Methodological proposal for hybrid modelling : consequences for climate policy analysis in an open economy (France)

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Résumé

Cette thèse aborde les enjeux de l'hybridation des données pour la modélisation énergie-économie-environnement, et ses implications pour la politique climatique dans le cas de la France. Le travail met l'accent sur l'importance de construire une représentation hybride de l'économie, articulant de façon cohérente le cadre économique de la comptabilité nationale et les flux physiques, fournis par des bilans de matières (ex : bilan énergétique). Partant du principe qu'il est possible de réduire les incertitudes dans la recomposition des données grâce à des contraintes d'équilibres de flux, cette thèse met d'abord en place une méthode permettant de dépasser les problèmes de nomenclatures non cohérentes, de données disparates, ou simplement manquantes. Nous montrons que l'hybridation permet de décrire plus précisément le poids de l'énergie dans l'appareil productif français, ainsi que celui de certains secteurs de l'économie (ciment, acier). Le cadre hybride sert alors de base au modèle d'équilibre général Imaclim . Ce modèle sert à explorer dans quelle mesure la comptabilité hybride permet de renouveler la discussion sur l'introduction d'une taxe carbone unilatérale en France. Nous mesurons d'abord l'importance de la procédure d'hybridation dans l'évaluation de l'impact macroéconomique de la politique climatique. La désagrégation sectorielle nous permet, dans un second temps, de conduire une discussion autour de paramètres centraux mais controversés de la modélisation : les élasticités-prix du commerce international, et la courbe salaire-chômage interprétée comme un indicateur du pouvoir de négociation des salaires. La thèse montre en particulier qu'il est possible, grâce au progrès sur la description sectorielle, de prendre en compte une hétérogénéité des régimes de formations salariales entre secteurs tout en les reliant à leur niveau d'exposition au commerce extérieur. Enfin, la thèse propose une méthode pour évaluer différents inventaires des émissions de CO_2, tels que les émissions liées à la consommation, ou les émissions incorporées dans les importations, tout en s'appuyant sur le cadre hybride. Ainsi, nous fournissons des informations originales sur les moteurs des émissions en France qui permettront de prolonger l'analyse à d'autres mesures telles que l'ajustement d'une taxe carbone aux frontières.

Mots-clés : modèle Imaclim politique climatique, modèle hybride, équilibre générale, compétitivité, analyse macroéconomique, inventaire d'émissions.

Abstract

This thesis addresses the issue of data hybridisation for energy-economy-environment modelling and its implications for climate policy in the case of France. The work emphasises the importance of building a hybrid representation of the economy, articulating coherently the economic framework of national accounts and the physical flows, provided by sectoral database (energy balance, industrial statistics). Assuming that it is possible to reduce the uncertainties of data construction, thanks to the equilibrium constraints of flows, this thesis first introduces a method which overcomes the problems of non-coherent nomenclatures, disparate data, or simply missing ones. We show that this hybridisation procedure allows to better describe the weight of both the energy in the French productive system and key sectors of the economy (cement, steel). The hybrid framework then serves to feed the Imaclim general equilibrium model. The model is used to explore to what extent the hybrid accounts give an opportunity to renew discussion on the introduction of a unilateral carbon tax in France. We first measure the importance of the hybridisation procedure for assessing the macroeconomic impact of climate policy. Then, the sectoral disaggregation allows us to conduct a discussion around central but controversial parameters of modelling: the international trade elasticity and the wage curve interpreted as an indicator of the wage bargaining power. The thesis shows in particular that it is possible, thanks to the progress on the sectoral description, to take into account heterogeneous representation of wage formation between sectors while linking them to their level of exposure to external trade. Finally, the thesis proposes a methodology to evaluate different emission inventories of CO_2, such as "consumption-based" emissions, and emissions embodied in imports while relying on the hybrid framework. We thus provide original insights on the drivers of emissions in France which could extend the analyses to other policies such as the adjustment of a carbon tax at the borders.

Keywords: Imaclim model, climate policy, hybrid model, general equilibrium, energy-intensive and trade-exposed sector, competitiveness, macroeconomic assessment, emission inventories.

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Le CIRED, c'est aussi un cadre de travail incroyable, entouré d'arbres, d'oiseaux, de grenouilles, de chouettes, et surtout de gens aussi intéressants que sympathiques. Lors de ma première arrivée au *Jardin Tropical* en tant que doctorante, je me souviens avoir été "inquiète" de devenir sédentaire pour trois ans. Je ne me doutais pas que cette sédentarisation serait l'opportunité de me lier si fortement d'amitié avec autant de personnes, et que nous partagerions bien plus que la science. Il y a d'abord la "team bateau", puis la "team escalade", et la "team jambon", ou encore la "team juste une bière" (mais qui dérape à coup -presque- sûr). William et Elsa alias Momo, mes compagnons de grimpe (ou de bières). Grâce à eux, j'ai redécouvert une activité, me motivant à finir les objectifs de la journée pour partir avec eux à la salle de block (ou à la bière). Avec son côté pragmatique et calme, Manon m'a donné bien du courage pendant les moments difficiles du doctorat que nous avons traversé ensemble. Nous avons beaucoup partagé et échangé sur tout un tas de sujet, et cela va continuer. Manon a aussi réussi là où beaucoup ont échoué : me réconcilier avec le bateau ! Meriem avec son énergie a bien été présente pour me (re)dynamiser quand mon moral était au plus bas. Formidable coach de fin de thèse, je n'oublierai pas ce qu'elle a fait pour moi lors de la vraie dernière ligne droite, pour ne pas que je baisse les bras, et m'aider à réaliser que je pouvais terminer dans le temps donné. Yaël a été une véritable amie au CIRED. Elle a ramené de la sérénité à mes pensées irrationnelles un nombre incalculable de fois. Toujours à l'écoute, toujours là pour rire, toujours là pour m'aider, et partager nos quotidiens. Au-delà de son soutien professionnel, et malgré nos innombrables fausses confrontations et prises de tête sur des sujets aussi futiles que profonds, Manu a une place de taille dans ces amitiés crediennes. Avec Arancha nous partageons deux langues (mais absolument pas l'accent), des loisirs communs et surtout la passion pour le jambon, qui a permis d'instaurer un événement annuel que nous attendons tous ! L'apéro-jambon est devenu notre moment à ne pas manquer ! Il y a aussi Aurélie, Christophe, Catherine ou encore Philippe ; des personnes de confiances avec qui je sais que je peux échanger franchement. Enfin, je pense à Carolina, je suis ravie qu'elle ait quitté Rio pour effectuer une partie de sa thèse parmi nous. Sans eux, je n'aurai pas mené "aussi sereinement" ma thèse (Ciel ! qu'est-ce que cela aurait donné si je n'avais pas été sereine, personne ne veut savoir !).

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À Victoria, À Hervé,
À Alain,
À Yolanda, À Alain

Résumé long

Introduction

Le travail de thèse, résumé ici, s'est largement déroulé dans le contexte de préparation de la 21ème Conférence des Parties (COP) en décembre 2015 à Paris marquant la fin d'un changement progressif de paradigme de la négociation-climat. Ce tournant, entamé à Cancun (Hourcade et al., 2015), s'est concrétisé par la signature de l'*Accord de Paris*. Le cœur de cet accord ne repose plus sur l'allocation d'un budget carbone, par pays, et la mise en place d'un marché carbone, pour respecter un objectif donné de stabilisation des températures (+2°C), mais sur des contributions climats volontaires à l'échelle nationale (NDCs).
Au lieu d'une approche *top-down* de répartition d'un droit à polluer, on adopte une démarche *bottom-up* où les gouvernements élaborent leurs propres plans de transition vers une économie bas carbone ; à charge pour la communauté internationale de mettre en place des mécanismes de collaboration, en particulier sur le plan financier, pour faciliter leur mise en œuvre et renforcer leur ambition. Ainsi, en France, la loi relative à la transition énergétique pour la croissance verte[1] définit les objectifs à atteindre pour les décennies à venir. La Stratégie Nationale Bas Carbone (SNBC) et la Programmation pluriannuelle de l'énergie (PPE) proposent les leviers sectoriels envisageables pour les atteindre.

Ce changement de paradigme à des implications pour la modélisation hybride énergie-économie-environnement (E3) en tant qu'outils d'aide à la décision. En effet, jusqu'alors, on pouvait s'appuyer sur des modèles mondiaux décrivant l'émergence d'un prix unique du carbone, et de son impact macro-économique global, pour différentes clés de répartition des droits d'émissions. Malgré une description plutôt agrégée des différents acteurs économiques, les modèles ont dû, peu à peu, intégrer de façon plus fine les contraintes techniques qui pèsent sur l'adaptation de ces acteurs. En effet, le maniement juxtaposé des modèles d'équilibre général calculable et des modèles technico-économiques ne permet pas d'analyser de façon suffisamment précise l'influence de ces contraintes sur les marges de manœuvres réellement disponibles ni pour le système productif (constance des élasticités de la fonction de production),

[1] Publiée au Journal Officiel du 18 août 2015.

ni pour les consommateurs (rigidités dues à la réalité des équipements et des infrastructures). Cela a débouché sur plusieurs essais autour de la modélisation hybride (Hourcade et al., 2006) dont la thèse de Lefèvre (2016) en propose une synthèse. L'enjeu scientifique est de poursuivre cette évolution puisqu'il faut désormais être en mesure de représenter l'articulation entre des politiques sectorielles à un niveau plus fin, des standards et des réglementations techniques, et des pratiques tarifaires spécifiques au contexte institutionnel d'un pays. Cette description est décisive pour comprendre la réalité des enjeux de compétitivité et d'acceptabilité sociale des mesures climatiques.

L'essentiel des travaux de cette thèse porte donc sur la modélisation hybride en repartant de son principe de base : une description duale de l'économie, en valeur et en quantités physiques, nécessaire pour obtenir un dialogue maitrisé entre modèles d'ingénieurs et modèles économiques. Elle prend comme cas d'étude le modèle Imaclim . Que cela soit dans sa version mondiale ou nationale, de nombreuses thèses au CIRED ont contribué à repousser les défis méthodologiques pour rendre le modèle plus apte à l'étude de scénarios pour l'atténuation au changement climatique.
Nous nous appuyons sur la version nationale du modèle, Imaclim-S France , qui permet d'étudier les NDCs tout en prenant précisément en compte les spécificités du pays (fiscalité, situation sociodémographique, etc.). Au commencement de la thèse, le modèle se déclinait en une version française et une brésilienne. Nous sommes parti du double-constat suivant :

- sur la technique : chaque version d'Imaclim-S est développée séparément. L'existence d'une plateforme commune faciliterait l'extension de la capacité de modélisation.
- sur les méthodes : des points doivent être éclaircis et discutés, que cela soit sur la justification du traitement des données, le niveau de représentation sectoriel utilisé, ou la façon de modéliser différentes visions du monde (ouverture au commerce international, formation des salaires).

Bien que la thèse prenne comme fil directeur les questions clefs autour de l'analyse des politiques climatiques (impact de la hausse des coûts du carbone sur la compétitivité, les revenus, l'emploi, etc.), sa contribution est essentiellement méthodologique. Le but est d'abord de souligner l'importance des techniques d'élaboration d'une comptabilité duale. Il s'agit ensuite de montrer comment un paramétrage controversé peut être utilisé pour établir un dialogue entre les différents acteurs économiques, et ce à plusieurs échelles de granularité : d'un niveau macro (impacts sur l'emploi, la dette, etc.) à un niveau plus fin (secteurs industriels). C'est pourquoi les travaux proposent des tests numériques balayant de larges intervalles de comportements pour mettre en évidence les principaux mécanismes à l'œuvre dans l'économie réelle, et comprendre les interactions entre plusieurs paramètres incertains (élasticités des échanges extérieurs, courbe salaire-chômage).

Chapitre 1 - La procédure d'hybridation

La description duale met en cohérence des flux physiques (par exemple les bilans énergétiques) et des flux monétaires sous forme de "matrices hybrides". Nous regroupons ce travail de traitement des données sous le nom de "procédure d'hybridation".
Différentes procédures d'hybridation existent pour obtenir une description duale de l'économie mondiale (Mcdougall and Lee, 2006; Rutherford and Paltsev, 2000; Sands et al.) avec différentes hypothèses pour retrouver une cohérence comptable[2].

