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Macroeconomic effects of achieving Carbon Neutrality in France

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ABSTRACT

In alignment with the Paris Agreement's objectives and the global commitment to limit global warming to +2 °C, France is committed to achieving Carbon Neutrality by 2050. To pave the way towards this ambitious goal, France has drawn up a roadmap known as the National Low-Carbon Strategy (NLCS). This paper aims to assess the macroeconomic impacts of the NLCS scenario. We use a Computable General Equilibrium model to assess the economic impacts of an energy transition scenario aiming for Carbon Neutrality in France by 2050. Our simulations show that climate change policies to reach carbon neutrality, including carbon taxation with full redistribution, could lead to an economic dividend. We find an increase in investments and jobs creations in green industries that are much higher than job destruction in fossil fuel intensive industries and energy sectors. Despite higher prices, demand increases, and GDP is higher than in the reference scenario. Ultimately, the energy transition induces a 3.4 % increase in GDP and a 2.8 % increase in employment compared to the baseline scenario in 2050.

1. Introduction

Within the framework of the Paris agreement, most countries and regions have committed to limiting the global temperature increase to + 2 °C above pre-industrial levels, and if possible, not to exceed 1.5 °C. To achieve this objective, following the IPCC recommendations, they have committed to reach Carbon Neutrality during the second half of the 21st century at the global level, and developed countries are called upon to achieve neutrality as quickly as possible [1].

Regarding the process of climate negotiations and the commitments in terms of policies implemented, Europe has always sought to play a significant role. With the aim of establishing a common EU energy and climate change policy, the EU adopted the Climate Plan in 2008. Revised in 2014, it aims, among other things, to reduce greenhouse gas (GHG) emissions by 40 % by 2030 compared to 1990 levels. In the context of the Paris Agreement, the EU is increasing its commitments and setting up the European Green Deal. Under the banner "Fit for 55″, the European Commission is proposing ambitious measures to reduce GHG emissions by at least 55 % by 2030 compared with 1990 levels, with the aim of achieving Carbon Neutrality in Europe by 2050 [2]. France, as an important member of the European Union, has also increased its ambition relative to its previous commitments and has committed at the national level to achieve Carbon Neutrality by 2050. In 2015, France made a significant commitment through its first National Low-Carbon Strategy (NLCS)[1] to reduce its GHG emissions by 75 % by 2050 compared with 1990 levels. Introduced by the Energy Transition Law for Green Growth[2] which aims to reduce greenhouse gas emissions, increase renewable energy use, and promote energy efficiency and a circular economy,[3] the NLCS serves as France's roadmap in the fight against climate change. It provides guidelines for transitioning to a low-carbon, circular, and sustainable economy across all sectors of activity. The NLCS is periodically revised to update the reference scenario at the light of the effective developments and to set new objectives. Subsequently, in 2020, the country committed to reducing its national emissions by 84 %

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[1] Known in France as the SNBC (Stratégie Nationale Bas-Carbone).

[2] Loi n° 2015-992 du 17 août 2015 relative à la transition énergétique pour la croissance verte.

[3] Among the key objectives of this law: a 40% reduction in greenhouse gas emissions by 2030, a 30% decrease in fossil fuel consumption, and achieving 32% renewable energy in the energy mix by the same time horizon, alongside measures to limit waste and improve waste management.

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compared to 1990 levels, which aligns with the ambitious goal of achieving Carbon Neutrality. This commitment was outlined in the National Low Carbon Strategy of 2020 and is enshrined in law [3].

The objective of Carbon Neutrality is defined as a steady state where anthropogenic GHG emissions are exactly compensated by natural and artificial carbon sinks. In physical terms, this neutrality for France means reaching a level of 80MtCO_2eq of emissions by 2050 while this level was 458 MtCO_2eq in 2015 and 445 MtCO_2eq in 2018. Achieving such a deep decarbonization at this time horizon means notable bifurcations in terms of socio-techno-economic pathways with, in particular, a deep transformation of lifestyles, consumption and productions patterns. Such a profound transformation can be considered as a major opportunity in terms of innovation, job creation, or economic reforms. This could help to rethink the economic model and place it on a sustainable pathway, avoiding thus important lock-ins given the path dependencies and inertia that characterize such deep and long-term horizon transformation projects [3]. Meeting these requirements, as stated in Article 4.19 of the Paris Agreement, calls for a strategic approach that encompasses long-term planning to guide short-term decisions in alignment with the requirements of the necessary transformations [4]. Furthermore, it requires the implementation of appropriate public policies that must receive ongoing and consistent support to ensure their effectiveness [5].

In order to help decision-makers put in place policies that will allow to follow such low-carbon trajectories, it is relevant and useful to assess the economic impact of the implementation of such policies and to understand what mechanisms are underlying the generated costs and/or benefits.

The macroeconomic effect of energy transition is a controversial topic. Is there a trade-off between welfare and climate change? Can a carbon tax generate a double dividend? There is no consensual answer in the literature to these questions. Economic evaluations often reach divergent conclusions that generally dependent on the type of models used and on the way the carbon tax is implemented. The study of France's energy transition, and the NLCS in particular, has sparked a great deal of interest in the academic world. For example, Ravigné et al. [6] analyze the effects of the French LCNS from a distributional point of view and using a micro-simulation model, while Giraudet et al. [7] or Bourgeois et al. [8], looking also at the distributional impacts, focus on the residential sector using a partial equilibrium model. Lebrouhi et al. [9] expose the main approaches and projects implemented in the framework of the French NLCS and Millot et al. [5] use a bottom-up energy model to highlight the challenges France faces in transforming its energy system. Furthermore, many studies in the recent literature investigate macroeconomic impacts of energy and low-carbon transition in Europe using CGE models, but they focus on the EU as a region ([10] (a) ; [11] (b) ; [12,13]) or on other countries rather than France such as Italy [14,15,16], Spain ([17,18]), Germany [19,20,21] or Poland ([22, 23]). But, as far as we know, there are no studies assessing the macroeconomic impact of the French NLCS using a national CGE that encompasses France's specific features. The objective of this paper is to fill this gap by providing such an evaluation. We analyze here the impact of an ambitious climate policy that makes it possible to achieve Carbon Neutrality in France. To do so, we come within a dynamic second-best modelling framework that takes market imperfections into account. We use the ThreeME model, a hybrid multi-sector Computable General Equilibrium model specifically designed to assess environmental and energy policies. In addition to providing information about the long term, it allows for analyzing transition phases over the short and medium terms, which is especially relevant when assessing the implementation of climate policies.

