stopping an energy transition in a time of fiscal consolidation would foster the level of the GDP in the next decade (between +0,2% and +0,4% of GDP in 2020) before depressing it afterwards, up to -1,0% in 2050.

Result 2: a fiscal consolidation diminishing public expenditures instead of raising taxes could trigger, as the implementation of an energy transition, short-term macroeconomic pains but significant long-run gains.[35] This is mainly because the latter depresses the accumulation of capital in the long run whereas the former does not. A permanent rise in social contributions financing PAYG pension regime cannot have any positive effect on savings, while a lower replacement rate strongly encourages agents to increase their saving to maintain their consumption level when retired (Gonand and Legros, 2009). Reimbursing the public debt by lower public spending between 2010 and 2030 rather than raising new taxes also has a positive effect on capital per unit of labour. Overall, lowering replacement rate of the pension regime and lessening public spending to reimburse the debt weighs on the GDP level by around -1,25% in 2015,[36] before fostering it from 2022 onwards. In 2050, the level of GDP is 0,6% higher than if fiscal consolidation had been achieved through higher taxes. The appropriate conclusion from the model on this specific point is not that public spending is bad *per se*, but that cuts to - *a priori*, lower-priority - public spending items might deliver significant gains compared with the alternative of raising taxes.

Result 3: if the prices of fossil fuels keep increasing in the future, energy transition could have broadly the same medium-run effects on the GDP level in the next decades than those of a fiscal

[34] Some remarks may be useful here before commenting on the results. First, when unanticipated reforms are announced in 2010, each living cohort redefines its optimal intertemporal path for consumption: accordingly, some non-linearities are observed in the endegenous variables of the model, notably GDP. Second, it should be reminded here that all scenarios involve a rise in the effective retirement age of 1,25 year per decade - a framework already slowing significantly the path of public spending. Third, we do not expand here on the dynamics of GDP growth rate in each scenario taken on a one-by-one basis, since these dynamics are influenced by the assumption concerning TFP which is common to all scenarios.

[35] This result stems from the comparison of results between scenario 2 and scenario 1 (cf. Figure 4).

[36] The effects of different types of fiscal consolidation in a context of high energy prices can be computed as the difference between GDP in scenario 2 and GDP in scenario 1, or by the difference between GDP in scenario 4 and GDP in scenario 3.

Impacts on GDP level of some reform scenarios

All the scenarios include a pension reform increasing the average effective age of retirement by +1,25 year per decade, and the reimbursement of around half the public debt between 2010 and 2030

Effect on the GDP level	2020	2025	2030	2050
Effect of stopping the energy transition (in a context of fiscal consolidation restraining public spending) (scenario 2 - scenario 4) *(the effect of implementing an energy transition would have the opposite sign)*	0,2%	0,1%	0,0%	-1,0%
Effect of stopping the energy transition (in a context of fiscal consolidation increasing taxes) (scenario 1 - scenario 3) *(the effect of implementing an energy transition would have the opposite sign)*	0,1%	0,0%	-0,2%	-1,0%
Effect of lowering public spending instead of raising taxes, and no energy transition (scenario 2 - scenario 1)	-0,1%	0,2%	0,3%	0,6%
Best policy response as concerns the GDP level: scenario…	**1**	**2**	**4**	**4**
Sensitivity analysis with lower prices of fossil energies on world markets 1/				
Effect of stopping the energy transition (with a fiscal consolidation restraining public spending)	*0,4%*	*0,2%*	*-0,1%*	*-1,0%*
Effect of lower world energy prices with no energy transition and tax hikes 1/	*1,8%*	*2,2%*	*2,3%*	*2,8%*
Effect of lower world energy prices with no energy transition and lower public spending 1/	*2,4%*	*2,7%*	*2,7%*	*3,3%*

1/ Hypothesis of lower energy price: from 2010 on, energy prices of world markets (oil, coal, natural gas) diminish in 2010-2020 up to their 30-years average level, before increasing again afterwards to follow a proxy of a Hotelling rule (+3% real per year) until 2050.

Figure 3: Impact on the GDP level of different reform scenarios

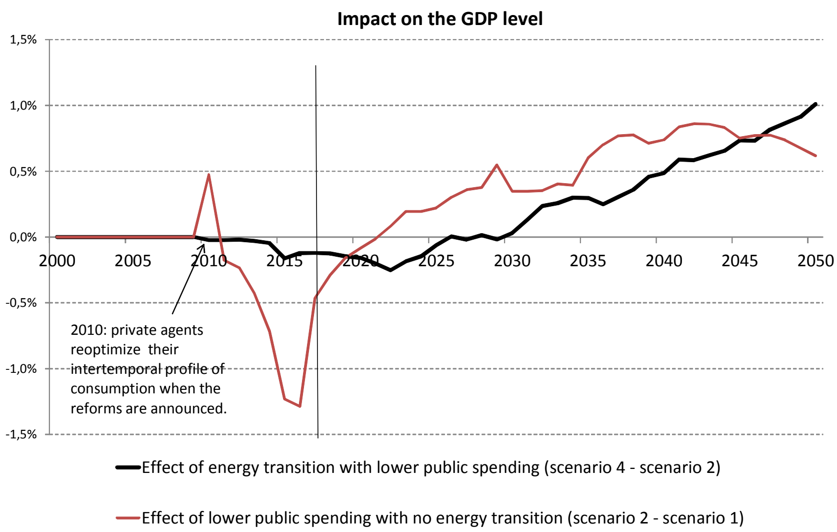


Figure 4: Impact on the GDP level

consolidation diminishing significantly public spending (cf. Figure 3 and 4). Both transitions lessen GDP during around a decade before fostering it somewhere during the 2020's. In the long run, the positive effect is close to +0,75% of GDP around 2045 in both policies (see Figure 4).

Result 4: the best policy response in terms of GDP depends on the horizon considered but always encapsulates an energy transition and lower public expenditures in the long run. The best policy response in terms of GDP is defined here as the policy package mixing a fiscal consolidation and an energy policy that maximises their joint impact on GDP. By definition, this optimal policy response depends on the horizon considered. From 2027 onwards, it involves in all cases triggering an energy transition and lessening public spending. Such a package entails a gain of 1,6% of GDP in 2050 in the model on French data.[37]

Result 5: the effect on GDP of significant variations of market prices of fossil fuels are far higher in the short run than those of the policies analysed here. This stems from the results of the sensitivity analysis as summarized in Figure 3 and detailed in annex. For instance, the effect on the GDP level of unanticipated, sizeably lower prices of fossil fuels during the next decade could be around 2% in 2020.

Result 6: the effects of an energy transition on GDP in the model does not contradict the conventional wisdom of the "elephant and rabbit" tale in energy economics, i.e.*, the impact on growth of energy transition remains relatively subdued.* In the long-run, around 2050, an energy transition is expected to have a favourable impact on the level of GDP of 1%. It could be shown that pension reforms incorporating a significant rise in the age of retirement entail much higher effects on the GDP level. Our results seem to be in line with the so-called tale of the elephant and the rabbit (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. Consequently, this result does not downplay the interest of studying the joint impact of energy transition and fiscal consolidation on growth.

Overall, these results suggest that stopping the energy transition in a time of fiscal consolidation would have detrimental effects on growth from the middle of the 2020's onwards, and that these effects are not negligible - at least on French data (see caveats below). In the long-run, the GDP would be maximised by implementing the energy transition and simultaneously lessening the public deficit by lowering some public expenditures.

Some caveats are in order when commenting on these results:

- in the model, the gains in energy efficiency are exogenous. In practice, they may require costly investments possibly crowding out other private projets. From this point of view, the model may underestimate the negative effects of energy transition on growth, *ceteris paribus.*

- this version of the model does not encapsulate an endogenous working time. Endogenising the labour market in such models raises specific issues (see Cournède and Gonand, 2006) without modifying strongly the quantitative results. However, it would allow for taking account of the distorsive effects associated with tax hikes. From this viewpoint, the model might somewhat undermine

[37] Before 2027, the best policy package as defined above does not encapsulate an energy transition. For the next years, the best policy package is either scenario 1 (up to 2021) or scenario 2 (between 2022 and 2026).

the favorable effects on growth of lower public spendings compared with higher tax rates, *ceteris paribus.*

- the model does not take account of the favourable economic effect of energy transition on domestic independance as concerns energy. Developing renewable sources of energy lessens the dependance vis-a-vis foreign producing countries, thus lowering, on average, the price of energy, with the associated favorable impact on growth.

- these results, stemming from a model parameterized on OECD/IEA data for a specific country (France), may apply to other similar European countries. France is now experiencing fiscal imbalances that are comparable in intensity to those of many other developed countries nowadays, notably in Europe. Whereas public debt, taxes and public spending are slightly higher in France compared to the European average, demographics is slightly more favorable. Overall, our results might also apply to other European countries having a fiscal situation comparable to France. Germany is obviously an exception since its public finances are broadly balanced nowadays.