La procédure développée pour la plateforme de modélisation Imaclim -pays s'attache à préserver l'information statistique la plus pertinente pour l'analyse énergie-économie-environnement. De fait, elle préserve la taille de l'économie ainsi que celles des grands agrégats monétaires fournis par la comptabilité nationale (valeur ajoutée, etc.), et elle intègre des données sectorielles en quantité physique, et en prix, selon le niveau de détail souhaité.

Concrètement, la procédure Imaclim se résume en deux étapes principales schématisées par la Figure 1. La première étape consiste à réorganiser les données de statistiques physiques (bilan énergétique en Mtep, production en tonne d'acier et de ciment) et les prix dans un format "entrées-sorties" compatible avec celui des comptes nationaux (harmonisation des nomenclatures, ventilation des usages et des ressources). Dans une deuxième étape, le tableau des factures de "matières" (en euros), reconstitué par le produit terme-à-terme des tableaux en volumes et en prix, remplace les factures du Tableau Entrées-Sorties (TES) de la comptabilité nationale. Ces factures ne sont spontanément pas cohérentes, et les écarts sont reportés en dehors de la description des flux physiques, sur le bien composite. Cette dernière étape permet de ne changer ni le niveau de richesse économique (*PIB*), ni l'ensemble des informations issues des statistiques spécifiques, et de reporter tous les ajustements sur un agrégat d'activités non critique pour la transition énergétique.

La procédure a été initialement développée pour les bilans énergétiques afin d'articuler les modèles macroéconomiques avec des modèles *technico-économiques* décrivant les systèmes énergétiques. Par rapport aux travaux antérieurs, nous franchissons une étape supplémentaire pour étendre la méthodologie à d'autres flux physiques, à savoir l'acier et le ciment. La méthode nous permet de reconstituer une représentation duale, en unités physiques et en monnaie, pour ces secteurs, initialement regroupés dans des agrégats sectoriels (métallurgie et minéraux non-métalliques).
La méthode a été appliquée à l'économie française pour l'année 2010, en considérant 15 produits

[2] Dans le manuscrit, nous comparons notre méthode à celle du modèle SGM, mais nous ne présentons pas cette dernière dans ce résumé.

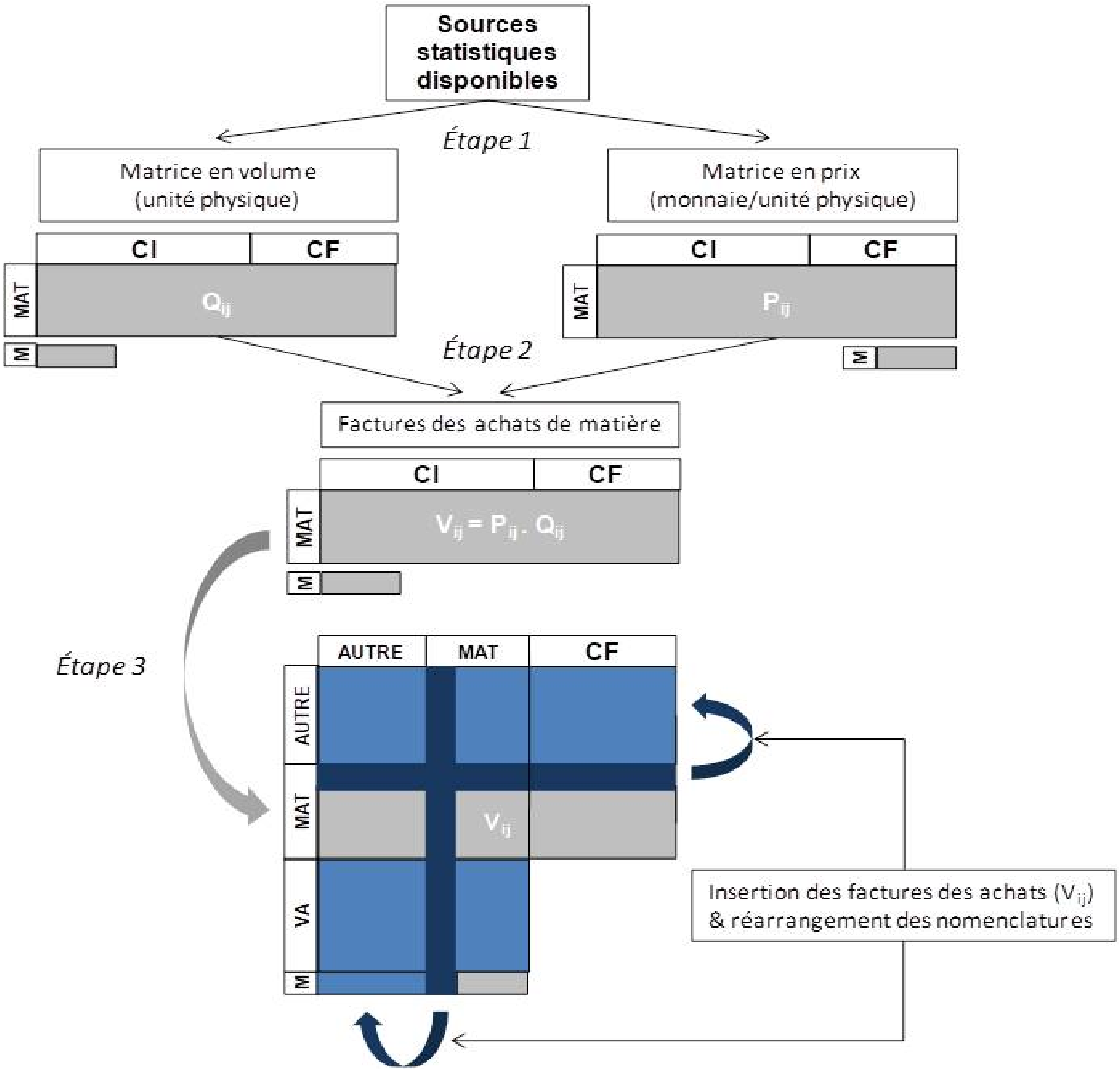


FIGURE 1 – Procédure d'hybridation pour IMACLIM

énergétiques[3], et 12 secteurs industriels[4].

La procédure d'hybridation change considérablement la description initiale de notre économie dont la taille globale reste pourtant la même, nous l'avons vu.

Dans un premier temps, nous montrons que la méthode corrige la taille et la répartition du secteur énergétique (agrégé) dans l'économie. Le Tableau 1 résume ces corrections.

France, 2010	**Comptabilité nationale** [a]	**TES Hybride Imaclim**[b]
Part de l'énergie dans l'économie	6,3%	4,3%
Ratio ménages/industries dans l'usage énergétique	0,5	0,8
Facture énergétique des ménages	7,4%	6,6%
Facture énergétique de la production	2,4%	1,7%

[a]Source : Institut national de la statistique et des études économiques (INSEE)
[b]Source : Calcul de l'auteur à partir des données de l'INSEE, l'AIE, ENERDATA

Table 1 – Différences macroéconomiques du système énergétique entre tableaux INSEE et Imaclim

On observe une baisse significative de l'énergie dans l'économie, et de la part des dépenses énergétiques à la fois pour les ménages et dans le système de production.
La réduction globale de l'énergie s'explique d'abord par le traitement des autoconsommations des secteurs énergétiques lors de la procédure. En effet, la comptabilité nationale enregistre dans ses TES des factures importantes, qui correspondent à un même volume d'énergie. Elles ont pour origine la libéralisation du marché, et en particulier le *trading* de l'électricité qui conduit à des échanges en valeur sans contre partie physique. Nous ne les prenons pas en compte dans le cadre comptable hybride.
Une autre partie de cet écart relève des différences de nomenclature. A l'inverse du cadre comptable Imaclim , la comptabilité nationale intègre les usages non-énergétiques de l'énergie (matières premières), et décrit ainsi une production plus vaste de la branche énergie. La procédure d'hybridation Imaclim s'attache, quant à elle, à décrire une production énergétique cohérente à celle soumise à une contrainte carbone.

Il est important de noter que le niveau de correction est très hétérogène lorsque l'on regarde le détail sectoriel (cf. Figure 2).

En raison essentiellement des différences de nomenclature, la correction est importante sur le secteur de la chimie et de la pharmacie, dont une grande part importante des dépenses

[3]Pétrole brut, Gaz naturel, Charbon à coke, Charbon bitumineux, Coke de charbon, Autres produits du charbon, Essence et bioéthanol, Gaz de pétrole liquéfié, Carburéacteur, Gazole et biodiesel , Fioul domestique , Fioul lourd, Autres produits pétroliers, Electricité, Chaleur, géothermie, solaire thermique.

[4]Sidérurgie, autre métallurgie, ciment, autre minéraux non ferreux, construction de bâtiments, chimie et pharmacie, papier et carton, extraction minière, équipement du transport, services de transport, agriculture et foresterie, pêche, industrie agroalimentaire

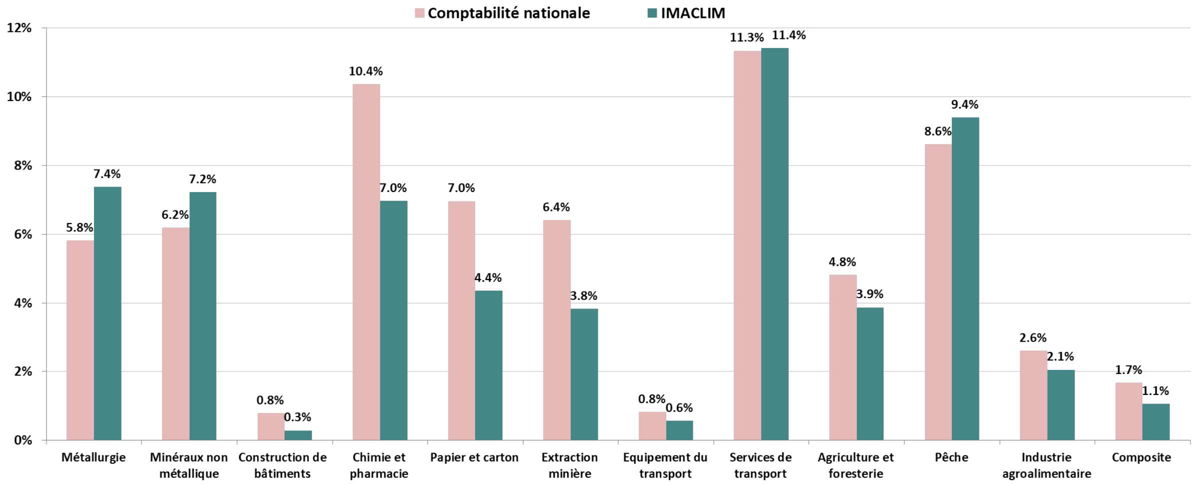


FIGURE 2 – Correction des dépenses énergétiques par secteur

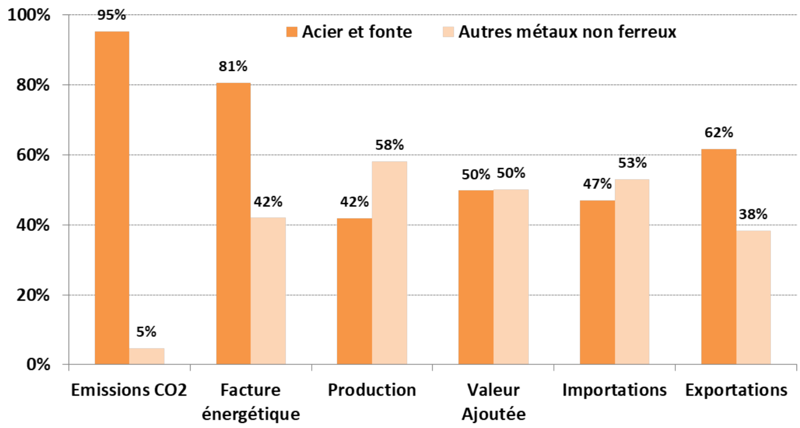
énergétiques est faite pour de la matière première à sa production. En revanche, nous notons que la part des coûts énergétiques des secteurs de la métallurgie et des minéraux non-métalliques a augmenté qui ont été en fait segmenté dans notre travail[5].