The remainder of this paper proceeds as follows: Section 2 describes the modelling framework by giving a short overview of the ThreeME model. Section 3 introduces the simulated scenarios, giving details of the energy and policies implemented. In Section 4, we show the outcomes of simulating the Carbon-Neutral energy transition scenario, analyzing its impacts on both macroeconomics and the environment. The document concludes in Section 5 with a reminder of the study's main findings, and a few recommendations to help decision-makers implement essential policies to achieve Carbon Neutrality by 2050.

2. Modeling framework

In this study, we use ThreeME (Multi-sector Macroeconomic Model for the Evaluation of Environmental and Energy policy) to assess the macro-economic impacts of achieving Carbon Neutrality by the mid-century in France. ThreeME is a country-generic and open-source model developed to support the energy-environment-climate debate[4] [24,25,26,27]. The online supplement Appendix B provides a technical description with the main equations of ThreeME whereas an exhaustive presentation can be found in Reynès et al. [28].

ThreeME can be classified as a Computable General Equilibrium (CGE) model since supply, demand and prices are all endogenous and influence one other (e.g. [29]). In partial equilibrium model, at least one of the three is assumed to be exogenous and therefore defined outside the model. Partial equilibrium models include Input-Output models (e.g. [30,31]) or bottom-up energy models such as TIMES [32] or LEAP [33].

However, ThreeME does not adopt the Walrasian assumption made by most CGE models where perfect flexibility of prices and quantities imposes that the desired supply and demand always match. Exemple of these models are GEM-E3 [34], ENV-Linkages [35], REMES or EXIOMOD. The latter two have recently be compared in Boonman et al. [36]. Instead ThreeME follows a neoKeynesian assumption where the dynamic of the model is defined by slow adjustment of prices and quantities which seems more consistent with empirical evidence[5]. This assumption leads to (transitory or permanent) disequilibrium between supply and demand on the different markets (e.g. involuntary unemployment).

A CGE model with a neoKeynesian closure has different simulation properties than a CGE with a standard Walrasian closure. In particular, the former is more likely to conclude that the economic impact of a low carbon policy scenario is positive than the latter. For instance, Meyer and Ahlert [37] presents the diverging results of the same low carbon scenario for the EU27 obtain with two models: with EXIOMOD model (Walrasian closure), the GDP by 2050 would be 0.6 % lower than the baseline scenario whereas it would be 7.9 % higher with the GINFORS model (neoKeynesian closure).

Pollitt and Mercure [38], Meyer and Ahlert [37] and Gueret et al. [39] identify and discuss the key hypotheses that are likely to explain this difference in result. Assumptions about the financial system where investment can only be financed by previous savings leads to crowding out of investment in the Walrasian neoclassical framework. The role of the bank system in neoKeynesian framework allows instead for crowding in effects.

Using the ThreeME model, Gueret et al. [39] perform a systematic analysis confronting various key assumptions that lead to positive economic impact of implementing a carbon tax. The main conclusions are: (1) the recycling of the carbon tax income is a necessary (but not sufficient) requirement to prevent an economic recession; (2) a positive economic impact generally arises when there is a low exposure to foreign competition (which corresponds also to the case where countries cooperate in an in international agreement) and where economy is flexible in terms of substitution possibilities (between energy and capital and energy sources); (3) In comparison, the impacts of the recycling

[4] The version used in this study can be retrieved from www.threeme.org.

[5] Macroeconometric models such as E3ME [48] or GINFORS [49] uses also a neo-Keynesian closure. Their authors however reserve the terminology CGE to Walrasian closure (see [37,38]). In our terminologies, a CGE may have a Walrasian or neo-Keynesian closure and the term "general equilibrium" is defined in oppositipon to "partial equilibrium".

mechanisms of the carbon tax (lumps sum redistribution versus reduction of employers social security contribution) and of the inflation dynamic (tested using various specification of the wage equation) are small.

We use a hybrid version of the model here, which combines the top-down approach of general equilibrium macroeconomic models with elements of energy bottom-up models developed by engineers. As in bottom-up models, the amount of energy consumed is related to its direct use, which is to the number of buildings or cars, and the energy class to which they belong. As formalized theoretically by Lancaster [40] and applied in other hybrid models ; [41,42], households do not consume energy for its direct utility but rather for the service energy provides when combined with capital goods such as a car or a house. There is no point buying gasoline if one does not have a car. A more realistic theoretical representation is therefore to assume that energy is an input used in combination with different types of capital in a household's production function.

3. Scenarios

To assess the macroeconomic effects of the Carbon Neutrality objective embedded in the NLCS, we compare two scenarios:

(a) a baseline scenario which includes only existing policy measures and therefore a limited reduction in GHG emissions.
(b) the NLCS scenario that introduces the objective of carbon-neutrality in 2050 through exogenous changes reflecting new policy measures or change in behaviors due to these measures.