- the specificities of the energy-mix in France, with the prominent role of nuclear in electricity generation, do not bias significantly our results. The role of nuclear in French electricity production is relatively large. It accounts for a share of electricity in the energy-mix slightly higher (23,5%) than the OECD average (21,9%). It shelters somewhat the economy against large variations of the prices of fossil fuels and lessens the average *level* of the production price of electricity. However, the difference remains small in absolute terms, and using other assumptions as for the electric-mix would not sizeably modify the main characteristics of the *dynamics* of the model.

4.3 Intergenerational redistributive effects of stopping an energy transition

4.3.1 Effects on future annual welfare of each cohort

The influence on economic growth of both reforms last several decades. Accordingly, they are bound to bring about intergenerational issues. The OLG framework of the model allows for studying them with precision.

A first detailed analysis of the cohorts loosing or gaining in different scenarios is possible using Lexis surfaces (Figure 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 *current* welfare of a cohort aged a in a given year t and in a given reform scenario, compared to its current welfare in the baseline scenario.[38] Current welfare refers here to the instantaneous utility function of a private agent in the model.

Before the announcement of a reform package in 2010, annual current welfare of one cohort is by assumption equal in all 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 as measured by their influence on current welfare.

[38] Baseline scenario is scenario 1 if world energy prices are high, or scenario 5 if they are relatively low in the next decade.

Current welfare mirrors consumption levels, which are defined in 2010 by perfectly forward-looking private agents.

Figure 5 displays the Lexis surface for current welfare at each year for each cohort in the model, in scenario 2 relative to scenario 4. Thus it materializes the intergenerational effects of stopping an energy transition. Fiscal policy is the same in both scenarios and involves lower spending.

Result 1: Stopping an energy transition would be moderately detrimental for the future annual *welfare of almost all cohorts, but slightly more so for young and and future generations.* Two mechanisms account for this intergenerational impact:

- for all the cohorts, the creation of a carbon tax, the rise in the price of electricity in line with the development of renewables and the acceleration of energy efficiency involve welfare consequences that do not depend primarily on age. Thus stopping an energy transition entails consequences that are not primarily related with age.

- however, since energy transition would have made the economy less dependant on costly prices of fossil fuels, stopping it would weigh on the annual current welfare of all cohorts from 2021 onwards. The effect remains subdued, though (around -1% to -2% of annual wellbeing). By contrast, stopping an energy transition would very slightly foster the annual wellbeing of any old-aged cohort whose representative individual dies before the 2020's.

Figure 6 displays the Lexis surface for current welfare at each year for each cohort in the model, in scenario 2 relative to scenario 1. Thus it materializes the intergenerational effects of a fiscal consolidation with lower spending compared to a fiscal consolidation with higher taxes.[39]

Result 2: Intergenerational effects on future annual wellbeing of switching to a consolidation with lower public expenditures rather than higher taxes are stronger than those of an energy transition (see Figure 6)*. They favor significantly the future annual welfare of young and future generations* and diminish the annual current welfare of cohorts aged more than 40 in 2010. Noteworthingly, in scenario 2, the PAYG pension regime is balanced via a lower future replacement rate whereas it is balanced with higher social contributions on income in scenario 1. The former is more favorable to the welfare of young workers than the latter.[40] Overall, fiscal consolidation involving lower public expenditures in the model is relatively more detrimental to the future annual wellbeing of "baby-boomers" than to their children.[41]

[39] In both cases, there is no specific energy policy and energy prices are the same in both scenarios.

[40] Indeed, as far as young workers are concerned, it involves switching from a situation where one has to pay more contributions to get an unchanged pension, to a scenario where one does not have to pay more to get a pension - admittedly lower, but far away in the future. The effect of a lower pension weighs far more on the welfare in future years of baby-boomers approaching the age of retirement, who will not benefit during a long period from the favourable effect stemming from relatively lower level of social contributions.

Moreover, in scenario 2, non-ageing related public spending diminish in order to finance the reimbursement of part of the public debt. Thus the rate of the tax financing these spending remains unchanged. Since the non-ageing related public spending is lump-sum in the model (as a proxy of public services) and since proportional taxes increase with income, the reform in scenario 2 weighs more on the welfare of aged workers, whose income is higher in the model than the one of young workers.

Additionally, it has been shown *supra* that tax hikes have a more detrimental impact on the capital per unit of efficient labour than expenditures restraints, and thus depress more the level of GDP, and accordingly weigh more on the welfare of private agents.

[41] This intergenerational effect would be strongly magnified if no PAYG pension reform increasing the age of retirement has been encapsulated in each scenario simulated here.

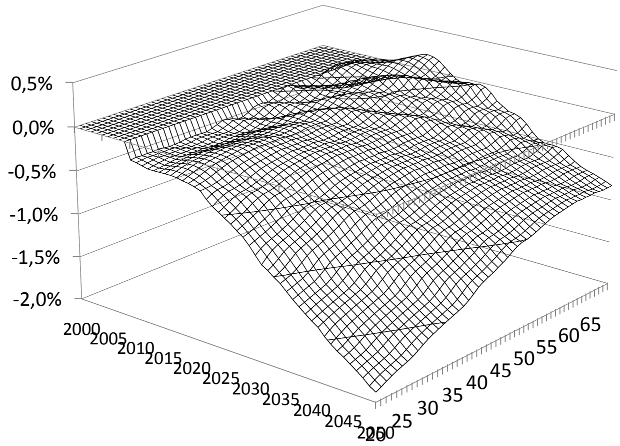


Figure 5: Intergenerational effects of stopping an energy transition (=current welfare at each year for each cohort in scenario 2 relative to scenario 4)

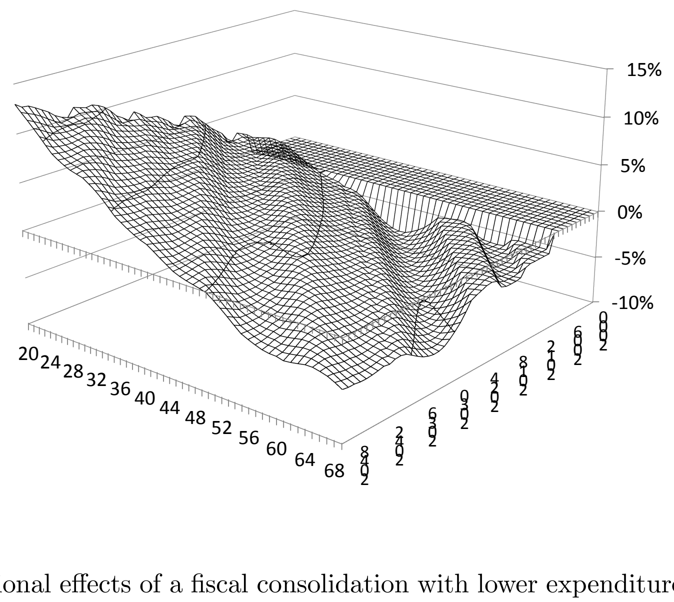


Figure 6: Intergenerational effects of a fiscal consolidation with lower expenditures rather than tax hikes (=current welfare at each year for each cohort in scenario 2 relative to scenario 1)

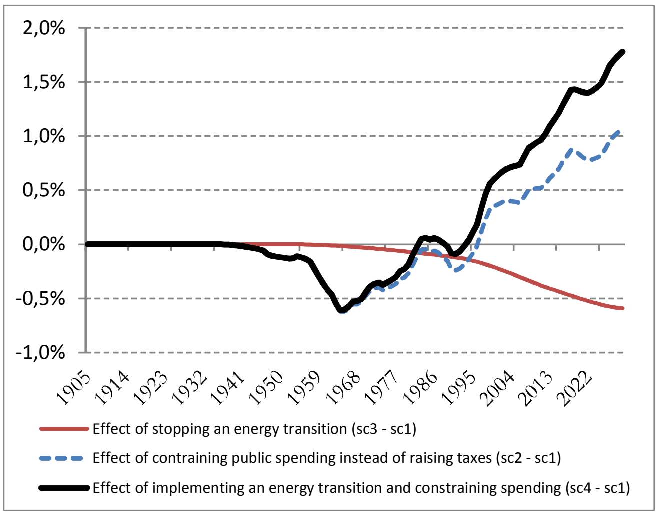


Figure 7: Effect on intertemporal welfare of reform scenarios relative to the no-reform scenario 1

These intergenerational redistributive effects are robust to different assumptions as concerns future prices of fossil fuels on world market. The Lexis surfaces obtained in scenarios with low prices of fossil fuels on world markets are not schown here but display the same patterns as those presented in Figures 5 and 6.

