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The changing response to oil price shocks in France : a DSGE type approach

Abstract

The recent rise in oil prices has brought concern about its eventual impact on economic growth. However, empirical studies seem to be reassuring. Actually, the link between oil prices and GDP growth estimated since the mid 80s is not as strong as it was before the mid 80s. Several explanations have been called to highlight this empirical evidence. One potential explanation is the non-linear or asymmetric nature of the oil price - GDP link. Other explanations are the fact that economies have become less oil-dependent, or changes in rules governing wage and price formation. Developing a fully micro-founded dynamic stochastic general equilibrium model, we examine the relevance of these different interpretations, focusing on France. Non-linear preferences generate oil price - GDP asymmetries that do not in the expected direction, and introducing adjustment cost do not trigger any. The observed diminution in oil intensities explains a reduction by one half in the GDP response to oil-price shocks. The desindexation of wages and prices further flattens the GDP response, but cannot explain the observed lack of GDP response. All these results claim for further analysis, including the examination of *causes* of the recent oil price hikes.

Keywords: DSGE model, GDP growth, oil shocks.

L'évolution de la réponse de l'économie française aux chocs pétroliers : une approche type MEGIS.

Résumé :

Les hausses récentes du prix du pétrole ont généré la crainte d'effets négatifs sur la croissance économique. Mais les dernières études empiriques sont plutôt rassurantes sur ce point. Le lien entre prix du pétrole et croissance économique s'est beaucoup affaibli depuis le milieu des années 1980. Plusieurs explications ont été avancées afin de rendre compte de ce résultat empirique. Une piste éventuelle est le caractère non-linéaire ou asymétrique du lien prix du pétrole - PIB. On peut aussi invoquer la moindre dépendance en pétrole de l'activité économique ou la modification des mécanismes de formation des prix ou des salaires. Nous évaluons la pertinence de ces différentes interprétations à l'aide d'un modèle d'équilibre général inter temporel et stochastique appliqué à la France. Des préférences non-linéaires dotent le modèle d'asymétries dans la relation prix du pétrole - PIB qui ne vont pas dans le sens attendu, et l'introduction de coûts d'ajustements ne génère pas d'asymétries significatives. Selon le modèle, la réduction de l'intensité en produits pétroliers, observée depuis les années 1970 en France, entraîne une réduction de moitié de la réponse du PIB à un choc pétrolier. La désindexation des salaires et des prix atténue aussi la réponse du PIB, mais ne permet pas pour autant de rendre compte d'une absence de réaction significative de la croissance à une hausse du prix du pétrole. D'autres explications sont à envisager, prenant notamment en compte l'évolution des *causes* des hausses de prix du pétrole.

Mots-clés : modèle MEGIS, croissance du PIB, choc pétrolier.

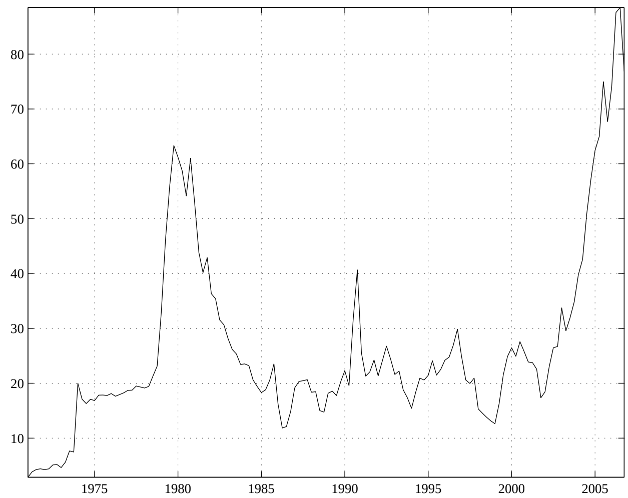
Classification JEL : C68, Q43.

Contents

1 Introduction

The study of oil-shock impacts is a research area that has already been largely explored by economists. The huge oil-price increases that occurred in 1974 and 1979 are often cited as the causes of the 70s recessions. Thus, since the beginning of the 80s, numerous researchers have tried to identify the channels through which such shocks impact economies. New focus on the subject has occurred since the notable crude oil price increases starting in 2002 (see figure 1).

Figure 1: *Price of crude oil barrel (Brent) in current euros*



Source: "Observatoire de l'Energie", Directorate-General for Energy and raw materials, French Ministry of Finance.

The oil-price formation is the first mechanism to model. When the economy under study is a small open one that does not produce oil, considering the oil price as exogenous seems the most sensible hypothesis. The oil price is not significantly influenced by national demand. The oil-price exogeneity has already been checked by empirical studies (see Jiménez-Rodriguez and Sanchez (2004) for evidence on different OECD countries). The exogeneity hypothesis is all the more reasonable when the considered period goes from the end of the second World War to the beginning or the middle of the 80s. More precisely, during the 70s, the nominal price was manipulated by the OPEC and its huge variations were often simultaneous to local military conflicts.

In numerous empirical studies, the oil price is introduced as an exogenous variable in regressions of GDP on itself. The oil price increases are found to have a negative influence on U.S. GDP (see for example Rotemberg and Woodford (1996)) and on U.S. GDP growth (see Hamilton (2005)). The relation is especially robust to different regression specifications and across countries when it is estimated on a period anterior to the middle 80s. On the other hand, it is more difficult to establish on later periods.

Studying the impact of a permanent increase in the nominal oil price on French GDP, Barlet and Crusson (2007) find a significant structural break most likely to be in 1983. Before this date, a 100% increase in the nominal oil price leads to a 5% decrease in the GDP level in the long run. After there is no significant link between oil price and GDP. We will also estimate an econometric model of the GDP-oil price relation in France. The latter model allows a transitory response of real oil price and GDP to a permanent increase in nominal oil price. We also observe the lack of significant GDP response to oil-price shocks after 1983.

Such a difficulty leads empirical research to consider non-linear or asymmetric representations of the GDP-oil price relation. The statistical intuitions for the necessity to depart from linear representations are easily understood when examining the oil price graph. Regarding the non-linear nature of the GDP-oil price relation, we can check that shocks observed from the mid 80s to 2002 have been of a much lower magnitude and persistence than those of the period 1971-1985. In short, big shocks are what matters. Another noticeable feature of the oil price evolution is the quasi absence of oil-price decreases from 1971 to the beginning of the 80s, whereas, from 1985 to 2002, there are numerous periods during which oil price decreases. Thus, if the GDP-oil price relation is strongly asymmetric, it seems natural not to find any significant relation on the subperiod beginning in the early 80s.

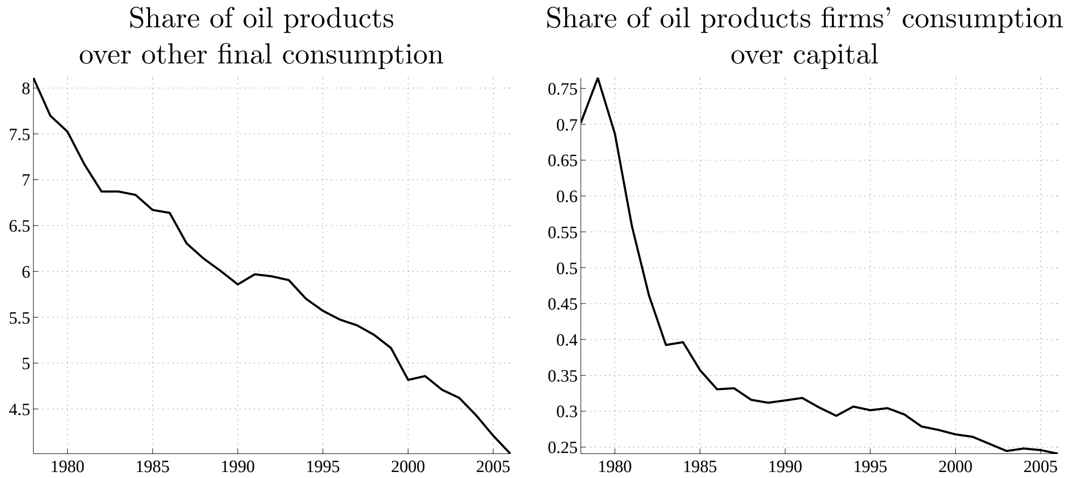
What could be the economic mechanisms underlying a non-linear GDP-oil price relation? The first to be quoted is the non linearity in preferences themselves. The second class of mechanisms, which is more intuitive, but is not studied in the paper, is the existence of threshold effects. For example, firms subject to fixed costs may remain profitable up to a certain oil-price level, above which they close down. If the heterogeneity in firms is sufficiently non equidistributed, non-linear aggregate effects are to be expected.

Diverse economic justifications could also be called to explain the difference between the effects of oil-price increases or decreases (asymmetries). The latter difference may come from heavy adjustment costs (more precisely costs of reallocation between capital and labor) or to downward rigidities on prices or wages.

We shall below refer to these two mechanisms, non-linear preferences and adjustment costs, as the "non-linear" mechanisms. However others mechanisms could also explain the break at the beginning of the 80s. Beyond the concept of disruption, this break could result from some progressive evolution. The year 1983 corresponds then to a critical point of a more profound structural evolution that had already begun during the 70s and that continued during and perhaps after the 80s. In other words, the response in the medium run to a shock depends on long-term decisions already taken, and, reversely, the shock itself may generate long-term decisions which affect the medium-term response of the economy in the future. Putty-clay models are particularly relevant to replicate the long-term response of the economy to permanent shocks on the real oil price, because they rationalize the evolution of the elasticity of substitution between factors.[1] Such an insight advocates for some changes in the production process of the economy. It could even be argued that not only the production process changed but that consumption preferences also evolved. Some proof of such structural changes can be seen through the evolution of oil intensities graphed in table 2.

[1]See Atkeson and Kehoe (1999), Gilchrist and Williams (2000), and Wei (2003), among others.

Figure 2: *Main oil intensities (in percentages).*



Source: INSEE annual National Accounts. Unit: 2000 year base volumes.

In France, several factors contributed to make the economy less oil-dependent. Aside from endogenous technical progress, the pro nuclear energy policy has been very strong since the 70s oil shocks.

Another possible structural change is to be considered: wage and price settings. How do prices and wages react to oil-price shocks? When oil price rises, it is expected that producers translate the increase from their costs to their prices. The first round effect is to raise inflation. Depending on the wage setting mechanism, such a rise in consumer prices lead to higher wage claims. If the latter are effective, firms' costs increase again and prices are evaluated again, affecting inflation in a second round. Then, an inflationist spiral is on the way, dragging dramatic effects on economic activity. The occurence of an inflationist spiral or not depends on the monetary policy conducted, and especially on its credibility. However, at the root of the phenomenon, there is the wage setting mechanism and the latter has changed a lot since the 70s.

To quantify the influence of non-linear preferences, adjustment costs on GDP-oil price relationship and to test whether lower oil dependency, desindexation of wages and prices can explain a reduction in the negative impacts of oil-price shocks, we use a Dynamic Stochastic General Equilibrium model (DSGE)[2]. DSGE models are fully micro-founded models. As such, they are very useful to assess the previous issues, because their structures give access to the structural parameters of the economy (even in the nominal sphere). Using DSGE to tackle the issue in the U.S. case has already been undertaken. The theoretical literature will be presented after the introduction.

[2]The stochastic dimension of the DSGE models is not extensively used in this study. The economic environment is uncertain, because we introduce oil price shocks. However, we limit our study to the non stochastic steady state and to first order deviations from it. We, thus, consider that the mere possibility of unforeseen oil price movements do not affect the agents' decisions. For example, we do not allow for precautionnary savings.

The modeled economy is a closed one, except for oil trade. The oil products used by firms and consumed by households are directly imported. The supply side of oil production is considered to be exogenous. Thus, the real price of oil is the main exogenous variable of the model.

Oil shocks impact the economy through two channels. On the one hand, households consume oil products that are directly imported. On the other hand, firms buy oil products to combine them with capital goods through a Constant Elasticity of Substitution (CES) aggregate. This aggregate, then, interacts with labor in a Cobb-Douglas production function.

The State is not included in the model. There is no tax, no public production. The only institutional feature incorporated in the economy is a Taylor rule which represents the reaction of a Central Bank guaranteeing the level of inflation.

Market structures feature monopolistic competition. Agents cannot set their prices instantaneously, rigidities à la Calvo are introduced in the goods' market as well as in the labor market. Real rigidities, such as habit formation and adjustment costs on investment, smooth the response of supply shocks and disentangle short-term and long-term oil products' price elasticities.

Note that the model, like most DSGE models, is best used to study short or medium-term responses to shocks, because it does not encompass endogenous structural changes. Nevertheless, we use it to quantify the long-term response to permanent real shocks to check whether reasonable effects are obtained.

To our knowledge, the use of a DSGE model meant to study the impact of oil shocks on the French economy had never been tried before. In the most recent French studies on the subject, the economy is modeled with VARs (or VECMs) or with standard macroeconometric models. Bouscharain and Ménard (2000) use both a VAR and a more structural model to quantify the impact of an oil-price increase on inflation and wages. They conclude that both models lead to similar results. Their evaluations are the following. When the oil price doubles, inflation (respectively wages) increases by 7% (resp. 5.5%) after two years, if the study is conducted between 1974 and 1986. Over the period 1985-1998, the increase in inflation (resp. wages) is only 2% (resp. 0.9%). They attribute the attenuation of the effects to wage desindexation after 1984. After 1980, oil-price shocks do not trigger any more the kind of inflationist spirals generated by price-wage loop mechanisms. The last simulations of the MÉSANGE model lead to a 1.4% decrease in GDP after two years (L'Angevin, Ouvrard, Serravalle, and Sillard (2005)).

This paper is organized as follows. First, we propose a survey of the way to incorporate oil products in DSGE models. Second, we present the long run of our model and its calibration. Sensitivity analysis of the long-term response to a doubling of the real oil price helps us to pin down parameters and realistically anchor the model. Static comparisons along the structural production parameters are conducted. They give insights about the magnitude of non-linear effects. In the third section, we introduce the dynamic aspects of the model and the rigidities that affect it. Its behavior is commented using impulse response functions. Asymmetry issues are considered. In the fourth section, we present the estimation of a VAR model, which is a guideline to the simulation of the DSGE model response to a transitory real oil price shock. Then we use the DSGE model to try to replicate the differences over periods in the dynamic response estimated in the previous VAR model and we highlight the importance of wage and price setting mechanisms.

2 Survey of "DSGE" macroeconomic models with oil products

2.1 The 90s debate: perfect or monopolistic competition?

What is the state of theoretical knowledge about incorporating oil products in structural macroeconomic models of DSGE type? The initial statement of this literature is the impossibility to reproduce the size of the 70s recessions if the only considered channel goes through an aggregate production function in a perfect competition environment. Actually, whether the oil shock is considered as an exogenous increase in oil price or as an exogenous break in supply, an upper-bound estimate of its effect on GDP is the share in GDP of oil-product spending, multiplied by the relative price increase in the first case. As is shown in empirical studies on US or French data, the recessions triggered by an oil-price increase are much deeper than what the share of oil spending in value added could predict.

Thus, after Kim and Lougani (1992), who do not take this difficulty into account, Rotemberg and Woodford (1996) propose a monopolistic competition model. Introducing monopolistic competition magnifies the oil-shock effect on real value added. In fact, monopolistic competition induces a further downward switch of the labor demand curve (which, also, explains the size of the real wage fall). Rotemberg and Woodford (1996) use a Capital-Labor-Energy-Materials (CLEM) production function, in which oil and intermediate consumptions are CES-combined[3]. Firms, which compete on a monopolistic market, apply a mark-up on their costs. This mark-up is not bound to be constant. Rotemberg and Woodford (1996) present different versions of their model, in which the mark-up varies differently according to the economic cycle. Two scenarios are considered: one with a procyclical mark-up and one with a contracyclical mark-up. The original idea of a procyclical mark-up dates back to Phelps and Winter (1970). The mark-up choice comes from a trade-off between taking advantage of usual customers, who have a low elasticity of demand, and gaining new ones, who have a high demand elasticity. It is found that, when the economic cycle is low, firms tend to enlarge their customer base, and, thus, reduce their mark-ups. The mark-up is procyclical. The contracyclical mark-up theory is founded on an implicit collusion argument. The mark-up can be interpreted as the result of strategic interactions between monopolistic firms. It is fixed in such a way that firms have no incentives to deviate, i.e. to fix a smaller price than those of their competitors. By deviating, a firm attracts the whole contemporaneous demand, but obtains no profit in the future. When the economic outlook is low, the relative value of staying in the collusion in the future over the deviation pay-off increases, and the equilibrium can sustain a higher mark-up. Among the four specifications that are simulated in Rotemberg and Woodford (1996) (perfect competition, monopolistic competition with constant mark-up, procyclical mark-up and contracyclical mark-up), the authors prefer the last one, which enable them to reproduce the size of the observed effects and the timing of the recession (the hardest time occurs in the second year after the shock).

[3]Both factor are combined through a Constant Elasticity of Substitution (CES) production function.

Finn (2000) puts in perspective the conclusion of Rotemberg and Woodford (1996), according to which monopolistic competition is a necessary structure to explain the economic effects of oil shocks. Finn introduces oil in the production function of her model via the capital utilization rate. As usual, capital market is cleared through the adjustment of the utilization rate. Moreover, in her model, the utilization rate also determines the energy intensity (ratio of oil over capital). The utilization rate is fixed such that the marginal productivity of capital is equal to the sum of utilization cost in energy and marginal depreciation in capital. Thus, an oil price increase induces a decrease in the utilization rate, which amplifies the direct negative income effect.

2.2 Monetary policy responses to oil-price shocks

The difficulty to reproduce satisfying quantitative response in Dynamic General Equilibrium models leads some analysts to even question the relevance of a direct significant real impact of oil price on economic activity. Bernanke, Gertler, and Watson (1997) observe that each 70s United States recession was preceded by both an oil-price shock and a concomitant monetary tightening. This makes it difficult to disentangle both effects empirically. Adding more structure than is usual in VAR models designed to evaluate the impact of oil price shocks, the authors conclude that monetary policy is the main cause to the 70s recessions.

The empirical strategy of the previous study has been largely criticized (see for example Hamilton and Herrera (2001)). In Carlstrom and Fuerst (2005), counterfactual experiments within a DSGE framework show that the Lucas critique is liable to seriously weaken the previous empirical results of the monetary tightening dominance. Leduc and Sill (2004) also use DSGE models to address the relative importance of monetary policy in US recessions. They find that less than the half of US recessions during the 70s is attributable to inadequate monetary policy. They also conclude that none of the commonly proposed monetary policies completely offset the recessionary consequences of oil price shocks.

The monetary policy channel can, thus, be considered as a significant amplifying mechanism of the oil-price shocks effects. This point leads numerous studies to try to characterize an optimal monetary policy. In de Fiore, Lombardo, and Stebunovs (2006), it is claimed that "optimal interest rates should be inertial and reacts strongly and positively to headline inflation and to output deviations from the non-stochastic steady state level, while it should react negatively to oil price inflation".

2.3 Open-economy and the causes of oil-prices hikes

The most recent studies on oil-price shock effects explore the influence of the causes of oil-price hikes in large scale DSGE models. In these papers, oil-price hikes are endogenously determined and caused by productivity shocks in trading partner countries. In line with New Open Economy Macroeconomics, they follow the seminal article of Backus and Crucini (2000).

Both Bebee and Hunt (2007) and Elekdag, Lalonde, Laxton, Muir, and Pesenti (2007) show that negative supply shocks in the OPEC's oil industry trigger long term recessions in the US and that positive productivity shocks in trading partners (such as Emerging Asia) have a long-term positive effect on the US GDP. Both perturbations are calibrated such that the real oil price evolution simulated in their models follows the one observed since 2003.

In Jacquinot, Mestre, and Spitzer (2006), the focus is on the euro zone GDP response to oil price shocks. Two symetric blocks, euro zone (EA) and the rest of the world (RoW), are modeled. Crude oil is extracted in a third block (OPEC zone), in which economic behaviors are extremely stylized. Crude oil is imported by the EA and the RoW, it is transformed in their energy sectors. The refined products are then used in each of the two other modeled sectors, which can be seen as the 'tradable good' and 'non-tradable good' sectors. Special attention is paid to the calibration of the model, performed with extensive use of input-output tables. The authors examine different shocks that could induce significant movements in oil prices. They find that "only oil supply shocks can lead to both oil prices increases and a significant drop in euro area GDP. Global demand shocks originating outside the euro area do increase oil prices but have limited impact on the euro area economy". Finally, in their model, restrictions in refining capacity induce oil price decrease.