Deviations from the baseline can only be attributed to the dynamic generated by the introduction of the new measures. These policy measures are calibrated to allow the model to reproduce the production and energy consumption patterns exposed in the SNBC scenario.

3.1. Baseline scenario

The baseline scenario is meant to be a realistic vision of a possible future rather than a real forecast. It is the virtual scenario simulated by the model for a given trajectory of the exogenous variables. In this case the energy scenario only includes measures already adopted in 2020. Although the impact of a new policy is measured as a relative difference from the baseline, the choice of the baseline may affect the results of the scenario simulated. Therefore, it is important to define a coherent vision of the future, but this may prove a difficult task in terms of calibration. To achieve the construction of a realistic baseline scenario, we focus on obtaining projections for a few key macroeconomic variables, such as GDP, population, evolution of labor productivity, and evolution of international energy prices. The baseline scenario is based on the following assumptions:

- In accordance to the assumptions used in the energy scenarios of the French Department of Climate and Energy, we assume that the productivity gains are increasing at a constant rate of 1.2 % and the annual population growth rate is 0.37 %. Thus, the growth rate of the economy converges endogenously to 1.57 %.
- The growth rate of most sectors' production follows closely the one of the GDP. This does not apply for food (that grows at the same rate as the population and not as income since it is a necessary good), for vehicles (the rate of household equipment quickly reaches a threshold), and for investments in housing (projections of the National Institute of Statistic and Economic Studies are 0.7 % per year). The same holds for energy, since its demand depends largely on the dynamic of the housing stock, of the fleet of vehicles, on technical progress and on the changes in the price of fossil fuels.
- According to the International Energy Agency forecasts, the prices of imported petroleum products and gas are expected to increase at a rate higher than the inflation rate, which corresponds to an average price increase of almost 2 % per year.[6]
- The electricity mix changes according to the scenario with current measures. The share of primary electricity generated by nuclear technology is reduced from 85 % in 2020 to 33 % in 2050. This leads to a significant reduction in the share of nuclear power in total primary energy production: from 47 % in 2020 to 16 % in 2050 (see Fig. 1 left). This reduction in nuclear power's share of electricity production is offset by the development of wind and solar power, whose share rises from 3 % in 2020 to 44 % in 2050.
- Climate change policy instruments remain unchanged (the price of the carbon tax remains constant over the whole period).
- A reduction of final energy consumption by 27 % between 2015 and 2050 (see Fig. 1 right), mainly through energy efficiency improvement in housing and automobile.
- With these assumptions, GHG emissions fall from 345 $MtCO_2$ in 2018 to 300 in 2050 (a 13 % reduction) which is far from the objective of Carbon Neutrality estimated at 37 $MtCO_2$.

3.2. NLCS scenario: carbon neutrality

Carbon neutrality refers to a target for GHG emissions that can be captured by the environment which is estimated at 82 MTeCO2 per year: the potential of the French carbon sink is estimated at 67 MTeCO2 per year to which is added the annual carbon capture and storage potential estimated at 15 MTeCO2. ThreeME model does not account for the emissions other than CO2. If we deduct from this potential the GHG emission targets other than CO2, such as methane and nitrous oxide, generated by agriculture (45 MTeCO2), combustion (3 MTeCO2), waste (4 MTeCO2) and industrial processes (3 MTeCO2), and if we assume a bonus of 10 MteCO2 to take into account the possible technical progress achievable by 2050 especially in industrial processes, the CO2 emission target to achieve Carbon Neutrality in ThreeME in 37 $MtCO_2$. This corresponds to drop of about 85 % in CO_2 emissions compared to 1990.

Such a decarbonization of the economy is achieved in the NLCS scenario thanks to an important reduction of the consumption of fossil fuel. In 2050, fuels only represent 10 % of primary energy consumption compared to 29 % in 2018 (see Fig. 2). The share of fossil fuel is expected to become marginal with an incorporation rate of biofuels of 88 %. The share of gas consumption increases to 22 % in 2050, compared to 14 % in 2018, but with a biogas incorporation reaching 97 %, compared to 31 % in 2018. Finally, this decarbonization is achieved thanks to higher electrification of the economy. Electricity consumption reaches 68 % of total energy consumption in 2050, compared to 55 % in 2018. The share of renewable energies (wind, solar and hydraulic) in the production of electricity increases from 6 % in 2018 to 62 % in 2050.

The General Directorate of Energy and Climate (Direction Générale de l'Energie et du Climat - DGEC) of the Ministry of Social and Energy Transition has defined a group of policy measures (absent from the baseline scenario) to achieve Carbon Neutrality. These measures defined in the SNBC scenario include fiscal, budgetary and reglementary policy both at the sectoral and transversal level. The transversal measures included in this scenario are:

- A carbon tax rising to 635 EUR2015 in 2050
- Change of the energy production mix.

On the transportation sector, we assume:

- Shift towards more sustainable transportation behaviors
- Improvement of the energy efficiency of private vehicles
- The tax bonus associated to the purchase of an electric vehicle to be extended until 2040

