# *Assessing short-term and long-term economic and environmental effects of the COVID-19 crisis in France*

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**Abstract**

In response to the COVID-19 health crisis, the French government has imposed drastic lockdown measures for a period of 55 days. This paper provides a quantitative assessment of the economic and environmental impacts of these measures in the short and long term. We use a Computable General Equilibrium model designed to assess environmental and energy policies impacts at the macroeconomic and sectoral levels. We find that the lockdown has led to a significant decrease in economic output of 5% of GDP, but a positive environmental impact with a 6.6% reduction in $CO_2$ emissions in 2020. Both decreases are temporary: economic and environmental indicators return to their baseline trajectory after a few years. $CO_2$ emissions even end up significantly higher after the COVID-19 crisis when we account for persistently low oil prices. We then investigate whether implementing carbon pricing can still yield positive macroeconomic dividends in the post-COVID recovery. We find that implementing ambitious carbon pricing speeds up economic recovery while significantly reducing $CO_2$ emissions. By maintaining high fossil fuel prices, carbon taxation reduces the imports of fossil energy and stimulates energy efficiency investments while the full redistribution of tax proceeds does not hamper the recovery.

**Key word:** Carbon tax; $CO_2$ emissions; Macroeconomic modeling; Neo-Keynesian CGE model; Post-COVID economy.

**JEL code:** E12, E17, E27, E37, E47, D57, D58

# 1. Introduction

Appearing in China in late 2019, the COVID-19 outbreak has spread extremely rapidly throughout most countries in the world over the first months of 2020, and was declared a pandemic by the World Health Organization on March 11, 2020 (WHO, 2020). To slow down the rate of its spread, most countries have imposed severe measures to encourage people to limit physical interactions, ranging from the banning of public events, closing of schools, non-essential businesses and borders up to complete country-wide lockdown. These unprecedented measures have significantly impacted both the economy and the environment at the global and national levels – at least over the short run. However, the environmental and economic impact of this crisis over the medium and long run remains unclear (Helm, 2020). Furthermore, the economic impact of climate policies, often thought to be positive[1], may be substantially modified in the context of the COVID-19 crisis. This paper thus seeks to address two main questions: (i) what are the economic and environmental effects of the COVID-19 crisis? (ii) what is the macroeconomic impact of climate policy in the post-COVID recovery?

In response to the COVID-19 pandemic, the French government has enforced a strict lockdown from March 17 to May 11, 2020. Travel was restricted to the absolute minimum within national borders, while borders across the Schengen area were closed. These measures have generated a significant improvement in air quality and a 30% reduction in greenhouse gases (GHG) during the lockdown period (CITEPA, 2020). The French High Council on Climate has estimated an induced drop in annual GHG emissions between 5% and 15% relative to 2019 levels. This wide range results from uncertainties over the length and depth of the crisis (HCC, 2020).

At the global level, the drastic contraction of global economic activity and the significant reduction of mobility have induced a drop in global energy demand. The International Energy Agency estimates that total final energy consumption will be reduced by 4% to 6% in 2020 compared to 2019, depending on the duration of travel restrictions and the speed of economic recovery. This would lead to the lowest level of global GHG

[1] The conditions of the existence of a double dividend from the implementation of a carbon tax has been widely discussed in the literature (e.g. Aubert et al, 2019; Hafstead et al, 2018).

emissions since 2010 with a decrease of 8% with respect to 2019 (IEA, 2020a). However, this positive short-term environmental effect may not be sustained. Indeed, Le Quéré et al. (2020) warn that the recovery could be carbon-intensive enough to bring emissions back on their original trajectory. This was the case after the global financial crisis of 2008-2009 (Peters et al., 2012). A repetition of this scenario would make it more difficult to limit global warming to below 2°C (IPCC, 2018). The current period is thus fraught with risks, since the economic slowdown could also negatively affect the funding and deployment of climate mitigation actions (Hepburn et al., 2020; Janardhanan et al., 2020).

Even though the pandemic is still ongoing, a number of studies have already attempted to assess the short-term macroeconomic impact of the COVID-19 crisis quantitatively[2]. The International Monetary Fund estimates a global GDP loss of 3% in 2020 compared to 2019 and projects a growth of 5.8% in 2021 in a baseline scenario, remaining below the forecasts estimated before the COVID-19 pandemic. Authors stress that these forecasts remain very uncertain as a result of numerous hard to measure health, financial, economic and behavioral parameters. Still, their projections point to the fact that service-based economies are most affected (IMF, 2020). In a static comparative exercise, using a global standard computable general equilibrium model, Maliszewska et al. (2020) consider two scenarios that differ in terms of lockdown duration, where the COVID-19 crisis is represented through shocks on production factors, international trade costs, travel services and demand. They find a global GDP contraction of 2.5% and 4% for the short and long lockdown scenario respectively. In both scenarios, developing economies are more impacted than industrialized countries, with service sectors being the most affected. Using a global hybrid DSGE/CGE general equilibrium model, McKibbin and Fernando (2020) analyze seven scenarios where several types of shocks related to the COVID-19 are envisioned (epidemiological and economic shocks to labor supply, cost of production, equity risks, consumption demand and governments expenditure). They provide GDP losses in 2020 compared to a baseline scenario for 24 countries and find that all economies are significantly affected even under the more contained outbreak

[2] Maliszewska et al. (2020) provide a literature review of studies quantifying the potential economic impact of the COVID-19 outbreak, and McKibbin and Fernando (2020) summarize the existing literature on the macroeconomic costs of outbreaks.

scenario. Their results for France range from -0.2% to -8% depending on the scenario. Finally, based on an input-output analysis, the French Economic Observatory assesses the very short-term impact of a one-month lock-down on GDP and employment for the world and major advanced economies (OFCE, 2020). Results are provided for April 2020, which can be useful for researchers who would like to calibrate the COVID-19 shock in their models. They found that the world economy experienced a -19% recession during the month of April, with an even larger reduction in employment. Labor intensive and mobility related sectors were the most affected, with Europe hosting the worst hit countries among developed economies – Spain, France and Italy, where lockdown was strictest – with a monthly GDP loss with respect to April 2019 of 35%, 30% and 29% respectively.

All these studies underline the negative short-term impact of the COVID-19 outbreak on the economy. Many policies have already been announced to foster a rapid economic recovery. Yet decisions that are taken today are crucial to avoid long-term lock-ins in carbon-intensive pathways (Le Quéré et al., 2020). While not necessarily relying on quantitative assessments, a number of researchers consider that the current crisis can be seen as an opportunity to develop inclusive and sustainable growth (Allan et al., 2020; Janardhanan et al., 2020; Rydge et al., 2020; World Bank, 2020a; World Bank, 2020b). In particular Stern and Zenghelis (2020) point out the importance of sustainable investments such as clean energy infrastructure investments, contrasting them with resource-intensive and carbon-intensive investments. Such investments would boost employment in the short term and reduce energy costs, generate economies of scale and productivity gains in the longer term. In the same vein, Hepburn et al. (2020) identify policies and measures that could avoid high economic, environmental and social damages from the COVID-19 crisis: “physical infrastructure, building efficiency retrofits, investment in education and training, natural capital investment, and clean R&D”. However, low oil prices could be a long-lasting characteristic of the post-COVID economy (Helm, 2020), which would significantly slow down and postpone the transition to a low-carbon economy.

Evaluating the economic and environmental impact of the COVID-19 crisis in the short, medium and long term and assessing its impact on the potential double dividend generated by carbon pricing is a real challenge. In this paper, we focus on France, which experienced one of the strictest lockdowns in the world and where an ambitious low carbon national strategy is seriously discussed. We use the French version of ThreeME, a

Computable General Equilibrium (CGE) model specifically designed to assess medium- and long-term impacts of environmental and energy policies at the macroeconomic and sectoral levels.

The modeling framework and a detailed description of the scenarios are provided in Section 2. Section 3 investigates (i) the economic and environmental impact of the COVID-19 crisis in the short and long term, and (ii) the macroeconomic impact of climate policy in the post-COVID recovery. Finally, Section 4 concludes with policy implications and avenues for further analysis.

## 2. *Modeling framework and scenarios*

ThreeME is a country-level open source Computable General Equilibrium model (CGE) originally developed to support policymakers in the design and evaluation of decarbonization pathways in France (Callonnec et al. 2013a; Callonnec et al. 2016)[3]. Since its first release, it has also been adapted to Mexico (Landa et al. 2015), Indonesia (Malliet et al. 2016) and the Netherlands (Bulavskaya and Reynès 2018).