3 Short presentation of our model

In this section, we explain our modeling choices, especially with regards to the introduction of oil products in a standard closed economy DSGE model. We do not detail, at this stage, the rigidities introduced in the model, which matter a lot for the dynamic properties (it is done in relevant sections below). The full formal presentation of the model (theoretical consistency, first order conditions' derivation, steady state solution) is reported in appendix A. It is noteworthy to stress that the model abstracts from any long-term growth consideration.

3.1 Households and aggregate labor

In the model, we make the assumption of the infinitely lived representative household, who maximizes its intertemporal utility. It gains utility from consumption and bears a cost increasing in the amount of hours worked ($V(h_t)$ where h_t is the amount of hours worked at time t). The marginal utility of consumption is decreasing in the level of consumption and the marginal disutility of work is increasing in the number of hours worked. These two components are chosen to be additively separable, meaning that the level of consumption does not affect the marginal disutility of work directly (and inversely).

The consumption basket is a CES aggregate of oil products ($e_{c,t}$) and other consumption goods directly produced in the economy (c_t). The elasticity of substitution between both components is denoted θ_U and the preference for non-oil products within the CES aggregate is α_U. The utility derived from consumption also directly depends on past consumption. It exhibits habit formation. The household, in some sense, values current consumption relatively to past cosnumption.

Finally, we can write in formal terms the utility in consumption as $U(c_t - b_c c_{t-1}, e_{c,t} - b_e e_{c,t-1})$ where b_c and b_e are the habit formation parameters.

The household is the owner of the capital stock, which partially depreciates. It takes the decision to invest, which is prone to adjustment costs. It rents the capital stock to firms during the following period after investment at the real rate r_t.

The household has access to complete financial markets. Because they are complete, we only need to model one single asset, government nominal bonds. The interest rate on bonds is controlled by the Central Bank of the economy. As capital owner and only private agent on financial markets, the household owns firms and is entitled to theirs profits.

The labor market is modeled as a monopolistic one. This choice is far from the current state-of-art labor market models, such as search models. It does not encompass frictional unemployment. However, there are some ”voluntary” unemployment behaviors, coming from the fact that labor supply is elastic. There is also, in some sense, ”Keynesian” unemployment. Because the household internalizes the labor demand that it faces, it choses his/her wage such that it is higher than the perfectly competitive one. As a consequence, the number of hours is less than in the perfect competition case. Within the monopolistic framework, wages are set à la Calvo[4]. This wage setting implies nominal rigidities.

3.2 Production

To implement a monopolistic structure on the production side of the economy, we need to introduce two types of firms. Some competitive firms aggregate the different varieties of the monopolistic firms. The former ones produce a homogenous final good which can be used by households as a final consumption good or investment good. The production function of the monopolistic firms combines capital, energy products and labor. It is defined formally as:

$$F\left(G\left(k_{t-1}, e_t\right), n_t\right) \tag{1}$$

where $G(\cdot)$ is a CES production function, $F(\cdot)$ a Cobb-Douglas production function[5], k_{t-1} the capital input (the capital stock is decided one period in advance), e_t the oil product input, n_t the aggregated labor input. It is noteworthy that we follow Rotemberg and Woodford (1996) and do not allow the multiplier effect à la Finn (2000) transiting through variable capital utilization.

As in the labor market, the firms decision dynamics come from the intertemporal price setting à la Calvo.

[4]A full description of the Calvo mechanism can be found in section 6.2. In formal terms it can be read in appendix A.

[5]Both production functions are increasing and concave with respect to each of theirs arguments

3.3 Market equilibrium

Market equilibrium is standard. However, we emphasize two fundamental aspects. The first and more technical one, is that aggregation must take the heterogeneity of price and wage setters into account. Detailed derivation can be found in annex A. The second one boils down to the fact that international trade is balanced. In the economy, there is no home production of oil products. Every oil product is imported. As we rule out international financial exchanges or current account imbalances, oil products imports are financed by homogenous good exports. Regarding this aspect, we follow Finn (2000). The real GDP accounting identity becomes:

$$c_t + p_{e,t}e_{c,t} + x_t = d_t - p_{e,t}e_t = GDP_t$$

where $p_{e,t}$ is the real oil price, x_t investment, d_t total production.

4 The long run of the model

We now turn to the description of the mechanisms explaining the long term response of the economy to a permanent increase of oil price. As a first step, we need to calibrate the parameters that matter for such response. We call them the "core" parameters. This group excludes some parameters that drive the deviations of the model around its steady state, such as nominal parameters (Taylor rule or Calvo parameters) as well as certain real-rigidity parameters such as those entering the adjustment cost function.

4.1 Calibration

Within the set of "core" parameters, some are directly taken from the DSGE literature, others are pinned down to match steady state macroeconomic ratios[6]. Special attention is paid to the parameters relevant to the introduction of oil products in the model. They are chosen within estimated ranges, taken from microeconometric or sectoral studies. With such parameters, the steady state of the model must reproduce oil intensities as they were observed before the 80s. In addition, the model long-term deviations to a permanent increase in oil price must correspond to those estimated before the 80s.

4.1.1 Non-oil parameters' calibration

The parameters[7] that can be found in table 1 are usual in the DSGE literature. We use Hairault and Portier (1993) as a benchmark on French data.

[6] The steady state macroeconomic ratios are taken from the annual 2000 base year National Accounts of INSEE.

[7] The detailled description of the functional forms, in which the parameters enter, can be found in annex B (subsection B.1).

Table 1: *Usual parameters' calibration.*

Parameter	Symbol	value
Discount factor	β	0.986
Inverse of intertemporal elasticity of substitution	σ_U	1
Elasticity of work disutility	σ_V	-1
Depreciation rate	δ	0.025
Real interest rate	r_{ss}	0.039
Mark-up rate on the labor market	μ_w	1.15
Mark-up rate on the good market	μ_w	1.2
Cobb-Douglas parameter	α_F	0.32
Weight of work disutility	α_V	10

A unitary intertemporal elasticity of substitution implies that the utility function is logarithmic.[8] The disutility costs of working are set quadratic. The steady state real interest rate comes directly from the choice of the discount factor and the depreciation rate. Actually, the steady state Euler relation[9] is: $1 = \beta(1 + r_{ss} - \delta)$. The mark-up rate on the labor market (resp. on the good market) implies an elasticity of substitution between different labor types θ_w (resp. good varieties θ_w) equal to 7.65 (resp. 6).

The Cobb-Douglas parameter is linked to the steady-state share of total wages in production through the following relation:

$$1 - \alpha_F = \mu_P \frac{w_{ss} h_{ss}}{d_{ss}}$$

Over the period, the mean share of labor income in value added is 0.58.

We set α_V such that working hours are normalized to 1 and the representative household works approximately one third of its time.

4.1.2 Oil parameters' calibration

To our knowledge, there is no microeconometrics studies on French panel data estimating the elasticity of substitution between final consumption of oil products and other products or the elasticity of substitution between capital and oil products used by firms. Using French data on firms and a translog specification for the production function, Chakir, Bousquet, and Ladoux (2002) estimate the elasticity of substitution between different energy factors to be 0.3. There are more empirical studies at sectoral or economy-wide level. Using aggregate quarterly data over the period 1978-2005, Barlet and Boissinot (2005) estimate the price elasticity of total energy consumption between 0.1 and 0.15. Berthelemy, Devezeaux de Lavergne, and Ladoux

[8] Such a choice can be criticized as this elasticity is critical to the degree of strategic complementary within the model (cf. chapter 2 in Woodford (2003)). However, it is dictated by the fact that it is the only utility function that enables both additive separability and balanced growth in the model (cf. Alvarez and Stockey (1998)). The model compatibility with balanced growth path is introduced in the scope of Bayesian estimation.

[9]See 54 in subsection A.6.

(1986) conduct an estimation on five different industries over the period 1959-1982. The authors conclude that energy and capital are complementary in all industries except in the agro industry.

In all these studies, it is shown that short-term and long-term elasticities are significantly different. Here, the calibration of θ_U and θ_G correspond to long-term elasticities. Confronting the previous studies, we take $\theta_U = 0.15$ and $\theta_G = 0.5$ as our benchmark calibration. Once these elasticities are pinned down, we use the mean real oil price[10] over 1971-2005 and oil intensities (see table 2) to choose the preference parameters for oil in each CES aggregate[11].

Table 2: *The main energy ratios (in percentage).*

$\frac{e_{c,ss}}{c_{ss}}$			$\frac{e_{ss}}{k_{ss}}$		
1978-1983	1984-2004	1978-2004	1978-1983	1984-2004	1978-2004
7.37	5.64	6.02	0.59	0.30	0.37

Source: INSEE annual National Accounts. Unit: 2000 year base volumes.

Because mean oil intensities are significantly different before and after 1983, two different benchmark calibrations are considered: the first-subperiod calibration (particularly relevant from 1978-1983) and the second-subperiod calibration (1984-2004). As a benchmark, we compute α_U and α_G under the assumption that there is as much habit formation in both consumption types. The values obtained are very close to unity. We checked their sensitivities to the calibration of the mean real oil price ($p_{e,ss}$). They are quite robust. The most critical parameters are the elasticities. They must be unreasonably high to drive α_U or α_G away from unity [12]. The same problem arises in most studies (cf. Dhawan and Jeske (2006)).

The long-term calibration of the model is fully specified. To check wether it is relevant, we simulate for different values of the elasticities (θ_U and θ_G) the deviation of the steady state when the real oil price doubles. This exercise is carried out, the model being calibrated according to the first-subperiod energy intensity. According to the results in figure 3, long-term recessions are less strong when the elasticities increase. Factors or products being more substitutable, the economy adapts in a more efficient way. The reaction is not sensitivite to the elasticity in the consumers' utility (θ_U), whereas it is to the elasticity in the production function (θ_G). When production factors are highly complementary, i.e. when $\theta_G < 0.25$, the deviation falls

[10] Its value is $p_{E,ss} = 1.2$. The mean real oil price chosen is the Oil Products Production Price index divided by the GDP deflator (see figure 23 for its evolution). This choice is not totally rigorous, because it is not the relative price of the volumes used in oil intensities computation. Calibration does not significantly change when this price is updated.

[11] The relevant steady state relationships are:

$$\alpha_U = \left(p_{e,ss} \left(\frac{e_{c,ss}}{c_{ss}} \frac{1-b_e}{1-b_c} \right)^{1/\theta_U} \frac{1-\beta b_c}{1-\beta b_e} + 1 \right)^{-1}$$

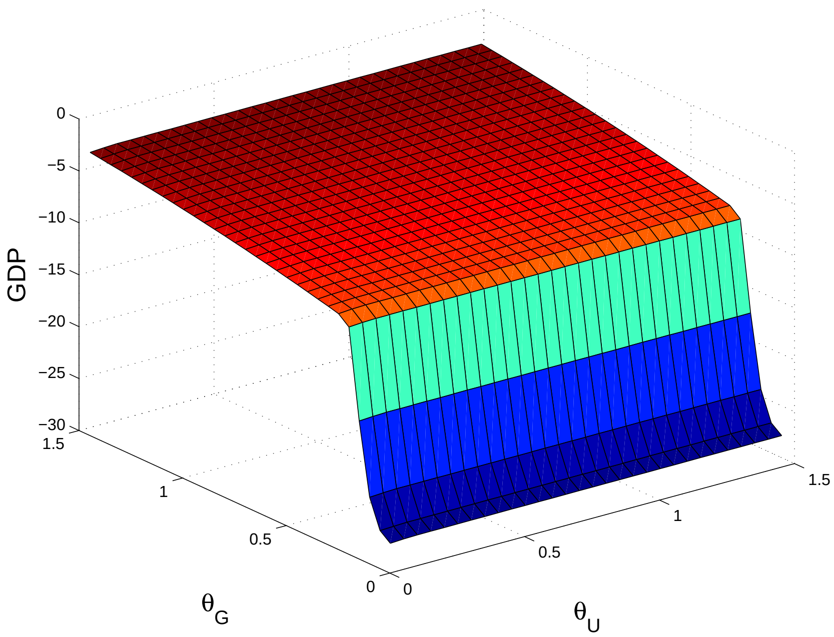
$$\alpha_G = \left(\frac{p_{e,ss}}{r_{ss}} \left(\frac{e_{ss}}{k_{ss}} \right)^{1/\theta_G} + 1 \right)^{-1}$$

[12] The elasticities must be over 0.65 to drive the αs below 0.95.

dramatically. When oil products and capital are just complementary ($0.25 < \theta_G < 1$), the amplitude of the recession is comprised between -8% and -4%. With such responses, it seems reasonable to keep the benchmark elasticities, which imply a long-term deviation up to -6%. Such a deviation is one point higher than what Barlet and Crusson (2007) estimate. A reason for this difference may come from the type of shocks considered. In Barlet and Crusson (2007), it is a doubling of the nominal oil price. Because of taxation, there is an incomplete pass-through between the nominal oil price and the real producer price of oil products in France.

Updating the energy ratios to simulate the long-term response on the second subperiod leads to a reduction by half of the GDP deviation (see figure 3). For the benchmark elasticities, the recession is, then, around -3%.

Figure 3: *Long-term GDP deviation (in percentage) for different elasticities (in level) - Oil intensity calibrated on the first subperiod.*



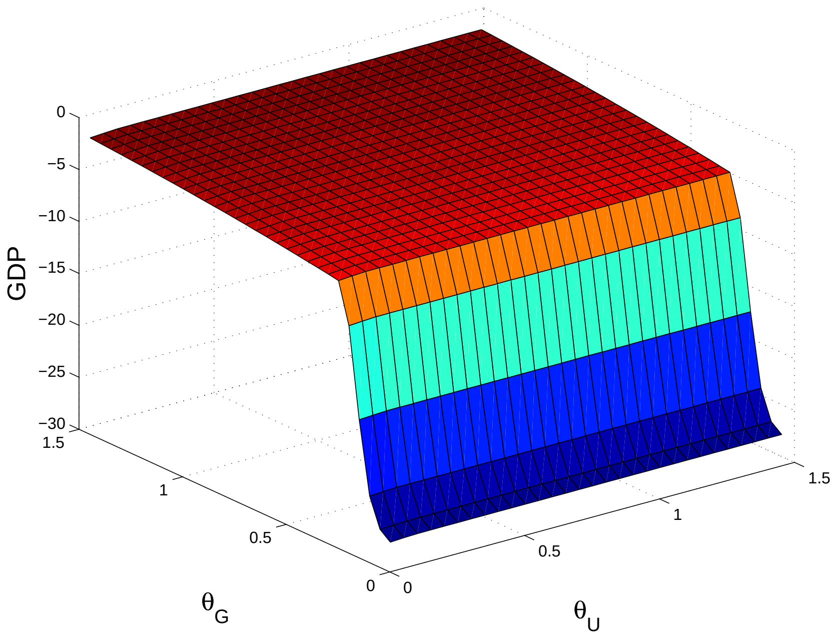
θ_U is the elasticity of substitution between final consumption of oil products and other products. θ_G is the elasticity of substitution between capital and oil products used by firms.

4.2 Economic mechanisms underlying the long-term response

When oil price increases[13], oil intensities decrease, as can be seen on the first two graphs of figure 5 below. Firms and households substitute away from oil products. As the long-run real marginal cost is pegged by the mark-up on the good market, other equilibrium factor prices

[13]The following discussion relies on the derivation of the non-stochastic steady state of the model presented in details in annex C.1.

Figure 4: *Long term GDP deviation (in percentage) for different elasticities (in level) - Oil intensity calibrated on the second subperiod.*



must decrease. The real rental rate is already determined by the discount factor and the rate of capital depreciation. Thus, in the long run, the higher oil price translates into a real wage decrease. To gain some complementary intuition on the production side response, the oil shock can be thought of as an adverse productivity shock. The production function can be rewritten[14] as:

$$F\left(G\left(k,e\right),h\right)=a(p_e)F\left(k,h\right)$$

where $a(p_e)$ represents the oil price shock on technology. The higher oil price reduces the marginal product on labor and, as a consequence, tends to reduce the real wage. In addition to the substitution effect from oil products to capital, there is a substitution effect from the capital - oil aggregate to labor. Moreover, each working hour demanded requires less capital. This last substitution effect arises because capital and oil products are complementary and less substitutable than the capital - oil products aggregate and labor.

To gain some further intuition on the production-side response, we can show[15] that the steady state value of GDP can be expressed as a function of capital, labor and the real oil price. It does not depend on oil products any more:

$$GDP=A(p_e)F\left(k,h\right)$$

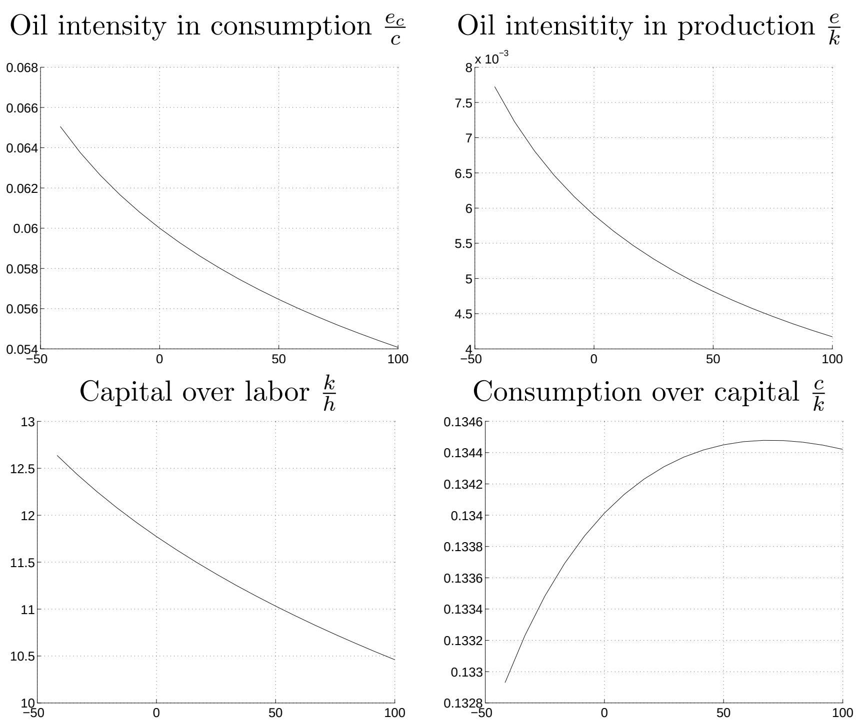
where $A(p_e)$ decreases in p_e. This proves that, despite the positive external demand shock linked to a potential increase in the oil burden, the oil shock has the same negative wealth effect as a negative technology shock would have.

[14]The details of the modifications are in appendix C.1
[15]The equivalence is derived in appendix C.1

How does the representative household adapt to the oil shock? To accommodate to the negative technology shock, the household chooses between consuming less or working more. The outcome of such a trade-off depends critically on the relative elasticity of the utility of consumption and the disutility of working. In the standard calibration presented here, a doubling of the real oil price leads to a 10% decrease in consumption and to a 0.2% percent increase in labor. It means that keeping labor supply at its pre shock level would imply a reduction in consumption that overwhelms the constant disutility of working, even if it is attenuated by the reduction in wages. It also means that trying to keep consumption at its pre shock level would result in an excessive disutility of working too.

As has been done for the comments relating to the supply side response, the household program can be simplified internalizing the oil consumption decision and the implied substitution effect. It can be shown[16] that a reduced household program features an exogenous term in utility depending on the oil price and a new budgetary constraint in which the price of consumption (other than oil consumption) is affected by the real oil price. The oil shock can thus be interpreted by the household as the combination of an adverse utility shock and a price shock, affecting directly the non-oil consumption price.