4.3.2 Effects on intertemporal welfare of private agents

Computing the *intertemporal welfare of each cohort over its whole lifetime* allows for precising and completing the above analysis of intergenerational redistributive effects. Figure 7 displays the effects on intertemporal welfare of each cohort of reform scenarios relative to the no-reform scenario 1[42].

Result 3: In the model, stopping the energy transition would be detrimental to the intertemporal wellbeing of almost all cohorts living in 2010. Thus, implementing an energy transition may be close to a Pareto-improving policy, as far as the intertemporal welfare of private agents is concerned. This result is relatively robust to the hypothesis about future world energy prices.

Result 4: Fiscal policy with lower public spending might be more favourable to young and future generations than implementing an energy transition itself (cf. Figure 7). Lower public spending allows for freezing the levels of taxes in a period when ageing puts Social Security under financial pressure. This effect is especially favourable to young workers (who, otherwise, would have paid higher taxes and social contributions during their whole working life). It is close to neutral for generations born during the 80's, and diminishes the intertemporal welfare of baby-boomers (*i.e.*,

[42] In the baseline scenario (scenario 1), there is no energy transition and fiscal consolidation relies mainly on tax increases.

cohorts born in the 50's, the 60's and the 70's). This result is in line with those obtained with the Lexis surfaces, but allows for defining more broadly - from an intertemporal viewpoint - the loosers and winners of this fiscal choice, depending on their year of birth. It is robust to the hypothesis about future world energy price.

Result 5: Renouncing to implement an energy transition would annihilate most of the favourable intergenerational, pro-youth effects of a fiscal consolidation with lower spending. This flows directly from results presented in Figure 7. This result sheds a new light on the possible arbitrage, presented in the introduction, that governments might see between implementing an energy transition and achieving a fiscal consolidation. By renouncing to the former, social planners would also undermine most of the pro-youth effects of the latter.

Result 6: Combining an energy transition with a fiscal consolidation incorporating public expenditures restraints would strongly favor the intertemporal welfare of current young and future generations. This is shown directly on Figure 7. *The result is all the more interesting as the previous sections suggest that this combination of policies (in scenario 4) delivers the best results as concerns the level of GDP in the long run.*

Result 7: In case the prices of fossil fuels decline strongly in the next 10-15 years, postponing the energy transition may foster somewhat the GDP during around 15 years without entailing strong intergenerational effects. This result flows from simulations made in the sensitivity analysis and summarized in Figure 3. Admittedly, the probability for the prices of fossil fuels to go down sharply in the next years is not very high, but it cannot be completely neglected either. This result does not imply any normative assessment on energy transition. It only suggests that the dynamics of the implementation of an energy transition should take account, as much as possible, of the dynamics of the prices of fossil fuels on world markets in the future.

5 Conclusion

This article adressed the issue of the empirical effects on potential growth of stopping - or implementing - an energy transition in a time of fiscal consolidation, their dynamics, and their intergenerational redistributive impacts. In doing so, it relied on a general equilibrium model including a detailed overlapping-generations module. It adopted closely the viewpoint of a national policy maker, trying to preserve potential GDP growth and intergenerational equity at the national level. It was parameterized on OECD/IEA data for France.

The results show that renouncing to the energy transition would slightly foster the level of GDP during 10 to 15 years - depending on the dynamics of the prices of fossil fuels on world markets - but weigh on it more significantly afterwards (up to -1% of GDP in 2050). A fiscal consolidation lessening public expenditures rather that increasing taxes would also foster long-run growth, mainly because the latter depresses the accumulation of capital whereas the former does not. Results also suggest that, if the prices of fossil fuels keep increasing in the future, implementing an energy transition could have broadly the same favorable medium-run effects on the GDP level in the next decades as those of a fiscal consolidation diminishing significantly public spending. Overall, stopping the energy transition in a time of fiscal consolidation would have significantly detrimental effects on growth from the 2025-2030 onwards. In the long-run, the GDP would be maximized by implementing an energy transition and simultaneously lessening the public deficit by lowering some public expenditures, a policy that would entail an overall gain of around 1,6% of GDP in 2050.

Stopping the energy transition would also bring about intergenerational issues. First, results suggest that stopping the energy transition would be detrimental to the intertemporal wellbeing of almost all cohorts alive in 2010. Accordingly, implementing an energy transition may be close to be a Pareto-improving policy. On the other hand, fiscal policy with lower public expenditures may be more favorable to young and future generations than implementing an energy transition. Lower public spending allows for freezing the levels of taxes in a period when ageing puts Social Security under financial pressure. This effect is especially favourable to young workers who, otherwise, would have paid higher taxes and contributions rates during their whole remaining working life. Renouncing to implement an energy transition would annihilate most of these favourable, pro-youth effects of a fiscal consolidation with lower spending, however. These results shed some new light on the possible arbitrage looming between implementing an energy transition and achieving a fiscal consolidation: by renouncing to the former, social planners would undermine most of the pro-youth effects of the latter.

Another result is that in the less probable case with prices of fossil fuels declining strongly in the next 10-15 years, postponing the energy transition may foster somewhat the GDP level during around 15 years without entailing strong intergenerational effects. This does not downplay the need for an energy transition but suggest that the dynamics of its implementation should take account of the dynamics of the pirces of fossil fuels on world markets in the future.

These results are relatively robust to alternative assumptions as concerns prices of fossil fuels on world markets. They are not significantly related, either, with the specificities of the energy-mix in France and its relatively prominent role of nuclear in electricity generation. They stem from a model parameterized on OECD/IEA data for a country (i.e., France) which is experiencing fiscal imbalances that are comparable in intensity to those of many other developed countries nowadays - with Germany being a notable exception.

This analysis would be expanded along different paths. First, the model could be duplicated using data for other countries with a different energy mix and a different fiscal situation (as Germany). Second, a version of the model with an endogenous labour time could be developed, adapting Cournède and Gonand (2006)'s framework, so as to take account of distorsive effects on labour supply of an energy transition. Third, some applied normative analysis could be developed in order to analyse the condition of public choice between different scenarios, using social welfare functions. This could, among other issues, raise the problem of the influence of the social discount rate on public choice. Fourth, the product of the carbon tax is used in the model to partly reimburse the public debt between 2010 and 2030. But other choices could be made (*e.g.*, a switch between a carbon tax and lower social contributions could be envisaged, other timing for redistributinf the income of the tax to households). They would involve a so-called "double-dividend" and/or a lower detrimental effect on growth, but would modify the path of fiscal consolidation. In any case, overlapping generation frameworks enshrined in EG modeling seem to offer some areas of future research on transitions in economy from the point of view of the social planners, especially those confronted with energy transition and fiscal consolidation in the next decades.

A Description of the GE-OLG model

The model used in this article is a dynamic general equilibrium (GE) model with a detailed module for energy prices and volumes. Most notably, it includes a detailed overlapping generations (OLG) framework.

GE models have been used regularly in energy economics to assess the macroeconomic effects of shocks in the energy sector. The litterature emerged in the 1970's in the wake of the global shock on the oil market, materializing in skyrocketting oil prices and depressed growth rate in many western countries. Since then, a whole litterature has developed. With the rise of debates about ecology, the litterature focuses nowadays more on the macroeconomic effects of lessening CO2 emissions of the energy sector in the long-run (Bhattacharyya, 1996).

A special issue of the *Energy Journal* published in January 2010 presents different models simulating the aggregate effects of policies limiting CO2 concentration at low levels in the coming decades (Knopf et al., 2010). In some models with energy, GDP growth is exogenous (GEMINI, POLES, TIMER) while, in other models, GDP growth is endogenous. This model belongs to the latter category. Among the models with endogenous GDP, two types can be distinguished, whether the macroeconomic module remains relatively simple and appears to coronate a more detailed, pre-existent, engineering-type modeling of the energy sector - following a so-called "bottom-up approach" - or a macroeconomic model enriched with a more or less detailed module representing the energy sector where technical progress remains mainly exogenous and substitution elasticities more or less constant over time - the so-called "top-down approach".

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 (as, for instance, in the REMIND model, see Leimbach et al., 2010). Most importantly, this GE model includes a detailed overlapping generations framework so as to analyse the intergenerational redistributive effects of energy and fiscal reforms.

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 theoretical modeling of Arrow and Debreu (1954) shows that the characteristics of the general equilibrium can be obtained by resolving a set of equations representing the optimal behaviour of agents, with a vector of prices as the equilibrium variable. Solow (1956) characterises the properties of the long-run equilibrium of an economy with decreasing returns and of the convergence towards this equilibrium. Life-cycle models provide with the basis of economic analysis as concerns intertemporal consumption behaviour and capital accumulation, where the economic behaviour of one cohort influences the behaviour of all the others. The development of applied GE-OLG models, using real data, is more recent. It owes much to Auerbach and Kotlikoff (1987) who inaugurated a litterature on fiscal policy in a dynamic general equilibrium setting which this article partly belongs to. The overlapping-generations setting of the present model stems mainly from Gonand and Legros (2009).