ThreeME is specifically designed to evaluate the short-, medium- and long-term impact of environmental and energy policies at the macroeconomic and sectoral levels. To this end, the model combines several important features:

- Its sectoral disaggregation allows for analyzing the transfer of activities from one sector to another, particularly in terms of employment, investment, energy consumption or balance of trade[4].
- The highly detailed representation of energy flows through the economy allows for analyzing the consumption behavior of economic agents with respect to energy. Sectors can arbitrage between capital and energy when the relative price of energy increases, and substitute between energy vectors. Consumers can substitute between energy vectors, transportation modes or consumption goods.

[3] The main equations are provided and described in Appendix B and a detailed description of the model can be retrieved from Callonnec et al. (2013b). The version used in this study can be retrieved from www.threeme.org.

[4] For this study, we used a version of the model with 17 sectors (see list in **Error! Reference source not found.**). The calibration of the base year (2010) is based on data from WIOD National Supply and Use Table (SUT) for France 2010 (WIOD, 2020).

As a CGE model, ThreeME fully considers feedbacks between supply and demand. Demand (consumption and investment) drives the supply (production). Symmetrically supply drives demand through the incomes generated by the production factors (labor, capital, energy products and materials). Compared to bottom-up energy models such as MARKAL (Fishbone and Abilock, 1981) or LEAP (Heaps, 2008), ThreeME goes beyond the mere description of the sectoral and technological dimensions by integrating these within a comprehensive macroeconomic model.

ThreeME is a neo-Keynesian model. Compared to standard Walrasian-type CGEs that are largely supply driven, prices do not adjust instantaneously to clear markets. Instead the model is dynamic, and prices and quantities adjust slowly. Producers adjusts their supply to the demand. This has the advantage to allow for situations of market disequilibria (in particular the presence of involuntary unemployment). This framework is particularly well suited for policy analysis. 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.

Within this modeling framework, in addition to a baseline reference scenario, we designed four alternative scenarios in order to investigate the impact of the COVID-19 crisis on the French economy with and without the implementation of a climate policy.

## 2.1. Baseline scenario: without COVID-19 or climate policy

This scenario is designed to provide a benchmark against which all other scenarios will be compared. It does not include any specific climate policy beyond those currently enacted by the French government, nor any macroeconomic shock linked to the COVID-19 crisis. In accordance with the assumptions used in the energy scenarios of the French Department of Climate and Energy, we assume productivity gains at a constant annual rate of 1.7% along with a population growth of 0.3%. Furthermore, ThreeME represents France as a small open economy having a relatively minor impact on the world economy. Since France only accounts for a small share of global fossil fuel demand, the French economy is unlikely to impact global fossil fuel prices substantially. We therefore consider oil, natural gas and coal prices exogenous in the model. In this scenario, the prices of imported petroleum products and natural gas are assumed to increase at the rate of inflation, close to 2% per year. Under these assumptions, simulations result in an average GDP growth of 2% per year over the period 2010-2040 and a corresponding 80% increase in $CO_2$ emissions over the same period. Total emissions reach 691 $MtCO_2$ in 2040, far from the carbon neutrality objective pegged at 37 MtCO2 in 2050 (SNBC, 2020).

## *2.2. Climate policy scenario*

We then simulate a first alternative scenario, "*Climate Pol.*", which includes the implementation of a fiscally neutral carbon tax: receipts are fully redistributed to households and firms through lump sum tax credits. There are no monetary transfers between households and firms: proceeds of the carbon tax paid by households are redistributed to them, while each sector receives a share of the carbon tax paid by the private sector proportional to its share of total employment. This mode of allocation is favorable to labor-intensive sectors. Following *France Stratégie* (2019), we assume a carbon price trajectory increasing by 250 € in 2030 and by 500 € by 2040 compared to its 2020 level. This trajectory is designed to be compatible with the French government's economy-wide carbon neutrality objective by 2050.

## *2.3. COVID-19 scenarios*

All of our remaining scenarios take the COVID-19 crisis into account. The 55 days of strict lockdown has led to a negative demand shock, with a very significant reduction in all components of final demand – households consumption, investments and exports. We simulate this drop in final demand in 2020, then assume a return to normal levels of economic activity thereafter [5]. Calibration of this demand shock is based on estimates

[5] The lockdown lifting period, still on-going during the implementation of the current study, is expected to lead progressively to a normal situation in terms of economic activity, depending on the evolution of the epidemic.

provided by OFCE (2020) and is reported in

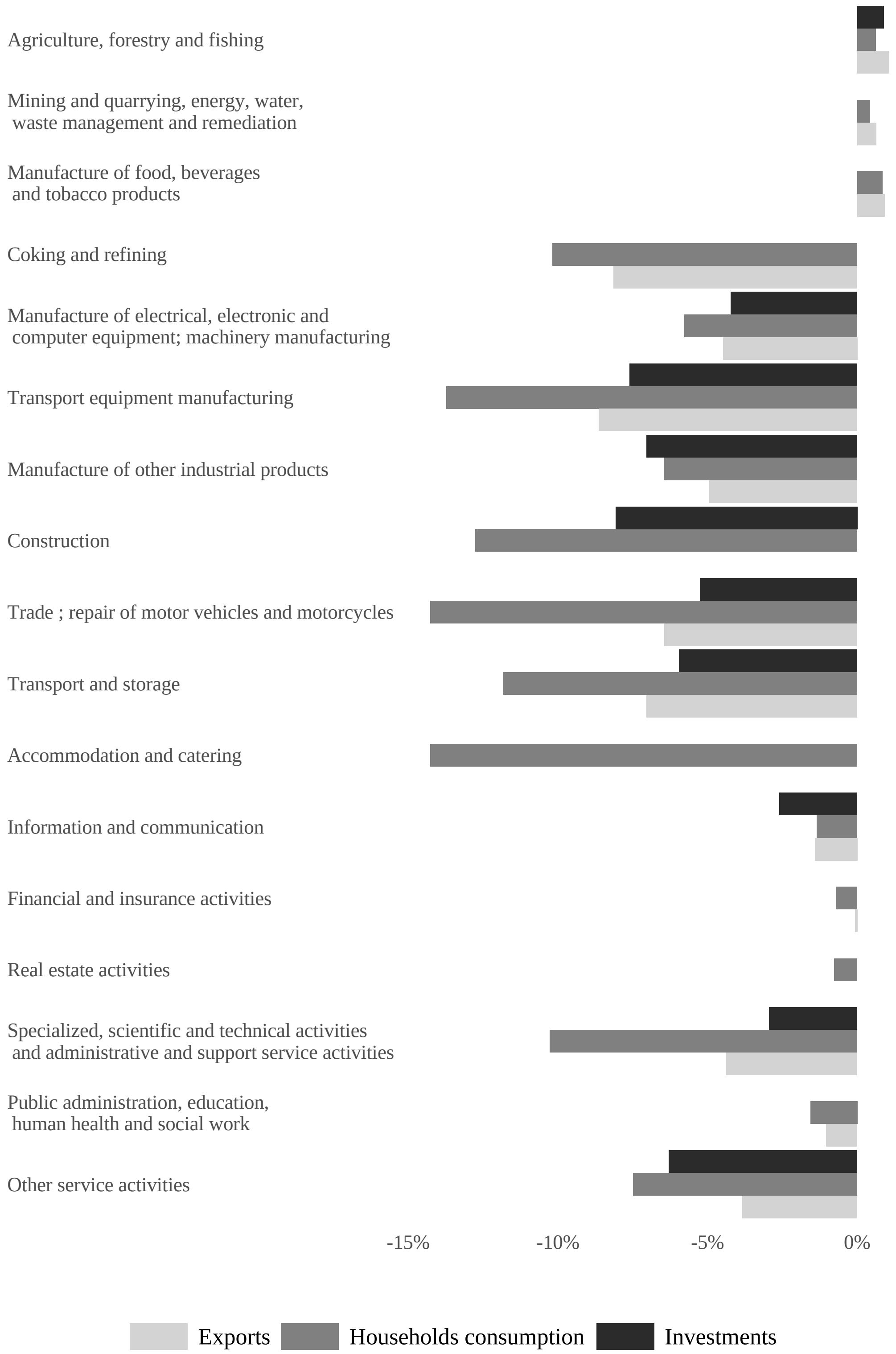


Figure 1. This scenario is referred to as "*COVID*".