[6] http://www.worldenergyoutlook.org/publications/

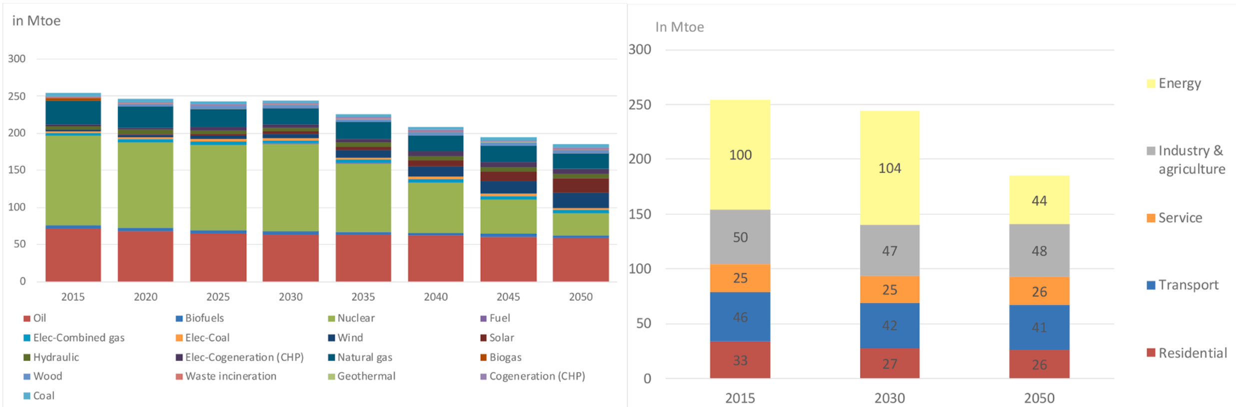

Fig. 1. Energy mix (left) and energy consumption by sector (right) in the reference scenario.

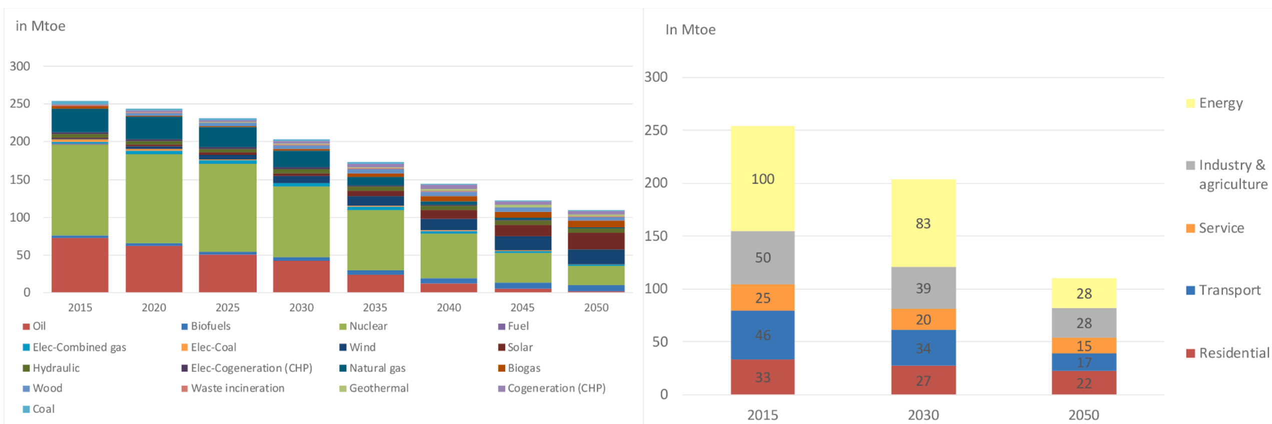

Fig. 2. Primary Energy mix (left) / Energy consumption by sector (right).

- Increase of the modal shift to public transport
- Substitution from gas and oil to electricity in the freight transport

Regarding the building sector, we assume that:

- The tax credit associated to retrofit is maintained until 2050
- The elasticity between the renovation cost and the energy price is increased, to represent the fact that tiers-funding for retrofitting is available
- The obligation of retrofitting in the tertiary sector is integrated into the model

For the industrial sector, we assume that:

- The industry increases its substitution between energy and capital in order to integrate the energy efficiency investments
- The substitution between electricity and fossil fuels is enhanced

As presented in Table 1, the energy transition scenario NLCS defines two types of targets. The first target concerns the level of primary energy demand that is expected to decrease to 110 Mtoe by 2050. This corresponds to a decrease of more than 57 % compared to 2015 level. The second target concerns the level of GHG emissions. Fuel and coal power stations are closed by 2030. The share of natural gas decreases from 85.9 % to 3.4 % in the supply of gaseous fuels and heat between 2015 and 2050. This reduction is offset by the increase in biogas and renewable heat (wood, waste, geothermal, solar, etc.). It is also assumed that the number of electric and hybrid vehicles will increase to 9.9 million of equivalent electric vehicles by 2050 representing 68.2 % of the vehicle fleet.

The decrease in energy demand is facilitated by (1) the introduction of a price signal (see Table 2) through an increasing energy taxation, based on the carbon content of fossil fuels (coal, petroleum products and natural gas), namely a carbon tax; and (2) the decarbonization of the electricity mix as well as by the adoption of energy efficiency and behavioral measures.

- The carbon tax

The rate of the carbon tax is calibrated to meet targets for consumption of fuels for transportation needs and heating defined in the scenario. It is 65 €^{2015} in 2020, 185 €^{2015} in 2030 and 635 €^{2015} in 2050

Table 1
Targets in the SNBC scenario.

Energy demand target	Reducing the primary energy production by 53 % by 2050 Reaching a share of 63 % of renewables in the electricity mix by 2050
Emissions targets	Reaching a level of 37 MtCO2 by 2050 (level of CO2 emissions compatible with the Carbon Neutrality)

Table 2
Policies to achieve targets.

PCO$_2$TAX	Implementation of a carbon tax
PSUB	Implementation of retrofitting subsidies and bonus-malus for private vehicles
PENTAX	Implementation of additional policy measures to enhance energy efficiency investments

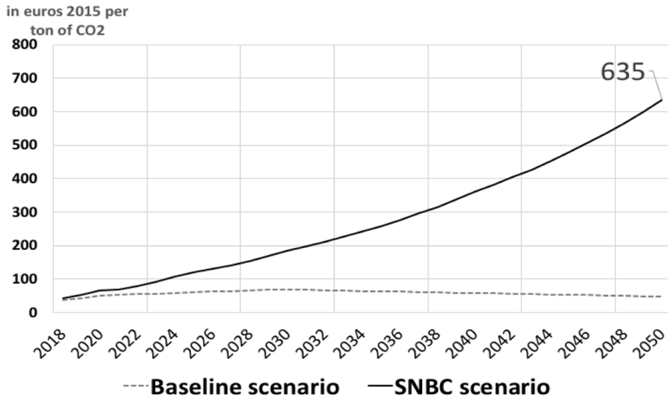

Fig. 3. Carbon tax trajectory.