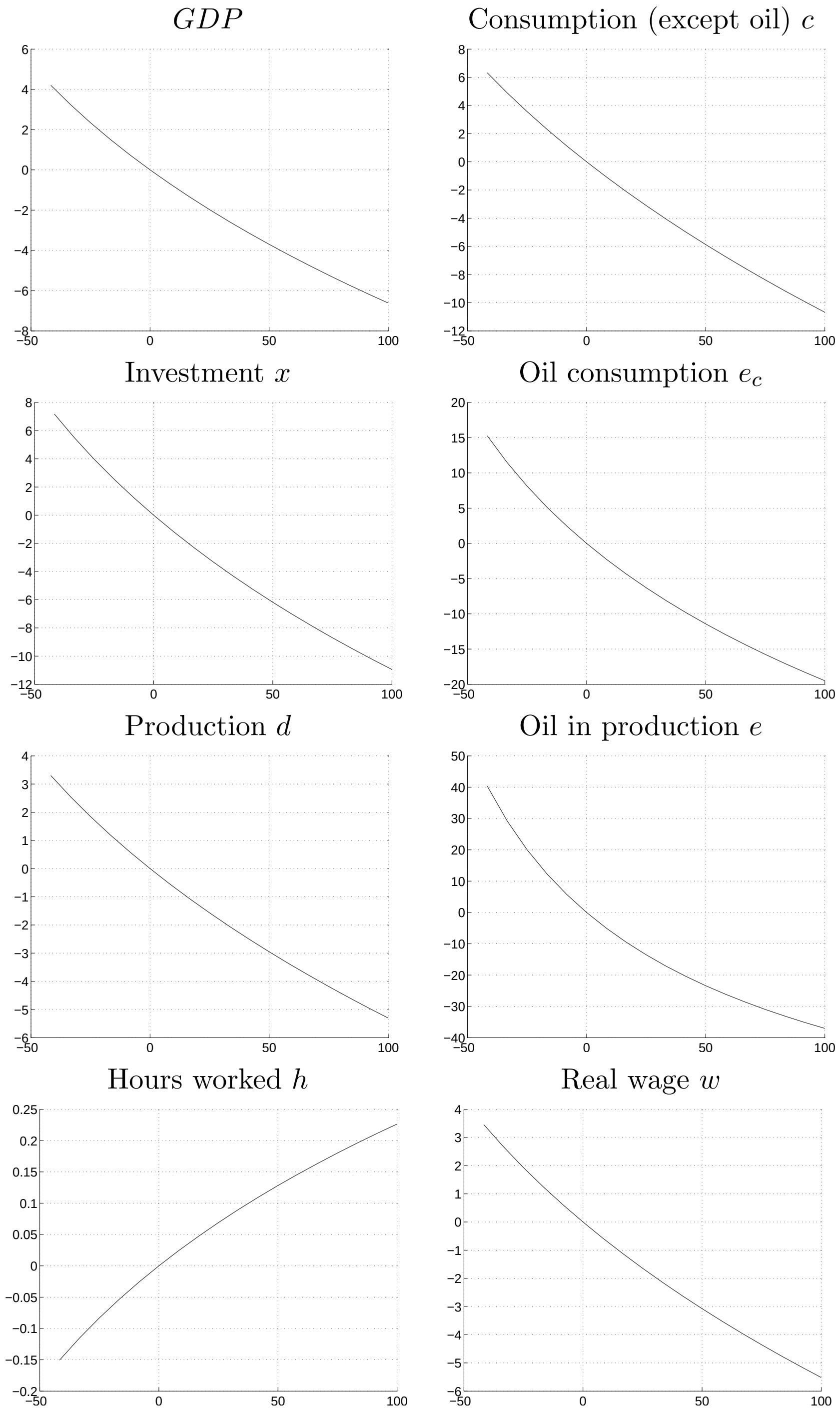
Figure 5: *Long term reactions of macroeconomic ratios' (in level) to real oil price variations (in percentage).*



Reading the graphs: when the price variation is zero, macroeconomic ratios correspond to the baseline claibration. For example, the oil intensity in production is 0.6%. When the real oil price increases by 50%, the oil intensity in production is lower than 0.5%.

[16]The details of the modifications are in annex C.2

Figure 6: *Long term reactions to real oil price variations (in percentage).*



Reading the graphs: percentage deviations are from the baseline calibration. Thus, the point $(0, 0)$ *belongs to each curve. A 50% increase in the real oil price generates a 4% decrease in real GDP.*

4.3 Sensitivity analysis

The orders of magnitude of the preceding static comparison are high, compared to standard estimations of permanent effects of oil shocks on French GDP. It has already been mentioned that such a difference between the simulated and estimated response might be partially explained by the type of oil-price shock considered. Nevertheless, it seems reasonable to think that such deviations necessarily imply internal and external disequilibria. The internal disequilibrium would trigger structural changes (production functions, market structures or/and anticipations). The demand prices for oil would, then, been revised downwards. The oil producing countries could not sustain such high supply prices in the long run, they should contract at some time.

The preceding remarks on implied non-rationalized disequilibria raise the following natural question. To what extent could structural parameters variations lead to an economic recovery? To answer this question, the first stage consists in simulating different steady states when a unique parameter varies (the calibration of the other parameters remaining the standard one). We consider variations in the elasticity of substituition between oil products and capital in the production function (θ_G), in the preference parameter on oil (α_G) and in the mark-up in the product market (μ_P). Then, we compare the implied deviations to the preceding ones (when only $p_{e,ss}$ varies)[17].

One of the most natural parameters to study is the elasticity of substitution between capital and oil products (θ_G). The more substitutable the two factors, the higher GDP. This relation is far from being linear (cf. figure 18 in annex D). The variations in GDP are particularly strong when the factors are very complementary. A 20% increase in the elasticity of substitution between the two factors would be sufficient to reverse the previous long-term negative effect of oil shock on GDP[18]. Note that it does not even require that factors become substitutable ($\theta_G > 1$). If one interprets the energy ratios observed from 1984 to 2005 as the long-term response to variations in the elasticity of substitution θ_G (keeping α_G constant), then, to match the cut by half in the energy intensity, factors should be more substitutable by less than 20%. Note that this is also the deviation needed to offset a recession triggered by the doubling of the oil price.

The figures 19 and 20 in appendix D show the results for the preference parameter of the oil products-intermediate consumption CES aggregate (α_G). Notice that the latter parameter is far less easy to manipulate than θ_G[19]. An increase in α_G results in a reduction in the energy intensity. To produce the same quantity of final product, oil products contribute relatively less than capital. The effect on GDP is quite notable. Increasing α_G by 0.1 (when it is close to 1) results in an increase in GDP greater than 25%. This could counterbalance the negative effect of oil shock.

[17]Note that the analysis does not take into account the effects of structural change on real oil prices, which is standard in small open economy analysis.

[18]By simulating the impact of changes in θ_G with $p_{e,ss} = 1.2$, we perform a standard static comparison. In the perspective of evaluating the extent to which structural changes may offset the negative impact of the oil price doubling , however, we make a linear approximation of the model deviations. In other words, we implicitly assume that the deviation by, say, a 10% increase in θ_G has the same effect on GDP whether the oil price is 1.2 or 2.4. To check the plausibility of such an approximation, we performed the sensitivity analysis to θ_G when the price is 2.4. We find that the assumption is quite strong as, in this simulation, only a 10% increase in θ_G offsets the oil price recession.

[19]This is due to the fact that, in the standard calibration, α_G is very close to 1.

The last proposed comparison concerns the competitive structure (variations in the mark-up rate in the product market μ_P). As can be checked in figure 21 in annex D, the degree of competition on the product market has no influence on the energy ratios. We find the classical conclusion which applies to the long run of the model. The closer the model to perfect competition, the more efficiently ressources are used. Orders of magnitude are also huge: reducing the mark-up from 1.2 to 1.0 makes GDP increase by more than 20%.

The results of the static comparisons show that the steady state is very sensitive to the parameters (especially to the elasticity of substitution between oil products and capital) and as a consequence to the calibration. Reasonable variations of these parameters induce GDP deviations that could offset recessions caused by oil price doubling. This result is in sharp contrast with the fact that the GDP response to an oil price hike has a low sensitivity along all parameters, especially along the same elasticity of substitution.

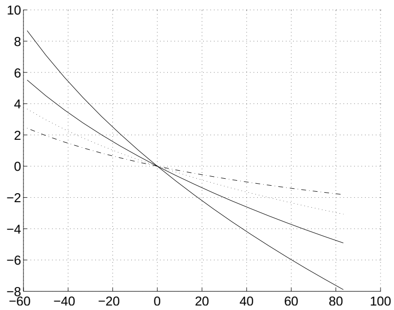
4.4 Nonlinearities?

In this subsection, the first explanation of the empirical result, stating the absence of GDP response to an oil price shock, is addressed. Do nonlinearities in preferences imply nonlinearities in the GDP - oil price relation? Long-term simulations contain all the relevant mechanisms to answer this issue. Let us examine figure 7. Each curve corresponds to the GDP response to some permanent oil price shocks using different sets of model calibration. From the curve exhibiting the largest deviations to the one exhibiting the smallest, the intertemporal elasticity of substitution, σ_U decreases regularly from 2 to 0.5, which is a reasonable range (cf. Hairault and Portier (1993)). Thus, the curve corresponding to the second largest deviation is simulated using the standard calibration (logarithmic utility). As can be seen figure 7, nonlinearities in preferences seem to induce only moderate non linearities in GDP - oil price relation, especially when the real oil price deviates within one standard deviation[20]. Considering large positive deviations from the mean real oil price, nonlinearities attenuate the GDP response. In the standard calibration, the GDP response to a 100% increase in oil price is only 80% greater than the one to a 50% increase. Symmetrically, considering large negative deviations, nonlinearities accentuate the GDP response. The possibility that nonlinearities in the GDP - oil price relation generated by non-linear preferences explain the estimated result is, thus, ambiguous.

Nonlinearities generated by non-linear preferences imply conterfactual asymmetries between an increase and a decrease in the real oil price. For example, the amplitude of the GDP response to a 25% decrease in real oil price is 30% greater than the amplitude of the response to a 25% increase. Do asymmetries generated by adjustment costs help to explain the estimated result? To answer this question, the relevant simulations to perform go along the dynamic path from one steady state to another.

[20]This result could have been expected. Constant elasticity functions are typically chosen because they can be well approximated at the first order, that is to say by linear forms. The dimension in which the model implies non linear relations is to be sought in links between parameters and variables, as testify the previous static comparisons.

Figure 7: *Long-term GDP reactions (in percentage) to real oil price variations (in percentage).*



Legend: the solid line corresponds to the model with $\sigma_U = 0.5$, the dashed one with $\sigma_U = 1$, the dotted line with $\sigma_U = 1.5$, the dash-dotted one with $\sigma_U = 2$.

5 Dynamic responses with real rigidities

In this section, we focus on real rigidities, i.e. habit formation and adjustment costs. They do not affect the steady state equilibrium, but the dynamics of the economy. First, we motivate their introduction and examine their consequences on impulse response functions. Then, we explore the asymmetries that they induce in the dynamic response to a permanent change in the real oil price.

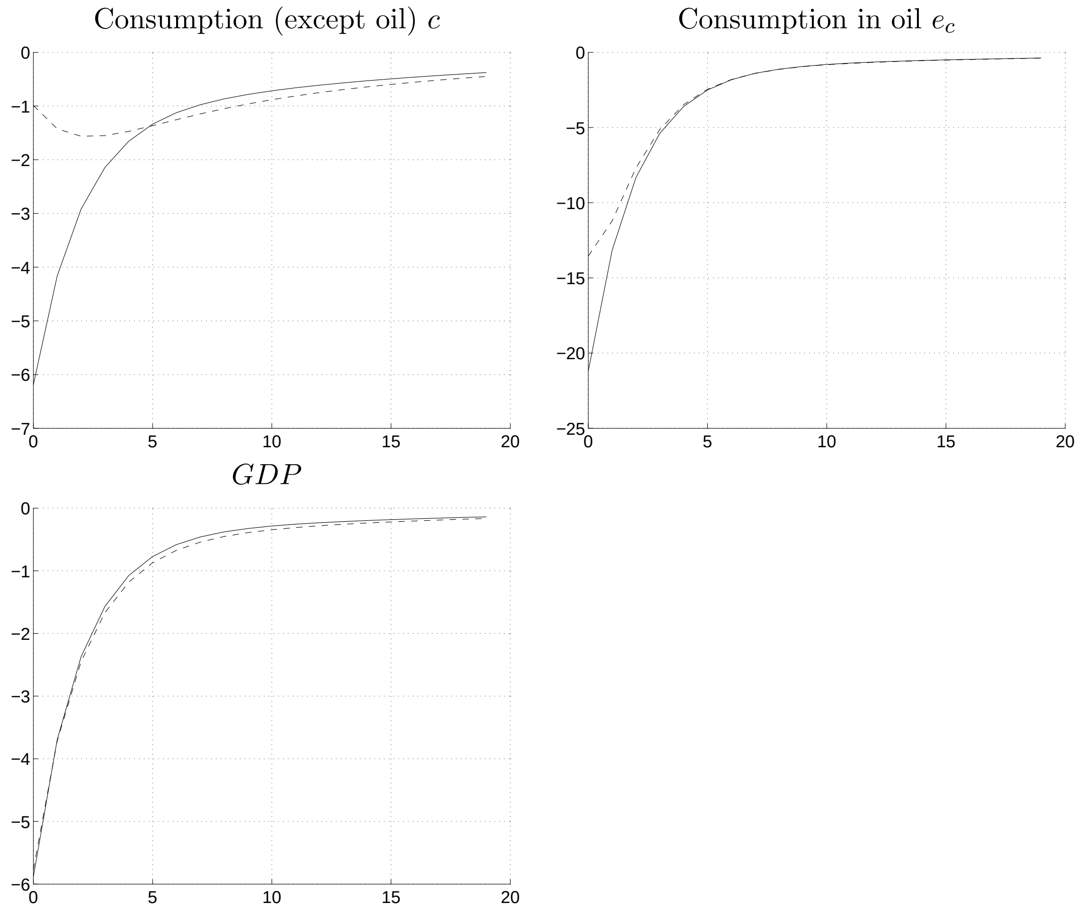
5.1 Motivations for introducing real rigidities

5.1.1 Habit formation

As already mentioned, in a model with habit formation, the representative household values past consumption. Then, he/she chooses current consumption in comparison with its past level. In some sense, the household cares on the current level of consumption, but also on its growth rate. The usual calibration of such a habit formation parameter b_c is above 0.5 and below 0.9 (this range covers also what has been estimated in various studies; see, for example, Christiano, Boldrin, and Fisher (2001) and Smets and Wouters (2003)). In our standard calibration, b_c is pinned down to 0.7. This calibration implies that the household never accepts its current level of consumption to be less than 70% of its past level. The direct effect of the habit formation mechanism is to delay the consumption response to standard shocks. This delay may spread to other variables such as GDP. Habit formation is also introduced in the final consumption of oil products. It also induces some delay in the oil products consumption. Such real rigidities on oil-products consumption lead to differences between short-term and long-term price elasticities. The short-term elasticity is smaller than the long-term one, satisfying the empirical estimates already quoted in subsection 4.1.2. In some sense, habit formation helps one to model the fact that it takes time for the household to switch from one energy source to another because he/she first needs to renew his/her equipment, which is locked to one energy source. The calibration of b_e is arbitrarily set to 0.2.

Figure 8 presents the impulse response functions of the model to an AR1 autoregressive real oil price shock[21]. The delay implied by habit formation generates U-shaped consumption response. Consumption decreases relatively less in the case of habit formation than without. This confirms that short-term elasticities are smaller. Finally, GDP response is not notably affected by the introduction of habit formation. However, habit formation generates more persistence in GDP.

Figure 8: *Impulse response functions (in percentage) to an autoregressive real oil-price shock.*



Reading the graphs: the solid curve corresponds to the model without habit formation, the dashed one to the model with habit formation. At t=0, the real oil price is doubled. The first endogenous lag of the AR1 real oil-price process has a coefficient equal to 0.6.

5.1.2 Adjustment costs

There exists several ways to model the fact that it is costly for firms to adjust factors. Among the costs incurred, one can think of searching costs to hire new workers, firing costs, fixed

[21]The model is simulated with the DYNARE matlab toolbox (for further precisions, see Collard (2003)). Impulse response functions are approximated at the first order. Thus, there is no scale effect due to the amplitude of the shock.

costs in new investment decisions and, more generally, information costs to evaluate the new environment triggered by the shocks. In factor hoarding models, information costs prevent firms from picking up up-to-date information. They choose their factors' combination before observing current shocks and can change it only marginally after observing them. Models with quadratic costs on factors' variations also focus the rigidities on firms' decision. In our model, the factor adjustment costs are not directly internalized in firms decision, but come from adjustment costs in household investment decisions[22]. Only a proportion of the total amount invested adds up to the capital stock[23]. This proportion is decreasing with the absolute difference between the current investment growth rate and the steady state one[24]. Adjustment costs imply a delay in the investment response to shocks. This delay spreads to capital and, thus, alters firms' adjustment capacity.

The impulse response functions of the adjustment-cost model to a persistent real oil price shock are drawn in figure 9. The delay implied by investment adjustment costs generates U-shaped investment response. Compared to the model without rigidities, the amplitude of the investment response is divided by 5 at the impact. Overall, the response is more persistent in the model with investment adjustment costs. As a direct consequence, capital deviation is attenuated, despite the fact that part of the investment is not turned into capital. GDP response is strongly affected relative to the effect implied by habit formation. Finally, the response of hours worked changes sign. In the model without rigidities, hours worked decrease with a transitory real oil-price hike. The intertemporal relative value of working make it more profitable for the household to wait before working. In the model with adjustment costs, because capital stays at a high level, the household needs to produce more to finance higher energy burden and adjustment costs.

5.2 Asymmetries?

Because adjustment costs are incurred both when the oil price increases or decreases, they may cause notable asymmetries. The dynamic responses to permanent changes in real oil price are drawn in figure 10. Asymmetries essentially come from nonlinearities in preference (for more precisions, see subsection 4.4). When the response to the decrease in real oil price is rescaled to offset the long-term asymmetries due to the non linearities in preferences, it is confounded with the response to an increase in real oil price.

At this stage, it can be stated that, within our model, nonlinearities and adjustment cost fail to explain the absence of significant link between GDP and oil price estimated after the mid 80s. The "non-linear" explanations are to be disregarded[25]. In the following section, other explanations are evaluated, such as lower oil dependency, structural change in the production function and desindexation of wages.

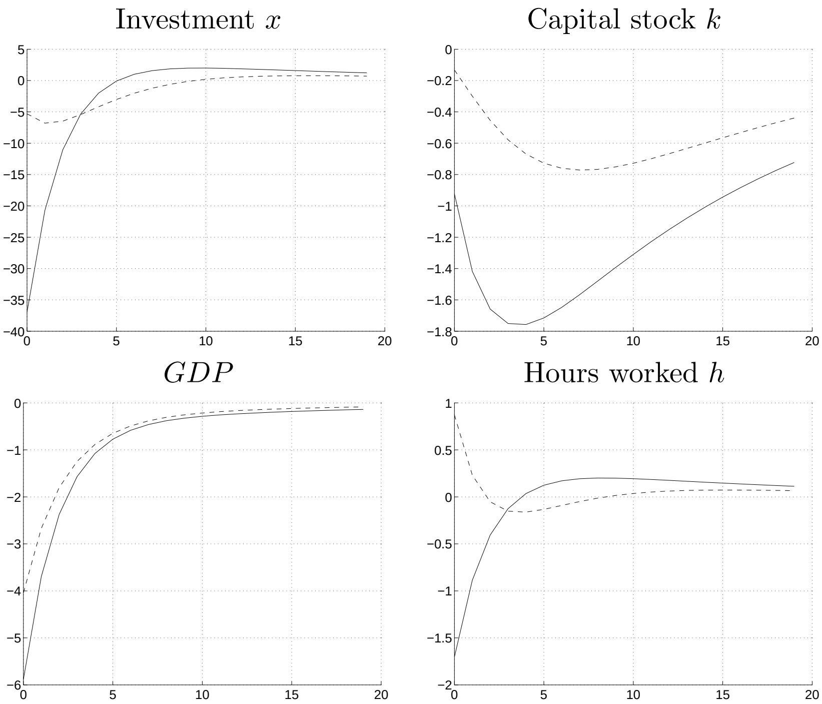
[22]This choice is conditioned by the nominal rigidities' choice. Modeling both prices à la Calvo and direct firms adjustment costs make the intertemporal pricing decision less tractable.