Au-delà des secteurs énergétiques, le travail d'hybridation a été étendu aux flux de l'acier et du ciment. En rassemblant un ensemble de données directement issues des sources statistiques sectorielles, nous isolons ces secteurs de leurs agrégats sectoriels initiaux pour prendre pleinement en compte leur hétérogénéité dans l'analyse. La Figure 3 illustre ces hétérogénéités.

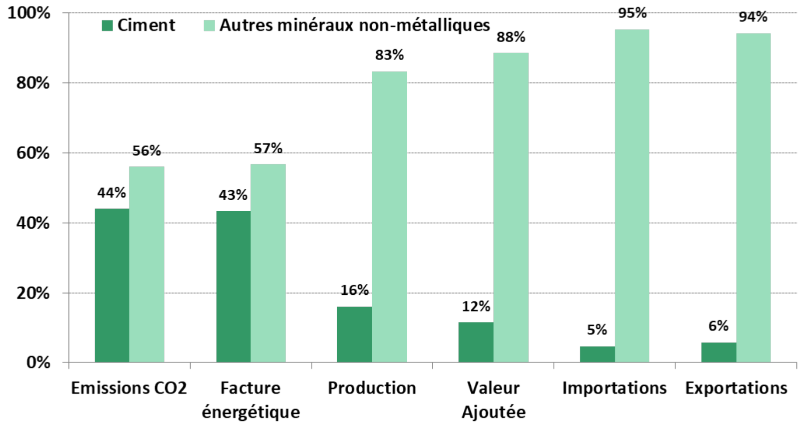
Au sein de la métallurgie (cf. Figure 3a), la transformation de l'acier représente moins de la moitié de la valeur ajoutée. Cependant, elle couvre, à cause de la cokéfaction, la grande majorité des dépenses énergétiques du secteur de la métallurgie, ainsi que la presque totalité des émissions de CO_2. Nous notons également que l'acier représente environ la moitié des échanges extérieurs de la métallurgie.
Au sein du secteur des minéraux non-métalliques (cf. Figure 3b), les hétérogénéités sont encore plus frappantes. Les ventilations des factures énergétiques et des émissions de CO_2 entre le ciment et le reste du secteur des minéraux non-métalliques sont assez équilibrées. Pourtant, les parts de la production, de la valeur ajoutée, et surtout, du commerce extérieur du ciment représentent une faible proportion au sein de l'agrégat des minéraux non-métalliques.

Ce diagnostic montre que l'hybridation est importante pour conduire des analyses de compétitivité à l'échelle d'un secteur. Sans ce gain en granularité sectorielle, nous ne contrôlons pas correctement les secteurs et les segments d'activités qui supportent le poids d'une politique environnementale conduisant à des effets macroéconomiques significatifs. Par ailleurs, nous

[5]Nous ré-agrégeons ces deux secteurs pour reconstituer les agrégats initiaux (métallurgie et minéraux non-métalliques) dans le but de comparer des parts énergétiques cohérentes à la comptabilité nationale.



(a) Métallurgie



(b) Minéraux non-métalliques

FIGURE 3 – Désagrégations sectorielles et hétérogénéités rétablies

verrons plus tard qu'une représentation sectorielle plus fine permet de modéliser différentes sensibilités (formation des salaires, degré d'exposition) suite à une hausse des prix domestique, et d'augmentation la précision de l'analyse.

La procédure d'hybridation pourrait être considérée comme purement technique si en pratique les trois sources majeures d'information (pour les valeurs, les prix et les volumes) étaient plus ou moins cohérentes spontanément, et si les différentes méthodes étaient "standardisées". Cependant, comme le montrent les résultats empiriques précédents, les écarts sont importants. Nous nous attendons à ce que les analyses d'une politique énergétique soient alors contrastées, entre un modèle calibré sur un TES de la comptabilité nationale, ou un TES hybride tel que nous l'avons constitué.

Chapitre 2 - Implications de la procédure d'hybridation sur l'analyse économique d'une politique environnementale

Dans la pratique, les modélisateurs ne s'attardent pas à détailler le processus d'hybridation des données pour développer les TES servant au calibrage de leurs modèles d'équilibre général calculable (EGC), et à notre connaissance aucune analyse de sensibilité des résultats de la modélisation aux données de référence n'existe réellement. Ce chapitre vise à révéler les impacts des traitements de données sur les évaluations des politiques énergétiques en utilisant un modèle EGC agrégé à deux secteurs (l'énergie et le reste) en économie ouverte. Le modèle est majoritairement basé sur des hypothèses néoclassiques. Une littérature croissante remet en question la pertinence de telles approches pour l'analyse de la politique énergétique, en particulier pour les changements techniques non marginaux sur le long terme (Hourcade et al., 2006). Néanmoins, nous conservons un cadre standard pour isoler la question spécifique des traitements de données et des innovations méthodologiques.

Nous calibrons alternativement le modèle EGC sur trois TES agrégés, donnant ainsi trois modèles construits sur la même base et prêts pour la simulation :

- ***TES comptabilité nationale*** : TES non hybride issu des comptes nationaux
- ***TES* Imaclim** : TES hybride issu de la procédure d'hybridation Imaclim présentée dans le chapitre précédent
- ***TES* Sgm** : TES hybride issu de la procédure d'hybridation du *Second Generation Model* (SGM)[6]

Nous évaluons ensuite les coûts en bien-être des réductions de consommation d'énergie permises par l'introduction d'une taxe sur les consommations énergétiques. L'objectif est d'examiner la dispersion des résultats liée à la variabilité des parts de coûts énergétiques de référence et à la ventilation de leurs consommations dans les différents TES.
Nous considérons trois types de politique en fonction des agents économiques ciblés par les objectifs de réduction de consommation énergétique : (i) la "*politique globale*" cible les ménages et les industries avec une taxe globale ; ii) la "*politique industrie*" ne cible que les entreprises, avec une taxe sur la consommation intermédiaire d'énergie ; iii) la *politique ménage* cible uniquement les ménages au moyen d'une taxe sur la demande finale spécifique. Nous utilisons un système de taxe qui s'appuie sur des volumes d'énergie. Cette caractéristique est cruciale dans un contexte de prix différenciés de l'énergie. Pour chaque type de politique, nous explorons un profil complet d'objectifs de réduction d'énergie - de 0% à 99%.

[6]Contrairement à la procédure Imaclim , celle-ci maintient un prix de l'énergie net-de-taxe identique pour tous les agents. Par soucis de concision, nous ne présentons pas les résultats issus de ce modèle dans ce résumé.

La hiérarchie des coûts en bien-être est identique et cohérente avec celle des systèmes énergétiques des bases de données utilisées pour le calibrage. En effet, le coût en bien-être est d'autant plus faible que la part des coûts énergétiques à l'année de référence est faible (cf. Tableau 1) pour l'ensemble des objectifs de réduction énergétique et pour tout type de politique (cf. Figure 4 pour la *politique globale*).

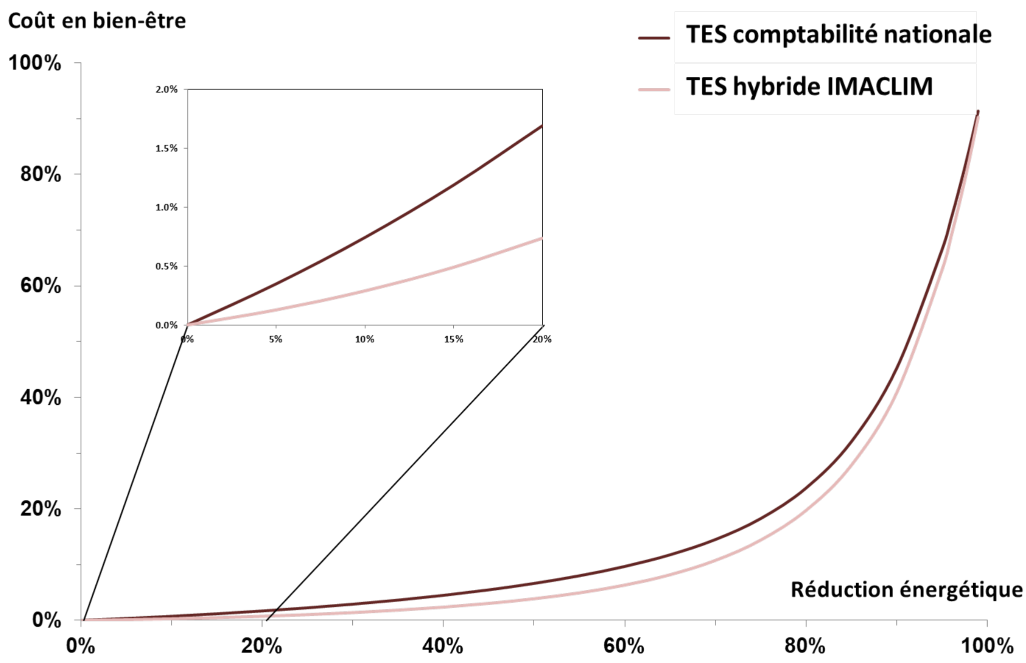


Figure 4 – Coût en bien-être des réductions d'énergie induites par une politique globale sur les prix

Le modèle calibré sur le TES de la comptabilité nationale, avec prix unique de l'énergie, et le modèle calibré sur le TES hybride Imaclim , avec des prix différenciés entre agents, donnent à première vue des résultats proches de coûts en bien-être. Néanmoins, en retenant des objectifs de réduction d'énergie allant de 0% à 20%, ce qui correspond à des politiques réalistes, les divergences apparaissent qu'une représentation en termes relatifs permet de mettre en évidence par un "zoom" (cf. Figure 5 pour tout type de politique).

Selon le type de politique mis en place, les écarts entre le modèle calibré sur des données hybrides et le modèle calibré sur la comptabilité nationale ne sont pas du même ordre. Une taxe supportée uniquement par les ménages donne des divergences entre les modèles moins fortes qu'une taxe supportée par les entreprises. Nous expliquons ce résultat par la propagation de la hausse du prix de production : cibler uniquement les entreprises implique des effets multiplicateurs qui se propagent dans toute l'économie, alors que cibler uniquement les ménages impacte la consommation finale, et donc à la fin du processus de production.

Par ces jeux de simulations, nous confirmons l'importance du traitement des données, et la

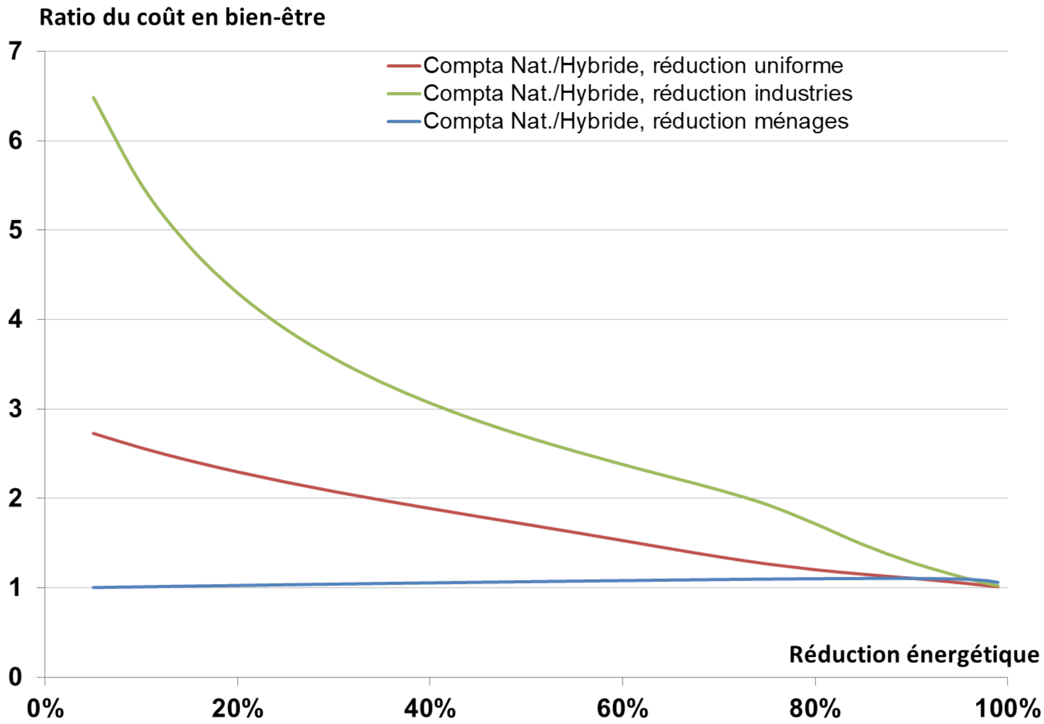


FIGURE 5 – Ratio des coûts en bien-être pour différents calibrage du modèle et différentes politiques de réduction