(Fig. 3). The evolution is very similar to the one proposed by the Quinet commission presented in 2019 [43]: experts had estimated it at 250 € in 2030 and a level between 600 € and 900€ /t CO_2 in 2050.

We assume that these carbon tax rates are the same for households and private firms. The revenues from this tax are totally recycled in the economy in a lump sum way. Households and firms receive respectively the amount they paid. We assume a decrease in income tax for households and a tax credit for economic sectors (in proportion to the turnover of the sector).

- Behavior of the rest of the world

The international environment is assumed to be generally favorable to climate change mitigation efforts. This assumption is integrated into the model by simulating a rise in foreign prices equivalent to one-third of the French inflation rate, representing the adoption of similar climate pricing policies in other countries around the world.

4. Simulation results

The results of these simulations point to a double dividend after implementation of the policies and measures described above. The emissions obtained after the simulation of the NLCS scenario decrease significantly. They are reduced by 25 % in 2030 and by more than 87 % in 2050 compared with their respective levels in the reference scenario (Fig. 4).

According to this simulation, the positive economic impacts of the energy transition surpass its negative effects. By 2050, under the NLCS scenario, the French GDP is projected to be 3.4 percentage points higher than the baseline, with employment increasing by 2.8 % compared to the baseline. This 3.4 % macroeconomic gain at the end of the period corresponds to an average annual increase of 0.1 % from 2018 to 2050. These outcomes are primarily driven by heightened activity in certain sectors, such as services, public transport, and building renovation, at the expense of traditional energy sectors.

The following subsections show the main macro-economic indicators obtained under the NLCS scenario compared to the baseline scenario. More output indicators and their values are provided in Table 3 given in Appendix A.

4.1. An improvement of disposable income of households

Household energy bill decreases despite the rising fuel prices and taxes because of the reduction of the energy demand (Fig. 5 left). Over time, the cumulative sum of energy savings exceeds the reimbursement of the burden of debt related to energy efficiency investments. This, coupled with the increase in employment (see Section 4.3) leads to an increase of their disposable income (Fig. 5 right). This increase leads in turn to a significant increase in household consumption compared to the reference scenario. Household consumption is already 1.45 % higher in 2025, and continues to increase by 3.15 % in 2030 and 5 % in 2050 (Table 3- appendix A).

4.2. New investments

The low-carbon strategy induces a significant increase in investment in some sectors, particularly service sectors (public and private), industry and transport. Investment increase progressively to nearly 140 billion euros per year in 2050 (see Fig. 6). The larger share of these investments are indirect in the sense that they spur growth in related industries and services. For example, increased spending in public transport and building renovations not only enhances infrastructure but also generates demand for materials, engineering services, and skilled labor. This chain reaction of economic activity reinforces the overall growth trajectory, leading to a broader economic expansion beyond the directly targeted sectors. The shift towards low-carbon technologies also fosters innovation and improves energy efficiency, further contributing

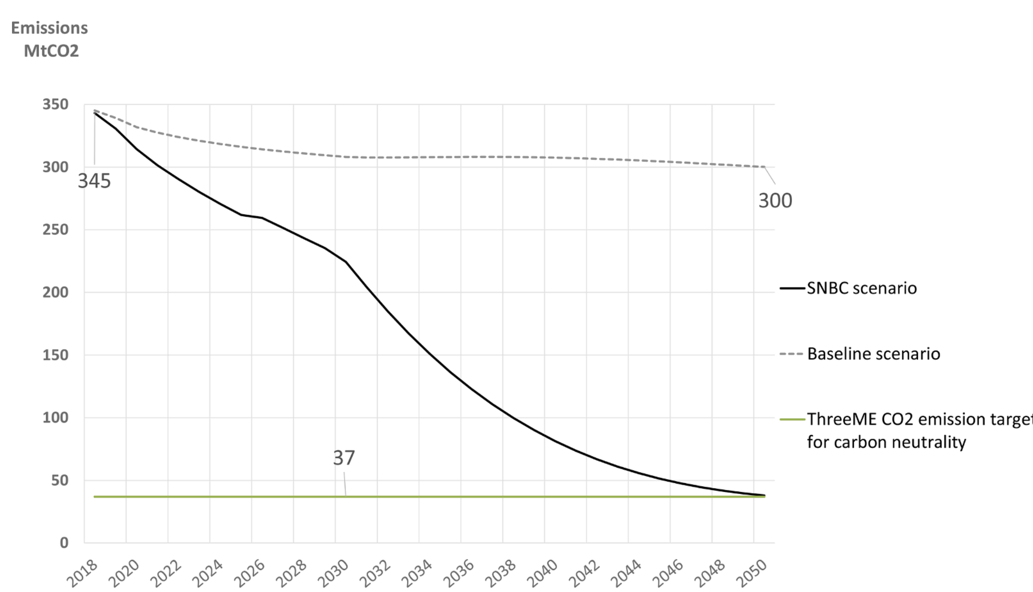

Fig. 4. CO_2 emissions.