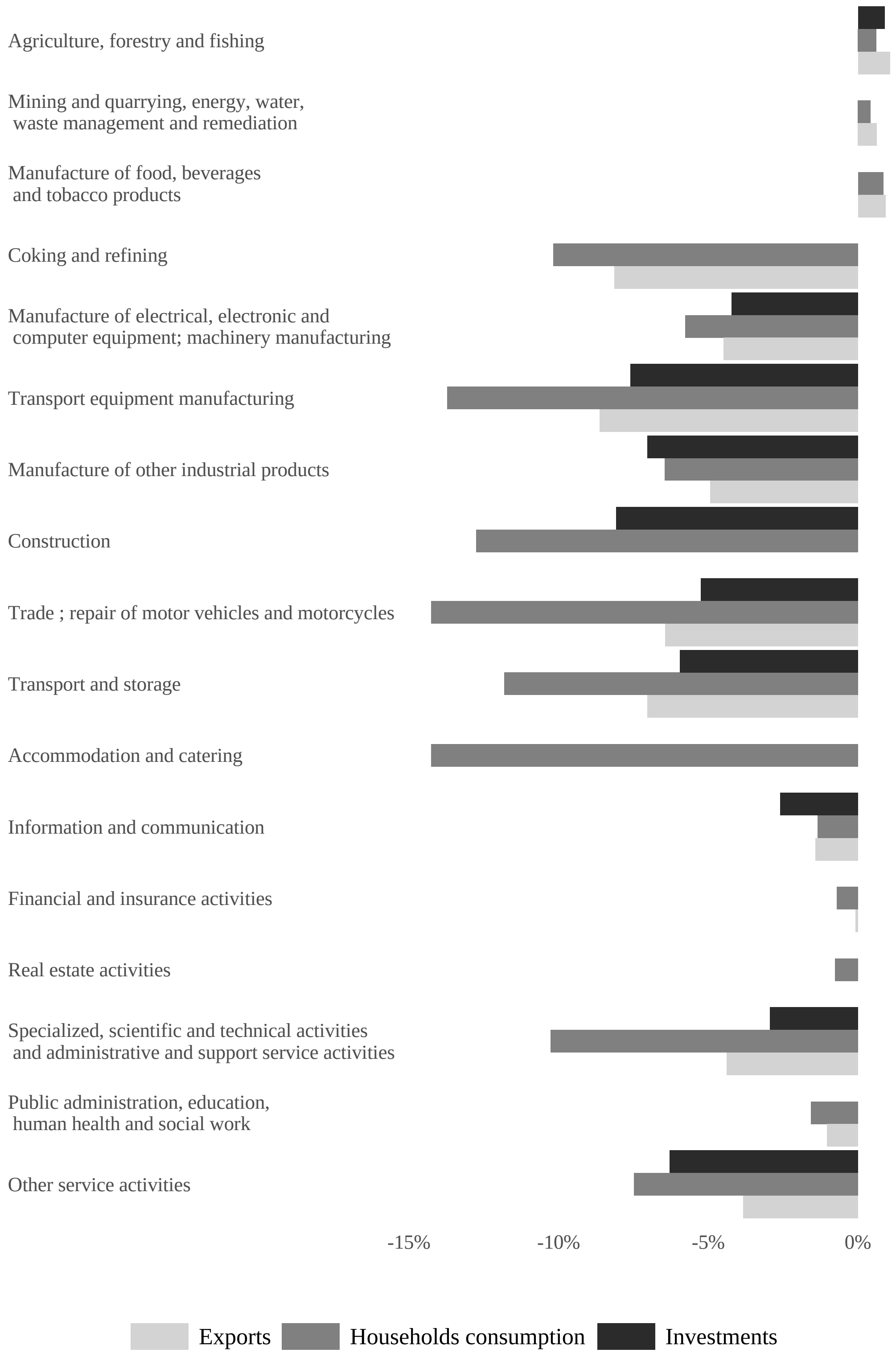


**Figure 1. Goods and services demand variation between the COVID scenarios and the baseline scenario, in 2020**

The COVID-19 crisis has also led to a sharp decrease in international oil prices. This collapse was magnified by pre-existing structural imbalances in global oil markets, with a combination of over-supply and poor coordination between OPEP and non-OPEP producers (IEA, 2019). Indeed, the global wave of lockdown began shortly after Russia and Saudi Arabia failed to reach an agreement on production quotas[6]. These factors have jointly triggered a dramatic decrease in oil price, which could be nearly 50% lower in 2020 than in 2019 (World Bank, 2020c, IEA, 2020b). Furthermore, the combination of structural over-supply and global efforts toward decarbonization may significantly depress oil prices in the medium to long term (Helm, 2020). We examine this in a second COVID-19 scenario, "*COVID & Low Oil*", where we assume a sharp decrease in the international price of oil followed by a slow recovery. Specifically, we consider a 50% drop in 2020 followed by a 2% a year increase.

A sustained decrease in oil prices could have hamper efforts to reduce greenhouse gas emissions. To explore this interaction, we finally analyze the joint impacts of the COVID-19 crisis, low oil prices and carbon pricing in our third COVID-19 scenario, "*COVID & Low Oil & Climate Pol.*". In this instance, we augment the previous scenario with the carbon tax introduced in the climate policy scenario. Table 1 summarizes the various scenarios considered in this study.

**Table 1:** Scenarios

| | *COVID-19 crisis* | *Persistent low oil price* | *Recycled carbon tax* |
|---|---|---|---|
| *Climate Pol.* | | | ✓ |
| *COVID* | ✓ | | |
| *COVID & Low Oil* | ✓ | ✓ | |
| *COVID & Low Oil & Climate Pol.* | ✓ | ✓ | ✓ |

[6] "Saudi Arabia launches oil price war after Russia deal collapse", Financial Times (2020/03/08) https://www.ft.com/content/d700b71a-6122-11ea-b3f3-fe4680ea68b5

## 3. Simulation results

We now turn to the simulation results of the scenarios. We focus our analysis on three main macroeconomic indicators – GDP, employment and aggregate investment – along with $CO_2$ emissions from 2020 to 2040. All simulation results are presented in terms of deviation to the baseline scenario. To test the robustness of our findings, we complement the core simulations with sensitivity analyses conducted on the values of key elasticities of substitution used by the model. These additional results, which include sectoral-level details, are provided in the companion extended working paper (Malliet et al., 2020), and concur with our main findings.