[23]For the detailed law of capital accumulation, see 4 in appendix A.1

[24]The cost function is quadratic. For more details, see the definition 68 in appendix B.1

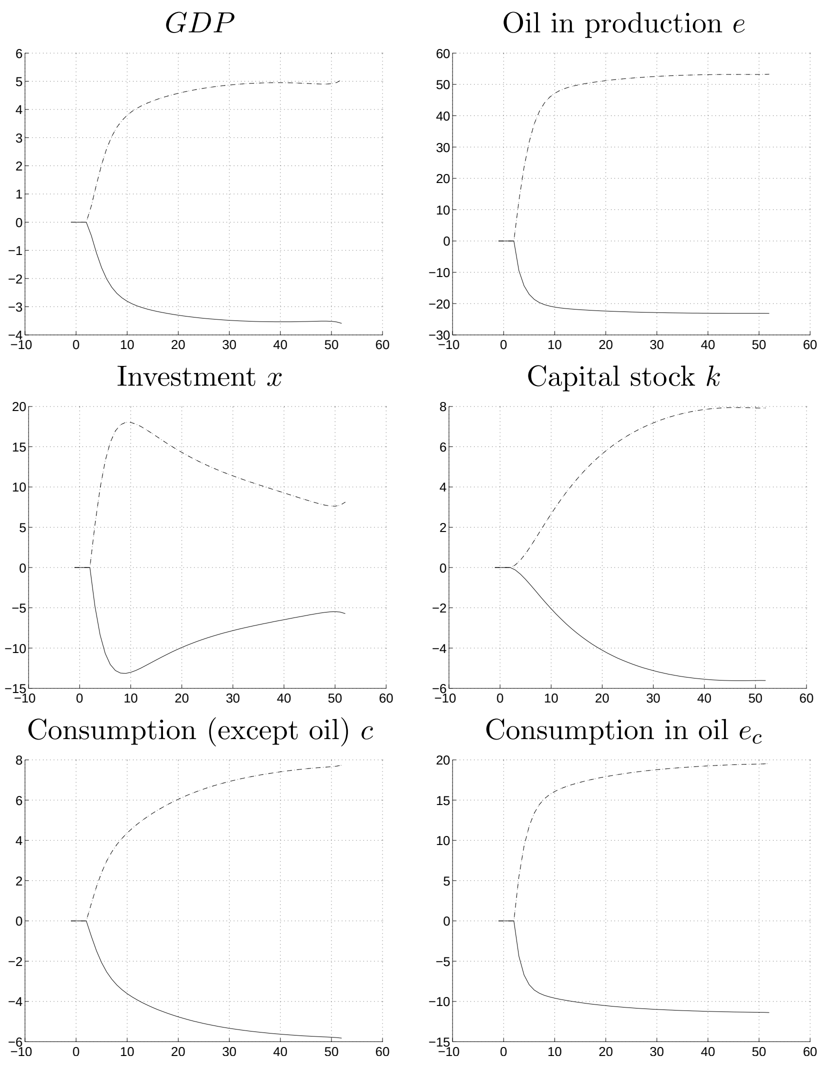
[25]This is consistent with the empirical results of Barlet and Crusson (2007). There is a significant break in the GDP - oil price relation even if the specification of the econometric model explicitly takes into account the possibility of asymmetric or non-linear relations.

Figure 9: *Impulse response functions (in percentage) to an autoregressive real oil-price shock.*



Reading the graphs: the solid curve corresponds to the model without rigidities, the dashed one to the model including investment adjustment costs. At t=0, the real oil price is doubled. The first endogenous lag of the AR1 real oil-price process has a coefficient equal to 0.6.

Figure 10: *Dynamic responses to a permanent real oil-price shock (in percentage).*



Legend: the solid curve corresponds to permanent real oil-price increase, the dashed one to the permanent decrease.

6 Dynamic responses to a transitory real oil-price shock with real and nominal rigidities

In subsection 4.1.2, a first evaluation of the lower oil dependency hypothesis has been made. Updating the oil intensities from the first sub-period to the second one, which means reducing them by half, reduces, all other parameters kept identical, the long-term response to oil price hikes by half. Thus, the model hardly explain the absence of a long-term effect of permanent real oil-price increases, as estimated after the mid 80s. Furthermore, figure 3 shows that structural changes in the production function do not affect the long-term GDP response to such an extent that it could become a plausible explanation for the same empirical fact. Even considering that oil products and capital are very substitutable still implies a significant negative impact on GDP (-2%).

Nevertheless, we may expect another story when the type of shock considered is transitory. A lower oil dependency or strictural change may flatten the GDP reaction to a transitory real oil price shock. This approach seems all the more relevant that non-modeled mechanisms bring back the real oil price to its pre-shock level, implying that the implmented shock should be transitory. Moreover, reaction to transitory shocks highlights the importance of the interaction between the real sphere and the nominal one and, thus, underlines wage and price setting characteristics, such as indexation.

To tackle with this new direction, we first perform an estimation of transitory real oil-price shock effects. Then, the calibration of the nominal parameters is explained. Finally, the responses generated by the model are studied.

6.1 Empirical work

To perform the VAR estimation, three time series have been used: the price of crude oil (Brent) in euros (see its evolution in 1), the real production price of oil products', hereafter referred as IPPI, and real GDP[26]. We abstract from the possible integrated character of the series, as is the case in mostof the DSGE litterature. As we are interested in responses on the short or medium run, series have been detrended[27].

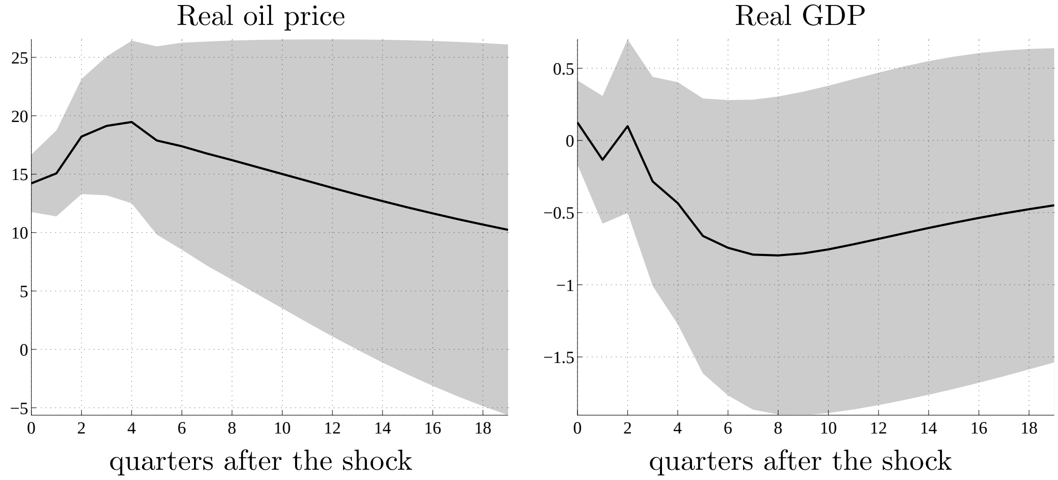
In the DSGE model, the real oil price is considered as exogenous. However, for estimation purposes, this assumption seems too strong, oil-price shocks should be identified in the nominal price series, as is suggested in Rotemberg and Woodford (1996). Therefore, we estimate a bivariate VAR (log(IPPI), log(GDP)) incorporating the growth rate of the Brent price as an exogenous variable.

On the following graphs, we have drawn the impulse response functions (IRFs) to a 100% increase in the Brent price. The simulated shock is a permanent shock on the level of the Brent price. Figure 11 corresponds to the estimation on the full available period, i.e. from the first quarter of 1971 to the first quarter of 2005.

[26]IPPI and real GDP series are taken from the quarterly 2000 year base French National Accounts.

[27]This operation could induce some phase disrupture in the series, namely for GDP.

Figure 11: *Estimated IRFs over 1971-2005 (in percentage deviation from their steady-state values).*



A 100% increase in the nominal oil price results in a significant real oil-price increase. The latter is maximum one year after the shock. At that time, the IPPI is at least 20% higher than before the shock. Then, the response resorbs progressively. The GDP response is not significant. However, the response shape seems overall satisfactory except for the first periods after the shock, during which GDP experiences perturbations. Following the empirical literature, we proceed to subperiod estimations. In the French case, the year 1983 represents an ideal candidate as a breaking date. The 1983-laws, which froze prices and indexes, as well as the wages' desindexation modified agents' behaviors. The estimation conducted on the sample from the first quarter of 1971 to the fourth quarter of 1983 suggests[28] a significant impact on GDP from the 3^{rd} to the 7^{th} quarter after the shock. The details of the estimated VAR are given in annex E.

The impact is maximum during the second half of the second year after the shock, when it reaches -2.5%. Although the impact on the IPPI is less pronounced on this first subperiod than on the entire period, GDP is much more affected.

As for comparison issues, Rotemberg and Woodford (1996) estimate that a 1% increase in nominal oil price innovation results in a contemporaneous real price increase of 1% and a maximal fall in GDP of 0.4%. As these estimation models are linear, multiplying the preceding results by 100% enables us to directly compare our conclusions with those of Rotemberg and Woodford (1996). On the one hand, the maximum real price response in France seems to be much less notable than in the U.S. The nominal oil-price increase is systematically attenuated. On the other hand, the induced French recession seems to be 20 times less severe than the U.S. one.

Figures 13 illustrate the difficulties that were mentioned in the introduction regarding the estimation of a significant impact after 1980.

[28]Because the period of estimation is short, the result must be interpreted with caution.

Figure 12: *Estimated IRFs over 1971-1983 (in percentage deviation from its steady-state value).*

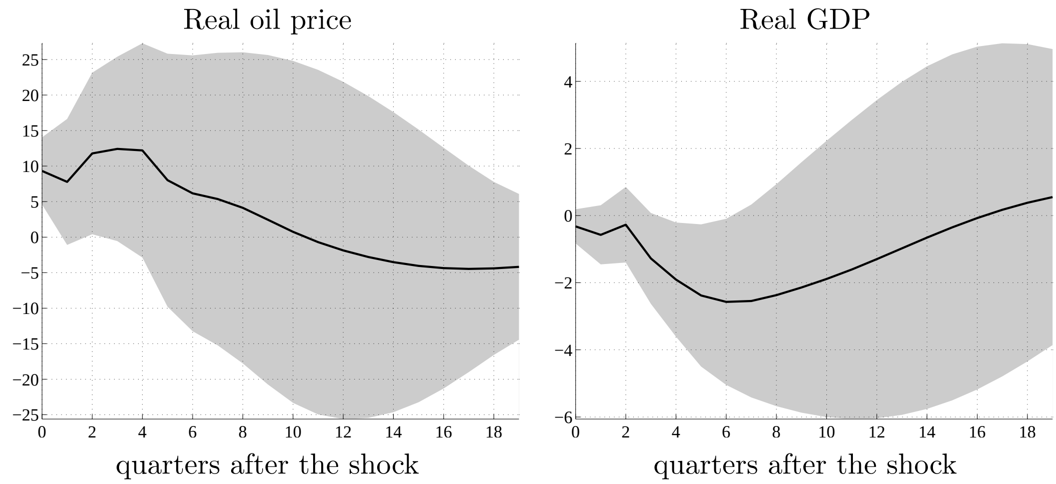
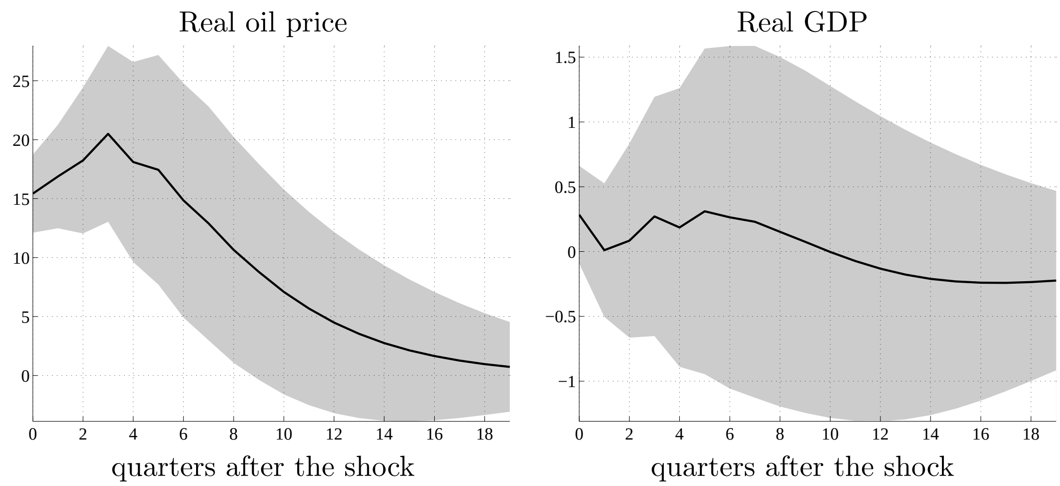


Figure 13: *Estimated IRFs over 1984-2005 (in percentage deviation from its steady-state value).*



6.2 Nominal sphere and its calibration

The interaction between the nominal and real spheres in the model is due to nominal rigidities and is strongly affected by the monetary policy rule. The latter is implemented as a standard Taylor rule, featuring interest rate movement inertia and retroaction to deviations from the Central Bank target rate of inflation. The calibration is inspired by Clarida, Gali, and Gertler (1998)[29] who perform an estimation of a Taylor rule for France. We make a strong asumption by calibrating the Taylor rule once and for all. It has already been explained in subsection 2.2 that the monetary policy response is very different between the 70s and the 90s and that it could explain the difference of response estimated. Here we focus on the first determinants affecting the interaction between the nominal and real sphere, namely the nominal rigidities themselves.

The nominal rigidities originate from the wage and price settings, which follow, in our model, a Calvo mechanism. This mechanism is not the most widely used nominal setting in the DSGE literature. Most of the models feature quadratic costs in price or wages variation, because it is easier to implement. However, microeconometric evidence supports the Calvo mechanisms to a broader extent than the quadratic costs assumptions[30]. Note that these different modeling choices imply an equivalent aggregate New Keynesian Philips Curve at the first order approximation.

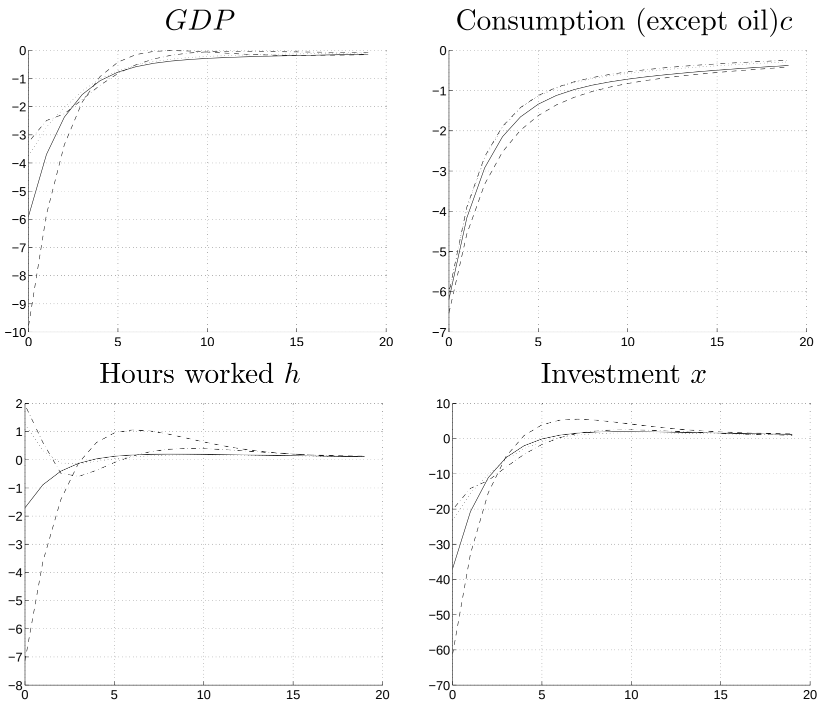
The best way to conceptualize the wage setting mechanism à la Calvo is to imagine a continuum of households, only a random part of which has the opportunity to fix new wages at each period. When they have this opportunity, they reoptimize their new wages in a forward looking manner. To do so, they form expectations on the future labor demand that will be addressed to them, their future marginal utility or work disutility. They also internalize the fact that they may have the possibility to reoptimize their wages at once. When they do not have the opportunity to reset their wages, the latter evolves as indexed on both steady state and past inflation rates. The crucial aspect of the Calvo mechanism that makes it tractable is that the probability to be able to reoptimize does not depend on the time elapsed since the last reoptimization. To fix ideas, we call α_W the probability for an individual household not to be able to reoptimize his/her wage. α_W is calibrated such that the mean time elapsed between two opportunities to reoptimize wages is one year. We also introduce γ_W, which measures the level of indexation to past inflation relative to the one to steady state inflation.

The price setting à la Calvo shares the same mechanism. It implies that, when setting their prices, firms care about the expected real marginal costs' future evolution, the expected demand and the expected inflation rate. Regarding the calibration, parameters are chosen such that the mean time elpased between two price reoptimizations is one year and a half.

[29] The order 1 autoregressive parameter is set to 0.85 and the retroaction parameter is 1.13.

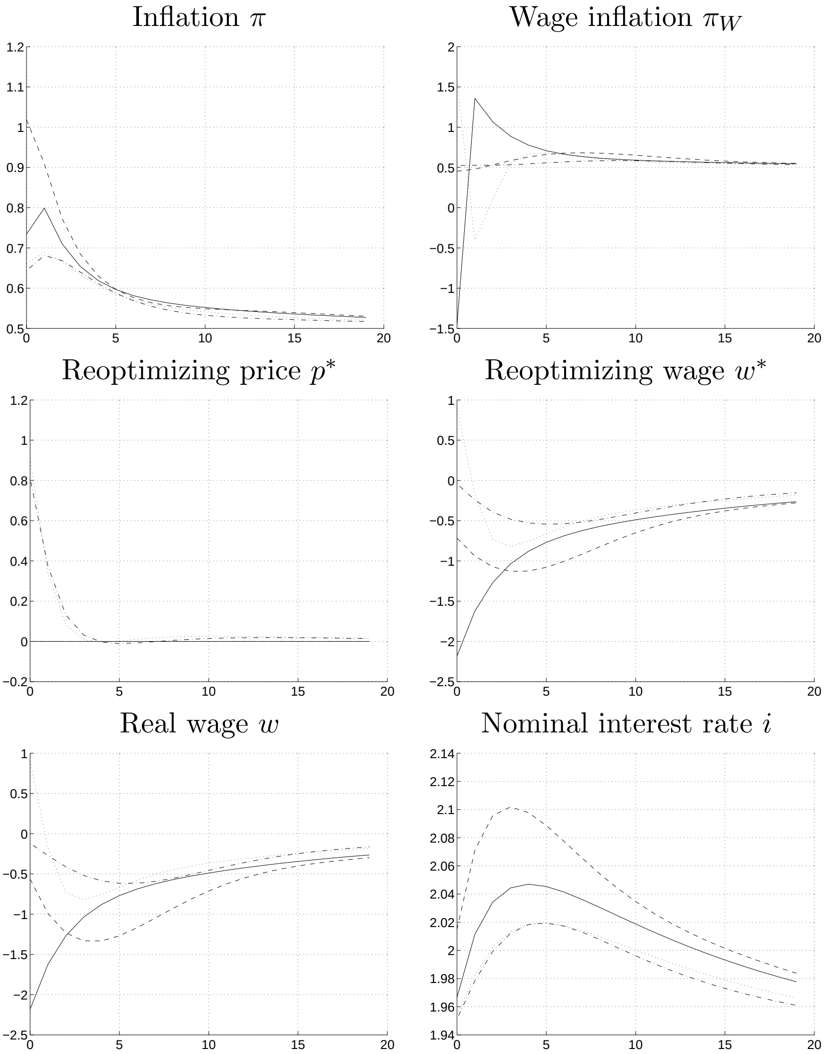
[30] In reality, not all the prices change every period, as suggested by the quadratic cost assumption. However, in other dimensions, the Calvo mechanism is far from microeconometric evidence. With regard to empirics, the menu costs' assumption seems to be the most reasonable one. It specifies that prices are changed when the implied gains are above a certain level. For further implications on microfoundations of macro models due to microeconometric evidence, see Angeloni, Gali, Aucremanne, Levin, Ehrmann, and Smets (2006).

Figure 14: *Real variables impulse response functions (deviation in percentage) to a persistent real oil-price shock.*



Reading the graphs: the solid curve corresponds to the model without nominal rigidities, the dashed one to the model with wage rigidities, the dotted one to the model with price rigidities, the dash-dot one to the model with both rigidities. At t=0, the real oil-price is doubled. The persistence of the real oil price process is 0.6.

Figure 15: *Impulse response function to a persistent real oil-price shock.*



Reading the graphs: the solid line corresponds to the model without nominal rigidities, the dashed one to the model with wage rigidities, the dotted one to the model with price rigidities, the dash-dot one to the model with both rigidities. For π, π_W and i, the level is plotted in base point (it is not a deviation in pourcentage as for the other variables). At t=0, the real oil price is doubled. The persistence of the real oil-price process is 0.6.

As can be seen in figures 14, nominal rigidities have a significant effect on real response to oil-price shocks. Nominal responses can be read in figures 15.