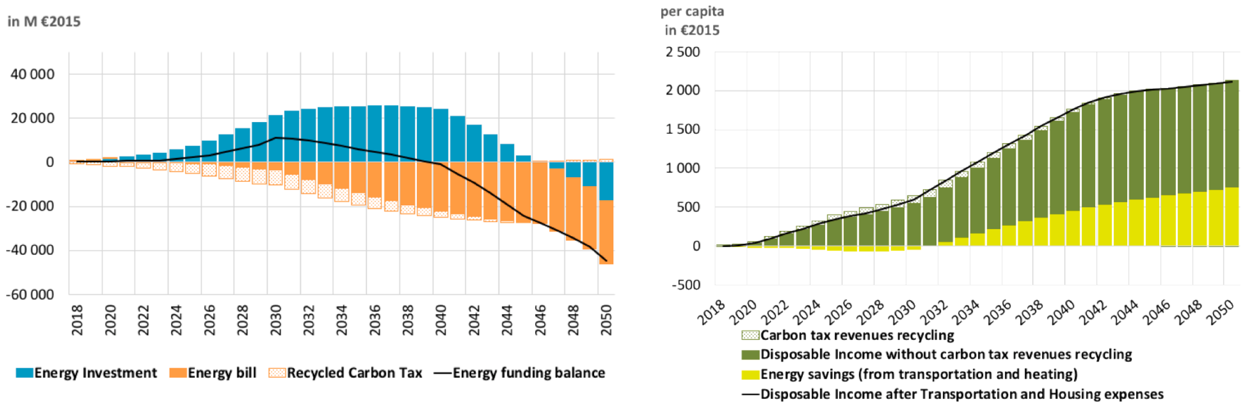

Fig. 5. Households' gross disposable income (left) and Households' energy bill (right).

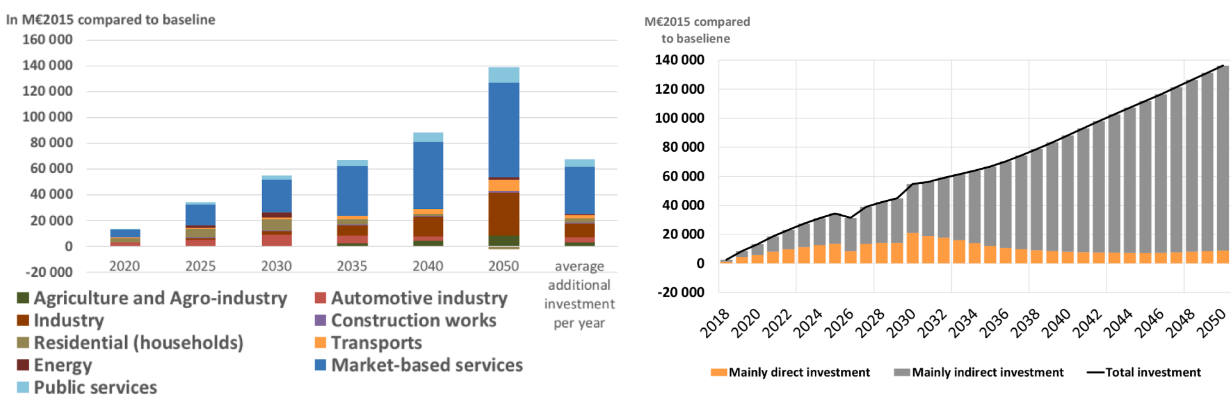

Fig. 6. Investment per sector (left) and direct and indirect investment (right).

to economic resilience and sustainability [44].

This increase is not entirely offset by lower investment particularly observed in combustion engine vehicle and thermal power plants, so that the additional investment compared to the baseline scenario would be 67 billion euros per year on average which represents almost 1.9 point of GDP per year. This assessment is consistent with estimates of the Stern report [45], according to which the fight against climate change requires the mobilization of 1 % of our annual wealth.

4.3. A positive impact on employment

The creation of direct and indirect jobs in the low-carbon sectors (services and construction) outweigh the losses in sectors in decline (fossil fuel, production and distribution of fossil fuels, automotive industry). The reduction in unemployment has a positive effect on the economy, so that the number of induced jobs is substantial particularly in other industries and service sectors. Eventually, the transition would generate 470 000 new jobs in 2030 and 790 000 jobs in 2050 (Fig. 7). The unemployment rate falls by 1.3 (resp. 2) percentage points in 2030 (resp. 2050).

The structure of the labor market will be modified but in relatively small proportions. This will include organizing the conversion of approximately 70 000 jobs in sectors negatively impacted. This task represents a real challenge but also a real opportunity. Note that the

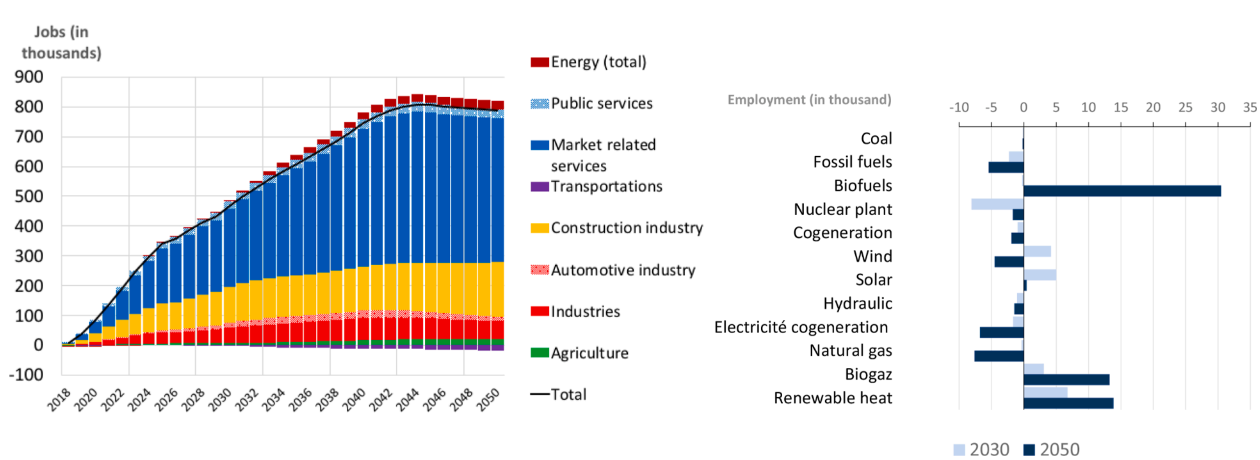

Fig. 7. Net Job creation in the overall economy (left) and in energy sectors (right).

conversion should take place gradually over a long period of almost 40 years in a growing market, where new jobs are expected to largely exceed jobs losses.