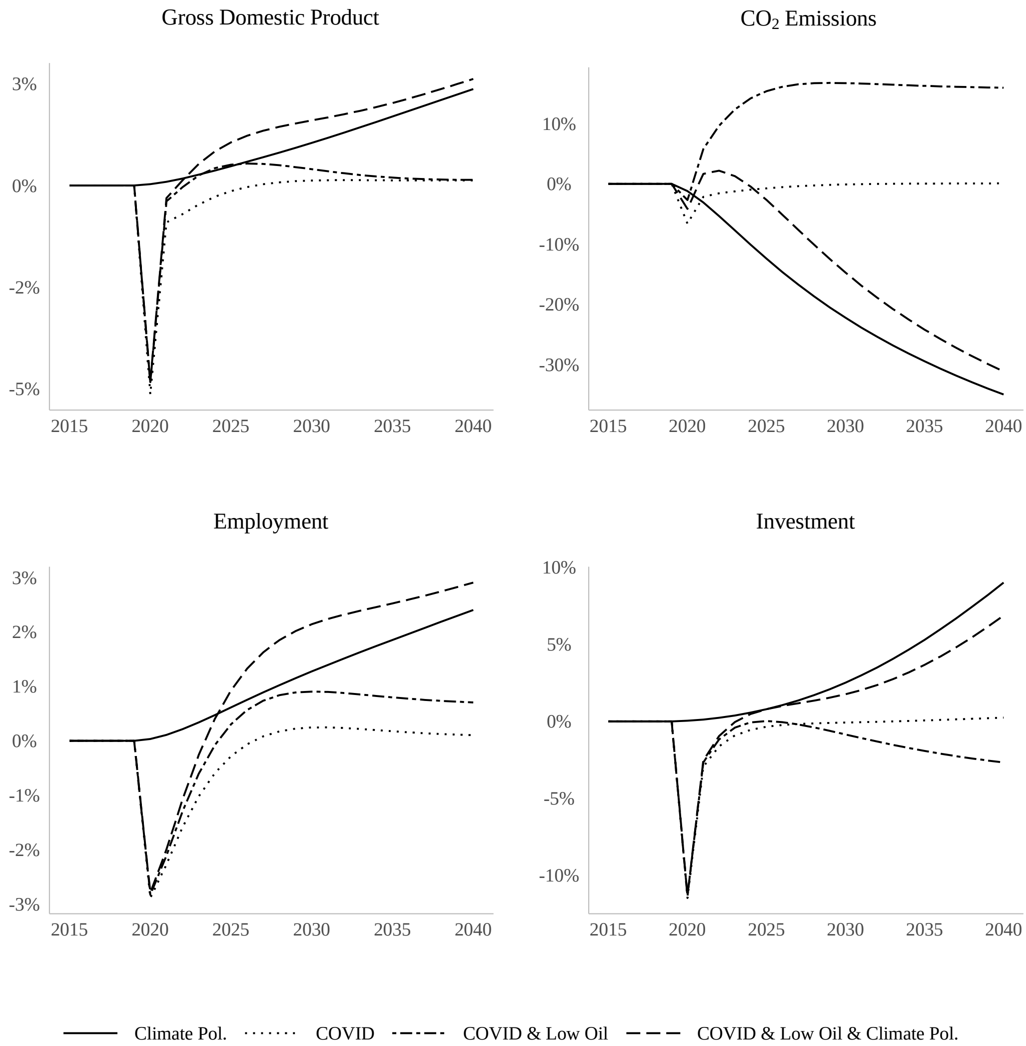


**Figure 2:Deviation from baseline along four economy-wide indicators for each scenario**

## *a.* Economic and environmental impacts of the COVID-19 crisis

We find a strong short-term GDP decrease in 2020, with an estimated reduction of -5.1% compared to the baseline. Our estimate is closely aligned with forecasts published by the OECD (-5.3%) and the Bank of France (-6%). This collapse in economic output results directly from the sudden drop in aggregate demand triggered by the lockdown. It is therefore shared across all COVID-19 scenarios. Such a large reduction in GDP triggers a correspondingly large increase in joblessness, with a jump of 2.9% in the unemployment rate. This finding is also in line with forecasts released by the Bank of France, which estimates that the French unemployment rate will increase by 2.5% in 2021 as a result of the COVID-19 pandemic (Banque de France, 2020). However, this spike proves transitory as the unemployment rate falls back to its pre-crisis level over the following decade. Similarly, investment is particularly affected, dropping by up to 11% in 2020. This is counterbalanced by a substantially faster recovery. Investment bounces back to 2.5% below its baseline level by 2021 and quickly converges back to its pre-crisis trajectory.

An economic slowdown of this magnitude triggers an instant drop in $CO_2$ emissions, of -6.6% in 2020. Yet the projected trajectory of $CO_2$ emissions is highly sensitive to the price of oil. The collapse in oil prices observed in the first half of 2020 leads to an increase in energy intensity and carbon intensity, but also stimulates economic activity. This explains the higher level of emissions estimated in the *COVID & Low Oil* scenario, observed as early as 2020 and sustained through 2040. The stimulus received from lower oil prices remains transitory though, and culminates at 0.5% of GDP by 2026.

The COVID-19 pandemic has devastating macroeconomic impacts in the short term – yet this damage could remain temporary with a return to the pre-crisis growth trajectory within a decade. Symmetrically, the reduction in $CO_2$ emissions is just as short-lived in the absence of strengthened carbon pricing. This would be made worse by a prolonged depression in world oil prices.

## *b.* Climate policy in the post-COVID recovery

The unexpected drop in $CO_2$ emissions resulting from the COVID-19 crisis could appear to provide a welcome respite to help achieve the Paris Agreement objectives. Yet our *COVID* and *COVID & Low Oil* scenarios illustrate that without further climate mitigation efforts, this reprieve will prove short lived. Worse, under the persistently low oil price scenario, French emissions end up higher than in the absence of the COVID-19 pandemic as early as 2022. In the present section, we explore how the introduction of strengthened carbon pricing interacts with the post-COVID recovery.

Long-term trends in emissions in our scenarios are driven by changes in relative energy prices, which result in turn from changes in international oil markets or the introduction of a carbon tax. In our modeling framework, the latter can result in a so-called "double dividend". The increase in carbon pricing fosters improvements in energy efficiency and discourages the use of fossil resources. This improves the balance of trade of a net fossil fuel importer such as France and stimulates energy efficiency investments, thereby yielding a macroeconomic benefit. Further, the carbon taxation scheme specified in the *Climate Policy* and *COVID & Low Oil & Climate Policy* scenarios is fully recycled as a lump sum tax credit without transfers between households and firms. In the private sector, the recycling scheme is implemented proportionally to the sector's share of total employment. Such a scheme favors labor-intensive industries, which increases aggregate employment. These mechanisms explain the expansionary impact of the *Climate Policy* scenario, which leads to a 2.6% higher GDP by 2040 compared to the baseline.

The main contribution of the present paper is to examine the impact of a similarly ambitious carbon pricing policy in the context of the post-COVID recovery, through the *COVID & Low Oil & Climate Policy* scenario. We find that despite the deep COVID-related downturn, carbon taxation still yields a macroeconomic co-benefit in the medium to long-term. Interestingly, the impact on GDP is even higher, at nearly 3% by 2040 than in the counterfactual *Climate Policy* scenario. This is explained by the conjunction with sustained lower oil prices over the period, which reduce households' and firms' energy bills. The fully recycled carbon tax acts as an additional economic stimulus reinforcing the expansionary impact of reduced oil prices while preventing an increase in $CO_2$ emissions. Nevertheless, $CO_2$ emissions still end up 5% higher than in the counterfactual

*Climate Policy* scenario due to the prolonged reduction in oil prices. This finding underlines the need for higher carbon pricing should oil markets remain depressed in the post-COVID recovery.

It should be noted that the positive macroeconomic impacts of climate change mitigation policies are felt early on in the recovery – as a direct result of the balance of trade and investment benefits highlighted above. Both GDP and employment increase beyond their baseline levels as early as 2023, compared with 2024 to 2026 in scenarios that do not implement carbon pricing. Long-term employment also benefits commensurately, with 900,000 jobs created by 2040. However, this aggregate impact is not uniformly distributed across sectors. In particular, energy sectors do see some job destruction when implementing carbon pricing (see Appendix A).

Outcomes on $CO_2$ emissions are the most contrasted across scenarios. In *COVID & Low Oil*, we find that without any strengthened mitigation, depressed oil prices would lead to an increase of 16% above baseline by 2040 despite the initial lockdown related drop. Conversely, the carbon taxation scheme implemented in *COVID & Low Oil & Climate Policy* achieves a 31% reduction in $CO_2$ emissions against the baseline by 2040. Our findings confirm that the COVID-19 crisis need not delay climate change mitigation. Indeed, implementing a fully redistributed carbon tax can even help speed up the economic recovery.

# 4. Conclusion

In order to slow down the rate of spread of the COVID-19 virus, the French government imposed an unprecedented national lockdown over a period of 55 days from March to May 2020. The simulations conducted in this paper pursue two main objectives. First, we aim to provide a quantitative assessment of the economic and environmental impacts of these exceptional measures in the short and long term. We find that the lockdown has had significant negative short-term consequences on economic activity with a 5% GDP decline in 2020 compared to its baseline trajectory. However, the demand shock induced by the lockdown is temporary: the economy progressively recovers toward its baseline trajectory over the following decade. This economic slowdown has an instant mechanical impact on $CO_2$ emissions, with an estimated 6.6% decrease in 2020 compared to the baseline path. Yet, as a consequence of the economic recovery, $CO_2$ emissions also quickly catch up to their baseline trajectory. The positive environmental impact of the COVID-19 crisis is thus purely temporary. Further, one of the main global macroeconomic consequences of the pandemic has been a significant decrease in oil prices – which could be sustained over the coming years. Our simulations suggest that this would make the long-term environmental consequences of the COVID-19 crisis negative. In the medium to long run, $CO_2$ emissions end up above their baseline trajectory since lower oil prices allow for a faster economic recovery while encouraging the development of carbon-intensive technologies.

Second, we investigate whether implementing carbon pricing can still yield positive macroeconomic dividends in the context of the post-COVID recovery. We find that implementing ambitious carbon pricing speeds up economic recovery by stimulating employment and investment while reducing $CO_2$ emissions significantly – even when combined with persistently low oil prices. Increasing fossil energy prices through a carbon tax leads to the substitution of energy for capital, in other words to energy efficiency investments. This in turn yields a decrease in energy use and $CO_2$ emissions. Over the long run, GDP even ends up larger than in a non-COVID-19 scenario implementing the exact same climate policy. By maintaining a high fossil fuel price, the carbon tax reduces the imports of fossil energy while fully redistributing carbon tax proceeds is primarily beneficial to the domestic economy. This acts as an additional economic stimulus which strengthens the recovery while preventing an increase in $CO_2$ emissions. However, low oil prices delay and reduce $CO_2$ emissions reductions achievable by a given level of carbon taxation. This underlines the need for higher carbon pricing should oil markets remain depressed in the post-COVID recovery.

The severity of the global economic crisis induced by the COVID-19 pandemic might appear to support the postponement of ambitious climate mitigation. Our results directly contradict this idea, and support instead the strengthening of climate policies at a critical junction where mishandling of the post-COVID recovery could have dramatic consequences for GHG emissions mitigation efforts.

The COVID-19 crisis is still unfolding as we write these lines. As uncertainty remains particularly high, these results should be considered with appropriate caution. Our analysis could be completed by integrating certain dimensions of the COVID-19 crisis that remain difficult to quantify given current data availability, such as estimating long-term supply-side effects or considering the impact of emergency measures taken by national governments and multilateral organizations. A macroeconomic comparison with a long-term full decarbonization scenario or a set of other climate policy instruments would also yield further insights into the role of climate mitigation in the post-COVID recovery.