nécessité de rendre explicite la procédure d'hybridation pour l'analyse d'une politique climatique. Le chapitre montre que les écarts non-marginaux entre les descriptions empiriques de l'économie, résultant de la construction de TES hybrides, ont un impact significatif sur l'analyse des politiques énergétiques, et ce même à un niveau élevé d'agrégation au sein du modèle néoclassique "standard". En effet, les procédures d'hybridation utilisées pour rapprocher les données énergétiques sur les prix et les quantités ont un impact direct sur la description des caractéristiques empiriques qui ne peuvent qu'influencer ce type d'analyse : la taille économique des flux énergétiques, la part relative des factures d'énergie payées par les secteurs productifs et les consommateurs finaux, les prix relatifs de l'énergie selon les agents économiques.
Evidemment, les écarts observés sur les implications des politiques varient avec les hypothèses de modélisation, notamment sur le changement technique, le bouclage macroéconomique, et le niveau d'agrégation des secteurs productifs. Les différences entre les analyses de politiques s'appuyant sur des modèles EGC hybrides et néoclassiques "standards" sont ensuite amplifiées par l'utilisation d'expertises techniques à la place de fonctions de production agrégées calibrées par des estimations économétriques. Même si les impacts des choix de modélisation et d'agrégation ont déjà commencé à être discutés dans la littérature, ils n'avaient pas été isolés jusqu'ici de l'impact des techniques d'hybridation sur la description empirique initiale.

La première motivation pour l'élaboration de matrices hybrides reste bien entendu d'intégrer dans le cadre d'un modèle EGC une expertise sur les changements techniques futurs et les possibilités d'économies d'énergie à différents horizons temporels. Par conséquent, cette thèse se poursuit naturellement en s'appuyant sur ce type de modèle hybride, que nous présentons au chapitre suivant.

Chapitre 3 - La plateforme de modélisation IMACLIM -pays

Différentes versions d' IMACLIM-S ont été développées de façon indépendante, conduisant à autant d'outils que de pays (France, Brésil, Afrique du Sud), avec différents supports (EXCEL, SCILAB). Même si une ancienne version peut toujours être utilisée comme point de départ pour le développement d'une nouvelle version d' IMACLIM-S , le traitement des données (procédure d'hybridation) et la restauration du système à résoudre demandent beaucoup de temps pour être adaptés à une étude différente.
C'est pourquoi cette thèse essaie d'établir un cadre de modélisation flexible permettant de calibrer "ad nutum" le modèle soit sur une description sectorielle étendue, soit sur une représentation compacte, pour in fine soutenir et faciliter les développements pour de nouveaux pays (Arabie Saoudite, Chine, Inde). Pour ces raisons, une nouvelle plateforme rationalisée a été développée en utilisant SCILAB, un logiciel open source pour le calcul numérique.

Architecture principale
IMACLIM est un modèle générique qui peut être décliné dans différentes versions. Notre premier objectif est de construire une plateforme grâce à une architecture commune qui supporte toutes ses versions. La Figure 6 illustre cette architecture. Les versions d' IMACLIM reposent sur des opérations communes (hybridation, calibration, résolution, etc.) identiques et modulaires pour s'adapter à des demandes propres de l'utilisateur (niveau d'agrégation, variables de résolution). Au final, chaque version se distingue par le détail des tableaux économiques et physiques qui sont mis en équation pour la simulation.

La plateforme commune a été développée dans cette thèse autour d'une version française d' IMACLIM-S calibré à l'année 2010. Grâce à la flexibilité de l'architecture, la version peut être décomposée en plusieurs "sous-versions" selon le niveau sectoriel choisi par l'utilisateur pour la modélisation via le "module d'agrégation". Le TES hybride initialement construit donne évidement la limite d'extension sectorielle (29 secteurs pour IMACLIM-S FRANCE). La procédure d'hybridation a également été automatisée. La désagrégation des ménages est aussi un choix de l'utilisateur, tant que la clé de répartition est disponible comme données d'entrée. Pour la version française, la désagrégation des ménages peut aller jusqu'à dix classes de revenus. Une dernière flexibilité notable est de pouvoir changer le système de résolution autour de différents modèles économiques qui traduisent des "visions" et des comportements

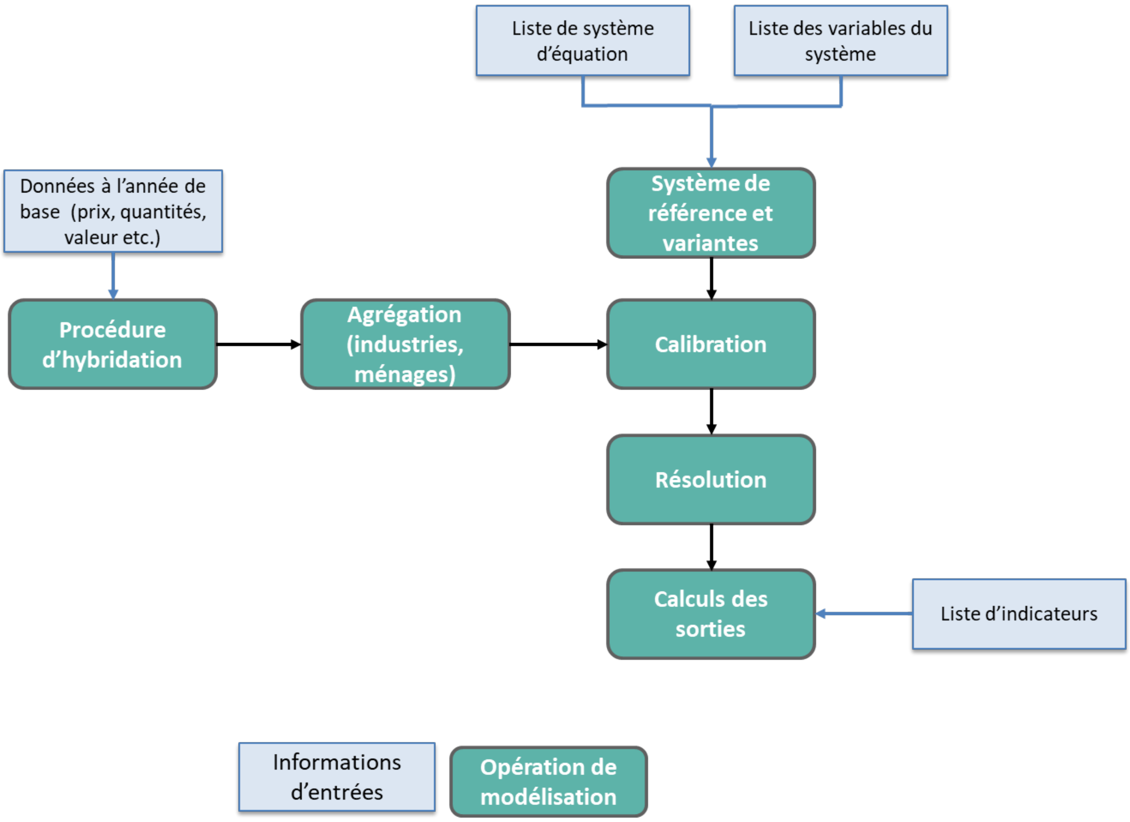


FIGURE 6 – Architecture de la plateforme IMACLIM -pays

différents pour l'économie. Les équations comptables font, quant à elles, parties du "noyau" de l'architecture commune à toutes les versions et ne peuvent être substituées, elles sont toujours vérifiées.

Principales caractéristiques de modélisation

Le modèle IMACLIM-S utilisé dans cette thèse représente une économie française ouverte sur l'extérieur, désagrégée en quatre catégories d'agents (les ménages, les sociétés, les administrations publiques et le "reste-du-monde"). Un état économique est décrit par des transactions qui sont réalisées, au cours d'une année, sur le territoire national. L'ensemble des transactions entre agents est schématisé par la Figure 7.

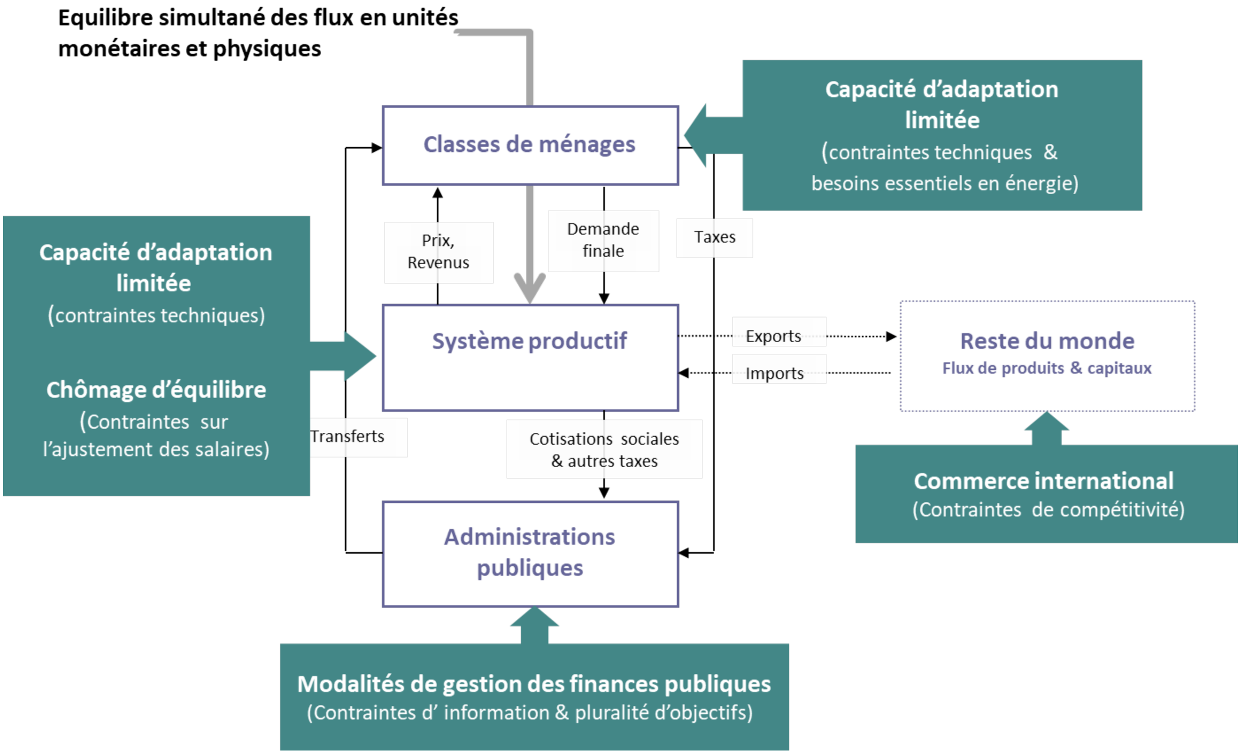


FIGURE 7 – Représentation schématique du modèle IMACLIM-S

Le modèle repose sur un ensemble de paramètres économiques sur lesquels "diverses croyances" s'expriment, et à partir desquels il faut conduire des tests de sensibilité systématiques : (i) l'ajustement des niveaux de consommation d'énergie en réponse aux signaux-prix, (ii) la réponse des salaires à l'évolution du chômage, (iii) l'efficacité de modalités alternatives de gestion des finances publiques, (iv) l'effet de la compétitivité-prix en observant la réponse à l'évolution des coûts de production des échanges extérieurs de la France avec le reste-du-monde, exogène au modèle. Ce dernier point est fondamental pour parvenir à une analyse conjointe des effets de la politique climatique française sur les émissions de CO_2 et les échanges extérieurs à un niveau sectoriel suffisant.