A.1 General structure of the model

The model aims at simulating energy transition and fiscal consolidation is a general equilibrium framework - so as to compute GDP growth - and with overlapping generations - so as to measure intergenerational redistributive effects. In doing so, it encompasses an energy module, a two-level nested CES production function, a demographic module and an OLG framework simulating the optimal behaviour of around 60 cohorts of different age.[43] The dynamics of the model is driven by demographics, reforms in the sector of energy, reforms of public finances, world energy prices, and optimal responses of economic agents to price signals (i.e., interest rate, wage, energy prices).

The final outputs of the model are, for each scenario of reform, annual GDP growth rate and welfare for each cohort.

A.2 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 ($D_{i,t-1}$):

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

- $q_{energy,t}$ 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) ($i = 5$).

A.2.1 Energy prices

Energy prices are exogenous inputs of the model for past and future periods.

[43] 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.

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:

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

- $q_{i,j,t,s}$ 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.

Noteworthingly, the import price of natural gas is $m_{1,1,t} = m_{1,2,t} = m_{nat\ gas,t}$, stemming from long-run contracts as well as market sourcing. In the French case, the real price of a barel of Brent (in euros constant 2010) is used to compute $m_{2,1,t} = m_{2,2,t} = m_{2,3,t} = m_{Brent,t}$. In France, the future domestic production of natural gas, oil and coal is assumed to remain nil: $\forall t > 2010,\ P_{1,j,t} = P_{2,j,t} = P_{3,j,t} = 0$.

- $q_{i,j,t,c}$ 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. 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. Overall one thus gets:

$$q_{i,j,t,\tau} = VAT_{i,j,t} + Excis_{i,j,t} + others_{i,j,t} + carbon\ tax_{i,j,t}$$

This modeling of prices of natural gas, oil and coal products in the model allows for simulating in a realistic way future end-use prices of energy by making assumptions over a limited set of exogenous variables, namely:

- the annual variation of the real import cost of natural gas: $\Delta m_{natgas,t}$
- the annual variation of the real price of a barel of Brent: $\Delta m_{Brent,t}$
- the annual variation of the real import cost of coal, which is assumed to be the same for steam coal and for coking coal in the future: $\Delta m_{coal,t} = \Delta m_{steam,t} = \Delta m_{coking,t}$
- the implementation, in some scenarios, of a carbon tax: $carbon\ tax_{i,j,t}$

For illustration purpose, the following graphs show the data for simulated energy prices of natural gas for households (i.e., $q_{1,1,t}$) and industry (i.e., $q_{1,2,t}$) in scenario 4.

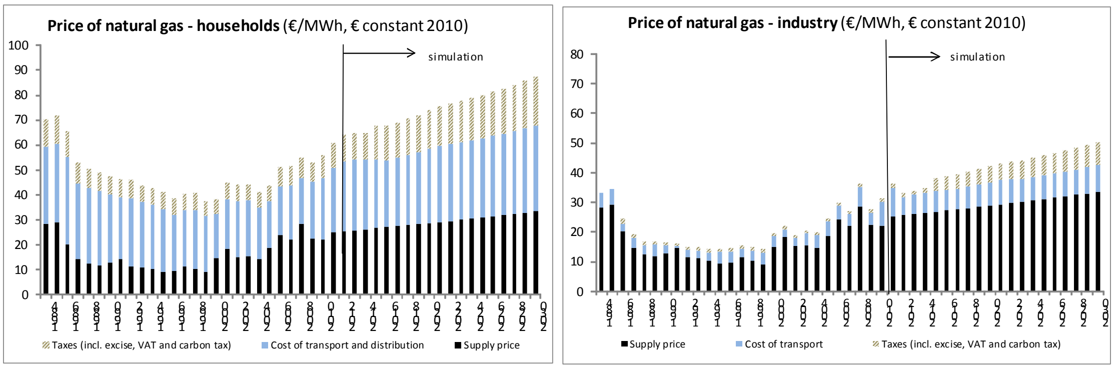


Figure 8: End-used real price of natural gas for households and industry in scenario 4 from 1984 until 2030

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:

$$(i = 4); \quad q_{4,t} = \sum_{j=1}^{2} a_{4,j,t} q_{4,j,t}$$

- $q_{4,j,t}$ 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 ($q_{4,t,s}$):

$$(i = 4); \ \forall j, \ q_{4,j,t} = q_{4,t,s} + q_{4,j,t,c} + q_{4,j,t,\tau}$$

Each variable at the right-hand of the above equation are presented in turn.

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:

$$q_{el,peak,t} = \frac{\left[\sum_{x=1}^{9} \xi_{el,x,t}\varrho_{el,x,t,prod}\right]\left(1+\xi_{el,import,t}\right)}{\left[\sum_{x=1}^{9} \xi_{el,x,t}\right] + \xi_{el,import,t} + \varpi_{fatal,t}}$$

- 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

Each item is analyzed below.

Cost of production of electricity among different technologies ($\varrho_{el,x,t,prod}$) Following, for instance, Magné, Kypreos and Turton (2010)'s approach, 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:

$$\forall x, \quad \varrho_{el,x,t,prod} = \left[\frac{\varrho_{el,x,t,fuel} + \varrho_{co2\ price,t} * \varrho_{el,x,t,co2em}}{\varrho_{el,x,t,therm}} + \varrho_{el,x,t,ops}\right] + \varrho_{el,x,t,fixed}$$

- $\varrho_{el,x,t,fuel}$ stands for fuel costs for technology x (either coal, oil, natural gas, uranium, water, biomass for costly fuel, or wind and sun for costless fuels), measured in €/MWh.

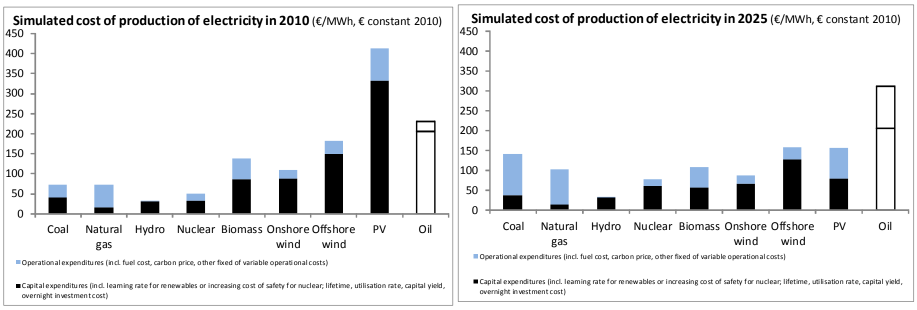
- $\varrho_{el,x,t,therm}$ stands for thermal efficiency (in %).

- CO2 costs are measured by the exogenous price of CO2 on the market for quotas (EU ETS) ($\varrho_{co2\ price,t}$, in €/ton), as applied to technology x characterised by an emission factor $\varrho_{el,x,t,co2em}$ expressed in t/MWh.

- $\varrho_{el,x,t,ops}$ stands for operational and maintenance variable costs (in €/MWh).

Fixed costs $\varrho_{el,x,t,fixed}$ are expressed in €/MWh and computed according to the following annuity formula:

$$\forall x, \quad \varrho_{el,x,t,fixed} = \frac{\varrho_{el,x,t,inv}\frac{1+\varrho_{el,x,t,prodloss}}{1+\varrho_{el,x,t,learning}}\varrho_{el,x,t,cap\ c}}{\left(1-(1+\varrho_{el,x,t,cap\ c})^{-\varrho_{el,x,t,life}}\right)\varrho_{el,x,t,util}}$$



Some simulation hypothesis

Wind, PV, hydro account for… **30%** of demand of electricity in 2020

Some results in the model as concerns electricity (in 2010)

Cost of production of electricity out of coal (€/MWh, 2010)	74	Peak price of electricity in the model (€/MWh, average 2007-2012)	54
Cost of production of electricity out of natural gas (€/MWh, 2010)	73	Mark-up over marginal cost of production	0%
Cost of production of electricity out of nuclear energy (€/MWh, 2010)	50	Observed market price of electricity (peak, €/MWh, average 2007-2012)	60
Annual productivity losses due to increased safety in nuclear power plants, from 2010 to 2025	*5%*		
Cost of production of electricity out of PV (€/MWh, 2010)	413	Switch price of carbon between coal and natural gas in 2012 (€/MWh)	48
Annual productivity gains in PV (from 2010 to 2025)	*10%*	Switch price of carbon between coal and n.gas in 2025 (€/MWh)	62
Cost of production of electricity out of onshore wind (€/MWh, 2010)	109	Is there a switch of main peaker? 0=no; -1= coal->n.gas; +1= n.gas->coal	yes
Annual productivity gains in onshore wind (from 2010 to 2025)	*2%*	If it exists, this switch occurs in year…	-1 en 2020
Cost of production of electricity out of offshore wind (€/MWh, 2010)	181		
Annual productivity gains in offshore wind (from 2010 to 2025)	*1%*	Cost of transport of electricity / industry (% of price excluding taxes, ave 2005-10)	27%
		Cost of transport + distribution of electricity / households (% price excl. taxes, ave 20	45%

Figure 9: Simulated costs of production of electricity in scenario 4

- $\varrho_{el,x,t,inv}$ 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 ($\varrho_{el,4,t,prodloss} = 5\%$ per year from 2013 to 2025) ;
- $\varrho_{el,x,t,learning}$ is the learning rate for renewables (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).
- $\varrho_{el,x,t,cap\ c}$ 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. For illustrative purpose, the following graphs show the data for $\varrho_{el,x,2010,prod}$ in scenario 4:

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 computed and computed in France by CRE (2012), the French Energy Regulation Authority. For future periods, the model uses the 2010 values which are frozen onwards, namely: $\xi_{el,3,t} = 1\%$ for oil, $\xi_{el,4,t} = 11\%$ for nuclear, $\xi_{el,5,t} = 25\%$ for hydroelectricity. The marginality rate of renewables is 0: $\xi_{el,6,t} = \xi_{el,7,t} = \xi_{el,8,t} = \xi_{el,9,t} = 0\%$.