# *Appendix A: Detailed simulations results*

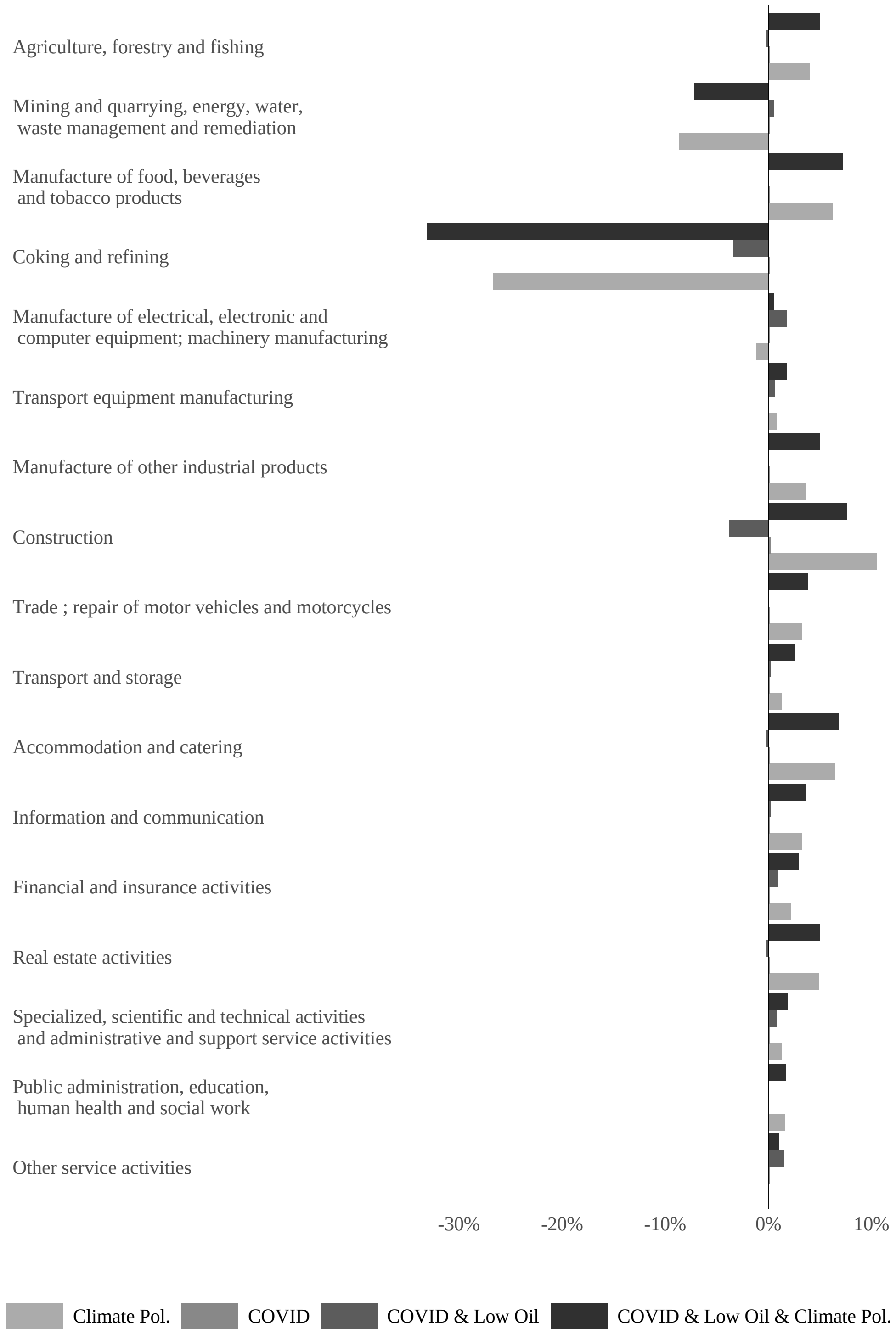


**Figure 3: Added Value variation in deviation to the baseline by sector in 2040**

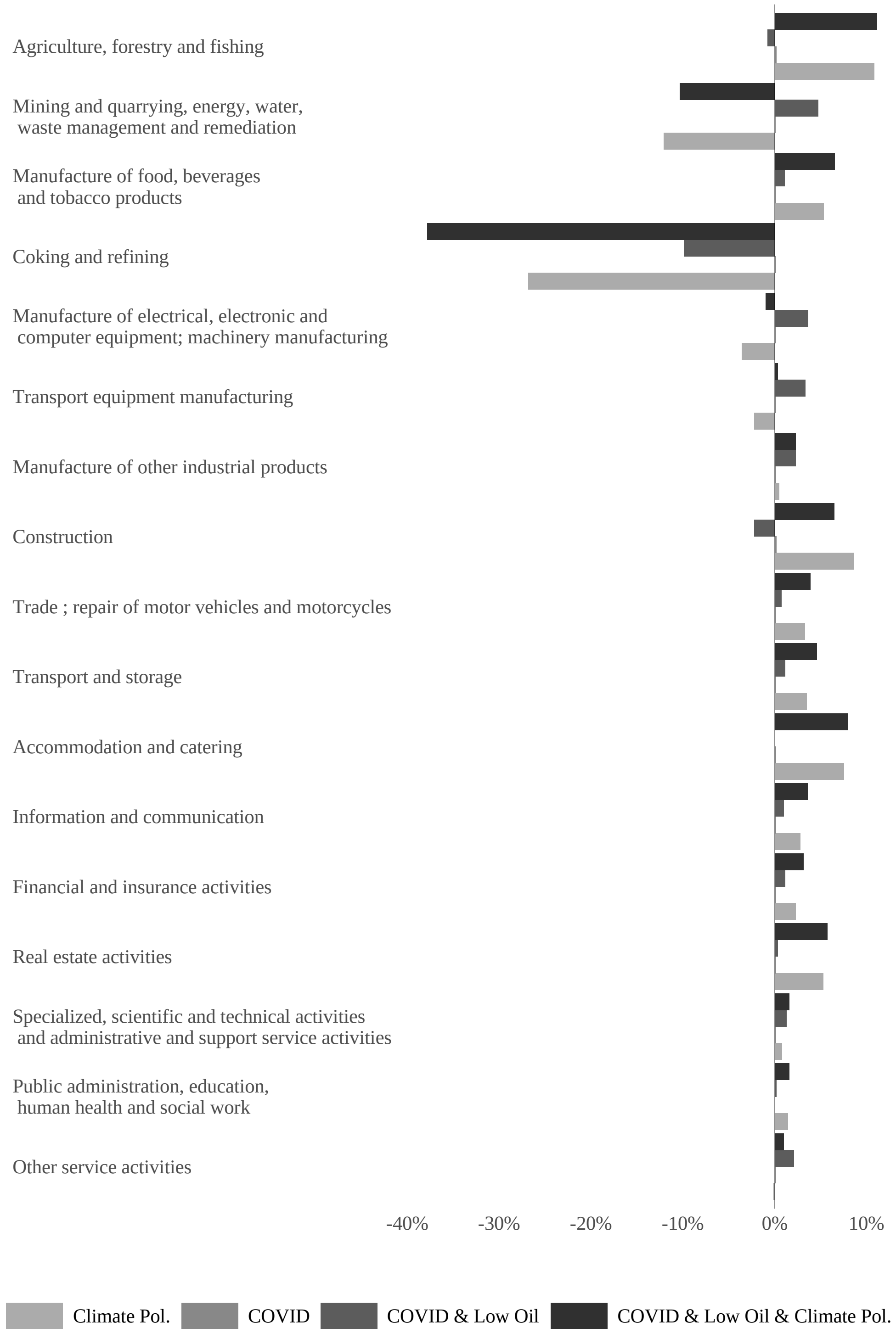


**Figure 4: Employment variation in % deviation to the baseline in 2040**

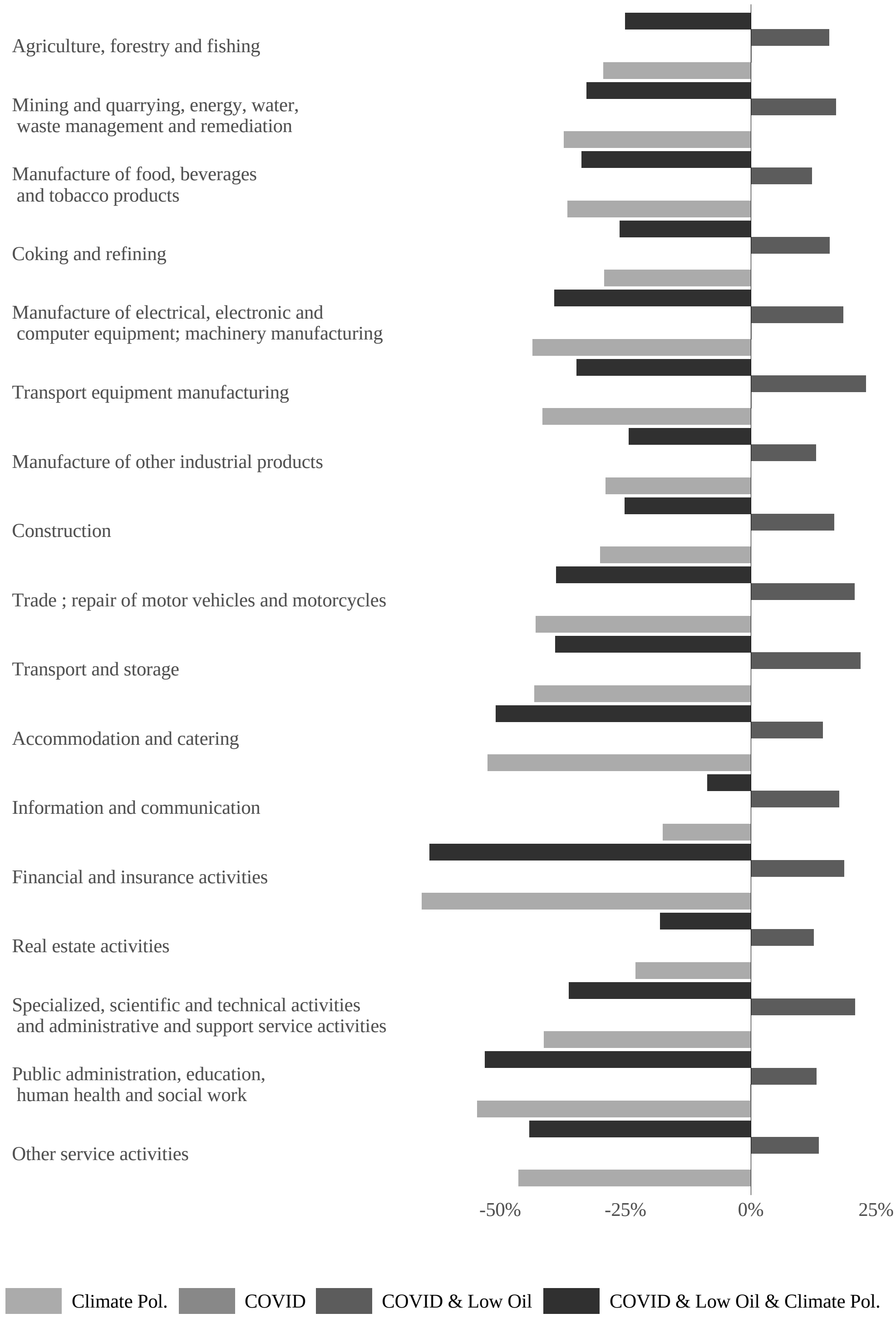


**Figure 5: CO2 emissions variation in % deviation to the baseline in 2040**

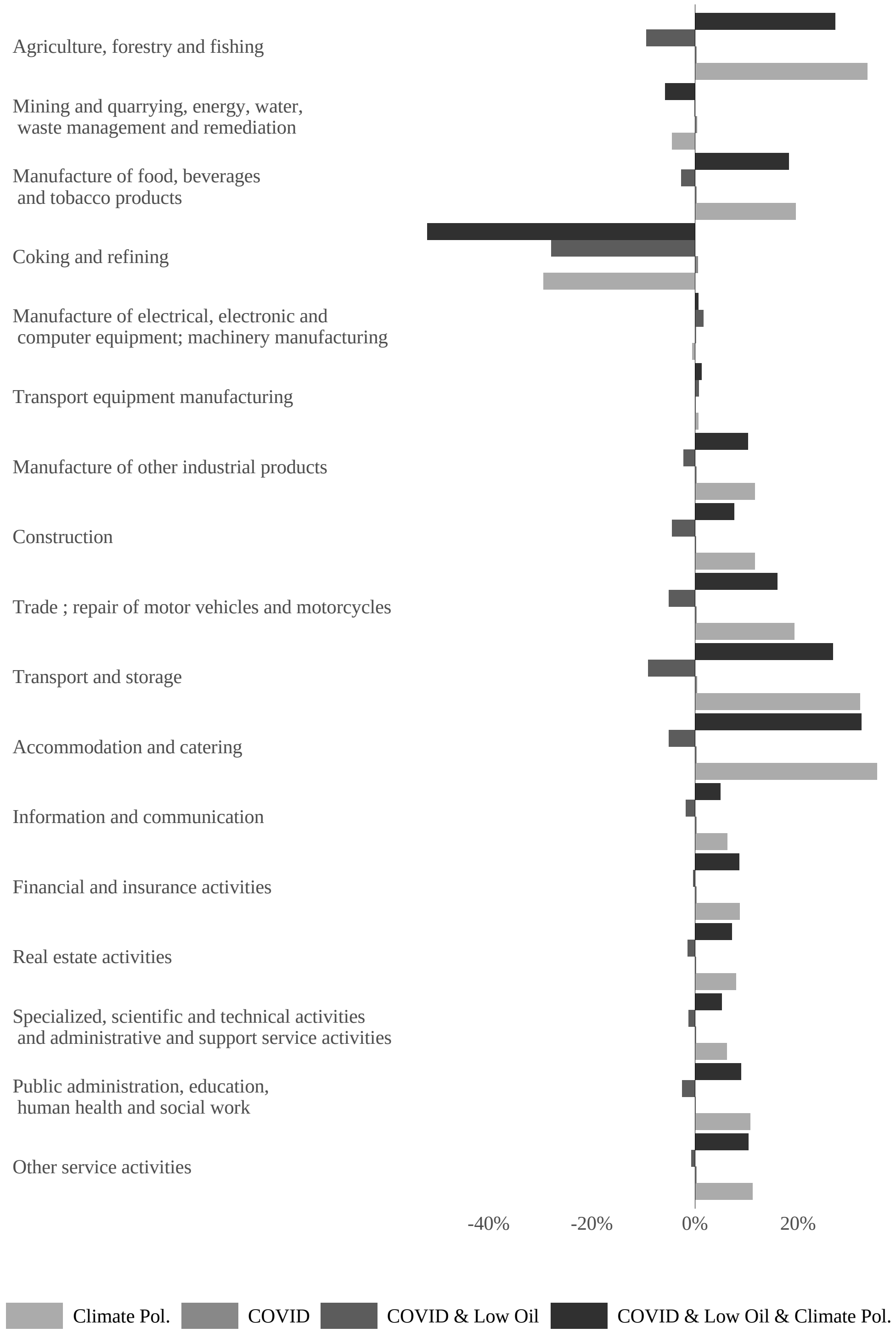


**Figure 6: Investment variation in % deviation to the baseline in 2040**

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# *Appendix B: Description of the main equation of ThreeME (online supplementary data)*

## 1 Specification of adjustment mechanisms

Unlike Walrasian models that assume that equality between supply and demand is achieved through a perfect flexibility of prices and quantities, ThreeME represents more realistically the functioning of the economy by taking into account explicitly the slow adjustment of prices and quantities (factors of production, consumption). In this Keynesian framework, permanent or transitory underemployment equilibria are possible and supply is determined by demand.

ThreeME assumes that the actual levels of prices and quantities gradually adjust to their notional level. The notional level corresponds to the optimal (desired or target) level that the economic agent in question (the company for prices and the demand for production factors, the household for consumption, the Central bank for the interest rate, etc.) would choose in the absence of adjustment constraints. These constraints mainly come from adjustment costs, physical or temporal boundaries and uncertainties. Formally, we assume that the adjustment process and expectations for prices and quantities are represented by the following equations:

$$\ln(X_t) = \lambda_0^X * \ln(X_t^n) + (1 - \lambda_0^X) * (\ln(X_{t-1}) + \Delta\ln(X_t^e)) \quad (1)$$

$$\Delta\ln(X_t^e) = \lambda_1^X * \Delta\, ln(X_{t-1}^e) + \lambda_2^X * \Delta\ln(X_{t-1}) + \lambda_3^X * \Delta\ln(X_t^n) \quad (2)$$

Where $X_t$ is the actual value of a given variable (e.g. the production price, labor, capital, etc.), $X_t^n$ is its notional level, $X_t^e$ its anticipated value at period $t$ and $\lambda_i^X$ are the adjustments parameters (with $\lambda_1^X + \lambda_2^X + \lambda_3^X = 1$).