Formation du prix domestiques	
Prix de production	$P_Y = P_{IC} \times \alpha + p_L \cdot l + P_K \cdot k + \overline{\tau_Y} \cdot P_Y + \overline{\Pi} \cdot P_Y$
Prix moyen	$P = [P_Y \cdot Y + P_M \cdot M]/[Y + M]$
Formation des revenus et usages	
Investissement	$R_{inv} = \sum P_I \cdot I$
Trade-offs	
Consommation finale	$C = f_C(R_{CONS}, P)$
Consommation intermédiaire	$\alpha = f_\alpha(P, \omega, P_K, \phi_L)$
Travail	$l = f_l(P, \omega, P_K, \phi_L)$
Capital	$k = f_k(P, \omega, P_K, \phi_L)$
Décomposition de la valeur-ajoutée	
Courbe salaire-chômage	$\omega = f_\omega(1 - \frac{L}{NS})$
Coût du capital	$P_k = (\sum p_I \cdot I)\ I$
Mark-up pricing	$\Pi = \overline{\Pi}$
Commerce international	
Exports	$X = f_X(P_Y, P_M, X)$
Imports	$M = f_M(P_Y, P_M, Y)$
Équilibre comptable en volume	
Marché des biens	$Y = Y \cdot \alpha + C + G + I + X - M$
Marché du travail	$L = \sum l \cdot Y$
Balance des capitaux implicite	$I = \overline{\beta} \sum k \cdot Y$
Moteur de croissance pour projection	
Population active	$NS = (1 + \omega_{NS})^t \cdot N_0$
Progrès sur le travail	$\phi_{L_i} \neq 0$

TABLE 2 – Représentation compacte des équations dans IMACLIM-S FRANCE

Les deux prochains chapitres utilisent le modèle Imaclim-S France à des fins méthodologiques pour conduire des tests de sensibilités autour de paramètres incertains ou instables. Nous montrons comment le modèle permet d'abord une meilleure compréhension des mécanismes économiques grâce à un gain en granularité sectorielle, et donne ensuite l'occasion de clarifier les dialogues autour de ces paramètres controversés.

Chapitre 4 - L'influence de paramètres clés et de la réprésentation sectorielle

Les modèles EGC manquent souvent de détails sur les secteurs intensifs en énergie et exposés au commerce international, secteurs pourtant clés pour la mise en œuvre de politiques climatiques domestiques. Récemment, des efforts ont été faits pour désagréger ces secteurs, et ces tentatives ont montré que leur prise en compte modifient significativement l'évaluation des effets distributifs de la politiques climatique (Alexeeva-Talebi et al., 2012; Caron, 2012).
Pour intégrer une "granularité" sectorielle pertinente à la conception de politiques environnementales, articulant à la fois compétitivité et environnement, nous profitons de la procédure d'hybridation exposée au chapitre I. En isolant certains secteurs – ceux de l'acier et du ciment - de leurs agrégats initiaux -respectivement le secteur de la métallurgie et le secteur des minéraux non-métalliques- tout en intégrant des données physiques, nous allons au-delà des techniques de désagrégation précédentes basées uniquement sur des données économiques (Böhringer et al., 2012).
En utilisant Imaclim-S France ce chapitre rappelle les principaux mécanismes macroéconomiques suite à la mise en place d'une taxe carbone, puis démêle les interactions entre les paramètres clés de la modélisation ainsi que l'influence de la représentation sectorielle.

En introduisant un prix unilatéral du carbone, les effets de propagation d'une hausse des coûts de l'énergie dans le système productif peuvent aboutir à un coût global encore plus important de la mesure. Pour atténuer la hausse des coûts énergétiques retombant sur le coût de production, la littérature s'accorde à dire qu'elle doit s'accompagner d'une baisse des charges sur le coût du travail, dans le cas des économies européennes tout du moins. La taxe conduit alors un double dividende possible selon deux paramètres controversés :

- la sensibilité au chômage des salaires, soit la possibilité de transformer une baisse des charges sociales en hausse des salaires,
- et la sensibilité des prix aux échanges extérieurs.

Il existe beaucoup d'incertitude sur les valeurs à donner à ces deux paramètres. Concernant la sensibilité des salaires au chômage, la valeur de Blanchflower and Oswald (2005) est retenue de façon presque automatique sans que l'on puisse en analyser les déterminants (par exemple l'impact de l'organisation de la négociation salariale). Pour la sensibilité des échanges extérieurs, nous sommes confrontés à ce que Fontagné et al. (2017) appellent le "puzzle des élasticités" du commerce international (cf. Chapitre 5).

Pour comprendre la nature des gains de granularité sectorielle, nous conduisons d'abord notre analyse sur un modèle compact à trois secteurs (énergie primaire, énergie finale et un composite). Plus particulièrement, nous étudions les incidences d'une taxe carbone unilatérale recyclée en baisse du coût du travail avec différents types de modélisation de la courbe salaire-chômage : les salaires suivent les prix internationaux ou les salaires suivent les prix à la consommation. Nous analysons alors la sensibilité des résultats aux élasticités du commerce extérieur (cf Figure 8).

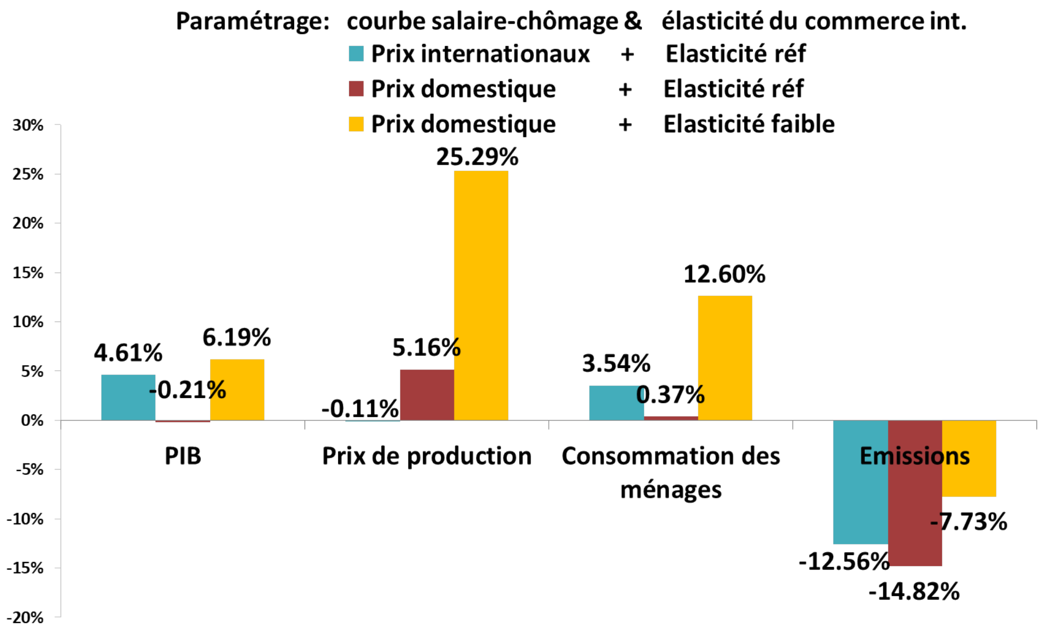


FIGURE 8 – Lien entre indexation des salaires et exposition de l'économie dans un modèle compact

Lorsque les salaires suivent les prix internationaux, la baisse des cotisations sociales permet une baisse du prix de production. Cela favorise la consommation des ménages, et l'activité économique : nous obtenons un double dividende avec une croissance du *PIB*.
En revanche, lorsque le pouvoir de négociation salariale est tel que les salaires sont indexés sur les prix à la consommation, l'économie est déprimée. La baisse des charges sociales ne permet plus une baisse du prix de production, qui augmente. Cette hausse entraîne une baisse des échanges extérieurs mais aussi une baisse du pouvoir d'achat des ménages : l'économie entre dans un cercle récessif. Ce résultat, qui est analytiquement intéressant, n'est pas tenable. En effet, il semble difficile d'obtenir une économie exposée à la concurrence internationale avec

des salaires indexés sur les prix domestiques.
Nous réduisons alors l'ouverture de l'économie en donnant des valeurs plus faibles aux élasticités des échanges extérieurs, tout en gardant cette même indexation des salaires sur les prix à la consommation. Cette indexation provoque une forte augmentation du prix de production. Néanmoins, l'augmentation des salaires dynamise la consommation intérieure avec une faible pénalité sur les marchés internationaux : nous obtenons un double dividende avec une croissance du *PIB*. Cependant, cette image positive est en partie trompeuse car, pour satisfaire la demande intérieure, il faut augmenter de 40% le déficit public grâce un reste du monde "prêteur".

L'enjeu qui résulte de ces simulations est le lien à établir entre degré d'exposition au commerce international et les emplois nomades et sédentaires tel que définis depuis quelques années par Pierre Noel Giraud (cf. Chapitre 5). Cette interaction nécessite une représentation sectorielle plus fine qu'un modèle compact, et l'hybridation nous permet de faire des progrès en ce sens.
Pour bien comprendre l'influence de la différenciation sectorielle, nous observons son impact seul sur l'analyse pour une même réforme fiscale. Pour cela, nous ouvrons la boîte de notre modèle compact à 3 secteurs pour passer à une modélisation à 13 secteurs (cf. Figure 9).Nous gardons un paramétrage homogéne pour la courbe salaire-chômage et la sensibilité des échanges extérieurs.

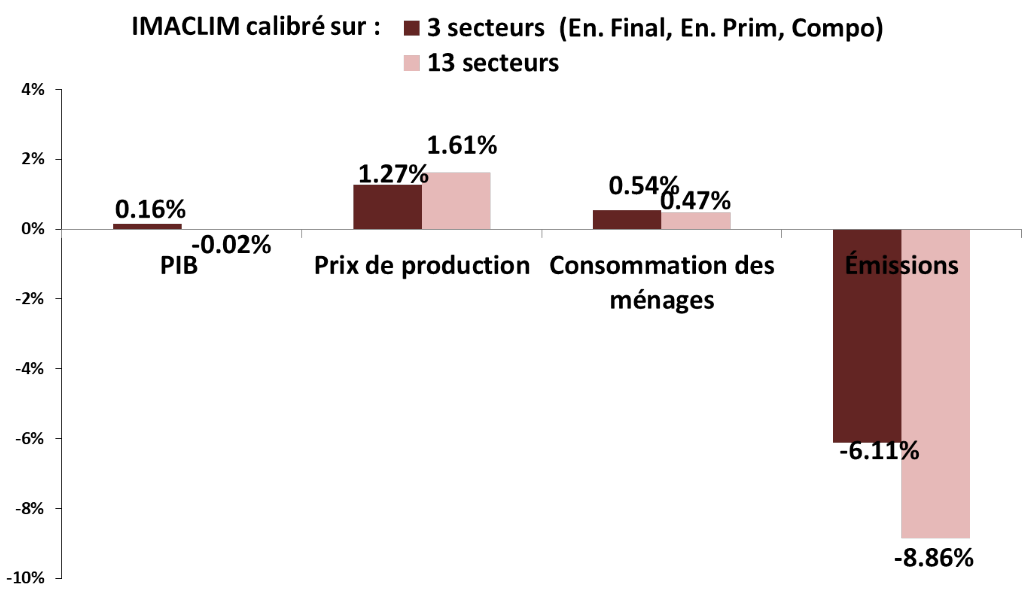


FIGURE 9 – Incidence d'un gain en granularité sectorielle au calibrage

Nous notons que l'écart de l'impact macroéconomique d'une même taxe est de faible amplitude entre les deux modèles. Pourtant, les effets intersectoriels suffisent à renverser le signe de l'incidence sur *PIB*. Il est aussi important que noter que l'intensité moyenne en CO_2

du système agrégé de production conduit à une baisse des émissions moins importante que celle observée dans le modèle désagrégé.
Dans l'analyse des résultats du modèle désagrégé, nous montrons que la prise en compte de certains secteurs dans la modélisation représente un enjeu réel (ciment et acier) avec des pertes importantes pour certains segments de la chaîne de production, masquées en travaillant à un niveau agrégé.