Imports of electricity are marginal 20% of time on the French market ($\xi_{el,import,t} = 20\%$).[44]

According to CRE, in 2010, coal was the main marginal producer of electricity during 35% of the year in France ($\xi_{el,1,2010} = 25\%$) whereas natural gas had been the peaker 5% of the year ($\xi_{el,2,2010} = 5\%$).

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 and the clean dark spread is negative, and if the clean dark spread alone is positive, then the main peaker is coal: thus $\xi_{el,1,t} = 35\%$ and $\xi_{el,2,t} = 5\%$. 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, as explained and measured for instance in Benhmad and Percebois (2013). We take account of this phenomenon by introducing a parameter $\varpi_{fatal,t}$ [45] 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 achieved 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, an order of magnitude much in line with the one computed by Benhmad and Percebois (2013).

• We assume implicitly in this model that the mark-up of market price of electricity over the average weighted cost of production is nil. A parameter $markup_{el,t}$ could have been included. On French data, the difference between the average wholesale price of electric on power markets observed over the last few years and the weighted cost of production simulated in the model is close to 10%, an order of magnitude very much comparable to the one computed by the French regulator (*Commission de Régulation de l'Energie*) in its public report on wholesale electricity markets in France. Including such a parameter would have brought about the question of the modelling of the associated surplus between economic agents. In any case, since this parameter would have remained constant, its effect on the dynamics of the model would have been very small. For simplicity, it is set to 0.

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

[44] 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.

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

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.[46]

Taxes on electricity ($q_{4,j,t,\tau}$): VAT, excise tax, tax financing feed-in tariffs for renewables $q_{4,j,t,\tau}$ stands for the amount, in real terms, of taxes paid by an end-user of electricity (either households ($j = 1$) or industry ($j = 2$)) at year t:

$$\forall j \in \{1;2\}\,,\; q_{4,j,t,\tau} = VAT_{4,j,t} + Excis_{4,j,t} + others_{4,j,t} + TafFTAR_{4,t}$$

For past periods, these data are provided by OECD/IEA databases. They include VAT, excise taxes and other taxes. For future periods, the rates of $VAT_{4,j,t}$ and $others_{4,j,t}$ are computed as a moving average over the latest 10 years before year t, and the absolute real level of $Excis_{4,j,t}$ (if any) is computed as a moving average over the latest 10 years before year t.

For future periods, depending on scenario reforms, $q_{4,j,t,\tau}$ can also include a tax financing feed-in tariffs for fatal producers of electricity ($TafFTAR_{4,t}$, in €/MWh). Indeed, government in the model is assumed, when it decides to implement an energy transition, to create a scheme compensating the difference between the market price of electricity ($q_{4,j,t,s}$) and the costs of production for onshore and offshore wind and solar PV ($q_{el,6,t,prod}$, $q_{el,7,t,prod}$, $q_{el,8,t,prod}$ resp.) 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 $\varrho_{el,8,t,learning}$).

This modeling of prices of electricity in the model allows for simulating in a realistic way future end-use prices by making assumptions over a limited set of exogenous variables, notably:

- the annual variation of the real prices of hydrocarbons inputs for thermic facilities (namely, $\Delta m_{natgas,t}$, $\Delta m_{Brent,t}$ and $\Delta m_{coal,t}$)
- an objective of development for wind and solar PV in the sector of electricity set by public authorities (see scenarios), which in turn requires a tax financing feed-in tariffs for fatal producers of electricity ($TafFTAR_{4,j,t}$) and implies rising network costs (transport costs in the case of industry: $q_{4,2,t,c}$, and transport and distribution costs in the case of households: $q_{4,1,t,c}$)
- rising productivity through learning rate for renewables, and productivity loss for nuclear

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

- CO2 prices ($\varrho_{co2\ price,t}$) which strongly influence the technology being the main peaker at year t.

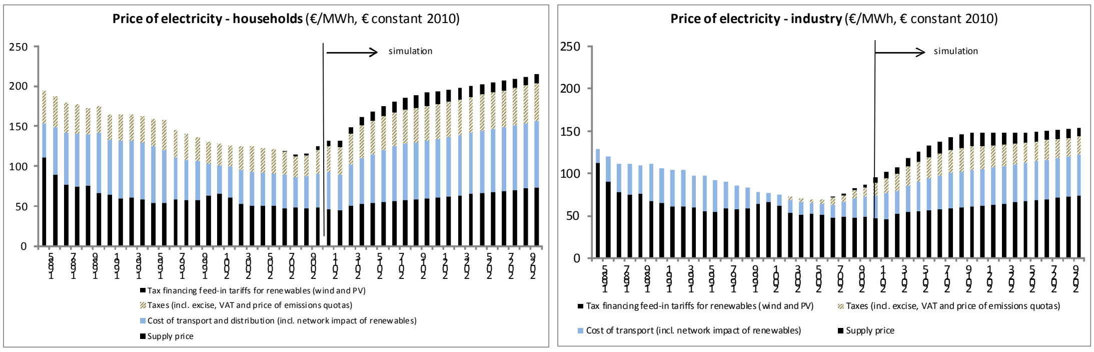


Figure 10: Price of electricity for households and industry in scenario 4 from 1985 to 2030

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.[47]

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.

Such a framework allow for modeling the dynamics of the energy mix depending on those of oil, natural gas and coal. The more the prices of the latter increase, the more the demand of the former rises.

[47] 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.

A.2.2 Energy demand in volume

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

Structure of the energy demand in the future The modeling framework used here follows the litterature (see for instance Leimbach et al. (2010) and their REMIND model) 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[48], 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 $D_{natgas,t}$. For illustrative purpose, the following graph show the energy mix evolution in scenario 4 (with relatively high energy prices and energy transition):

This completes the description of the energy module of the GE-OLG model.

[48] 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 developement 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.

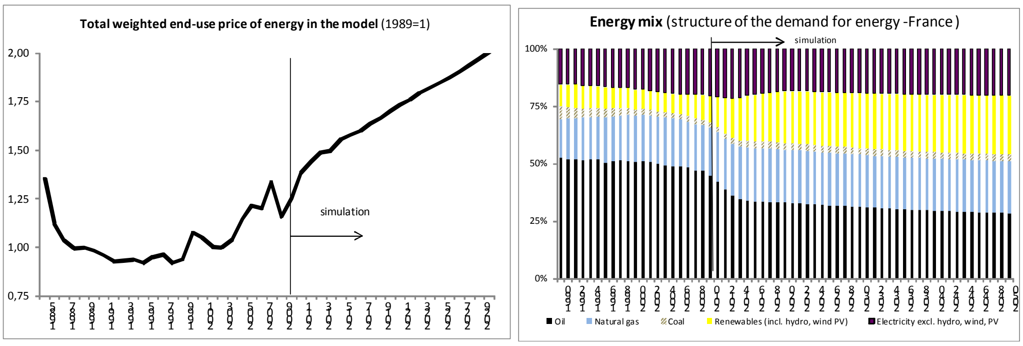


Figure 11: Total weighted end-use price of energy in scenario 4 from 1985 to 2030 (*left panel*) - Energy mix dynamics in scenario 4 from 1990 to 2050 (*right panel*)

A.3 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.[49] The proportion $\pi_{t,a}$ of pensioners in a cohort is then computed as a residual.

Demographic simulations for France are computed by Gonand (2005) using official demographic assumptions. These simulations are very close to French official forecasts. They are transformed from five-year periods (2005, 2010, ..., 2050) and age groups (20-24 years, 25-29 years...) into annual data (20, 21, ... , years in 2000, 2001, ... 2050) using a linear interpolation.