In the model with wage rigidities only, nominal wages' sluggishness delays the real wage moderation, although producers anticipate the wage setter resistance (prices increase more than in the standard scenario). Wage moderation has a negative effect on hours worked, which decreases by 7% (to be compared to -2% in the scenario without nominal rigidities). As a result, GDP is strongly affected and deviates by -10% at the impact.

In the scenario with price rigidities only, the GDP deviation is reduced to -4%. As prices cannot accommodate, some firms are still bound to satisfy a high product demand. To stimulate work supply, they accept higher wages. As a consequence, the response of labor is reversed compared to the standard scenario.

When both rigidities are considered, the GDP deviation is close to the one in the price rigidity scenario. Wage rigidities tend to worsen the GDP response. This channel leads to an increase in the marginal utility of consumption, moderating the wage increase that is observable in the price rigidity scenario. This explains why the labor supply response is still positive while real wages decrease.

6.3 Response to the estimated real oil-price shock

The real oil-price shock used in the following simulation is the real oil-price response to a permanent doubling of nominal oil prices as estimated in the VAR analysis. Two ways of implementing such a shock can be considered, under perfect or imperfect foresight. Under perfect foresight, the real shock evolution is triggered by only one innovation. There is one particular period when the shock occur. Once the shock has occured, the whole real oil-price evolution is known to the agents, for example they know that the real oil price will be higher one period after the shock, etc... The simulation results under perfect foresight are reported in the appendix F. In this section, we focus on the simulations under imperfect foresight.

Under imperfect foresight, the real shock is generated by a series of innovations. The real oil price is an order 1 autoregressive process. The autoregressive parameter is set to 0.95 to represent the high persistence found in the observed real oil price series.

When the model is calibrated on the first subperiod, i.e. with the energy ratios observed before 1983, the overall shape of the GDP response follows the estimated shape. The simulation under the first subperiod calibration corresponds to the solid curve in the figures 16. The GDP response is within the estimated confidence interval. There is not much deviation at the impact (at $t = 0$). Then, the recession dampens gradually until date $t = 5$, when the GDP deviation falls at its minimum (-1.4%). Thus, the model underestimates the minimum GDP deviation observed in the data. The timing of the GDP response is correctly reproduced, namely there is a delay between the peak of the real oil price and the minimum GDP deviation. This delay, as explained previously, is due to the various rigidities introduced in the model.

Concerning the GDP demand side, the model predicts up to a 1.4% fall in non-oil consumption, nearly a 6% fall in investment and a 4.5% fall in oil products' final consumption. As expected from the previous simulations, the production factor combination switches away from oil products. Oil products used in production experiment a 11% fall, when the real oil price peaks. Meanwhile the labor intensity increases. While the real oil price increases, the labor deviation is even positive. As explained in the simulations exploring real rigidities, households need to pay for the adjustment of the economy. After the peak, when the situation is the worst and households expect better times, labor supply depresses. The labor response is without doubt one of the failures of our model. Another one to be noticed is the amplitude of the inflation response. While the overall shape of inflation deviation is satisfactory, its amplitude is much lower than what was observed after the 70s oil shocks[31].

When the economy is less oil dependent, does the GDP response flatten? According to the simulation performed under the second subperiod calibration (dashed lines), GDP response is almost reduced by half. This is consistent with what has been previously simulated (in figure 4 for example). This reduction is not negligible. GDP response lies within the confidence interval of the second-subperiod estimation.

Does a more flexible production structure explain the flattening of GDP negative response further? The simulation performed to answer this question is caried out under the second subperiod calibration with a higher elasticity of substitution between capital and oil products (θ_G is set to 0.6). The modification in the production structure does not significantly alter the model response[32]. This is consistent with what is observed from the long-term GDP deviations under different production structures (see figure 3).

Does desindexation of wages and prices on past inflation attenuate the negative effects of real oil-price shocks on GDP? When the degrees of indexation on past inflation (γ_P, γ_W) are set to zero, GDP response is reduced to -0.6%. Because agents do not expect their future prices not to increase when they cannnot reoptimize, they set prices to fully react to the shock. Typically, prices are higher at $t = 0$ than in all other simulations. Similarly, wages are not pegged by past inflation, and deviate more at shocks impact. Inflation response is less hump-shaped. Without indexation, the inflation persistence is only due to the rolling Calvo characteristics and to the fact that the shock is the result of a series of innovations.

The interpretation of the switch from price and wage indexation on past inflation to indexation on steady state inflation is not straight-forward. What could trigger such a switch? The desindexation policy at the beginning of the 80s seems a good explanation. In 1983, prices and wages were frozen, possibly resulting in changes in agents' anticipations.

[31] This result was to be expected, as the reason of introducing a Taylor type rule is to refrain high inflation. A more realistic price setting, namely that enables the frequency of price changes to evolve with shocks, could be a first step to generate high inflation periods.

[32] To keep oil intensities consistent with the ones observed during the second subperiod, updating the production structure also implies updating the relative weight on capital and oil products in the production function.

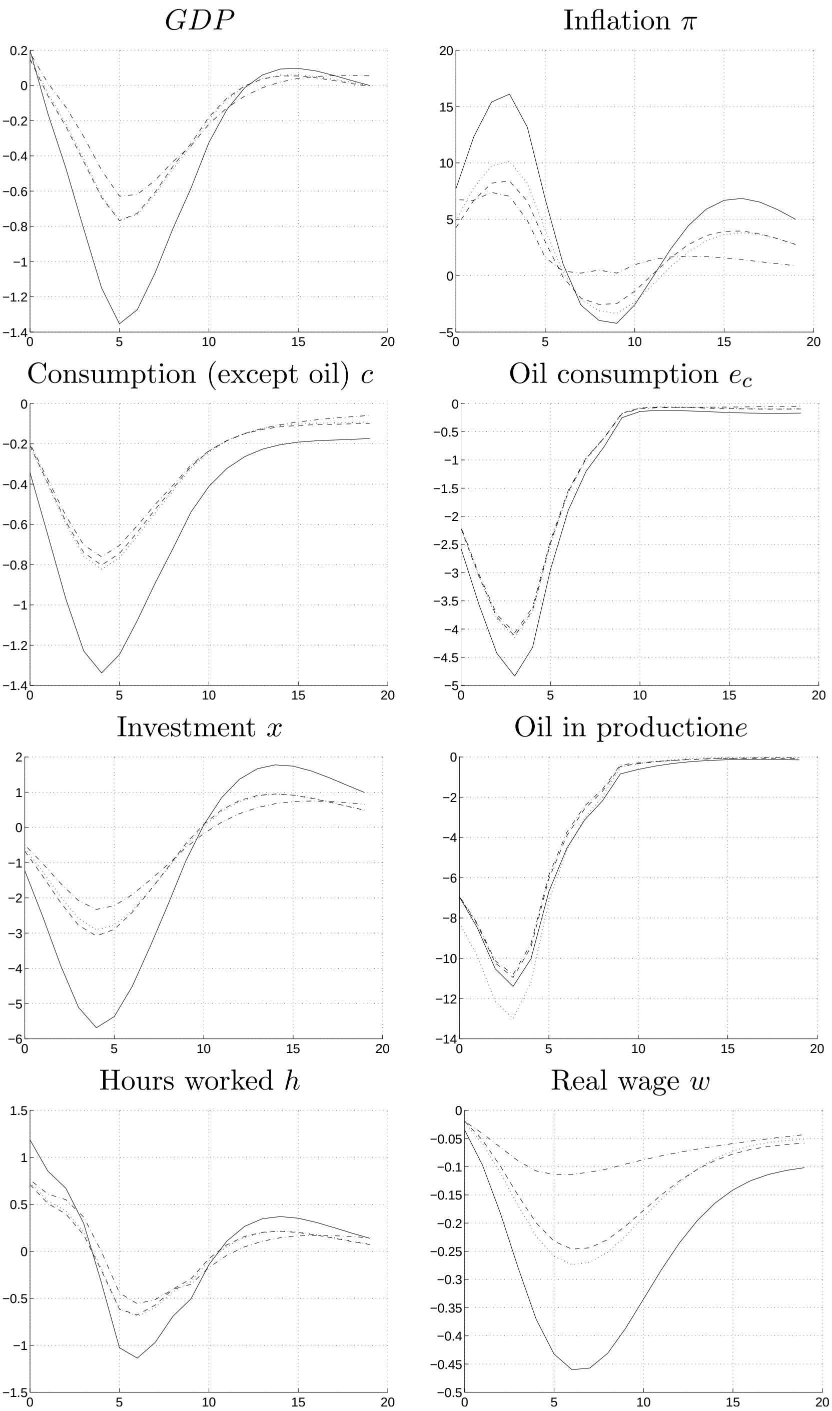
Concerning the labor market, one effect or one of the instruments[33] of the desindexation policy is the evolution of the practice in minimum-wage setting. From early 70s to the beginning of the 80s, the gouvernement systematically raised the minimum wage by more than the increase of the mean wage. Since roughly 1983, it has no longer been the case (see CSERC (1999)). Reduction in wage inequality does not seem to be one of the main objectives of the minimum-wage policy any more.

Beyond the change in practices quoted above, there seems to be a more fundamental reason which could be understood as the belief in a more credible monetary policy. Such a reason is appealing because it also works to explain the price desindexation, which is less regulated.

Even if the different explanations brought forward imply an attenuation of the GDP response, none is sufficient to fully explain the absence of estimated GDP response to oil-price shocks.

[33]It is hard to tell whether the change in practice of the minimum-wage setting is an instrument or a consequence of the desindexation policy. The interactions between the minimum wage and the mean wage are complicated. On the one hand, conventional wages cannot be automatically indexed on minimum wage legally. On the other hand, the rule of minimum wage setting explicitelt take into account the evolution of the mean wage. However, it is usually considered that the minimum wage pins down the mean wage.

Figure 16: *Model responses (deviation in percentage) to the estimated real oil-price shock - under imperfect foresight.*



Reading the graphs: the solid line corresponds to the model calibrated on the first sub period, the dashed one to the model on the second subperiod, the dotted one to the model on the second subperiod with θ_G revisited, the dash-dot one to the model on the second subperiod with no indexation on past inflations. For π, the level is plotted in base point (it is not a deviation in pourcentage as for the other variables).

7 Conclusion

A reasonably calibrated Dynamic General Equilibrium model reproduces the long-term GDP responses to a permanent oil price shock as estimated before the mid 80s. Taking into account the decrease in oil intensities after the mid 80s, the response is cut by half.

None of the ”non-linear” explanations (nonlinearities, asymmetries) that are easily modeled in the DSGE model helps to understand the absence of GDP response to an oil-price shock as estimated after the mid 80s.

Changes in the elasticity of substitution between capital and oil products cannot explain the stylised facts alone. Wage and price desindexation further reduces the GDP response. This result gives a determining part to monetary policy credibility.

There are a lot of possible tracks for future research. Let us focus on the two main ones: estimation and economy opening. The procedure used in the present study to evaluate the model against the data can be described as illustrative. Testing the model against a more complete set of series in a more quantified way is desirable (GMM or Bayesian estimation). Before trying to estimate the model, it seems essential to enrich the behaviors of oil-exporting countries and, more generally, to open the modeled economy.

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A The model: Full derivation

In the following presentation, we have introduced more shocks than needed for the paper simulations. These shocks are necessary when bayesian or maximum likelihood estimation is performed.

A.1 Households and aggregate labor

Let us first consider the program of a typical household indexed by υ. The intertemporal utility function of the latter household is:

$$\mathrm{E}_0 \left\{ \sum_{t=0}^{\infty} \beta^t \zeta_{U,t} \left[U \left(c_t \left(\upsilon \right) - b_c c_{t-1} \left(\upsilon \right), e_{c,t} \left(\upsilon \right) - b_e e_{c,t-1} \left(\upsilon \right) \right) - \zeta_{V,t} V \left(h_t \left(\upsilon \right) \right) \right] \right\}, \tag{2}$$

where E_t is the expectation operator conditional to the information available at time t, β the subjective discount factor, c_t the consumption of final good, $e_{c,t}$ the final consumption of oil, b_c (b_e) the habit formation parameter on core consumption (on energy consumption) and $h_t(\upsilon)$ the labor supply. We assume that $U(\cdot)$ is strictly concave and increasing, and $V(\cdot)$ is strictly convex and increasing. $\zeta_{U,t}$ and $\zeta_{V,t}$ are preference shocks, modeled as stationary processes with mean equal to one.

Households own firms, which makes them entitled to their monopolistic profits. They also own capital, which they rent to firms.This modeling choice can be read in the budgetary constraint.

Thus, the typical household υ maximizes (2) such that the following constraints are satisfied

$$P_t c_t + P_{e,t} e_{c,t} + B_t / \left(1 + i_t \right) + P_t x_t \leq W_t \left(\upsilon \right) h_t \left(\upsilon \right) + B_{t-1} + \Phi_t + R_t k_{t-1}. \tag{3}$$

$$k_t \leq \left(1 - \delta \right) k_{t-1} + \left(1 - \zeta_{H,t} H \left(\frac{x_t}{x_{t-1}} \right) \right) x_t \tag{4}$$

where P_t (resp. $P_{e,t}$) is the nominal price of the final consumption good (resp. oil products), B_t the quantity of nominal bonds acquired in t and expiring in $t+1$, i_t the nominal interest rate on bonds, x_t the quantity of investment decided at t and bought at price P_t, Φ_t the aggregate profit distributed by firms, $W_t(\upsilon)$ the nominal wage payed for υ's labor, and k_{t-1} the capital resulting from the investment decision taken at $t-1$ (which can be used for production at time t and gives the nominal interest rate R_t). A variable indexed by t comes from a decision taken at time t. In the capital accumulation equation, δ is the depreciation rate and $H(.)$ embodies the presence of investment adjustment costs. We assume that $H(.)$ obeys the following restrictions: $H(1) = H'(1) = 0$. We also enable the capital adjustment cost to be shocked (via $\zeta_{H,t}$).

The Lagrangian[34] associated to the problem is:

$$\begin{aligned}
&\mathrm{E}_0 \sum_{t=0}^{\infty} \beta^t \zeta_{U,t} \{ U(c_t - b_c c_{t-1}, e_{c,t} - b_e e_{c,t-1}) - \zeta_{V,t} V(h_t(\upsilon)) \\
&- \Lambda_t \left[P_t c_t + P_{e,t} e_{c,t} + B_t/(1+i_t) + P_t x_t - W_t(\upsilon) h_t(\upsilon) - B_{t-1} - \Phi_t - R_t k_{t-1} \right] \\
&+ \Lambda_t \Psi_t \left[(1-\delta) k_{t-1} + \left(1 - \zeta_{H,t} H\left(\frac{x_t}{x_{t-1}} \right) \right) x_t - k_t \right] \}.
\end{aligned}$$

The first-order conditions[35] (FOCs) deduced from the maximization with respect to B_t, c_t , $e_{c,t}$, x_t and k_t are:

$$\Lambda_t = (1+i_t) \beta \mathrm{E}_t \{ \Lambda_{t+1} \}$$

$$\Lambda_t P_t = U_c(c_t - b_c c_{t-1}, e_{c,t} - b_e e_{c,t-1}) \zeta_{U,t} - \beta b_c \mathrm{E}_t \{ \zeta_{U,t+1} U_c(c_{t+1} - b_c c_t, e_{c,t+1} - b_e e_{c,t}) \}$$

$$\Lambda_t P_{e,t} = U_e(c_t - b c_{t-1}, e_{c,t} - b_e e_{c,t-1}) \zeta_{U,t} - \beta b_e \mathrm{E}_t \{ \zeta_{U,t+1} U_e(c_{t+1} - b_c c_t, e_{c,t+1} - b_e e_{c,t}) \}$$

$$\Lambda_t P_t = \Lambda_t \Psi_t \left[\left(1 - \zeta_{H,t} H\left(\frac{x_t}{x_{t-1}} \right) \right) - \zeta_{H,t} H'\left(\frac{x_t}{x_{t-1}} \right) \frac{x_t}{x_{t-1}} \right] + \beta \mathrm{E}_t \left\{ \Lambda_{t+1} \Psi_{t+1} \left(\frac{x_{t+1}}{x_t} \right)^2 \zeta_{H,t+1} H'\left(\frac{x_{t+1}}{x_t} \right) \right\}$$

$$\Lambda_t \Psi_t = \beta \mathrm{E}_t \{ \Lambda_{t+1} R_{t+1} + (1-\delta) \Lambda_{t+1} \Psi_{t+1} \}$$

From now on, we define $\lambda_t = \Lambda_t P_t$ and $\psi_t = \frac{\Psi_t}{P_t}$. We need to introduce the relative oil price ($p_{e,t} = P_{e,t}/P_t$) and the inflation rate ($\pi_t = P_t/P_{t-1}$). Thus, the preceding FOCs can be rewritten as:

$$\lambda_t = (1+i_t) \beta \mathrm{E}_t \left\{ \frac{\lambda_{t+1}}{1+\pi_{t+1}} \right\}, \tag{5}$$

$$\lambda_t = U_c(c_t - b_c c_{t-1}, e_{c,t} - b_e e_{c,t-1}) \zeta_{U,t} - \beta b_c \mathrm{E}_t \{ \zeta_{U,t+1} U_c(c_{t+1} - b_c c_t, e_{c,t+1} - b_e e_{c,t}) \} \tag{6}$$

$$\lambda_t p_{e,t} = U_e(c_t - b c_{t-1}, e_{c,t} - b_e e_{c,t-1}) \zeta_{U,t} - \beta b_e \mathrm{E}_t \{ \zeta_{U,t+1} U_e(c_{t+1} - b_c c_t, e_{c,t+1} - b_e e_{c,t}) \} \tag{7}$$

$$1 = \psi_t \left[\left(1 - \zeta_{H,t} H\left(\frac{x_t}{x_{t-1}} \right) \right) - \zeta_{H,t} H'\left(\frac{x_t}{x_{t-1}} \right) \frac{x_t}{x_{t-1}} \right] + \beta \mathrm{E}_t \left\{ \frac{\lambda_{t+1}}{\lambda_t} \psi_{t+1} \left(\frac{x_{t+1}}{x_t} \right)^2 \zeta_{H,t+1} H'\left(\frac{x_{t+1}}{x_t} \right) \right\} \tag{8}$$

$$\psi_t = \beta \mathrm{E}_t \left\{ \frac{\lambda_{t+1}}{\lambda_t} (r_{t+1} + (1-\delta) \psi_{t+1}) \right\} \tag{9}$$

Household υ acts as a monopolistic supplier of υ-type labor. We assume that, at each date, only a fraction $1-\alpha_w$ of households has the opportunity to negotiate a new wage. The other households revise their wages according to the rule $W_T(\upsilon) = (1+\delta^w_{t,T}) W_t(\upsilon)$, where $\delta^w_{t,T}$ is defined as follows:

$$1 + \delta^w_{t,T} = \begin{cases} \prod_{j=t}^{T-1} (1+\pi^w_{ss})^{1-\gamma_w} (1+\pi^w_j)^{\gamma_w} & \text{if } T > t \\ 1 & \text{else} \end{cases} \tag{10}$$

[34]To make notations more readable, we omit the household's indice on all variables except on wage and hours worked.