4.4. Effects on the trade balance and public finance

Initially, the positive impact on the trade balance remains marginal under two combined effects. First, the rising energy prices lead to higher production costs of all sectors that deteriorate their competitiveness abroad, despite the rise in prices assumed in the rest of the world (see in Section 3.2 - Behavior of the rest of the world). Secondly, at the beginning of the period, investments in renewable energy generate more imports of capital goods until these sectors develop in France. But those effects are more than offset by the reduction of imports of oil and gas. France also strengthens its energy independence, which contributes to the security of energy supply (see Fig. 8 left).

Furthermore, we find that implementing environmental taxation with the recycling of its revenues in the economy induces a reduction in the ratio of public debt to GDP (Fig. 8 right). This reduction is driven by the deficit reduction (Fig. 9 right), which is related to increasing revenues from taxes on electricity and heat, a decrease in expenses due to the reduction of unemployment, and the increase in national income. The recycling of the carbon tax generates economic growth, leading to higher economic activity. This results in increased tax revenues, which subsequently reduce the public deficit and, by extension, public debt. The simultaneous increase in GDP and decrease in debt result in a lower Debt-to-GDP ratio.

4.5. Aggregated positive effect on GDP

The NLCS scenario shows an improvement in the macroeconomic situation with a higher GDP (than in the reference scenario) throughout the period. We observe an increase of 1.7 % from 2025, 2.9 % in 2035 and 3.4 % in 2050 (Fig. 9 left). This net improvement is made possible by consumption and investment, the improvement of which offsets the negative contribution of the trade balance.

The negative contribution of the trade balance (grey bars in Fig. 9) is explained by three combined effects. First, the rise in energy prices due to the carbon tax leads to higher production costs for all sectors, which deteriorates their competitiveness abroad. Second, at the beginning of the period, investments in renewable energies generate more imports of capital goods until these sectors develop in France, even if these effects are more than offset by the reduction in imports of fossil fuels. Finally, the positive dynamic induced by the improvement in investment and consumption increases imports and generates higher inflation than in the rest of the world, which leads to a drop in exports. Note that in a global model, other countries would also experience inflationary pressures, which would affect international trade dynamics and mitigate the relative drop in exports.

The significant increase in employment (see Section 4.3) has a positive effect on consumption, which increases continuously over the whole period. In addition, the policies implemented induce a substitution effect on household consumption. Indeed, as carbon energies become more expensive, agents reduce their consumption of fossil fuels and replace it with electricity; their disposable income excluding energy increases (see Section 4.1) and so does their consumption of other goods and services, which has a positive effect on investment. Thus, the increase in consumption and investment has positive feedback on economic activity, offsetting the deterioration of the trade balance and generating an increase in GDP.

5. Conclusion and policy implications

This article provides an assessment of the macroeconomic effects of implementing France's National Low-Carbon Strategy (NLCS, SNBC in French), which aims to achieve Carbon Neutrality by 2050, in line with the Paris Agreement. The NLCS provides for targeted measures to reduce greenhouse gas emissions in various sectors of the economy, while promoting innovation and the creation of green jobs. However, implementing this strategy requires a strong political will, careful planning, and ongoing collaboration with stakeholders, to ensure that the measures put in place are effective, equitable and acceptable to all.

Since 1990, France has reduced its territorial emissions per capita by 27 %. However, over the last 10 years, the fall in emissions has been relatively modest compared to the emission reduction ambitions it has set itself, with an average annual fall of 1.5 % between 2010 and 2019. At this rate, dividing French emissions by 4 would be reached in 2095 and Carbon Neutrality in 2130. To achieve carbon neutrality in 2050, we would therefore need to accelerate drastically, with a reduction of 5.4 % per year [46]. This article could help encourage decision-makers to put the right policies in place, as it shows that the energy and low-carbon transition can have positive effects on the economy.

In this study, we use the neoKeynesian Computable General Equilibrium model ThreeME (Multi-Sector Macroeconomic Model for the Evaluation of Environmental and Energy Policy). The decrease in GHG emissions to reach the Carbon Neutrality are achieved by improving energy efficiency in all sectors without assuming major new technological innovation and by more sobriety in energy consumption patterns, both induced by price signals and particularly by a carbon tax.