Future paths for the labour force and the working population over the simulation period are in line with a rise in the average effective age of retirement of 1.25 year per decade from 2010 on, following a reform of the PAYG pension regime implemented by the goverment from 2010 on. Accordingly, future age-specific participation and employment rates of workers above 50 years of age increase in line with the changes in the age of retirement. For instance, in 2045 participation rates of 60 year old workers are the same as those of 55 year old workers in 2005, and so on.

For illustrative purpose, the following graph show the dynamics of the dependency ratio in all scenarios:

[49] 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.

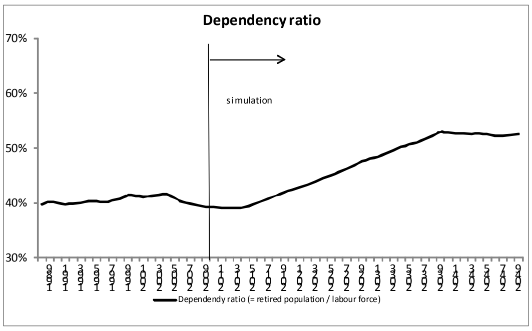


Figure 12: Dependency ratio in all scenarios from 1989 to 2050

A.4 The Production function

The litterature about energy as an item enshrined in a production function has been abundant since the 1970's. This interest stemed from the fact that the production function in the Solow growth model included only factors of production (i.e., physical capital and labour) and excluded intermediary consumptions - as energy. From the 1970's on, energy has increasingly been plugged into production functions to get the so-called K-L-E models (see Percebois (1989) or Stern (2003) for historical insights). In so doing, many papers follow Sato (1967) and Solow (cf. Solow, 1974) in designing the energy-augmented production function as a two-level (or more) nest of CES production functions. Some critics have drawn the attention to the fact that such modeling approach is not without drawbacks: the use of constant elasticities of substitution in these nested CES functions may bias the results of the models when extreme and/or very long-run scenarios are simulated (see notably Ghersi and Hourcade, 2006). For the sake of comparability with different models already existing in the litterature, we abide by the tradition of CGE models incorporating energy, bearing in mind that the design of the scenarios should remain caution in order to avoid, as much as possible, Hourcade's criticism.

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

The K-L module of the CES-nested production function is:

$$C_t = \left[\alpha K_t^{1-\frac{1}{\beta}} + (1-\alpha)\left[A_t \bar{\varepsilon}_t L_t\right]^{1-\frac{1}{\beta}}\right]^{\frac{1}{1-\frac{1}{\beta}}}$$

where:

- 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 $\bar{\varepsilon}_t = \sum_{a}^{\max(a,t)} \varepsilon_a \frac{\nu_{t,a} N_{t,a}}{L_t}$ 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.[50] Parameter $\nu_{t,a}$ is the fraction of a cohort of age a in t which is employed and receives a wage. With these notations, $A_t \bar{\varepsilon}_t L_t$ is the optimal total stock of efficient labour in a year t - or, in other words, optimal total labour supply.

Dividing both inputs by $\left[A_t L_t \sum_{a}^{\max(a,t)} \left(\varepsilon_a \frac{\upsilon_{t,a} N_{t,a}}{L_t}\right)\right]$ yields the production function in its intensive form:

$$c_t = f(k_t) = \left(\alpha k_t^{1-\frac{1}{\beta}} + (1-\alpha)\right)^{\frac{1}{1-\frac{1}{\beta}}}$$

where k_t is the capital per unit of efficient labour. Profit maximization yields optimal factor prices, namely, the equilibrium cost of physical capital $r_t = \alpha k_t^{\frac{1}{\beta}} \left(1-\alpha+\alpha k_t^{1-\frac{1}{\beta}}\right)^{\frac{1}{\beta-1}}$ and the equilibrium gross wage per unit of efficient labour $w_t = A_t(1-\alpha)\left(\alpha k_t^{1-\frac{1}{\beta}} + 1 - \alpha\right)^{\frac{1}{\beta-1}}$. The long-run equilibrium of the model is characterised by a constant capital per unit of efficient labour k_t and a growth of real wage equalising annual labour productivity gains.

The model is built on real data exclusively: the price of the good produced out of physical capital and labour p_{c_t} is constant and normalized to 1.

[50] 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.

A.4.2 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 does Solow (1974), however, yields a more realistic *production* function Y_t , again in volume, associated with the value-added which remunerates labour and capital:

$$Y_t = \left[a\left(B_t E_t\right)^{\gamma_{en}} + (1-\alpha)\left[C_t\right]^{\gamma_{en}}\right]^{\frac{1}{\gamma_{en}}}$$

where a is a weighting parameter; 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 $Y_t^{\gamma_{en}} = a\left(B_t E_t\right)^{\gamma_{en}} + (1-a)\left[C_t\right]^{\gamma_{en}}$. It is worthwhile 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: $E_t = \frac{q_t^{\frac{1}{\gamma_{en}-1}} a^{\frac{-1}{\gamma_{en}-1}} C_t}{p_{C_t}^{\frac{1}{\gamma_{en}-1}} (1-a)^{\frac{-1}{\gamma_{en}-1}}}$. This expression displays intuitive features:

- when the GDP (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 (since $0 < \gamma_{en} < 1$).
- when energy efficiency (B_t) accelerates, the demand for energy (E_t) is also lower.

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.5 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 intertemporal budget constraint. This utility function has one argument - i.e., consumption.[51]

The $c_{t,a}$'s are obtained by maximising the intertemporal utility function of the average individual of a whole cohort, *i.e.*:

$$U_{t,a} = \frac{1}{1-\sigma} \sum_{j=a}^{\Psi_{t-a,0}} \left[\frac{1}{(1+\rho)^{j-a}} (c_{t+j-a,j})^{1-\sigma} \right]$$

where $c_{j,a}$ stands for the consumption level of the average individual of the cohort of age a in t, ρ is the subjective rate of time preference (or psychological discount rate), σ is the relative-risk aversion coefficient. The intertemporal budget constraint for the cohort of age 20 (i.e. $a = 0$) in year t is:

$$y_{t,0} + \sum_{j=1}^{\Psi_{t,0}} \left[y_{t+j,j} \prod_{i=1}^{j} \left(\frac{1}{1+r_{t+i}} \right) \right] = c_{t,0} + \sum_{j=1}^{\Psi_{t,0}} \left[c_{t+j,j} \prod_{i=1}^{j} \left(\frac{1}{1+r_{t+i}} \right) \right]$$

where $y_{t+j,j}$ stands for the total income net of taxes of the average individual representative of a cohort, such that :

$$\begin{aligned} y_{t+j,j} &= w_t \varepsilon_a \nu_{t,a} (1 - \tau_{t,P} - \tau_{t,R} - \tau_{t,H} - \tau_{t,NA}) + d_{t,NA} - d_{t,energy} + \Phi_{t+j,j} \\ &= w_t \varepsilon_a (1 - \tau_{t,P} - \tau_{t,R} - \tau_{t,H} - \tau_{t,NA}) + d_{t,NA} - d_{t,energy} + \Phi_{t+j,j} \end{aligned}$$

- w_t stands for the gross wage per efficient unit of labour.[52] The parameter ε_j a links the age of a cohort to its productivity. Following Miles (1999), a quadratic function is used: $\varepsilon_a = e^{0.05(a+20)-0.0006(a+20)^2}$ which displays an inverted U-shape pattern with a peak at 42 years.[53]

- As presented in the demographic module, a proportion $\nu_{t,a}$ of individuals of a cohort aged a are working at year t.

- $\tau_{t,P}$ stands for the proportional tax rate financing the PAYG pension regime (see *infra*), paid by households on their labour income.

- $\tau_{t,R}$ stands for a proportional tax on labour income and pensions financing the reimbursement of the public debt, from 2010 to 2030 (see below, public finance module).

- $\tau_{t,H}$ stands for the rate of a proportional tax on labour income, which finances an always balanced health care regime (see supra). Health expenditure has a favourable impact on the utility

[51] Introducing an endogenous working time in general equilibrium models with OLG raises several challenges. Cournède and Gonand (2006) expand on this issue and develop an EG-OLG model in which private agents endogenously choose how long they work. In Cournède and Gonand (2006), their decision to participate in the labour force remains exogenous. In other words, the intensive margin of labour supply is endogenous in the model while the extensive margin is exogenous. Overall, this setting allows for taking account of the distorsive effects of increasing contributions rates. This does not modify very strongly quantitative results.

[52] As defined in the demographic module, the parameter $\nu_{t,a}$ stands for the fraction of a cohort which is active and working.