[35]U_c (resp. U_e) is the partial derivative of U with respect to c (resp. e).

where π^w_{ss} is the wage inflation rate at the steady state, π^w_j is the wage inflation rate at time t=j ($\pi^w_j = W_j/W_{j-1}$) and $\gamma_w \in [0,1]$ is the degree of indexation on the last available measure of inflation. The different labor inputs, indexed on $[0,1]$, are aggregated in a unique index h_t by competitive firms according to a CES technology:

$$h_t = \left(\int_0^1 h_t\left(\upsilon\right)^{(\theta_w-1)/\theta_w} \mathrm{d}\upsilon\right)^{\theta_w/(\theta_w-1)}. \tag{11}$$

where θ_w is the elasticity of substitution between the different types of labor (θ_w must be greater than 1). Let us note $W_t\left(\upsilon\right)$ the nominal wage associated with the υ-type labor, which labor demand takes as given. Then υ-type labor demand verifies:

$$h_t\left(\upsilon\right) = \left(\frac{W_t\left(\upsilon\right)}{W_t}\right)^{-\theta_w} h_t, \tag{12}$$

where the nominal aggregate wage is:

$$W_t = \left(\int_0^1 W_t\left(\upsilon\right)^{1-\theta_w} \mathrm{d}\upsilon\right)^{1/(1-\theta_w)}. \tag{13}$$

Since the household is a monopoly supplier, it will take the demand function (12) into account when setting its wage. Additionally, it takes into account the fact that this wage rate will presumably hold for more than one period -except for the automatic revision. Now, let $W^*_t(\upsilon)$ denote the wage rate chosen at period t, and let $h^*_{t,T}\left(\upsilon\right)$ denote the hours worked at period T if household υ last reoptimized its wage at period t. According to eq. (12), $h^*_{t,T}\left(\upsilon\right)$ obeys the relationship:

$$h^*_{t,T}\left(\upsilon\right) = \left(\frac{(1+\delta^w_{t,T})W^*_t\left(\upsilon\right)}{W_T}\right)^{-\theta_w} h_T. \tag{14}$$

Then, $W^*_t\left(\upsilon\right)$ is chosen as to maximize[36]:

$$\mathrm{E}_t \sum_{T=t}^{\infty} \left(\beta\alpha_w\right)^{T-t} \left\{\lambda_T \frac{(1+\delta^w_{t,T})W^*_t\left(\upsilon\right)}{P_T} h^*_{t,T}\left(\upsilon\right) - \zeta_{U,t}\zeta_{V,t} V(h^*_{t,T}\left(\upsilon\right))\right\}. \tag{15}$$

The first-order condition [37] is:

$$\mathrm{E}_t \sum_{T=t}^{\infty} \left(\beta\alpha_w\right)^{T-t} h^*_{t,T}\left(\upsilon\right) \left\{\lambda_T w_T \frac{1+\delta^w_{t,T}}{1+\pi^w_{t,T}} \frac{w^*_t\left(\upsilon\right)}{w_t} - \zeta_{U,t}\zeta_{V,t}\mu_w V_h\left(h^*_{t,T}\left(\upsilon\right)\right)\right\} = 0, \tag{16}$$

[36] A necessary condition to write the program in such a simple way is the financial market completeness. Agents exchange state-contingent claims. This gives them perfect insurance on their consumption (except for macro shocks). In such a framework, other intertemporal decisions (such as capital accumulation) are orthogonal.

[37] To derive the condition, we use the following relations:

$$\frac{\partial h^*_{t,T}\left(\upsilon\right)}{\partial W^*_t\left(\upsilon\right)} = -\frac{\theta_w}{W^*_t\left(\upsilon\right)} h^*_{t,T}\left(\upsilon\right)$$

$$\frac{\partial\left(W^*_t\left(\upsilon\right) h^*_{t,T}\left(\upsilon\right)\right)}{\partial W^*_t\left(\upsilon\right)} = \left(1-\theta_w\right) h^*_{t,T}\left(\upsilon\right)$$

where $w_t(\upsilon) = W_t(\upsilon)/P_t$ is the real wage, $\mu_w = \theta_w/(\theta_w - 1)$ and $\pi_{t,T} = P_T/P_t - 1$.

We assume that all agents face the same constraints: $w_t^*(\upsilon) = w_t^*$. Therefore, we can write the equation defining the aggregate wage as an index of its components:

$$1 = (1 - \alpha_w)\left(\frac{w_t^*}{w_t}\right)^{1-\theta_w} + \alpha_w\left[\frac{(1 + \pi_{ss}^w)^{1-\gamma_w}(1 + \pi_{t-1}^w)^{\gamma_w}}{1 + \pi_t^w}\right]^{1-\theta_w}. \tag{17}$$

Before heading to the description of the production side, simply note that:

$$\frac{w_t}{w_{t-1}} = \frac{1 + \pi_t^w}{1 + \pi_t}$$

A.2 Production

Competitive firms produce a homogeneous composite good d_t using the inputs of intermediate goods $d_t(\varsigma)$, according to the CES technology:

$$d_t = \left(\int_0^1 d_t(\varsigma)^{(\theta_p-1)/\theta_p}\, \mathrm{d}\varsigma\right)^{\theta_p/(\theta_p-1)}, \tag{18}$$

where d_t is the quantity of final good produced at period t and $d_t(\varsigma)$ is the corresponding input of intermediate good ς. Intermediate goods are imperfectly substitutable, with elasticity of substitution $\theta_p > 1$. The final good can be either consumed, invested or exported to oil-exporting countries. The aggregate price index of the composite good obeys the relationship:

$$P_t = \left(\int_0^1 P_t(\varsigma)^{1-\theta_p}\, \mathrm{d}\varsigma\right)^{1/(1-\theta_p)}. \tag{19}$$

The above assumptions imply the following relationship:

$$d_t(\varsigma) = \left(\frac{P_t(\varsigma)}{P_t}\right)^{-\theta_p} d_t. \tag{20}$$

Monopolistic firms produce the intermediate goods $(\varsigma)_{\varsigma\in[0,1]}$. Each firm $\varsigma \in [0,1]$ is the sole producer of intermediate good ς. Given demand $d_t(\varsigma)$, firm ς faces the following production possibilities:

$$d_t(\varsigma) \leq F\left(G\left(k_{t-1}(\varsigma), e_t(\varsigma)\right), \mathrm{e}^{z_t} n_t(\varsigma)\right) \tag{21}$$

where $F(\cdot)$ and $G(\cdot)$ are homogeneous of degree 1, increasing and concave according to each of their arguments, $n_t(\varsigma)$ is the aggregated labor input, $e_t(\varsigma)$ the oil product input, $k_{t-1}(\varsigma)$ the capital input (demand determined at time t). Finally, z_t denotes a productivity shock.

We assume that, at each time period, a monopolistic firm can reoptimize its price with probability $1 - \alpha_p$, irrespective of the elapsed time since it last revised its price. The remaining firms simply rescale their prices according to the simple rule $P_T(\varsigma) = (1+\delta^p_{t,T})P_t(\varsigma)$, where $\delta^p_{t,T}$ is defined by:

$$1+\delta^p_{t,T} = \begin{cases} \prod_{j=t}^{T-1}(1+\pi_{ss})^{1-\gamma_p}(1+\pi_j)^{\gamma_p} & \text{if } T>t \\ 1 & \text{else} \end{cases} \tag{22}$$

where $\pi_t \equiv P_t/P_{t-1} - 1$ is the inflation rate, π_{ss} the the steady state value of π_t, and $\gamma_p \in [0,1]$ measures the degree of indexation to the most recently available inflation measure.

The different factor demands are instantaneous decisions. The minimization cost program is:

$$\begin{aligned} &\min_{k,n,m,e} \{w_t n_t(\varsigma) + r_t k_{t-1}(\varsigma) + p_{e,t}e_t(\varsigma)\} \\ &\qquad\qquad\qquad\qquad\text{s.t.} \\ &d_t(\varsigma) \leq F\left(G\left(k_{t-1}(\varsigma), e_t(\varsigma)\right), \mathrm{e}^{z_t}n_t(\varsigma)\right). \end{aligned}$$

The associated Lagrangian is:

$$\mathcal{L}_t = w_t n_t(\varsigma) + r_t k_{t-1}(\varsigma) + p_{e,t}e_t(\varsigma) - \kappa_t\left[F\left(G\left(k_{t-1}(\varsigma), e_t(\varsigma)\right), \mathrm{e}^{z_t}n_t(\varsigma)\right) - d_t\right]$$

where κ_t is the Lagrangian multiplier. The latter can be interpreted as the firm's real marginal cost. As the production function is homogenous of order 1 ($F(.,.)$ and $G(.,.)$ are homogenous of order 1), the real marginal cost is also the real mean cost, which, thus, does not depend on the production level. Note that the cost is the same across firms as it only depends on the current prices of inputs.

The FOCs[38] derived from the program are:

$$r_t = \kappa_t F_G\left(G\left(k_{t-1}(\varsigma), e_t(\varsigma)\right), \mathrm{e}^{z_t}n_t(\varsigma)\right) G_k\left(k_{t-1}(\varsigma), e_t(\varsigma)\right) \tag{23}$$

$$p_{e,t} = \kappa_t F_G\left(G\left(k_{t-1}(\varsigma), e_t(\varsigma)\right), \mathrm{e}^{z_t}n_t(\varsigma)\right) G_e\left(k_{t-1}(\varsigma), e_t(\varsigma)\right) \tag{24}$$

$$w_t = \kappa_t \mathrm{e}^{z_t} F_n\left(G\left(k_{t-1}(\varsigma), e_t(\varsigma)\right), \mathrm{e}^{z_t}n_t(\varsigma)\right) \tag{25}$$

$$d_t(\varsigma) = F\left(G\left(k_{t-1}(\varsigma), e_t(\varsigma)\right), \mathrm{e}^{z_t}n_t(\varsigma)\right) \tag{26}$$

Being a monopoly supplier, firm ς takes the demand function (20) into account when setting its price. Additionally, it takes into account the fact that this price rate will presumably hold for more than one period -except for automatic revisions. Now, let $P^*_t(\varsigma)$ denote the price chosen at period t and $d^*_{t,T}(\varsigma)$ the production of good ς at period T if firm ς last reoptimized its price at period t. According to (20), $d^*_{t,T}(\varsigma)$ obeys the relationship:

$$d^*_{t,T}(\varsigma) = \left(\frac{(1+\delta^p_{t,T})P^*_t(\varsigma)}{P_T}\right)^{-\theta_p} d_T. \tag{27}$$

[38] F_G (resp. F_n) is the partial derivative of F with respect to its first argument (resp. to its second argument). G_k (resp. G_e) is the partial derivative of G with respect to its first argument (resp. to its second argument).

Then, $P_t^*(\varsigma)$ is chosen to maximize:

$$\mathrm{E}_t \sum_{T=t}^{\infty} (\beta\alpha_p)^{T-t} \lambda_T \left\{ \frac{(1+\delta_{t,T}^p) P_t^*(\varsigma)}{P_T} d_{t,T}^*(\varsigma) - \kappa_t d_{t,T}^*(\varsigma) \right\}.$$

We introduce $p_t^* = P_t^*/P_t$ and $\mu_p = \theta_p/(\theta_p - 1)$ such that the associated first-order condition can be written as:

$$\mathrm{E}_t \sum_{T=t}^{\infty} (\beta\alpha_p)^{T-t} \lambda_T d_{t,T}^*(\varsigma) \left\{ \frac{(1+\delta_{t,T}^p)}{(1+\pi_{t,T})} p_t^*(\varsigma) - \mu_p \kappa_t \right\} = 0 \tag{28}$$

Note that, from the combination of this first-order condition and 20, we can deduce that $p_t^*(\varsigma)$ does not depend on the firm type.

Finally, the aggregate price law of motion is:

$$1 = (1-\alpha_p)(p_t^*)^{1-\theta_p} + \alpha_p [\frac{(1+\pi_{ss})^{1-\gamma_p}(1+\pi_{t-1})^{\gamma_p}}{1+\pi_t}]^{1-\theta_p}. \tag{29}$$

A.3 Monetary authority

The description of the institutional background is limited to the incorporation of a Taylor rule[39].

$$i_t - i_{ss} = \rho_i(i_{t-1} - i_{ss}) + (1-\rho_i)(t_\pi(\pi_t - \pi_{ss}) + t_y(gap_t)) + \zeta_{i,t}$$

There are several possible definitions of gap_t. The theoretically most consistent definition should be the deviation of the current output from the flexible price equilibrium. As a first approximation, we take the deviation from the steady state equilibrium $\frac{y_t - y_{ss}}{y_{ss}}$. Then, in the preceding rule, i_{ss} could also be called the natural interest rate. We note that $\zeta_{i,t}$ is the unanticipated component of the monetary policy.

A.4 Market equilibrium

Equilibrium on the oil-product market leads to:

$$e_t = \int_0^1 e_t(\varsigma)\,\mathrm{d}\varsigma.$$

On the aggregate labor market:

$$h_t = n_t = \int_0^1 n_t(\varsigma)\,\mathrm{d}\varsigma.$$

On the capital market:

$$k_{t-1} = \int_0^1 k_{t-1}(\varsigma)\,\mathrm{d}\varsigma.$$

[39] Variables taken at their non-stochastic steady-state value are subindexed by ss.

The model is closed by the aggregate household budget constraint:

$$c_t + p_{e,t}e_{c,t} + x_t = d_t - p_{e,t}e_t$$

This equality enables us to define the GDP (or value added) of the economy in a standard way $GDP_t = d_t - p_{e,t}e_t$. Defining aggregate composite consumption by $C_t = c_t + p_{e,t}e_{c,t}$, we find the National Account equality: $GDP = C_t + x_t + \text{Net Exports}$. It is clear that, in our model, $\text{Net Exports} = 0$. Every oil import has its counterpart in final good export. Here, we follow the Finn (2000) specification, international trade is balanced. [40]

Next, we need to incorporate the aggregate definitions of each quantity (e_t, n_t and k_{t-1}) in the FOCs derived from the firm program. Let us begin with the FOCs of the minimization program. As $F(\cdot)$ and $G(\cdot)$ are homogenous of degree 1, their derivatives are homogenous of degree 0. Then, as firms consider the real price of their inputs as exogenous, the ratio $k_{t-1}(\varsigma)/e_t(\varsigma)$ does not depend on ς (it is easy to show this property by dividing the first two FOCs of the minimization program). Thus, for every firm ς, $\frac{k_{t-1}(\varsigma)}{e_t(\varsigma)} = \frac{\int_0^1 k_{t-1}(\varsigma)\mathrm{d}\varsigma}{\int_0^1 e_t(\varsigma)\mathrm{d}\varsigma} = \frac{k_{t-1}}{e_t}$. We, then, take the first FOC. We let the capital input out of the $G(.,.)$ aggregate and we find that the ratio $k_{t-1}(\varsigma)/n_t(\varsigma)$ does not depend on ς. Again, we integrate to show that: $\frac{k_{t-1}(\varsigma)}{n_t(\varsigma)} = \frac{\int_0^1 k_{t-1}(\varsigma)\mathrm{d}\varsigma}{\int_0^1 n_t(\varsigma)\mathrm{d}\varsigma} = \frac{k_{t-1}}{n_t}$. The FOCs can be rewritten as:

$$\begin{aligned}
r_t &= \kappa_t F_G\left(G\left(k_{t-1}, e_t\right), \mathrm{e}^{z_t} n_t\right) G_k\left(k_{t-1}, e_t\right) \\
p_{e,t} &= \kappa_t F_G\left(G\left(k_{t-1}, e_t\right), \mathrm{e}^{z_t} n_t\right) G_e\left(k_{t-1}, e_t\right) \\
w_t &= \kappa_t \mathrm{e}^{z_t} F_n\left(G\left(k_{t-1}, e_t\right), \mathrm{e}^{z_t} n_t\right)
\end{aligned}$$

The minimization program constraint is a little bit more demanding. Incorporating the demands yields:

$$\left(\frac{P_t(\varsigma)}{P_t}\right)^{-\theta_p} d_t = k_{t-1}(\varsigma) F\left(G\left(1, \frac{e_t}{k_{t-1}}\right), \mathrm{e}^{z_t}\frac{n_t}{k_{t-1}}\right)$$

We integrate the equation and obtain:

$$d_t \int_0^1 \left(\frac{P_t(\varsigma)}{P_t}\right)^{-\theta_p} \mathrm{d}\varsigma = F\left(G\left(k_{t-1}, e_t\right), \mathrm{e}^{z_t} n_t\right)$$

We define an auxiliary variable a_t such that:

$$a_t = \int_0^1 \left(\frac{P_t(\varsigma)}{P_t}\right)^{-\theta_p} \mathrm{d}\varsigma.$$

[40] Rotemberg and Woodford (1996) choose to consider $c_t + x_t = d_t$, which is imbalanced. They implicitly assume that the country contracts foreign debts to finance the oil bill, without explicitly modeling debts and debt constraints.

Using the aggregate price law of motion 29, a_t can also be defined as follows:

$$a_t = \int_0^1 \left(\frac{P_t(\varsigma)}{P_t}\right)^{-\theta_p} \mathrm{d}\varsigma = (1-\alpha_p)\,(p_t^*)^{-\theta_p} + \alpha_p \left[\frac{(1+\pi_{ss})^{1-\gamma_p}(1+\pi_{t-1})^{\gamma_p}}{1+\pi_t}\right]^{-\theta_p}. \tag{30}$$

A.5 Summary

Here, we group the model equations:

$$(1-\delta)\,k_{t-1} + \left(1-\zeta_{H,t} H\left(\frac{x_t}{x_{t-1}}\right)\right) x_t = k_t \tag{31}$$

$$\lambda_t = (1+i_t)\,\beta \mathrm{E}_t \left\{\frac{\lambda_{t+1}}{1+\pi_{t+1}}\right\} \tag{32}$$

$$\lambda_t = U_c\left(c_t - b_c c_{t-1}, e_{c,t} - b_e e_{c,t-1}\right)\zeta_{U,t} - \beta b_c \mathrm{E}_t\left\{\zeta_{U,t+1} U_c\left(c_{t+1} - b_c c_t, e_{c,t+1} - b_e e_{c,t}\right)\right\} \tag{33}$$

$$\lambda_t p_{e,t} = U_e\left(c_t - b c_{t-1}, e_{c,t} - b_e e_{c,t-1}\right)\zeta_{U,t} - \beta b_e \mathrm{E}_t\left\{\zeta_{U,t+1} U_e\left(c_{t+1} - b_c c_t, e_{c,t+1} - b_e e_{c,t}\right)\right\} \tag{34}$$

$$1 = \psi_t \left[\left(1 - \zeta_{H,t} H\left(\frac{x_t}{x_{t-1}}\right)\right) - \zeta_{H,t} H'\left(\frac{x_t}{x_{t-1}}\right)\frac{x_t}{x_{t-1}}\right] + \beta \mathrm{E}_t \left\{\frac{\lambda_{t+1}}{\lambda_t}\psi_{t+1}\left(\frac{x_{t+1}}{x_t}\right)^2 \zeta_{H,t+1} H'\left(\frac{x_{t+1}}{x_t}\right)\right\} \tag{35}$$

$$\psi_t = \beta \mathrm{E}_t \left\{\frac{\lambda_{t+1}}{\lambda_t}\left(r_{t+1} + (1-\delta)\,\psi_{t+1}\right)\right\} \tag{36}$$

$$\mathrm{E}_t \sum_{T=t}^{\infty} (\beta\alpha_w)^{T-t} \left(\frac{1+\delta_{t,T}^w}{1+\pi_{t,T}^w}\frac{w_t^*}{w_t}\right)^{-\theta_w} h_T \left\{\lambda_T w_T \frac{1+\delta_{t,T}^w}{1+\pi_{t,T}^w}\frac{w_t^*}{w_t} - \zeta_{U,t}\zeta_{V,t}\mu_w V_h\left(\left(\frac{1+\delta_{t,T}^w}{1+\pi_{t,T}^w}\frac{w_t^*}{w_t}\right)^{-\theta_w} h_T\right)\right\} = 0 \tag{37}$$

$$1 = (1-\alpha_w)\,(\frac{w_t^*}{w_t})^{1-\theta_w} + \alpha_w[\frac{1+\delta_{t-1,t}^w}{1+\pi_t^w}]^{1-\theta_w} \tag{38}$$

$$\frac{w_t}{w_{t-1}} = \frac{1+\pi_t^w}{1+\pi_t} \tag{39}$$

$$d_t = F\left(G\left(k_{t-1}, e_t\right), \mathrm{e}^{z_t} h_t\right)/a_t \tag{40}$$

$$a_t = (1-\alpha_p)\,(p_t^*)^{-\theta_p} + \alpha_p \left[\frac{(1+\pi_{ss})^{1-\gamma_p}(1+\pi_{t-1})^{\gamma_p}}{1+\pi_t}\right]^{-\theta_p} \tag{41}$$

$$r_t = \kappa_t F_G\left(G\left(k_{t-1}, e_t\right), \mathrm{e}^{z_t} h_t\right) G_k\left(k_{t-1}, e_t\right) \tag{42}$$

$$p_{e,t} = \kappa_t F_G\left(G\left(k_{t-1}, e_t\right), \mathrm{e}^{z_t} h_t\right) G_e\left(k_{t-1}, e_t\right) \tag{43}$$

$$w_t = \kappa_t \mathrm{e}^{z_t} F_n\left(G\left(k_{t-1}, e_t\right), \mathrm{e}^{z_t} h_t\right)\right) \tag{44}$$

$$\mathrm{E}_t \sum_{T=t}^{\infty} (\beta\alpha_p)^{T-t} \lambda_T \left(\frac{(1+\delta_{t,T}^p)}{(1+\pi_{t,T})} p_t^*\right)^{-\theta_p} d_T \left\{\frac{(1+\delta_{t,T}^p)}{(1+\pi_{t,T})} p_t^* - \zeta_{\mu,T}\mu_p\kappa_t\right\} = 0 \tag{45}$$

$$1 = (1-\alpha_p)\,(p_t^*)^{1-\theta_p} + \alpha_p[\frac{(1+\pi_{ss})^{1-\gamma_p}(1+\pi_{t-1})^{\gamma_p}}{1+\pi_t}]^{1-\theta_p} \tag{46}$$

$$c_t + p_{e,t} e_{c,t} + x_t = d_t - p_{e,t} e_t \tag{47}$$

$$i_t - i_{ss} = t_\pi (\pi_t - \pi_{ss}) + t_y (gap_t) + \zeta_{i,t} \tag{48}$$

The endogenous variables being:

$$k_t, i_t, x_t, \lambda_t, c_t, e_{c,t}, \psi_t, r_t, w_t^*, w_t, \pi_t^w, h_t, d_t, a_t, e_t, \kappa_t, \pi_t, p_t^*.$$

A.6 Non-stochastic steady state

The aim of this subsection is to determine the non-stochastic steady state of the model. First, we abstract from growth consideration: there is no exogenous population growth or technical progress ($z_{ss} = 0$). Other stationary shocks are set to their mean: $\zeta_{U,ss} = \zeta_{V,ss} = \zeta_{H,ss} = 1$. The real oil price is equal to $p_{e,ss}$. In the non-stocastic staedy state, every endogenous variable is constant. We take the equations of the summary of the model one by one and derive the implied condition for the steady state equilibrium.