Equation (1) assumes a geometric adjustment process. Taking into account the anticipations guaranties that the actual variables converge to their notional levels in the long run. Equation (2) assumes that the anticipations are adaptive (« backward-looking »). One can see that Equation (1) and Equation (2) can be reformulated into an Error Correction Model used in the econometric estimations to take into account the non-stationary propriety of some variables: $\Delta \ln(X_t) = \alpha_1 * \Delta\ln(X_{t-1}) + \alpha_2 * \Delta \ln(X_t^n) - \alpha_3 * \ln\left(\frac{X_{t-1}}{X_{t-1}^n}\right)$. For this, the following constraints must hold: $\lambda_0^X = \alpha_3$, $\lambda_1^X = 0$, $\lambda_2^X = \alpha_1/(1-\alpha_3)$, $\lambda_3^X = (\alpha_2 - \alpha_3)/(1-\alpha_3)$.

We also assume that the substitution effects (*SUBST_X*) adjust slowly to the notional substitution effects (*SUBST_X^n*):

$$SUBST\_X_t = \lambda_4^X * SUBST\_X_t^n + (1 - \lambda_4^X) * SUBST\_X_{t-1} \qquad (3)$$

The three equations above allow a rich set of adjustment as they integrate different types of rigidity (on prices and quantities, on expectations and on substitution mechanisms). For illustrative purposes, we present the full specification of the demand for labor (*L*). For simplicity, the sector index is omitted. The notional labor demand ($L^n$) is derived by minimizing production costs. It depends positively on the level of the output (*Y*), negatively on the labor productivity (*PROG_L*) and on an element gathering all the substitution phenomena with the other production factors (*SUBST_L*):

$$\Delta\ln(L_t^n) = \Delta\ln(Y_t) - \Delta\ln(PROG\_L_t) + \Delta SUBST\_L_t \qquad (4)$$

We introduce a distinction between the actual and notional substitution effects to account for the fact that labor demand generally responds more quickly to changes in the level of production than to substitution phenomena: while it is "physically" necessary to increase employment to meet rising production, substitutions involve changes to the structure of production whose implementation takes longer. The actual substitution therefore adjusts gradually to the notional substitution ($SUBST\_L^n$) which depends on the relative prices between the production factors:

$$\Delta SUBST\_L_t^n = -\eta^{LK} \varphi_{t-1}^K \ \Delta \ln(C_t^L / C_t^K) - \eta^{LE} \ \varphi_{t-1}^E \ \Delta \ln(C_t^L / C_t^E) - \eta^{LMat} \varphi_{t-1}^{Mat} \ \Delta \ln(C_t^L / C_t^{Mat}) \tag{5}$$

Where $\eta^{LK}$, $\eta^{LE}$, $\eta^{LMat}$ are the elasticity of substitution between labor and the other production factors respectively capital, energy, material (i.e. non-energy intermediate consumption). $\varphi^K$, $\varphi^E$, $\varphi^{Mat}$ are respectively the capital, energy and materials shares in the production costs. $C^K, C^L, C^E$, $C^{Mat}$ are respectively the unitary costs of production of capital, labor, energy and material. The next section provides more information on the derivation of factors demands.

Finally, the adjustment mechanisms being defined according to the equations (1), (2) and (3), the three following relationships are used:

$$\ln(L_t) = \lambda_0^L * \ln(L_t^n) + (1 - \lambda_0^L) * (\ln(L_{t-1}) + \Delta \ln(L_t^e))$$

$$\Delta \ln(L_t^e) = \lambda_1^L * \Delta \ln(L_{t-1}^e) + \lambda_2^L * \Delta \ln(L_{t-1}) + \lambda_3^L * \Delta \ln(L_t^n) \tag{6}$$

$$SUBST\_L_t = \lambda_4^L * SUBST\_L_t^n + (1 - \lambda_4^L) * SUBST\_L_{t-1}$$

# 2 *The production function and the production factors demand*

The production structure is decomposed into three levels (see

Figure 1). The first one assumes a production function with 4 inputs (or production factors), often referred as KLEM (capital, labor, energy and materials). The first level has a fifth element: the transport and commercial margins. Stricto sensu, they cannot be considered as production factors since they intervene after the production process. Thus they are not substitutable with the production factors. But they are closely related to the level of production since once a good has been processed, it has to be transported and commercialized. At the second level, the investment, energy, material and margins aggregates are further decomposed by type of commodities (e.g. energy sources). At the third level, the demand for each factor or margin is either imported or produced domestically.

The demands for production factors are derived from the minimization of the firm's production costs. We assume a production function with constant returns-to-scale more general than the CES (Constant Elasticity of Substitution) insofar as substitution elasticities may differ between different inputs pair (Reynès, 2019). The production costs minimization program leads to the following equations for the notional factors demand. This holds for every economic activity, but for algebraic simplicity the sector index is omitted here:

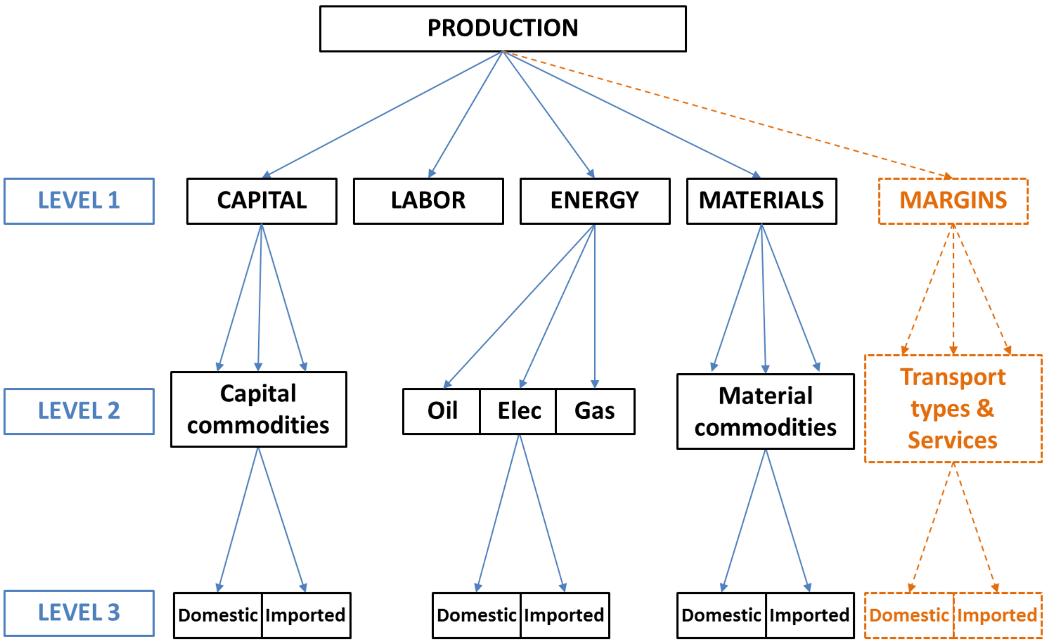
$$\Delta \ln\left(FP_{j,t}^{n}\right) = \Delta \ln(Y_t) - \Delta \ln\left(PROG\_FP_{j,t}\right) + \Delta SUBST\_FP_{j,t} \tag{7}$$

$$\Delta SUBST\_FP_{j,t}^{n} = -\sum_{\substack{j'=1 \\ J'\neq j}}^{J} \eta_{j,j'}\,\varphi_{j',t-1}\,\Delta \ln\left(C_{j',t}^{FP}/C_{j,t}^{FP}\right)\ ) \tag{8}$$

with $$\varphi_{j,t-1} = \frac{C_{j,t}^{FP} * FP_{j,t-1}}{\sum_j C_{j,t}^{FP} * FP_{j,t-1}} \qquad and \quad j = \{\,K, L, E, M\,\} \tag{9}$$

Where $FP_j^n$ is the notional demand of input *j* (KLEM), $\eta_{j,j'}$ the elasticity of substitution between the pairs of inputs *j* and *j'*, $PROG\_FP_{j,t}$ the technical progress related to input *j*, $C_j^{FP}$ the cost/price of input *j* and $Y$ the level of production of the sector under consideration.

**Figure 1. Structure of production in ThreeME**




According to national accounts data, ThreeME assumes that each commodity may be produced by more than one sector. For instance, electricity can be produced by several sectors such as nuclear or wind power. The production of each sector is defined by the following equations:

$$Y_{c,a} = \varphi_{c,a} YQ_c \qquad (10)$$

$$Y_a = \sum_c Y_{a,c} \tag{11}$$

Where $YQ_c$ is the aggregated domestic production of commodity c. It is determined by the demand (intermediate & final consumption, investment, public spending, exports and stock variation). $\varphi_{c,a}$ is then the share of commodity c produced by the sector a (with $\sum_a \varphi_{c,a} = 1$) and $Y_a$ is the aggregated production of sector a.