Certes, les effets de la désagrégation sectorielle pure (via le jeu des nomenclatures) semblent de deuxième ordre à l'échelle macroéconomique. Pourtant, nous avons retenu à ce stade des paramètres identiques pour tous les secteurs (élasticité du commerce extérieur, courbe salaire-chômage). Il est donc déjà important de noter que l'adoption d'échelles différentes dans la granularité sectorielle de l'activité économique conduit à des différences non négligeables dans les résultats. Un pas de plus est nécessaire pour étudier comment ces différences sont amplifiées lorsque l'on profite de la désagrégation pour intégrer des paramètres hétérogènes, spécifiques à chaque secteur, tout en introduisant plus de réalisme dans une analyse, conduite jusqu'ici, en balayant un large spectre de paramètres. C'est que nous faisons dans le Chapitre 5 en montrant comment l'hybridation permet, sinon de réduire, de mieux contrôler les incertitudes paramétriques.

Chapitre 5 - L'articulation entre la formation des salaires et le dégré d'exposition au commerce extérieur

La littérature a récemment insisté sur le lien entre la fragmentation géographique de la chaîne de valeur mondiale, et la dynamique de la formation des salaires dans les pays industrialisés. Le postulat de base est que pour certains segments de la production, les travailleurs peu qualifiés des pays en développement ont un avantage compétitif par rapport aux travailleurs peu qualifiés des pays développés. Cet avantage introduit une concurrence sur les salaires qui tend à réduire le pouvoir de négociation des travailleurs dans les pays industrialisés. Il y a alors une tendance à la hausse pour une demande d'emplois qualifiés avec des salaires plus élevés, ce qui est une source d'inégalités croissantes dans les économies développées (Timmer et al., 2014).
Frocrain and Giraud (2016) vont plus loin en soulignant l'existence de deux catégories d'emplois. Une première catégorie correspond à des *emplois sédentaires* qui ne peuvent être réaffectés ailleurs car ils seront toujours nécessaires localement (par exemple le coiffeur). Une deuxième catégorie correspond à des *emplois nomades* qui sont exposés aux marchés internationaux car ils peuvent être sous-traités à l'étranger[7]. Les travailleurs des *emplois sédentaires* ont un levier

[7] En conséquence, l'augmentation de la demande finale nationale pourrait ne pas entraîner une augmentation de l'emploi dans le pays.

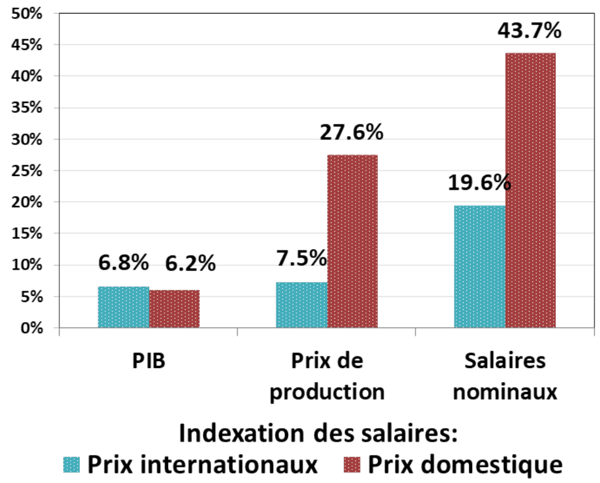
de négociation salariale important tandis que les salaires des travailleurs des *emplois nomades* dépendent de la concurrence salariale internationale. Dans cette thèse, nous ne distinguons pas le degré d'exposition des activités du degré d'exposition des emplois. Nous supposons une définition univoque entre ces deux terminologies.

Ce chapitre vise à montrer que des progrès peuvent être réalisés pour l'analyse des politiques climatiques grâce au gain de granularité sectorielle dans la modélisation permis par l'effort d'hybridation. En effet, si la différenciation des comportements sectoriels est parfois négligée, nous supposons qu'elle est cruciale pour comprendre la dynamique des changements structurels industriels.
Nous montrons ici la possibilité de mieux contrôler, sous une contrainte de politique climatique, l'articulation entre deux paramètres incertains : les élasticités des échanges extérieurs et la courbe salaire-chômage en différenciant les secteurs selon leurs activités, qu'elles soient orientées vers l'intérieur ou l'extérieur de l'économie.

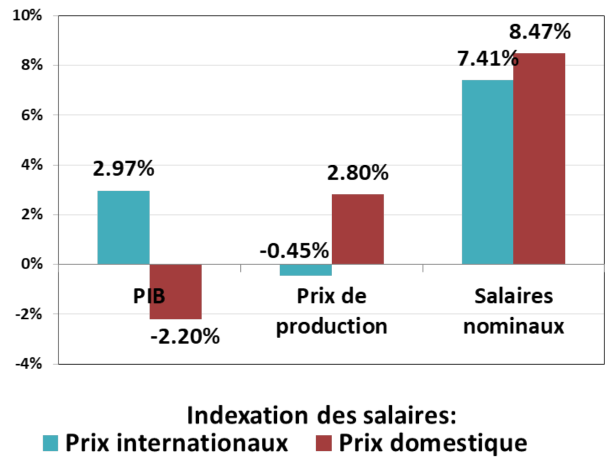
Dans un premier temps, nous nous confrontons à la controverse autour de l'évaluation des élasticités des échanges extérieurs (Fontagné et al., 2017) dont les analyses manquent au niveau sectoriel. Les seules études trouvées sont celles de Erkel-Rousse and Mirza (2002) et Fouquin et al. (2001). Faute d'études plus récentes, nous les avons utilisées et adaptées à notre échelle sectorielle pour analyser les incidences de cette information hétérogène sur l'évaluation de la politique du carbone (Figure 10a).

Il apparait qu'avec ces élasticités, même en cas d'indexation des salaires sur les prix domestiques, nous obtenons un double dividende avec une hausse de *PIB*. Ce résultat, à priori contradictoire avec les résultats théoriques vus dans le chapitre précédent, permet de souligner les dangers à importer, sans précautions, dans une structure de modélisation précise, des informations calculées avec un référentiel significativement différent. Les élasticités-volumes que nous avons trouvées sont inférieures à 1 et conduisent à un paradoxe : une politique généreuse en hausse des salaires décrit un pays qui tire plus de revenues de ses exports tout en n'en produisant moins.

Nous mettons en évidence une erreur de méthode qui vient du fait que les élasticités utilisées reposent sur des indices chainés de volume, calculés sur des séries en valeur, et qui ne sont pas comparables aux volumes physiques que nous décrivons dans Imaclim . Néanmoins ces informations nous renseignent sur la sensibilité relative des secteurs aux échanges extérieurs. Nous les avons alors retenues comme des élasticités en "valeur", puis nous avons proposé une méthode pour dériver ensuite en des élasticités en "volume" physique compatible avec nos exercices de modélisation. Pour différents types de modélisation de réactions des salaires, nous retrouvons le mécanisme de base observé dans le Chapitre 4, conforme à la théorie : un double dividende pour des salaires qui suivent les prix internationaux et une perte de *PIB* pour une négociation salariale alignée sur les prix domestiques (Figure 10b).



(a) Elasticités en "valeur"



(b) Elasticités en "volume"

FIGURE 10 – Intégration d'élasticités différenciées et compatibles avec IMACLIM

Jusqu'à présent, nous avons supposé un paramétrage homogène de la formation des salaires pour tous les secteurs, avec deux cas extrêmes de réactions (suivant soit les prix internationaux soit les prix domestiques), et surtout, nous n'avons fait aucun lien entre régime de formation salariale et élasticités des échanges extérieurs. Pour tenir en compte du lien entre la capacité de négociation et d'évolution des salaires en fonction du type d'activités, et de leur degré d'exposition ou d'insertion dans l'économie mondiale, nous avons introduit une courbe salaire-chômage hétérogène où nous définissons trois niveaux de réajustement des salaires. Les salaires des secteurs exposés au commerce international sont indexés sur les prix internationaux, tandis que les secteurs protégés ont des salaires qui se négocient davantage sur l'évolution des prix domestiques. Nous définissions également un cas intermédiaire. L'introduction de cette méthode a pour but d'expliciter où l'on se situe dans un intervalle de visions contrastées de formation des salaires. Dans ce cas présent, la taxe implique des pertes de *PIB* mais qui s'accompagnent d'un gain en emplois de 1.6% (cf Figure 11).

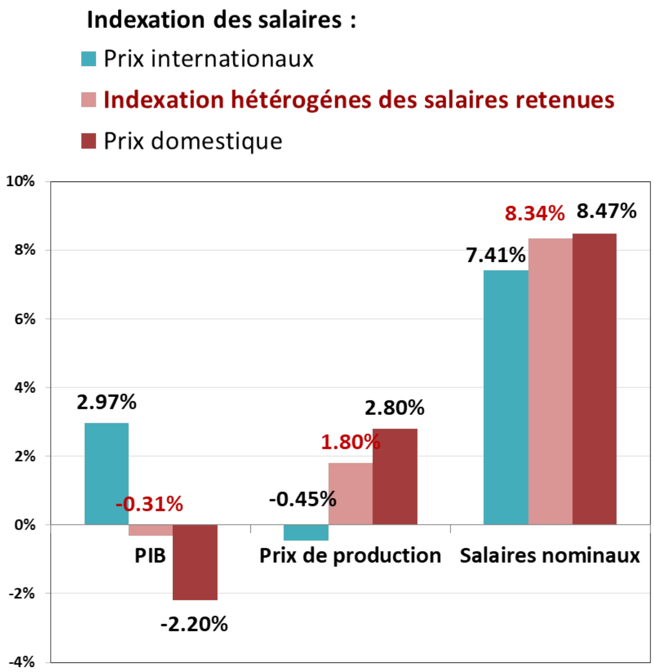


Figure 11 – Indexation sectorielle non uniforme de la courbe salaire-chômage

A ce stade, l'objectif n'est pas d'établir une prédiction quant aux conséquences de la taxe carbone en France. L'idée est plutôt de montrer comment l'introduction de la différentiation sectorielle permettra de mieux maîtriser les conséquences sur les secteurs exposés pour, in fine, mieux les accompagner dans une transition vers une économie bas carbone. L'outil développé permettra également de voir quelles stratégies pourront être envisagées pour relancer l'activité sédentaire. Enfin, les apports méthodologiques devraient permettre à l'avenir de mieux discuter la réalité des pratiques salariales face à l'évolution des prix, et cela secteur par secteur.

Evidemment, un tel outil a pour objectif de trouver des synergies possibles, suite à la mise en place d'un signal-prix du carbone, sans peser sur la compétitivité du pays. La compétitivité est l'un des premiers arguments avancés pour éviter la mise en œuvre de toute action ambitieuse contre le changement climatique, bien que les différents sens que l'on peut attribuer à ce terme soient souvent ignorés par ceux qui l'utilisent (Krugman, 1994). La compétitivité n'a pas le même sens à l'échelle nationale qu'à l'échelle sectorielle. Quoi qu'il en soit, les impacts sur la compétitivité nationale dépendent évidemment de la structure de l'économie : la part des secteurs exposés qui supportent la taxe, et la part des secteurs protégés qui en bénéficient. Ainsi, dans ce chapitre, nous introduisons cette hétérogénéité dans le cadre de la modélisation, grâce notamment à la procédure d'hybridation qui isole des secteurs à forte consommation d'énergie - secteurs du ciment et de l'acier. Une étape suivante consistera à différencier les segments amont de production de ces secteurs (fonte et clinker), puisque ces segments sont à forte intensité énergétique mais ne représentant qu'une faible part de la valeur ajoutée, et ne peuvant être externalisés en raison des coûts de transport et de capacité d'investissement.