The steady state inflation is chosen by the central bank. The nominal interest rate is, then, implied by:

$$1 = (1 + i_{ss})\, \beta / (1 + \pi_{ss}) \tag{49}$$

The determining equations of some endogenous variables simplify dramatically:

$p_{ss}^* = 1$, $a_{ss} = 1$,$\pi_{ss}^w = \pi_{ss}$ and $w_{ss}^* = w_{ss}$.

The other endogenous variables solve the following system:

$$x_{ss} = \delta k_{ss} \tag{50}$$

$$\lambda_{ss} = (1 - \beta b_c) U_c \left((1 - b_c) c_{ss}, (1 - b_e) e_{c,ss} \right) \tag{51}$$

$$\lambda_{ss} p_{e,ss} = (1 - \beta b_e) U_e \left((1 - b_c) c_{ss}, (1 - b_e) e_{c,ss} \right) \tag{52}$$

$$1 = \psi_{ss} \tag{53}$$

$$1 = \beta \left(r_{ss} + 1 - \delta \right) \tag{54}$$

$$\lambda_{ss} w_{ss} = \mu_w V_h (h_{ss}) \tag{55}$$

$$d_{ss} = F \left(G (k_{ss}, e_{ss}), h_{ss} \right) \tag{56}$$

$$r_{ss} = \kappa_{ss} F_G \left(G (k_{ss}, e_{ss}), h_{ss} \right) G_k (k_{ss}, e_{ss}) \tag{57}$$

$$p_{e,ss} = \kappa_{ss} F_G \left(G (k_{ss}, e_{ss}), h_{ss} \right) G_e (k_{ss}, e_{ss}) \tag{58}$$

$$w_{ss} = \kappa_{ss} F_n \left(G (k_{ss}, e_{ss}), h_{ss} \right)) \tag{59}$$

$$1 - \mu_p \kappa_{ss} = 0 \tag{60}$$

$$c_{ss} + p_{e,ss} e_{c,ss} + x_{ss} = d_{ss} - p_{e,ss} e_{ss} \tag{61}$$

B Implementing the model using DYNARE

To simulate the effects of real oil-price shocks in our model, we use DYNARE matlab toolbox (for further precisions, see Collard (2003)). To implement the model in DYNARE, we need to specify the functional forms used and to solve explicilty the model steady state.

B.1 Functional forms

The utility functions used is:

$$U(c,e) = \frac{1}{1-\sigma_U}\left(\left(\alpha_U c^{(\theta_U-1)/\theta_U} + (1-\alpha_U)\, e^{(\theta_U-1)/\theta_U}\right)^{\theta_U/(\theta_U-1)}\right)^{1-\sigma_U} \tag{62}$$

$$V(h) = \alpha_V \frac{1}{1-\sigma_V} h^{1-\sigma_V}, V'(h) = \alpha_V h^{-\sigma_V}, V''(h) = -\alpha_V \sigma_V h^{-\sigma_V - 1} \tag{63}$$

We clarify the derivatives of the utility over consumption and consumption of oil products:

$$U_c(c,e) = \alpha_U c^{-1/\theta_U} \frac{\left(\left(\alpha_U c^{(\theta_U-1)/\theta_U} + (1-\alpha_U)\, e^{(\theta_U-1)/\theta_U}\right)^{\theta_U/(\theta_U-1)}\right)^{1-\sigma_U}}{\alpha_U c^{(\theta_U-1)/\theta_U} + (1-\alpha_U)\, e^{(\theta_U-1)/\theta_U}} \tag{64}$$

$$= \alpha_U c^{-1/\theta_U} \frac{(1-\sigma_U)\, U(c,e)}{\alpha_U c^{(\theta_U-1)/\theta_U} + (1-\alpha_U)\, e^{(\theta_U-1)/\theta_U}} \tag{65}$$

$$U_e(c,e) = (1-\alpha_U)\, e^{-1/\theta_U} \frac{\left(\left(\alpha_U c^{(\theta_U-1)/\theta_U} + (1-\alpha_U)\, e^{(\theta_U-1)/\theta_U}\right)^{\theta_U/(\theta_U-1)}\right)^{1-\sigma_U}}{\alpha_U c^{(\theta_U-1)/\theta_U} + (1-\alpha_U)\, e^{(\theta_U-1)/\theta_U}} \tag{66}$$

$$= (1-\alpha_U)\, e^{-1/\theta_U} \frac{(1-\sigma_U)\, U(c,e)}{\alpha_U c^{(\theta_U-1)/\theta_U} + (1-\alpha_U)\, e^{(\theta_U-1)/\theta_U}} \tag{67}$$

The precise form of the investment adjustment cost function is not so determining, as long as there is no cost at the steady state.

$$H(X) = \alpha_H \frac{1}{1-\sigma_H} (X-1)^{1-\sigma_H}, H'(X) = \alpha_H (X-1)^{-\sigma_H}, H'(X) = -\alpha_H \sigma_H (X-1)^{-\sigma_H - 1} \tag{68}$$

The convexity assumptions on the labor desutility function and on the investment adjustment cost function imply $\sigma_V < 0$, and $\sigma_H < 0$.

The production technology is defined by:

$$F(G,n) = G^{\alpha_F} n^{1-\alpha_F} \tag{69}$$

$$G(k,e) = \left(\alpha_G k^{(\theta_G-1)/\theta_G} + (1-\alpha_G)\, e^{(\theta_G-1)/\theta_G}\right)^{\theta_G/(\theta_G-1)} \tag{70}$$

We calculate the derivatives of the production function:

$$F_G(G,n) = \alpha_F \left(\frac{n}{G}\right)^{1-\alpha_F} \tag{71}$$

$$F_n(G,n) = (1-\alpha_F)\left(\frac{G}{n}\right)^{\alpha_F} \tag{72}$$

$$G_k(k,e) = \alpha_G k^{(\theta_G-1)/\theta_G-1} \frac{G(k,e)}{\alpha_G k^{(\theta_G-1)/\theta_G} + (1-\alpha_G)\, e^{(\theta_G-1)/\theta_G}} \tag{73}$$

$$G_e(k,e) = (1-\alpha_G)\, e^{(\theta_G-1)/\theta_G-1} \frac{G(k,e)}{\alpha_G k^{(\theta_G-1)/\theta_G} + (1-\alpha_G)\, e^{(\theta_G-1)/\theta_G}} \tag{74}$$

B.2 Steady state derivation

$$\frac{e_{ss}}{k_{ss}} = \left(\frac{1-\alpha_G}{\alpha_G} \frac{r_{ss}}{p_{e,ss}} \right)^{\theta_G} \tag{75}$$

$$\frac{k_{ss}}{h_{ss}} = \left(\frac{\alpha_F (1-\alpha_G)}{p_{e,ss}\mu_P} \left(\frac{e_{ss}}{k_{ss}} \right)^{-1/\theta_G} \left(\alpha_G + (1-\alpha_G) \left(\frac{e_{ss}}{k_{ss}} \right)^{(\theta_G-1)/\theta_G} \right)^{\theta_G \alpha_F/(\theta_G-1)-1} \right)^{1/(1-\alpha_F)} \tag{76}$$

$$w_{ss} = \frac{1-\alpha_F}{\mu_P} \left(\frac{k_{ss}}{h_{ss}} \right)^{\alpha_F} \left(\alpha_G + (1-\alpha_G) \left(\frac{e_{ss}}{k_{ss}} \right)^{(\theta_G-1)/\theta_G} \right)^{\theta_G \alpha_F/(\theta_G-1)} \tag{77}$$

$$\frac{e_{c,ss}}{c_{ss}} = \frac{1-b_c}{1-b_e} \left(\frac{1-\alpha_U}{\alpha_U} \frac{1-\beta b_e}{1-\beta b_c} \frac{1}{p_{e,ss}} \right)^{\theta_U} \tag{78}$$

$$\frac{d_{ss}}{k_{ss}} = \left(\alpha_G + (1-\alpha_G) \left(\frac{e_{ss}}{k_{ss}} \right)^{(\theta_G-1)/\theta_G} \right)^{\theta_G \alpha_F/(\theta_G-1)} \left(\frac{k_{ss}}{h_{ss}} \right)^{\alpha_F-1} \tag{79}$$

$$\frac{y_{ss}}{k_{ss}} = \frac{d_{ss}}{k_{ss}} - s_e p_{e,ss} \frac{e_{ss}}{k_{ss}} \tag{80}$$

$$\frac{c_{ss}}{k_{ss}} = \frac{\frac{y_{ss}}{k_{ss}} - \delta}{1 + s_e p_{e,ss} \frac{e_{c,ss}}{c_{ss}}} \tag{81}$$

$$h_{ss} = \left(\frac{\mu_W \alpha_V}{(1-\beta b_c) w_{ss} \alpha_U} \left(\frac{(1-b_c)c_{ss}}{k_{ss}} \frac{k_{ss}}{h_{ss}} \right)^{\sigma_U} \left(\alpha_U + (1-\alpha_U) \left(\frac{1-b_e}{1-b_c} \frac{e_{c,ss}}{c_{ss}} \right)^{(\theta_U-1)/\theta_U} \right)^{1-\theta_U/(\theta_U-1)(1-\sigma_U)} \right)^{1/(\sigma} \tag{82}$$

C Some intuitions on "equivalent" programs

We present, here, some intuitions on how "equivalent" programs could be derived. The aim of "equivalent" programs is to simplify the model, such that complicated shocks, for example a real oil-price shock, can be viewed as the combination of more usual shocks. We assume that the utility and the production functions have the particular functional forms chosen in the simulation. More precisely, the production function combines as a Cobb-Douglas the capital - oil product aggregate with labor and utility is logarithmic. We claim (without proving it) that the properties derived here are robust to more general specifications. To derive the "equivalent" programs, we extensively use the siolution of the non-stochastic steady state presented just above in subsection C.1.

C.1 The firm program

The production function can be written:

$$F\left(G\left(k,e\right),h\right)=F\left(G\left(\frac{e}{k}\right),1\right)F\left(k,h\right)$$

Moreover, (75) in subsection shows oil intensity is a function of the real oil price, exclusively. Thus, we define:

$$a(p_e)=F\left(G\left(\frac{e}{k}\right),1\right)$$

Consequently, the GDP supply side can be written as:

$$\begin{aligned} GDP &= F\left(G\left(k,e\right),h\right)-p_e e \\ &= a(p_e)F\left(k,h\right)-p_e e \\ &= \left(F\left(1,\frac{h}{k}\right)\right)^{-1}\left(a(p_e)F\left(1,\frac{h}{k}\right)-p_e\frac{e}{k}\right)F\left(k,h\right) \end{aligned}$$

In addition, combining (75) and (76), it can be shown that, at the steady state, the capital - labor ratio depends on the real interest rate and the real oil price only. It can, also, be proved that this ratio decreases with real oil price. Thus, we can define:

$$A(p_e)=\left(F\left(1,\frac{h}{k}\right)\right)^{-1}\left(a(p_e)F\left(1,\frac{h}{k}\right)-p_e\frac{e}{k}\right)$$

. Using (58), the second factor of the latter expression can be written:

$$a(p_e)F\left(1,\frac{h}{k}\right)-p_e\frac{e}{k}=\frac{r\mu_P}{\alpha_G}\left(\alpha_G+(1-\alpha_G)\left(\frac{e}{k}\right)^{1-1/\theta_G}\left(1-(r\mu_P)^{-1}\right)\right)$$

. Because $r << 1$, it is also decreasing in p_e. As a consequence, $A'(p_e)<0$.

Note that the original program and a new program with monopolistic firms whose production function is GDP are not fully equivalent. The first order conditions of the original program (57), (58) and (59) cannot be reduced as:

$$
\begin{aligned}
r &= \kappa A(p_e) F_k\left(k,h\right) \\
w &= \kappa A(p_e) F_n\left(k,h\right)
\end{aligned}
$$

C.2 The household program

We abstract from habit formation. In fact, for the following manipulation, habit formation does not matter. Because, at the steady state, the latter reduces to a multiplicative constant. To derive the following expressions of the utility function and of the consumption expenditures, we use (78):

$$
\begin{aligned}
U(c,e_c) &= log(c) + \frac{\theta_U}{\theta_U - 1} log(\alpha_U + (1-\alpha_U)\left(\frac{1-\alpha_U}{\alpha_U}\right)^{\theta_U - 1} p_e^{1-\theta_U}) \\
c + p_e e_c &= \left(1 + \left(\frac{1-\alpha_U}{\alpha_U}\right)^{\theta_U - 1} p_e^{1-\theta_U}\right) c
\end{aligned}
$$

We define:

$$
\begin{aligned}
U(p_e) &= \frac{\theta_U}{\theta_U - 1} log(\alpha_U + (1-\alpha_U)\left(\frac{1-\alpha_U}{\alpha_U}\right)^{\theta_U - 1} p_e^{1-\theta_U}) \\
P(p_e) &= \left(1 + \left(\frac{1-\alpha_U}{\alpha_U}\right)^{\theta_U - 1} p_e^{1-\theta_U}\right) c
\end{aligned}
$$

, and verify that $U' < 0$ and $P' < 0$.

As well as, in the firm case, the original household program and the new program including the previous modifications are not equivalent. This is due to the first order conditions of the original program (51) and (52), which cannot be reduced to:

$$
\lambda P(p_e) = 1/c
$$

D Steady state simulation results

D.1 Static comparisons along the elasticity of substitution between capital and oil products

Figure 17: *Long-term reactions of macroeconomic ratios (in level) to variations in the elasticity of substitution between capital and oil products (in percentage).*

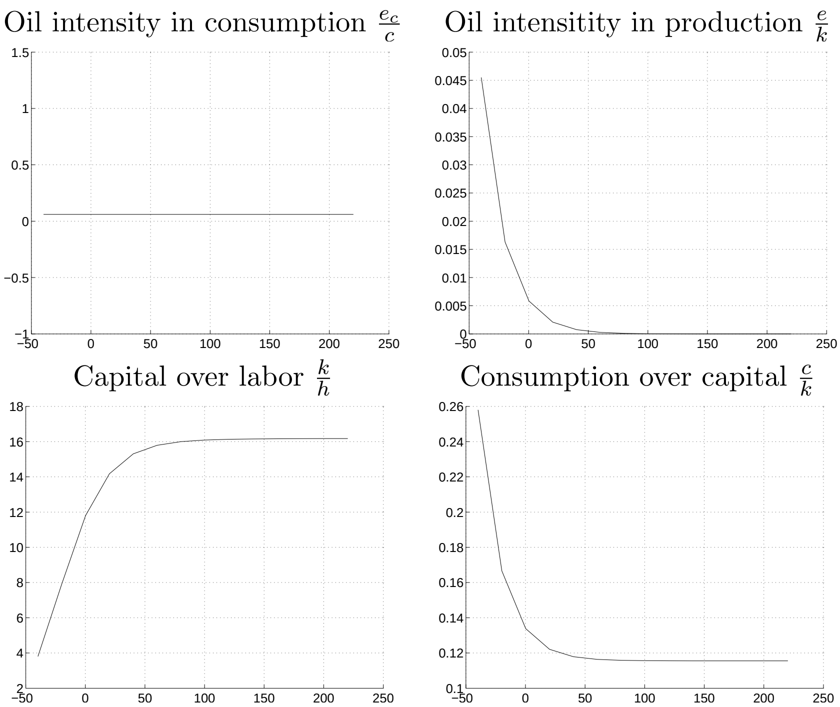
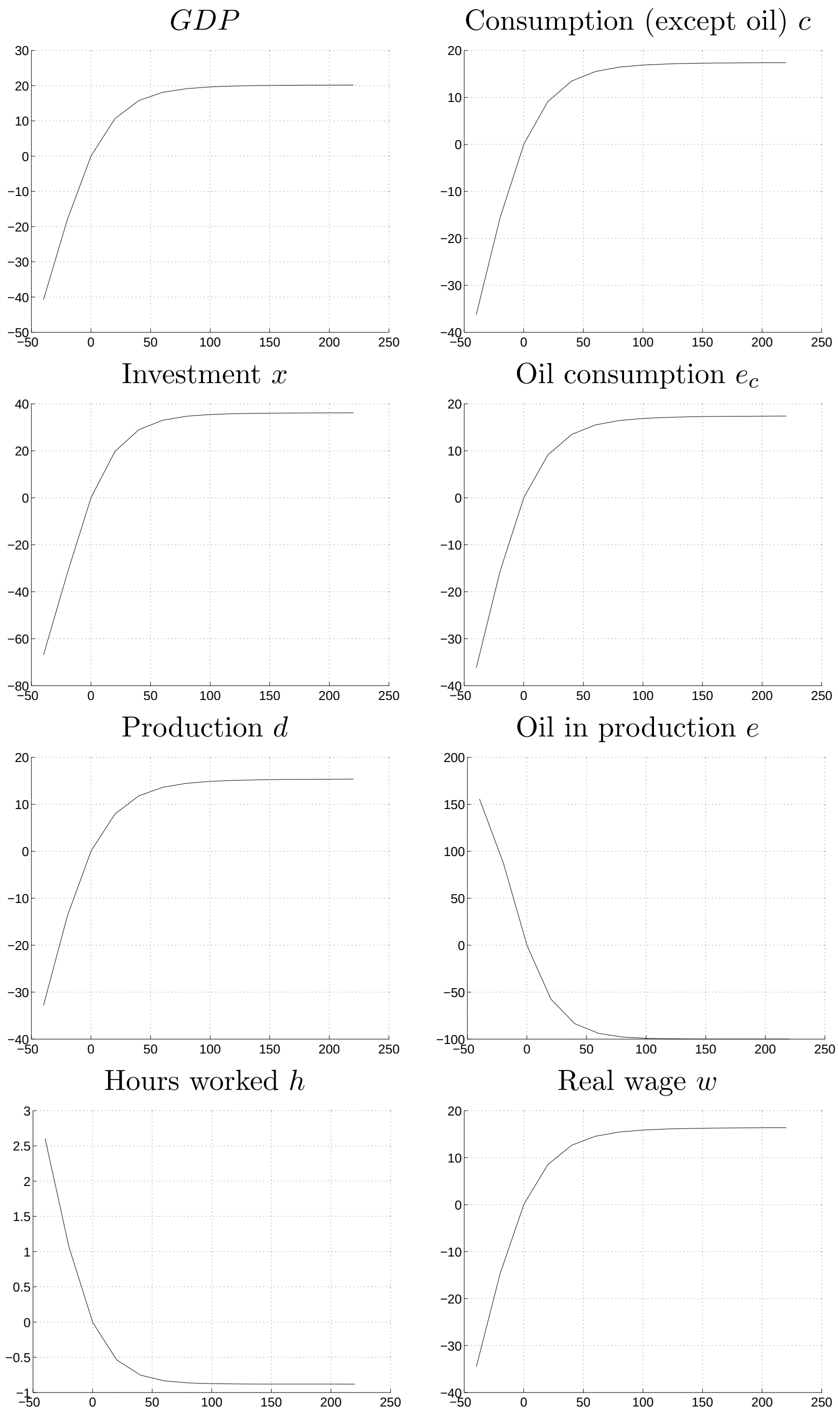


Figure 18: *Long-term reactions (in percentage) to variations in the elasticity of substitution between capital and oil products (in percentage)*



D.2 Static comparisons along the weight on capital in the capital - oil product aggregate

Figure 19: *Long-term reactions of macroeconomic ratios (in level) to variations in the weight on capital in the capital - oil products aggregate (in percentage).*