[53] The Ingenue team (2001) uses the same function. Yet more recent econometric studies (Aubert and Crepon, 2003) do not confirm the decrease of individual productivity for older workers. However, sensitivity analysis shows that the impact on macroeconomic variables, especially growth, of the choice between these two assumptions is negligible.

of individuals because it underpins longevity gains. To avoid double counting, the model therefore does not account for health expenditure as income transfers received by households (in contrast to other categories of public spending).

- $\tau_{t,NA}$ stands for the rate of a proportional tax levied on labour income and pensions to finance public non ageing-related public expenditure $d_{t,NA}$.[54]

- $d_{t,NA}$ 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.

- $\Phi_{t+j,j}$ stands for the pension income received by the retirees of a cohort (see below, public finances module, for its computation).

- $d_{t,energy}$ stands for the energy expenditures paid by one individual to the energy sector, such that:

$$d_{t,energy} = C_{en} \frac{\sum_a [w_t \varepsilon_a \upsilon_{t,a} N_{t,a} + \Phi_{t,a} \pi_{t,a} N_{t,a}]}{\sum_a N_{t,a}} \frac{q_{energy,t} E_t}{A_t}$$

where $[w_t \varepsilon_a \upsilon_{t,a} N_{t,a} + \Phi_{t,a} \pi_{t,a} N_{t,a}]$ is the aggregate tax base, C_{en} is a constant of calibration and $\frac{q_{energy,t} E_t}{A_t}$ mesures the dynamics of energy expenditures as a share of income.

The optimal path for consumption stems from the Euler equation using a Lagrangian. One gets $\frac{c_{t,a}}{c_{t-1,a-1}} = \left(\frac{1+r_t}{1+\rho}\right)^{\kappa}$ where the intertemporal substitution parameter in 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:

$$c_{t,0} = \left[y_{t,0} + \sum_{j=1}^{\Psi_{t,0}} y_{t+j,j} \prod_{i=1}^{j} \left(\frac{1}{1+r_{t+i}} \right) \right] / \left[1 + \sum_{j=1}^{\Psi_{t,0}} (1+\rho)^{-j\kappa} \prod_{i=1}^{j} (1+r_{t+i})^{\kappa-1} \right]$$

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 no-reform, baseline scenario 1 (o scenario 5 in case of low energy price on world markets). 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. The initial point of the new intertemporal path of consumption for a cohort aged a in 2010, starts at $c_{2010,a}$ defined as:

[54] Tax revenues are raised only on labour income and pensions in the model. A scenario incorporating a proportional tax on capital income has been built. The results suggested that the receipts from the capital income tax were very small compared with the revenues from taxes on labour income and pensions. This variant was not used further because adding capital taxation seriously complicates the analysis of the optimisation behaviour of households for little benefit in terms of improving the modelling of public sector accounts.

$$c_{2010,a} = \frac{(1+r_{2010})\Omega_{2009,a-1} + y_{2010,a} + \sum_{j=a+1}^{\Psi_{2010-a,0}} \left[y_{2010+j-a,j} \prod_{i=a+1}^{j} \left(\frac{1}{1+r_{2010+i-a}} \right) \right]}{1 + \sum_{j=a+1}^{\Psi_{2010-a,0}} \left[(1+\rho)^{-(j-a)\kappa} \prod_{i=a+1}^{j} (1+r_{2010+i-a})^{\kappa-1} \right]}$$

with $\Omega_{2009,a-1}$ as the accumulated wealth of cohort aged $a-1$ in 2009.

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.

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 completes the description of the OLG framework in the model.

A.6 The public sector and the scenarios of fiscal consolidation

The public sector is modeled via a PAYG pension regime, a healthcare regime, a public debt to be reimbursed and non-ageing related lump-sum public expenditures. Two types of reforms of public finances are considered: tax-based consolidations or consolidations mainly with lower public spending.

A.6.1 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:

- No pension can be received before the age of 50: $[a+20 < 50] \rightarrow [\Phi_{t+j,j} = 0]$.
- 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,[55] which corresponds approximately to actuarial neutrality for current PAYG regimes. Thus:

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

$$[50 \leqslant a+20 < \zeta_t] \rightarrow \left[\Phi_{t,a} = \max\left(p_t w_t \varepsilon_{\psi_t} \pi_{t,a}\left(1 - \frac{\zeta_t - 20 - a}{100/6}\right); 0\right)\right]$$

where p_t is the average replacement rate of the regime when retiring at age ζ_t.

- an individual will obtain a full pension if his or her age is above or equal to ζ_t. Thus:

$$[\zeta_t \leqslant a+20] \rightarrow \left[\Phi_{t,a} = \Phi_{t-1,a-1}\frac{\pi_{t,a}}{\pi_{t-1,a-1}}\right]$$

This implies that 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 all scenarios, the legal effective age at which an individual can receive a full pension is raised by 1.25 years every 10 years, from 2010 onwards and until 2050.[56] This contributes to lessen sizeably the imbalances of the PAYG regime in the future.

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 the following recursive formula (where $\chi_{t,a} = \frac{N_{t,a}}{N_t}$):

$$p_t = \frac{\bar{\tau}_{t,P} \sum_{a=0}^{\max(a,t)} w_t \varepsilon_a \upsilon_{t,a} \chi_{t,a} - \sum_{a=x+1}^{\max(a,t)} p_{t+x-a} \varepsilon_{\psi_{t+x-a}} w_{t+x-a} \pi_{t,a} \chi_{t,a}}{w_t \varepsilon_{\psi_t} \sum_{a=30}^{x} \left[\max\left(1 - \frac{\psi_t - 20 - a}{100/6}; 0\right) \pi_{t,a} \chi_{t,a}\right]}$$

A.6.2 The healthcare system

The health regime is financed by a proportional tax ($\tau_{t,H}$) on labour income and is always balanced, such that:

$$\tau_{t,H} = \frac{\sum_a C_H h_{a,H} A_t N_{t,a}}{\sum_a w_t \varepsilon_a \upsilon_{t,a} N_{t,a}} \qquad \forall t$$

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 such that $\tau_{2009,H} \approx 11\%$. In all scenarios, the health regime is balanced through higher social contributions. This is

[56] This order of magnitude is roughly in line with national forecasts of future life expectancy increases. It is assumed that age-specific participation rates of workers above 50 years of age increase in line with the changes in the age of retirement. For example, individuals work five years more in 2050 than in 2010.

because this entitlement programme is presumably one where keeping spending stable as a ratio to GDP is most difficult in the face of ageing.[57]

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.6.3 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 good ($d_{t,NA}$) which does not depend on his/her age and verifies:[58]

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

A.6.4 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 (equal, on French data, to $Debt_{2009} = 93,9\%$ of GDP_{2009}) will start being partly paid back (service included) from 2010 until 2030. The rate on the public debt is assumed to be equal to the long-run cost of productive capital (r_t) minus 3%.

In tax-based consolidations, the public debt is paid back thanks to a special, additional proportional tax ($\tau_{t,D}$) levied on labour income and pensions between 2010 and 2030, such that:[59]

$$\tau_{t,D} = \frac{Debt_{2009}/41 + (r_{t-1} - 3\%) Debt_{t-1}}{\sum_a \left[w_t \varepsilon_a \upsilon_{t,a} N_{t,a} + \Phi_{t,a} \pi_{t,a} N_{t,a} \right]} \qquad \forall t \in [2010; 2029]$$

In consolidations with lower public spendings, the reimbursement of the public debt accumulated up to 2009 is financed by lowering non-ageing related public expenditures. Thus $\tau_{t,D} = 0$ et $d_{t,NA}$ becomes solution of ($\forall t \in [2010; 2029]$):

[57] 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 heath regime.

[58] 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*.

Additionally, 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.

[59] Thus $\tau_{t,D}$ enters negatively in the definition of $y_{t+j,j}$, the total income net of taxes of the average individual representative of a cohort (see above).

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

The dynamics of the stock of public debt ($Debt_t$) is also influenced by...

- an annual structural public deficit (assumed to remain constant at 1% in France in the future decades),
- the affectation of the carbon tax ($carbon\ tax_{i,j,t}$) levied, in some scenarios, from 2015 onwards.[60] If the product of the carbon tax is affected exclusively to the reimbursement of the debt, then it lowers $\tau_{t,D}$ (the special, additional proportional tax levied to pay back part of the public debt)[61] and it also lowers $Debt_t$. If the whole product of the carbon tax is redistributed to the households through lump-sum public expenditures, then it raises $d_{t,NA}$ but does not lower $Debt_t$. It is possible to model some variable sharing of the income of the carbon tax between the households and the reimbursement of the public debt during the reimbursement period. After 2030, the model assumes that the income of the carbon tax is fully redistributed to the households through higher lump-sum public expenditures.

In all scenarios, the level of public debt, expressed in % of GDP, reaches some unique threshold value in 2030 that is assumed to be slightly below 60% (on French data, 55% of GDP in 2030).