In addition to the environmental dividend obtained by construction, our simulations show that climate change policies could lead to an economic dividend: increase in investments; jobs creations in green industries that are much higher than job destruction in fossil fuel intensive industries and energy sectors. Despite higher prices, demand increases, and GDP is higher than in the reference scenario. Ultimately the energy transition induces a gain equivalent to the income from two years of

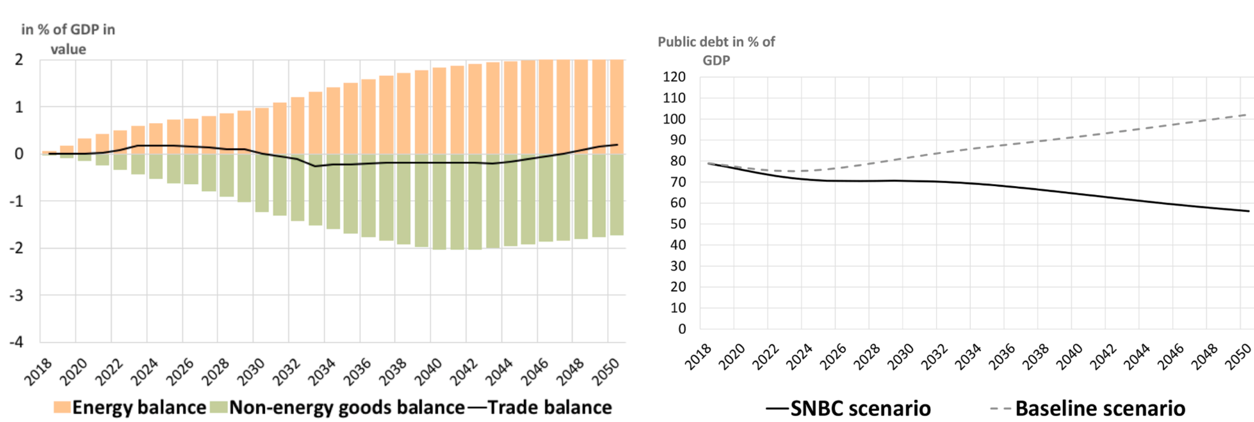

Fig. 8. Trade Balance (left) and public debt (right).

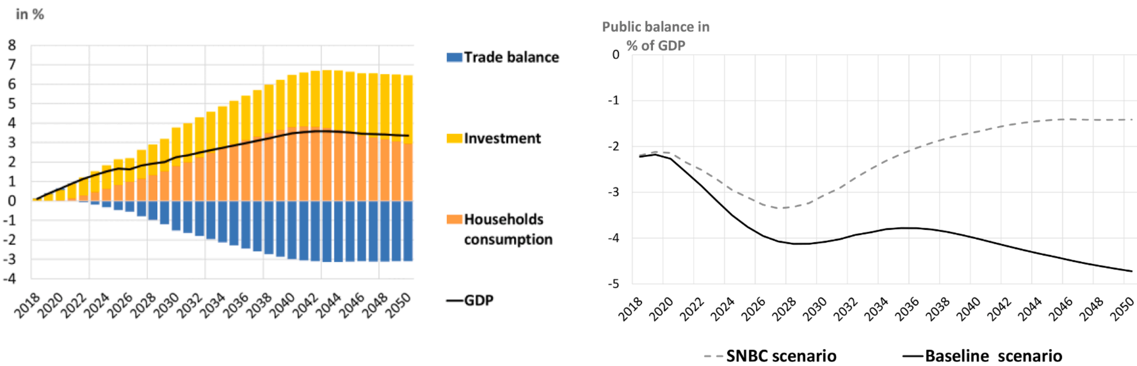

Fig. 9. GDP and its contributions (left) and public balance (right).

additional growth over the period, or a 3.4 % increase in GDP and a 2.8 % increase in employment compared to the baseline scenario in 2050. Eventually, the cumulative sum of energy savings and induced income supplements (including the wage increases) compensate the investment cost required to the financing of the transition.

This modeling work supports the view that the energy transition is not inevitably expensive, simply because of the increase in energy prices in the short and medium term. Moreover, it does not necessarily reduce the purchasing power of households and business competitiveness.

The decrease of greenhouse gas emissions does not imply a reduction in economic activity. Decoupling GDP and CO2 emissions seems possible. If the energy transition has a positive impact on employment, it is logical that GDP, which is equal to the sum of distributed incomes into the economy, is higher. The labor market's structure will undergo adjustments, primarily involving the conversion of jobs in sectors facing negative impacts. Accomplishing this task poses both a significant challenge and a promising opportunity for training institutions and competent authorities. We have not included the matching cost in terms of skills and competence related to the transformation of job during the energy transitions. They may not be negligeable as other studies suggest that there is skill-biased employment dynamic [47]. This implies that while new jobs in green sectors are expected to be substantial, they may require different or higher skill levels compared to the jobs lost in fossil fuel-intensive industries. As a result, there could be a mismatch between the skills of workers displaced from declining sectors and the qualifications needed for new roles. If carefully anticipated, these mismatch costs can be kept under control since the conversion process will span over 40 years within a burgeoning market where the number of new job opportunities is expected to far outweigh job losses. While these effects are unlikely to significantly alter the long-term results of this study, they could lead to temporary additional transition costs (e.g. unemployment increase, inflationary pressure). Considering different qualification levels in the labor market within the ThreeME general equilibrium framework would be an interesting avenue for future research. This approach would offer promising opportunities to better support decision-making and policy development.

Finally, it should be noted that the French NLCS is also part of a wider international framework of cooperation to fight climate change. France continues to work with other nations to achieve the Paris Agreement targets for reducing greenhouse gas emissions on a global scale. Of course, these results will have to be subjected to sensitivity analyses, notably by making variants on what is happening in the rest of the world (world demand, world prices). It will also be interesting to test the robustness of the results by varying the model parameters, but also by considering other climate and energy policies, in particular by considering variants of the carbon tax trajectory. These exercises will be carried out with the new version of the model.

CRediT authorship contribution statement

Gaël Callonnec: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Hervé Gouëdard:** Writing – original draft. **Meriem Hamdi-Cherif:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis. **Gissela Landa:** Writing – original draft. **Paul Malliet:** Writing – original draft, Software, Investigation, Formal analysis, Data curation. **Frédéric Reynès:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Aurélien Saussay:** Software, Methodology, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.egycc.2025.100174.

Data availability

Data will be made available on request.

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