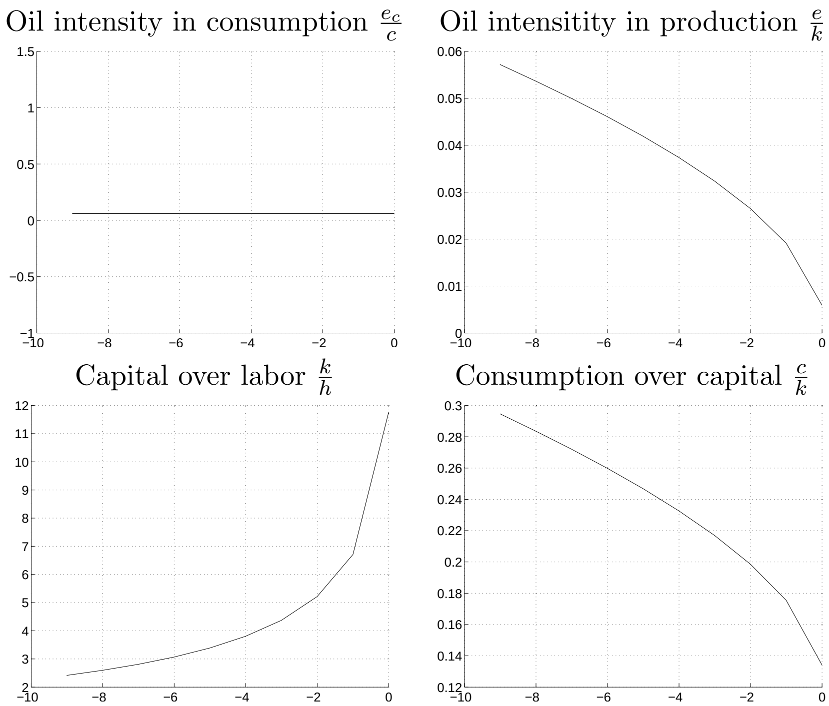
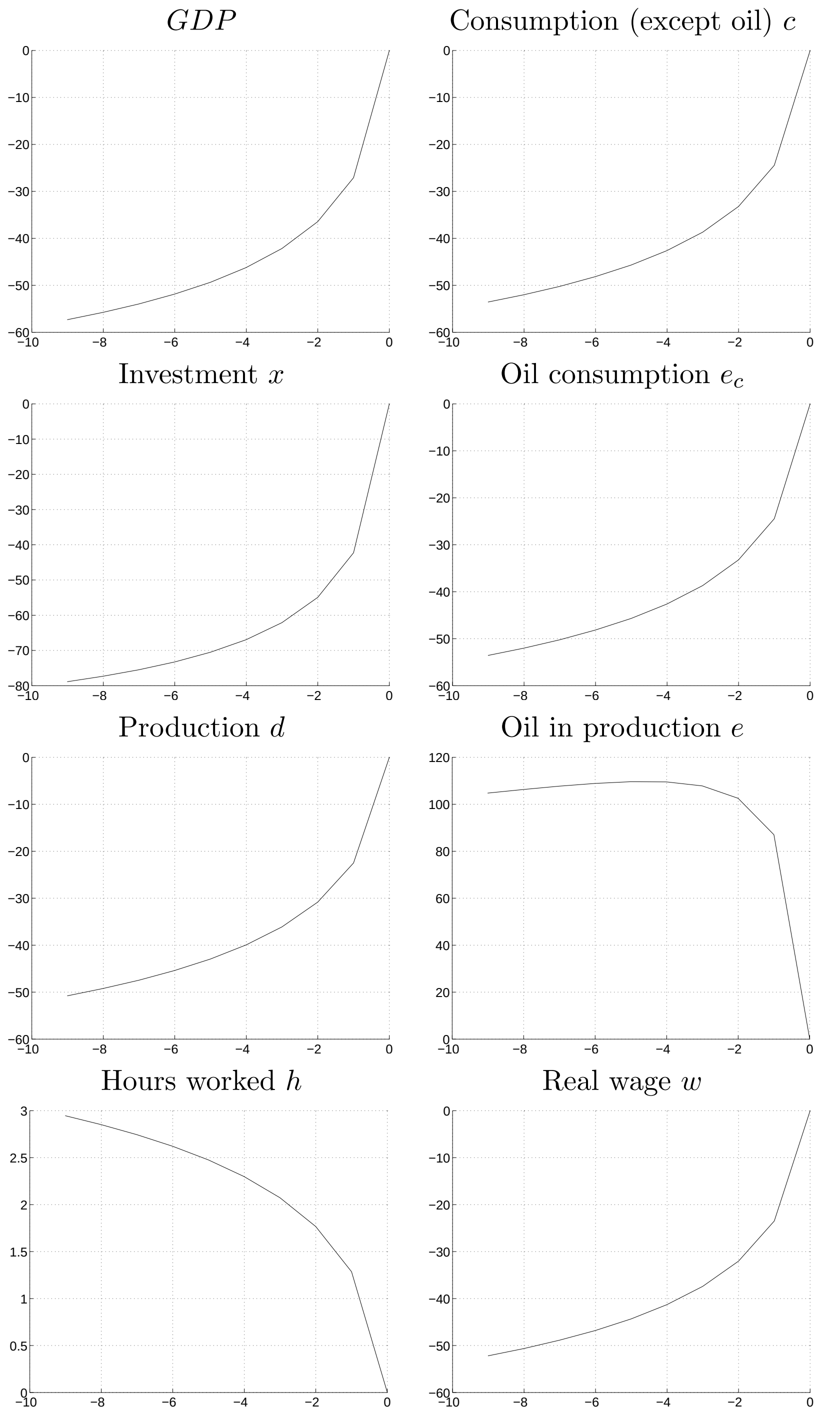


Figure 20: *Long-term reactions (in percentage) to variations in the weight on capital in the capital - oil product aggregate (in percentage)*



D.3 Static comparisons along the degree of monopolistic competition in the good market

Figure 21: *Long-term reactions of macroeconomic ratios (in level) to variations in the mark-up on the good market (in percentage).*

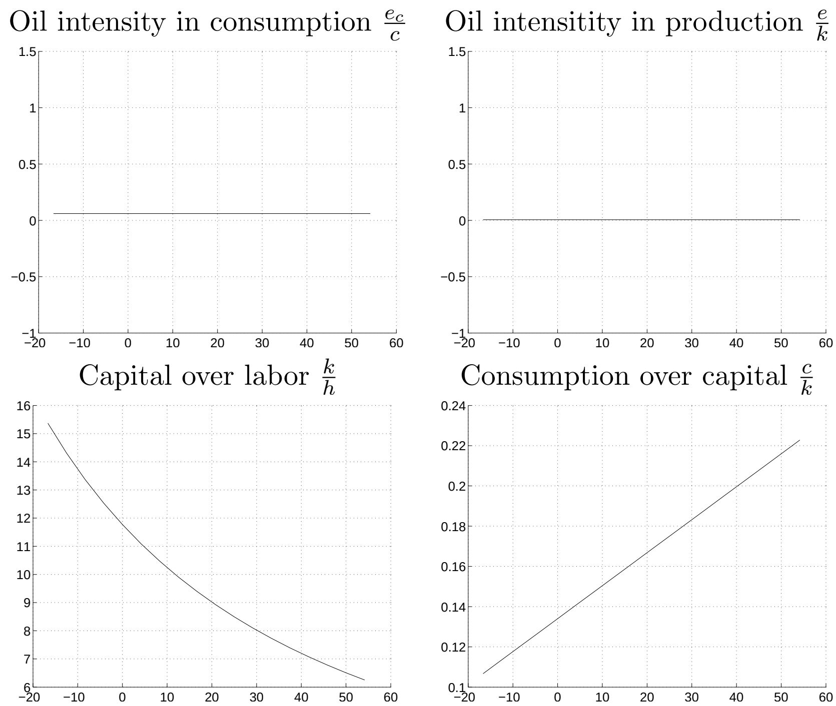
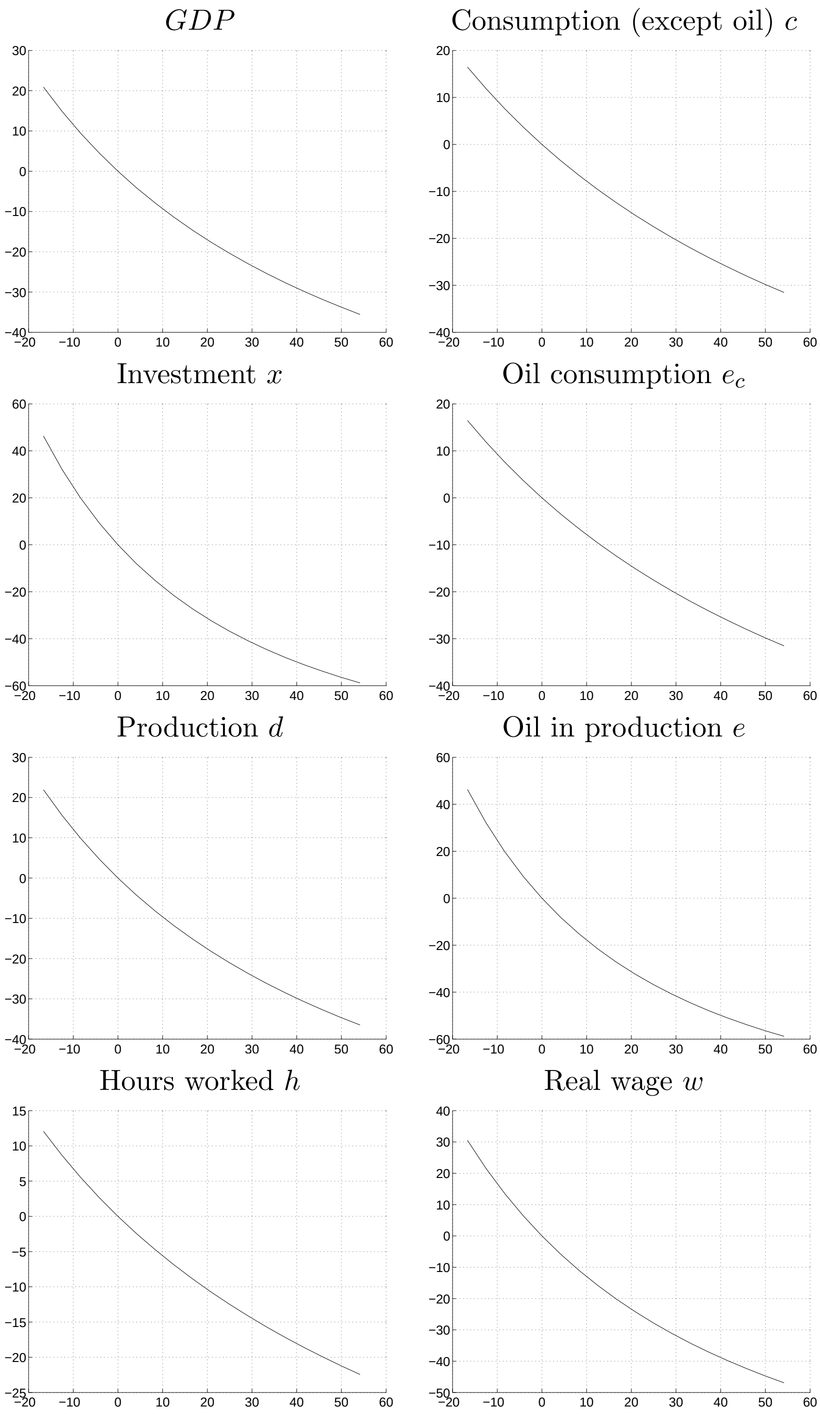


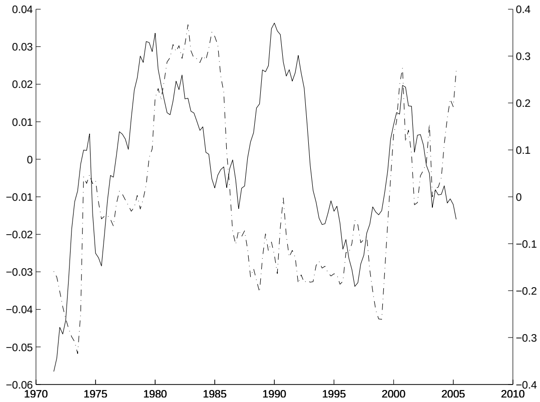
Figure 22: *Long-term reactions (in percentage) to variations in the mark-up on the good market (in percentage)*



E Details of the VAR estimation of the GDP response to a permanent nominal oil-price shock

The endogenous series of the VAR model are drawn on the following figure 23.

Figure 23: *The endogenous variables of the VAR model (log-detrended and drawn in logs).*



Reading the graph: the solid line corresponds to GDP (scale on left), the dashed one to IPPI (scale on right).

We, now, detail the estimated VAR model that leads to a significant response of GDP to an oil price shock. Notations are identical to those of the model except for the nominal oil price P_{brent}. The variables are cleaned for their exponential growth rate and recentered so that we correctly interpret the response to the exogenous shock, i.e. in deviation from its long-term equilibrium. In the following VAR model, we indicate the t-values of each estimated coefficient (under the estimated value of the corresponding coefficient). The hypothesis of overall nullity of coefficients is rejected.

$$\begin{pmatrix} \ln p_{e,t} \\ \ln GDPt \end{pmatrix} = \begin{pmatrix} \underset{(6.80)}{1.20} & \underset{(-0.31)}{-0.55} \\ \underset{(-0.26)}{-0.005} & \underset{(5.33)}{1.02} \end{pmatrix} \begin{pmatrix} \ln p_{e,t-1} \\ \ln GDP_{t-1} \end{pmatrix} + \begin{pmatrix} \underset{(-1.58)}{-0.46} & \underset{(-0.29)}{-0.70} \\ \underset{(-0.79)}{-0.03} & \underset{(-0.60)}{-0.15} \end{pmatrix} \begin{pmatrix} \ln p_{e,t-2} \\ \ln GDP_{t-2} \end{pmatrix} +$$

$$\begin{pmatrix} \underset{(0.60)}{0.18} & \underset{(0.87)}{2.05} \\ \underset{(-0.44)}{-0.01} & \underset{(-0.09)}{-0.02} \end{pmatrix} \begin{pmatrix} \ln p_{e,t-3} \\ \ln GDP_{t-3} \end{pmatrix} + \begin{pmatrix} \underset{(-0.15)}{-0.03} & \underset{(-0.46)}{-0.61} \\ \underset{(0.15)}{0.004} & \underset{(-0.09)}{-0.01} \end{pmatrix} \begin{pmatrix} \ln p_{e,t-4} \\ \ln GDP_{t-4} \end{pmatrix} +$$

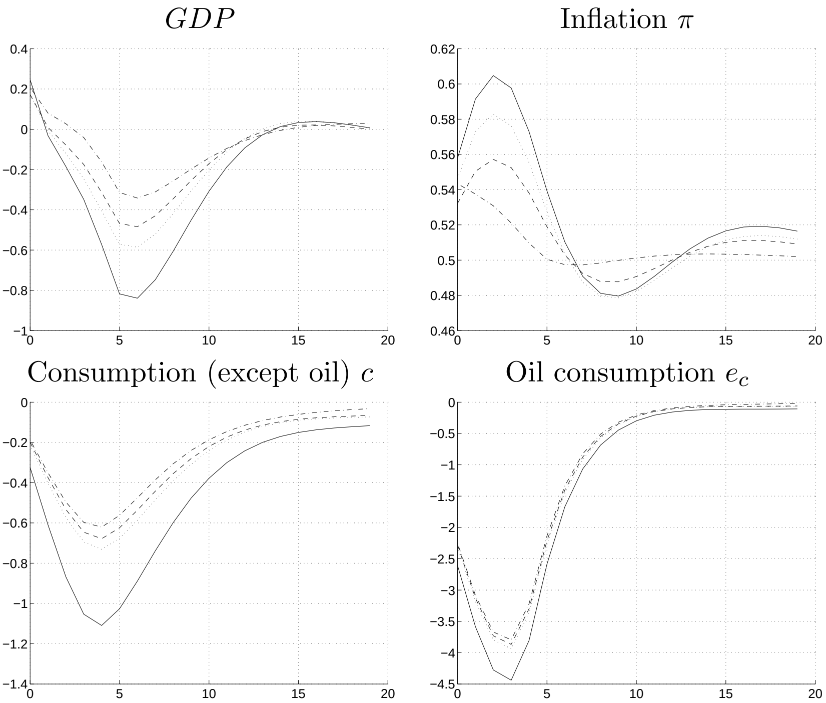
$$\begin{pmatrix} \underset{(2.62)}{0.14} \\ \underset{(-0.85)}{-0.005} \end{pmatrix} \Delta \ln P_{brent,t} + \begin{pmatrix} \underset{(-0.84)}{-0.05} \\ \underset{(-0.46)}{-0.003} \end{pmatrix} \Delta \ln P_{brent,t-1} + \begin{pmatrix} \underset{(1.62)}{0.09} \\ \underset{(1.29)}{0.008} \end{pmatrix} \Delta \ln P_{brent,t-2} +$$

$$\begin{pmatrix} \underset{(0.11)}{0.007} \\ \underset{(-1.52)}{-0.01} \end{pmatrix} \Delta \ln P_{brent,t-3} + \begin{pmatrix} \underset{(0.52)}{0.03} \\ \underset{(-0.58)}{-0.003} \end{pmatrix} \Delta \ln P_{brent,t-4} + \begin{pmatrix} \underset{(-1.20)}{-0.06} \\ \underset{(-0.36)}{-0.002} \end{pmatrix} \Delta \ln P_{brent,t-5}$$

F Response to a transitory real oil price shock: perfect foresight version

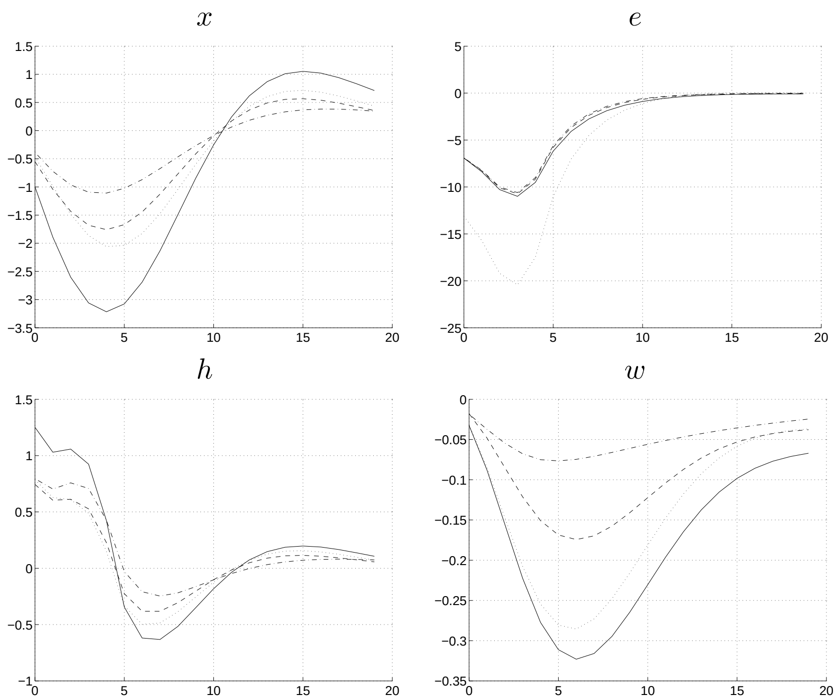
Under perfect foresight, the real oil-price shock is generated by a single innovation at date $t = 0$. Then, the real oil price evolves according to an ARMA structure, inducing a hump-shaped response. As a consequence, once the innovation has been drawn, agents exactly predict the evolution of the real oil price and of the economy as a whole.

Table 3: *Model's responses (deviation in percentage) to the estimated real oil-price shock - under perfect foresight.*



Reading the graphs: the solid line corresponds to the model calibrated on the first sub period, the dashed one to the model calibrated on the second subperiod, the dotted one to the model calibrated on the second subperiod with θ_G revisited, the dash-dot one to the model calibrated on the second subperiod with no indexation on past inflations. For π, the level is plotted in base point (it is not a deviation in pourcentage as for the other variables).

Table 4: *Model's responses (deviation in percentage) to the estimated real oil price shock - under perfect foresight (2).*



Reading the graphs: the solid line corresponds to the model calibrated on the first sub period, the dashed one to the model calibrated on the second subperiod, the dotted one to the model calibrated on the second subperiod with θ_G revisited, the dash-dot one to the model calibrated on the second subperiod with no indexation on past inflations.