A.7 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 $A_t \bar{\varepsilon}_t L_t$ 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 $(\Xi_t)_d = K_t / A_t \bar{\varepsilon}_t L_t$ and $(\Xi_t)_s = W_t / A_t \bar{\varepsilon}_t L_t$, i.e. the demand and supply of capital per unit of efficient labour respectively. The convergence process begins with an educated guess for the demand of capital per unit of efficient labour $(\Xi_t)_d$. From this guess are derived successively r_t, w_t, $y_{t+j,j}$, $c_{t+j,j}$, $s_{t+j,j}$, W_t and eventually $(\Xi_t)_s = W_t / A_t \bar{\varepsilon}_t L_t$ which is the supply of capital by households per unit of efficient labour. A numerical convergence process is used so that $(\Xi_t)_d$ and $(\Xi_t)_s$ converge. When the convergence process is completed, the equilibrium stock of capital per unit of efficient labour defines the equilibrium r_t and w_t associated with $W_t = K_t$ and L_t each year. With capital and labour markets clearing, Walras' law ensures that the market

[60] See above, presentation of the method for simulating the future prices of fossil fuels.

[61] To give some orders of magnitude on French data, $\tau_{2015,D}$ is 3,7% in scenario 1 in 2015 (which does not include a carbon tax) and 3,5% in scenario 3 (in which a carbon tax of 16€/t is created in 2015). In 2025, the rate of the carbon tax is 26€/t and the value of $\tau_{2015,D}$ is 2,9% in scenario 1 and 2,7% in scenario 3.

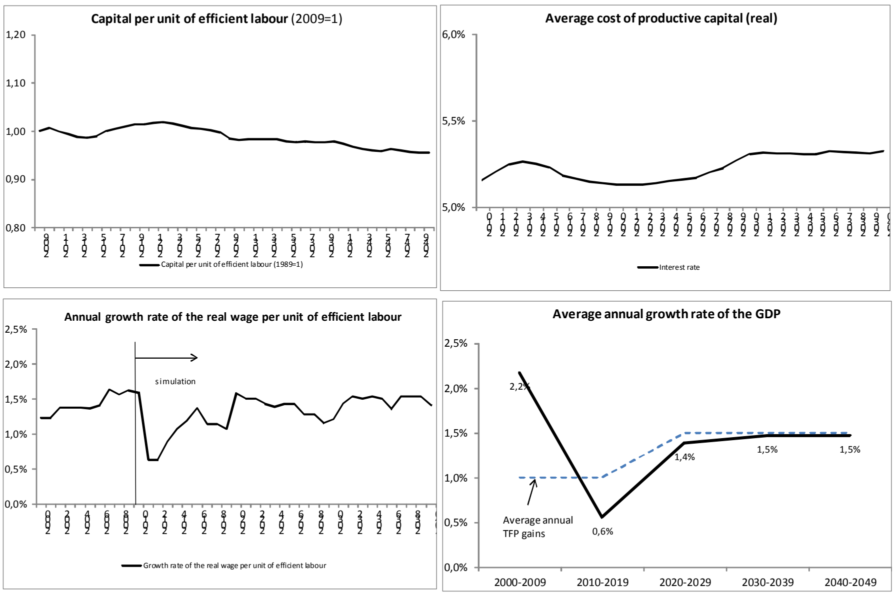


Figure 13: Aggregate variables in scenario 4

for goods is cleared too. This result is ensured in the model because it requires respecting national accounts identities (*i.e.*, investment equals saving and total value added equals the sum of the remunerations of production factors).

A.8 Parameterization of the model

As concerns demographic data, for the period 2000 to 2050, we use the results of a demographic model developed by Gonand (2005) which closely reproduce national population projections, while allowing for other scenarios. 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, reaching close to 79 years in 2000. The growth in life expectancy decelerates in line with national projections of member countries over the projection period. After 2050, average life expectancy remains stable at 84 years.

The model is back to its long-run steady-state in 2080. In this situation, GDP per capita growth is exclusively determined by the exogenous growth in TFP. By contrast, during the demographic transition, the dynamic equilibrium is driven mainly by ageing, public finance reforms, energy policy and prices of fossil fuels on world markets.

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. This parameter should be distinguished from the age-productivity profile $\varepsilon_a(a)$ which describes the amount of efficient labour depending on the age a of a worker. Lastly, 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 households' psychological discount rate is set at 2% per annum, in line with much of the empirical literature. Different methods can be used to estimate this parameter. Analytical models, such as that by Gallon and Masse (2004), suggest using a discount rate between 2% and 3% in real terms. Alternatively, econometric models like that of Gourinchas and Parker (2002) suggest a value around 3%.

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 in 2007. This is in line with the model's specification. This parameter is used as a proxy for the generosity of the pension system. The weighted average replacement rate for compulsory pension regimes is around 62%. While other values for replacement rates would modify baseline levels (notably the saving rate and the capital / income ratio, the dynamics in simulations would not be substantially modified as suggested by sensitivity analysis (see below).

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). This parameter assesses the intensity of the relative risk aversion or equivalently the inverse of the inter-temporal substitutability coefficient. A standard result in financial and behavioural economics is to consider this parameter as greater than 1 (cf. Kotlikoff and Spivak, 1981). Börsch-Supan et al. (2003) use a risk aversion parameter of 2.7, but this choice results from the specific calibration of their model to reproduce observed orders of magnitude around the base year. Such a high value might account for the relative insensitivity of saving behaviour to interest rate variations in their model and thus might bias the results. Kotlikoff and Spivak (1981) use 1.33. Epstein and Zin (1991) suggest values between 0.8 and 1.3

while Normandin and Saint-Amour (1998) use 1.5.

The model is calibrated on an 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 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.

The elasticity of substitution between energy and capital (defining γ_{en}) is set at 0,4. Following Hogan and Manne (1977), this value is obtained by assessing its proxy, the price-elasticity of energy demand.

The weighting parameter (a) in the CES production function with energy is set at 0,1. This value is obtained through the input-output matrix in national accounts. In the CES nest, C_t refers to GDP (i.e., added value) in volume, whereas Y_t refers to aggregate production in volume, and thus takes account of intermediate consumption (here, B_t). Accordingly, the weighting parameter (a) should not be computed as the share of the value added of the energy sector in GDP but, preferably, as the share of intermediate consumption in energy items as a fraction of GDP. 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).

A.9 Sensitivity analysis

In order to check the robustness of the results of the model to alternative specifications and parameter values, extensive sensitivity analysis was carried out on earlier version of the OLG-GE framework (Cournède and Gonand, 2006). Overall, the dynamics of the results appear relatively robust to changes in some key parameters (the capital share in value-added α, the risk-aversion coefficient σ, the age-individual productivity function $\varepsilon_a(a)$, the elasticity of substitution between capital and labour β and the discount rate ρ). Joint sensitivity analysis was also carried out. Details are available on demand.

We expand more here on the sensitivity analysis carried out concerning the hypothesis as for future prices of fossil fuels on world energy markets. The model rely on relatively high future energy prices. 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, though 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.[62] These prices remain constant after 2050 in the model.

Scenarios were run with relatively low energy prices environment. It is assumed that, from 2010 on, energy prices of world markets (oil, coal, natural gas) diminish in 2010-2020 up to their 30-years average level, before increasing again afterwards to follow a proxy of a Hotelling rule (+3% real per year) until 2050.[63] Private agents modify their expectations and economic behaviour accordingly in 2010, in a forward-looking manner. This context may correspond for instance to new discoveries or possibilities of producing oil (including in arctic areas) or natural gas (including with shale gas).

- As far as the effects of an energy transition on the GDP level in the long run are concerned, the results are not sizeably modified with different assumptions as concerns the prices in the next decade of fossil fuels on world energy markets. In the long run, an energy transition would fosters the GDP level by +0,9% (in 2050), compared to +1,0% in a scenario with ever increasing prices of energy (see Figure 3 in the main text).

- This sensitivity analysis allows for measuring the aggregate effect of lower prices of energy on world markets. Unsurprisingly, the aggregate implications are sizeable in the next decade. The total weighted end-use price of energy plunges by 15% in real terms in 2030 compared to 2010 (in scenario 1 with lower prices of fossil fuels). The total demand for energy increases by 13% over the same period, mainly because of plummeting prices of fossil fuels. The size of the renewable substitutes in energy demand does not increase in this context - they represent only 10,4% of total energy demand in 2025, compared to 12% in 2010.

- The characteristics of the *intergenerational redistributive effects* are not strongly modified with this different set of assumptions concerning prices of fossil fuels on world energy markets. Lexis surfaces display a very similar pattern whether prices of energy decrease temporarily in the 2010's or keep increasing from now on.

[62] 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.

[63] Accordingly, the price of a barel of Brent is 46$\$_{2010}$ in 2025; the end-use price of natural gas for household reaches 32€$_{2010}$/MWh in 2025; the real supply price of a ton of coal is 62€$_{2010}$ in 2025.

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