Ce chapitre restreint l'analyse de la politique climatique à celle d'une taxe unilatérale sur le carbone. Pour aller plus loin, il serait intéressant de pouvoir mettre en œuvre d'autres réformes. Si la politique climatique est conçue pour avoir un effet positif sur l'environnement, l'impact de la mesure sur les secteurs intensifs en énergie et exposés au commerce international peut annuler cet effet positif. En effet, la délocalisation des secteurs, dans un contexte de mondialisation des échanges, entraîne une augmentation des émissions incorporées dans les importations. En raison des fuites de carbone et selon les spécificités des pays, l'efficacité globale de la mesure peut s'avérer négatif pour l'environnement. Il est alors nécessaire de bien comprendre les interactions entre questions de compétitivité et préoccupations environnementales pour lever les obstacles à la mise en œuvre de la politique climatique. Evidement cela implique de pouvoir décrire avec précision les incidences environnementales de notre économie, y compris celles de ses échanges extérieurs. C'est une telle illustration qu'aborde le Chapitre 6 soulignant l'intérêt de l'hybridation une dernière fois.

Chapitre 6 - Les différents inventaires d'émissions de la France

Les progrès réalisés par un pays en matière de réduction des émissions de gaz à effet de serre (GES) dépendent du périmètre des inventaires des émissions. La convention-cadre des Nations Unies sur le changement climatique (CCNUCC) mesure les objectifs sur la base d'inventaires territoriaux, et n'évalue pas les émissions incorporées dans le commerce international alors que celles-ci représentent un levier pour contrôler les fuites de carbone et comprendre les problèmes de compétitivité.
La prise en compte de ces émissions reste impopulaire auprès des parties prenantes car il existe des incertitudes quant à leur utilisation dans les politiques, et, elles minimisent souvent les efforts déployés pour réduire les émissions dans les pays industrialisés. Au-delà des considérations politiques, leurs estimations ne sont pas évidentes, et il existe dans la littérature plusieurs méthodes permettant d'aboutir à différents types d'inventaires (Sato, 2013). Comme elles exigent beaucoup de données, les modèles s'appuient principalement sur quelques bases de données mondiales existantes dont les flux commerciaux bilatéraux sont équilibrés. Pourtant, le contrôle de ces bases de données et l'articulation avec les modèles prospectifs à l'échelle nationale restent difficiles.

En s'appuyant sur l'analyse Input-Ouput (AIO) pour un pays, l'objectif de ce chapitre est de définir une méthode de calcul de différents types d'inventaires d'émissions de CO_2 -en passant

notamment d'une logique d'attribution par "lieu de production" à une logique d'attribution par "lieu de consommation"- tout en tenant compte des spécificités des systèmes de production des principaux partenaires commerciaux du pays. Enfin, la technique repose sur des données issues de la procédure d'hybridation présentée au 1 pour ensuite être articulée avec le modèle d'équilibre général Imaclim-S .
Nous appliquons cette méthode à la France (2010), dont la loi sur la transition énergétique inclue des objectifs de réduction des émissions territoriales sans augmenter les émissions liées à ses importations. Nous décrivons les quinze principaux partenaires commerciaux français couvrant 75% de ses importations. De plus, nous supposons que la France est un petit pays face au reste monde, et nous négligeons les flux des exportations de la France qui pourraient être réimportés dans le pays après transformation dans un pays tiers.

Les résultats permettent de mettre en avant des écarts non substantiels entre les différents type d'inventaires de CO_2 français, prenant en compte ou non les émissions incorporées dans le commerce international (cf. Figure 12).

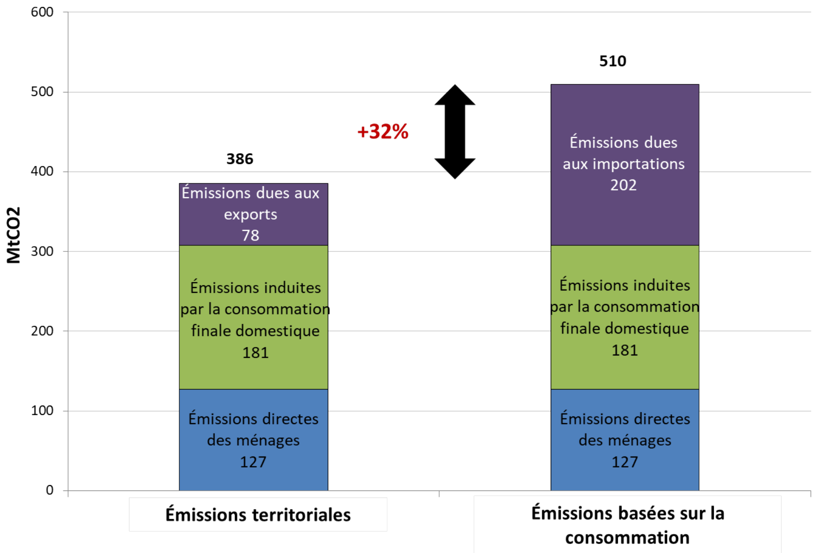


Figure 12 – Émissions territoriales vs. émissions basées sur la consommation

Notre estimation des émissions de CO_2 liées à la production territoriale ($386 MtCO_2$) est satisfaisante avec une valeur proche de celle proposée par les comptes européens NAMEA[8] ($384.5 MtCO_2$). Il apparaît clairement que le passage d'un inventaire d'émissions basé sur la production territoriale à un inventaire basé sur la consommation augmente la contribution française aux émissions mondiales. En effet, les émissions basées sur la consommation du pays s'élève à $510 MtCO_2$, ce qui correspondant à une augmentation de +32% du bilan des émissions de la France. Ce résultat confirme qu'il est important de se concentrer non seulement sur les émissions directes mais aussi sur le suivi des émissions incorporées dans les biens importés.

[8]National Accounting Matrix with Environmental Account

Par ailleurs, nous estimons que si les produits importés avaient été produits localement, en France, ils auraient générés 135$MtCO_2$. En comparant ces émissions aux 202$MtCO_2$ "cachées" dans les importations françaises, la mondialisation des échanges induit 67$MtCO_2$ d'émissions additionnelles.

Le chapitre fournit des informations originales sur les moteurs des émissions en France. En particulier, nous notons que pour de nombreux secteurs, les émissions de CO_2 attribuées aux exportations compensent les émissions incorporées dans les importations. Cela reflète la part du commerce intra-branche des échanges[9]. Cependant, pour certains secteurs, il existe un écart important entre les émissions allouées aux exportations et les émissions incorporées dans les importations qui font de la France un importateur net de CO_2 (cf. Figure 13).

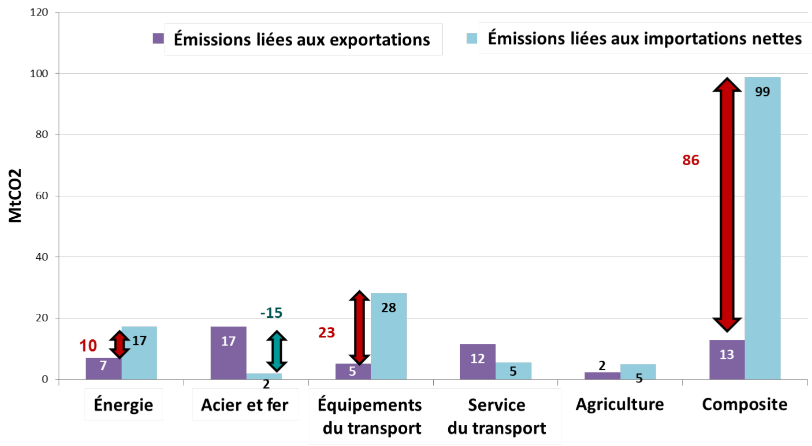


FIGURE 13 – Émissions sectorielles des échanges extérieurs

Le secteur composite est en grande partie responsable du solde positif des importations nettes de CO_2 de la France (86$MtCO_2$). Ce secteur regroupe les industries et les services de l'économie française que nous n'avons pas décrites lors de la procédure d'hybridation (Chapitre I). Il comprend tous les services, mais aussi certaines industries telles que l'industrie textile et électronique dont la France est un importateur net et dont la production à l'étranger est intensive en CO_2. L'écart des émissions du secteur des équipements de transport est également frappant (23$MtCO_2$). Il s'explique par le fait que les segments de la chaîne de production qui sont intensifs en émissions ont lieu à l'étranger alors que la France exporte des produits quasi-finis, peu intensifs en émissions mais à haute valeur monétaire.

Finalement, ce chapitre donne un aperçu des différents schémas qui permettent d'allouer des émissions à la France. La méthode proposée ne nécessite pas une harmonisation des flux du commerce international du monde entier. Toutefois, elle requiert un effort important sur le

[9]Le commerce intra-branche désigne l'importation et l'exportation de produits similaires entre les pays. Selon l'OCDE, ce commerce est de plus en plus prononcé dans les pays développés principalement entre les pays membres de l'Union Européenne

rassemblement des données, et nous montrons que les résultats sont sensibles à la granularité sectorielle qui décrit notre image initiale. Au-delà de cet "inventaire" pour une année de référence, nous avons développé une méthode que nous articulons avec le modèle d'équilibre général IMACLIM-S FRANCE , pour être en mesure d'analyser les effets d'une politique domestique sur les échanges extérieurs, en valeur, ainsi qu'en volume d'émissions. Des développements futurs permettront de prolonger l'analyse à d'autres mesures telles que l'ajustement d'une taxe carbone aux frontières.

Conclusion

Malgré les grands progrès de la modélisation E3, des efforts importants doivent se poursuivre sur la transparence des représentations, leurs limites et leurs incidences sur les résultats. Les modèles hybrides "complexes" offrent des informations pertinentes pour l'élaboration de politiques, mais leur validation nécessite du temps pour comprendre les mécanismes sous-jacents et éviter de les considérer comme des "boîtes noires".
En s'appuyant sur l'économie française, cette thèse fournit un cadre de modélisation capable de contribuer aux débats sur les contributions-climat nationales et leurs implications, tout en améliorant la précision des modèles pour l'aide à la décision des politiques.

Dans un premier temps, la thèse remet en question les limites des outils de modélisation macroéconomique pour l'analyse de la politique climatique tout en clarifiant les approches techniques suivies. Le travail commence par la construction de la base de données hybride à un niveau de granularité sectorielle suffisant pour mettre en avant des impacts différenciés d'une politique environnementale ambitieuse. Par rapport aux travaux précédents, nous allons plus loin dans l'hybridation des données en rassemblant de nombreuses sources d'information (bilan énergétique, études sectorielles, etc.) pour aboutir à une description duale de notre économie en flux monétaire et physique sur l'énergie, le ciment et l'acier. En modifiant de façon significative l'image initiale de l'économie, nous confirmons l'intérêt de la méthode d'hybridation. D'abord, par rapport à des modèles qui ne font pas l'effort du traitement des données, nous réduisons le coût d'une politique climatique. Ensuite, la procédure permet d'ouvrir la boîte des modèles compacts pour aller vers un gain en granularité sectorielle. Finalement, au-delà d'une capacité à mieux assurer le lien avec les études techniques, elle permet aussi de mieux comprendre les mécanismes économiques.

En développant une nouvelle version du modèle IMACLIM-S FRANCE , nous nous intéressons à mieux comprendre les interactions entre régime de formation des salaires et échanges extérieurs au travers de paramètres controversés (élasticités-prix des échanges extérieurs, et sensibilité des salaires au chômage) dont nous rappelons la sensibilité d'abord à un niveau agrégé de la

modélisation.
Nous montrons ensuite l'incidence d'un gain en précision sectorielle pour l'analyse de la politique. En ouvrant la boîte d'un modèle compact, nous définissons une représentation des interactions, secteur par secteur, entre emplois exposés et problème de compétitivité. Plus particulièrement, l'introduction d'un nouveau paramètre de modélisation nous permet de lier la dynamique salariale au degré d'exposition de l'économie.

Au-delà des résultats montrés, la contribution concrète de cette thèse est d'avoir mis en place une plateforme de modélisation qui permet de rassembler des expertises souvent éclatées pour s'appuyer sur des informations plus précises et documentées. Cela permet de réduire les incertitudes sur l'évaluation de la politique climatique tout en capitalisant progressivement sur les analyses sectorielles.
L'outil peut nourrir pleinement le débat de la transition bas carbone en France, sous contrainte de compétitivité, en étudiant dans quelles mesures elle peut profiter à la relance domestique par les investissements. De fait, la thèse met en évidence des mécanismes macroéconomiques sans prétendre apporter une réponse définitive à une question qui demande des analyses supplémentaires, et un débat économique et sociale.