# 3 Equations for investment & capital

Investment in ThreeME depends on the anticipated production, on its past dynamic, on substitution phenomena and on a correction mechanism, which guaranties that companies reach their level of long-term notional capital stock. The stock of capital is deducted from the investment according to the standard capital accumulation equation:

$$\begin{aligned}\Delta\ln(IA_t) = {} & \theta_1^{IA} * \Delta ln(IA_{t-1}) + \theta_2^{IA} * \Delta\ln(Y_t^e) \\ & + \theta_3^{IA}(\ln(K_{t-1}^n) - ln(K_{t-1})) + \Delta SUBST\_K_t \end{aligned} \tag{12}$$

$$K_t = (1 - \delta^K)K_{t-1} + IA_t$$

Where *IA* is the investment, $Y^e$ the anticipated production, *K* and $K^n$ the actual and notional stocks of capital, *SUBST_K* a variable gathering substitution phenomena between capital and the other inputs, and $\delta^K$ the depreciation rate of capital. Moreover, we impose the constraint $\theta_1^{IA} + \theta_2^{IA} = 1$ in order to guaranty the existence of the stationary equilibrium path.

This specification is a compromise between the short-term dynamics empirically observed and the consistency of the model in the long run. Like the MESANGE econometric model (Klein and Simon, 2010), it is common to estimate an investment equation rather than capital stock equation for serval reasons. Firstly, time series capital stock data are often unreliable. Secondly, this approach better represents the short-term dynamics of investment. In particular, it avoids capital destruction phenomena (negative investment) that are in practice unusual, since companies generally prefer to wait for the technical depreciation of their installed capital. Unlike MESANGE, we assume in addition that investment depends on the difference between the actual and notional capital stock. This element ensures that the effective capital stock converges over time towards its notional level. In the long-term, the model is then consistent with the production function theory that establishes a relationship between the levels of production and capital stock (and not with the flow).

# 4 Wage equation

Several studies have shown that the theoretical arguments and empirical estimates difficultly allow choosing between the two specifications. However, this difference of specification has important implications on the definition of the equilibrium unemployment rate (NAIRU) and thus on the inflationary dynamic and the long-term proprieties of a macroeconomic model (e.g. Blanchard and Katz, 1999). In ThreeME, we choose a general specification that includes the Phillips and WS curves. It assumes that the notional nominal wage ($W_t^n$) positively depends on the anticipated consumption price ($P_t^e$) and on the labor productivity ($PROG\_L_t$), and negatively on the unemployment rate ($U_t$):

$$\Delta ln( W_t^n) = \rho_1^W + \rho_2^W * \Delta ln(P_t^e) + \rho_3^W * \Delta ln(PROG\_L_t) \quad (13)$$

$$- \rho_4^W U_t - \rho_5^W \Delta U_t$$

This relation can alternatively be identical, either to the Phillips curve, or to the WS curve depending on the value of the selected parameters (Heyer et al., 2007; Reynès, 2010). The Phillips curve corresponds to the case where $\rho_4^W > 0$ whereas the WS curve assumes $\rho_4^W = 0$. For the model to have a consistent steady-state in the long-run, the WS curve must also impose the constraints identified by Layard et al. (2005) : a unit indexation of wages on prices and productivity: ($\rho_2^W = \rho_3^W = 1$) and $\rho_1^W = 0$.

# 5 *Equation of households' consumption*

In the standard version of the model, consumption decisions are modeled through a *Linear Expenditure System* (LES) utility function generalized to the case of a non-unitary elasticity of substitution between the commodities Brown & Heien (1972). Households' expenditures for each commodity evolve (more or less) proportionally to their income:

$$(EXP_c^n - NEXP_c).PEXP_c = \beta_c^{EXP}\left[(1 - MPS).DISPINC\_VAL - \sum_c PEXP_c * NEXP_c\right] \quad (14)$$

With $\sum_c \beta_c^{EXP} = 1$

Where $EXP_{c,h}^n$ corresponds to the volume of notional consumption (expenditures) in commodity c and $PEXP_c$ to its price. $NEXP_c$ is the incompressible volume of expenditures in commodity *c*, $DISPINC\_VAL$ is the households' disposable income and $MPS$ their marginal propensity to save.

In the case of no incompressible expenditures ($NEXP_c = 0$), households aim at allocating a share $\beta_c^{EXP}$ of their total expenditure (in value), $(1 - MPS).DISPINC\_VAL$, to commodity *c*. This share is constant if the elasticity of substitution between the commodities is equal to one (Cobb-Douglas assumption). In this case (Cobb-Douglas utility function without incompressible expenditures), commodity c expenditures stay exactly proportional to income. In the case of a CES function where the elasticity of substitution is $\eta^{LES\_CES}$, the marginal propensity to spend varies depending on the relative prices according to the following specification:

$$\Delta\beta_{c,t}^{EXP} = (1 - \eta^{LES\_CES}) * \Delta\frac{PEXP_{c,t}}{PEXP_t^{CES}} \quad (15)$$

$$PEXP_t^{CES} = \left(\sum_c \beta_{c,0}^{EXP} * PEXP_{c,t}^{\ (1-\eta^{LES\_CES})}\right)^{\frac{1}{1-\eta^{LES\_CES}}} \tag{16}$$

# 6 Equations of prices and of the mark-up rate

The production price for each sector is set at the lowest level by applying a mark-up over the unit cost of production (which includes labor, capital, energy and other intermediate consumption costs) :

$$PY_t^n = CU_t * (1 + TMD_t) \tag{17}$$

$$\Delta\ln(1 + TM_t^n) = \sigma^{TM} * (\Delta\ln(Y_t) - \Delta\ln(Y_{t-1})) \tag{18}$$

$$TMD_t = \lambda^{TM} * TM_t^n + (1 - \lambda^{TM}) * TMD_{t-1} \tag{19}$$

Where $PY_t^n$ is the notional price, $CU_t$ the unitary cost of production and $Y_t$ the level of production. $TMD_t$ and $TM_t^n$ are respectively the desired and notional mark-up.

The equation of notional price is a behavioral equation: by assuming that the addressed demand to a firm is a negative function of its price, one can easily demonstrate that the optimal price corresponds to a mark-up over the marginal cost of production. The mark-up equation reflects the fact that the returns-to-scale are decreasing in the short-term. Therefore, a non-expected increase in production results into a higher marginal cost of production and therefore into a higher notional price.

The other prices are calculated according to their accounting definition and are therefore (directly or indirectly) a function of the producer price. The price of the domestically produced commodity *c* is a weighted average of the production prices of activities (indexed by a) producing that commodity. For example, the price of electricity is a weighted average of the production prices of the sectors producing electricity. The price paid by the final user (consumer, government, sector, rest of the world) integrates in addition the commercial and transportation margins, and the taxes net from subsidies. Combined with the price of imports, we get the average price for each commodity paid by each end user.

# 7 *Equations of foreign trade*

Exports are determined by the external demand addressed to domestic products and the ratio between the export and world prices:

$$\Delta \ln\left(X_{c,t}\right) = \Delta \ln\left(WD_{c,t}\right) + \Delta SUBST\_X_{c,t} \qquad (20)$$

$$\Delta SUBST\_X^{n}_{c,t} = -\eta^{X} * \Delta \ln(P^{X}_{c,t}/P^{W}_{c,t}/TC_{t})$$

Where $WD_{c,t}$ is the world demand, $P^{W}_{c,t}$ its price. $P^{X}_{c,t}$ is the export price that depends on the production costs and which reflects the price-competitiveness of the domestic products. $TC_t$ is the exchange rate; $\eta^{X}$ is the price-elasticity (assumed constant).

We assume imperfect substitution between domestic and imported goods (Armington, 1969). The demand for domestic and imported products is :

$$\Delta\ln\left(A^{D}_{c,t}\right) = \Delta\ln\left(A_{c,t}\right) + \Delta SUBST\_AD_{c,t}$$

$$\Delta SUBST\_AD^{n}_{c,t} = \eta^{A}_{c} * \Delta\ln\left(P^{AD}_{c,t} / P^{AM}_{c,t}\right) * \frac{P^{AM}_{c,t-1} * A^{M}_{c,t-1}}{P^{A}_{c,t-1} * A_{c,t-1}} \qquad (21)$$

$$A^{M}_{c,t} = A_{c,t} - A^{D}_{c,t}$$

Where $A_{c,t}$ represents the demand for each type of use (intermediary consumption, investment, consumption, public spending, exports, etc.), $P_{c,t}^{A}$ is its price. $A_{c,t}^{M}$ and $A_{c,t}^{D}$ are the imports and the domestic products demanded for each type of use $A$, $P_{c,t}^{AM}$ and $P_{c,t}^{AD}$ are their respective prices. The elasticity of substitution $\eta_{c}^{A}$ by type of use $A$ of a given commodity $c$ can potentially be different, which allows a high degree of flexibility.

Supplementary data to this article can be found online at www.threeme.org.