Finalement, la plateforme Imaclim -pays construite autour du cas français a été développée en anticipant des besoins de nouvelles capacités de modélisation pour d'autres économies. Grâce à une grande modularité du modèle, elle sera facilement étendue à d'autres économies. Dans une perspective plus large, le déploiement de la plateforme à de nombreux pays permettra de conduire des exercices de comparaison inter-économies, dans un cadre cohérent pour une même politique environnementale, complémentaires aux exercices mondiaux.

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Acronyms

CES Constant Elasticity of Substitution. 34–36, 38, 39, 45–47, 75, 190

CET Constant Elasticity of Transformation. 26

CGE computable general equilibrium. 5, 8–10, 26, 30, 31, 33, 34, 36, 37, 40, 44, 46, 47, 49, 50, 55, 56, 61, 64, 65, 67, 68, 78, 83, 84, 121, 129, 146, 174–177

COP Conference of Parties. 1, 3

E3 Energy-Economy-Environment. 3, 4, 7, 9, 14, 176

EEBT embodied emissions in bilateral trade. 148, 149, 158

EITE energy-intensive and trade-exposed. 2, 22, 30, 83, 84, 107, 144, 163

EU ETS European Union Emissions Trading System. 2

FOB free on board. 151

FTE full-time equivalent. 87

GDP Gross Domestic Product. 2, 11, 36

GFCF Gross Fixed Capital Formation. 61

GHG greenhouse gas. 1, 9, 36, 55, 145, 146

GTAP Global Trade Analysis Project. 9

IEA International Energy Agency. 10, 11, 15, 25, 77

IIASA International Institute for Applied Systems Analysis. 11

INDC Intended Nationally Determined Contribution. 83

INSEE Institut national de la statistique et des études économiques. xxiii, 25, 48, 56, 68, 86, 188, 191

IO Input-Ouput. 30, 47, 49, 149

IOA Input-Ouput analysis. 147–149, 161, 170, 178

IOT Input-Ouput table. lv, lvii–lix, 4, 5, 8–11, 14, 18–20, 22–24, 26–28, 30, 31, 33, 34, 36, 37, 40–45, 50, 52, 56, 60, 68, 84, 86–88, 99, 100, 115, 123, 124, 147–155, 159, 160, 163, 167, 170–173, 176, 178, 182, 201, 211

IPCC Intergovernmental Panel on Climate Change. 7, 155, 160

ktoe kilo tonne of oil equivalent. 87

LCA lifecycle assessment. 147
LES Linear expenditure system. 74

MRIO multi-regional input-output. 149, 158, 174
Mtoe million tonnes of oil equivalent. 12

NDC Nationally Determined Contribution. 1, 2, 4, 175, 176

OECD Organisation for Economic Co-operation and Development. 167

PPE Programmation pluriannuelle de l'énergie. xix, 1

SAM Social Accounting Matrix. 9, 34, 49, 56
SDG Sustainable Development Goal. 2
SGM Second Generation Model. lv, 11, 23, 26, 36, 37, 41, 42, 44, 48
SNA System of National Accounts. 7, 147
SNBC Stratégie Nationale Bas Carbone. xix, 1

TICPE Taxe intérieure de consommation sur les produits énergétiques. 190
toe tonne of oil equivalent. 4, 155

UNFCCC United Nations Framework Convention on Climate Change. 1, 145–147

WTO World Trade Organization. 83

Introduction

This thesis took as its starting point the debate on emissions embodied in international trade, which criticises the United Nations Framework Convention on Climate Change (UNFCCC) territorial boundary for national emissions inventories. In a globalisation context, such inventories ignore part of the country responsibility which consumes imported goods (Sato, 2013; Peters et al., 2011). Imports involve emissions but abroad, they are then out of the national inventory scope, and thus, they have, so far, not been taken into account for climate policy implications.
Part of this thesis work has also been done in parallel with the preparation of the 21^{st} Conference of Parties (COP) in December 2015 in Paris, which was meant to be a turning point for climate negotiations. At the end of the conference, the international community has for the first time universally recognised climate change challenges by signing the *Paris agreement*. Basically, the Agreement aims at holding the increase in the global average temperature well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels. It also materialises a significant paradigm shift that had been first arise in Copenhagen (COP15, 2009) by abandoning the Kyoto Protocol design for a flexible approach : all signatory "parties" define their individual efforts for greenhouse gas (GHG) emissions reduction, namely called the Nationally Determined Contributions (NDCs). By reviewing and strengthening the NDCs every five years, the Agreement both includes a new iterative and long term dimension.

Despite a global agreement, the concrete actions are national, and, countries' governments have to build their own environmental plans with the appropriate policies and the investments needed for transition.
A lot of studies are emerging on carbon transition pathways that fit with NDCs. In France, energy transition laws for a green growth define goals to be reached by climate actions for the decades to come. The French Low Carbon Strategy[10] and the Energy Plural-annual Program[11], among other public plans, give guidelines, and prospective planning for major sectors to succeed with the law goals.

[10] The French denomination is the Stratégie Nationale Bas Carbone (SNBC).
[11] The French denomination is the Programmation pluriannuelle de l'énergie (PPE).

Thus, the *Paris agreement* seems to be also a turning point for energy-environment-economic modelling that provides a precious help and support for policy-makers. In this context, it became clear that one of the main challenges for hybrid modelling is to narrow the gap between the needs of expertise on the NDCs and responses capacity of existing modelling tools. Actually, decision support tools for the NDCs require both a certain level of sectoral description, and a dialogue between bottom-up experiments based on technological realities and top-down analyses to handle concerns on the macroeconomic and social impacts of climate policy.

Past experiences with climate policy have shown that they faced implementation issues. In fact, individual actions, and especially unilateral carbon pricing, drive concerns about social acceptability. To overcome them, climate policies must be extended to a broad range of economic constraints, by articulating for instance concerns on equity/competitiveness/the wages formation. For developing countries Sustainable Development Goals (SDGs) must be taken into account as well.
Competitiveness and carbon leakage are among the first arguments put forward to avoid any attempt for ambitious environmental actions in developed countries. At the end of the first phase of the European Union Emissions Trading System (EU ETS), national governments have been accused to overestimate the caps to protect their industries from international trade losses, which resulted in a fall of carbon price. Although the value-added of the energy-intensive and trade-exposed (EITE) industries represents often a small fraction of Gross Domestic Product (GDP) for the industrialised countries, their production remains highly strategic, and the power of industrial lobbies has enable exemptions.
If regional climate policy is designed to reduce the territorial-based emissions, the impact of the measure on some sectors may reduce the expected positive effect on environment and even turn it into a negative one by considering the worldwide scale. Indeed, local carbon market involves a relocation risk for some industries, which in turn involves a risk of carbon leakage. The EU ETS Directive identified a list of sectors representing significant risk of carbon leakage[12] which received special treatment with higher share of free allowances compared to the other industries.
Europe, but also France, have suffered many failures to implement a carbon tax: the carbon/energy tax (1992) for Europe, and the successive government projects in France (1990, 1999, 2009). The projects faced political and societal acceptability issues magnified by a lack of will from institutions to instore sensitive measures. Indeed, they often argued that such reforms are punitive for both the industries, which production are often strategic, and the vulnerable households, who cannot but bear the negative consequences of the tax (Combet, 2013).

Governments seem to have a renewed interest for carbon price signals to achieve their

[12]The main criteria for the identification of sectors deemed exposed to a significant risk of carbon leakage are defined in the ETS Directive, in Article 10a(15) and 10a(16).

commitment. Some new regions within G20 have either scheduled or considered to implement a carbon pricing increasing thus the coverage (see Figure 1 taken from the work of Edenhofer et al. (2017)).

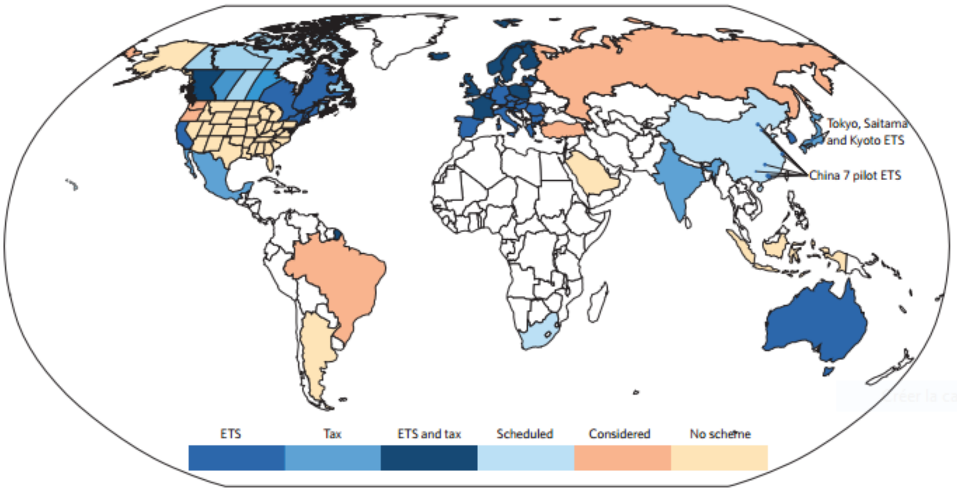


Figure 1 – Operating, scheduled and considered schemes of carbon pricing within the G20 (Edenhofer et al., 2017)

The initiative of Ségolène Royal, president of the COP21, to create a High-Level Commission on Carbon Prices chaired by Joseph Stiglitz and Lord Nicholas Stern is also a demonstration of this rebound. The report has been released in 2017 (Stiglitz et al., 2017). It gives corridors of carbon prices which are compatible with the Paris Agreement. Although the report points out that the prices assessed are intented to be more incentive than prescriptive, authors make clear that prices may vary from a country to other depending on their economic situation and their development issues. This sounds as a reminder that national politics need specific tools that fits with regional specificities to guide them with their decisions.

To be accepted by both industries and households, quantitative measures around carbon policy implication must be clarified. What values of carbon for what incidence on macroeconomics, industries and CO_2 emissions for a specific area in interaction with the rest of the world?
To answer this question, research needs to provide robust modelling tools to support policy-makers. With the idea of contributing to the modelling capacity, and exploring methodological issues about Energy-Economy-Environment (E3) models, the IMACLIM model has emerged at CIRED. Over the years, the thesis works of Ghersi (2003), Crassous (2008), Guivarch (2010), Waisman (2012), Combet (2013), (Lefèvre, 2016), without citing them all, have largely contributed to enhance methodological issues for modelling tools relevant for climate policy and mitigation trough the uses of IMACLIM .

The IMACLIM model is *hybrid* in the sense that it relies on a macroeconomic approach but it still incorporates a physical representation of the economy. The model comes in two versions. A worldwide version (IMACLIM-R) analyses the mitigation efforts carried by different regions of the world, and, explores for example to what extent the resulting global emissions trajectories are compatible with the "2°C objective". A national version (IMACLIM-S) takes into account the full country specificities (existing taxation, socio-demographic situation, etc.) and provides detailed studies on the modalities and the impacts of setting up a carbon price signal. This last version, which is essential for supporting the realisation of the NDC, is that at the heart of our interest. At the starting time of the thesis, the model already existed for France and Brazil, and the declinations for other countries were already in perspective.
Building on the previous work around IMACLIM-S , the starting point of the thesis corresponds to a double observation:

- at technical level: each IMACLIM-S country version is separately developed. To fruitfully extend the modelling capacities, it is necessary to build a common platform facilitating the development of the model to a new region.
- at methodological level: gaps remain to be discussed, be it on the justification of the data processing, the level of sectoral representation and its incidence, or the core of the modelling choices reflecting different "visions" of the World.

In view with the challenges for decision supports, and relied on the scientific heritage from CIRED, the thesis deals with these issues. The aim is thus to obtain a transparent modelling framework that clarifies discussions on economic instruments and modelling choices impacts for a national low-carbon transition analysis. More precisely, the ultimate objective is to clarify the link between competitiveness, in its physical sense, and the formation of income under climate constraint. This cannot be done without an additional effort on sectoral representation compared to the later version of IMACLIM-S FRANCE , and thus on hybridisation work. Our work is exclusively based on the French economy.

At first, we focus on gathering enough data for further sectoral calibration of an E3 modelling tool.
In Chapter 1, we explicit an innovative method to build hybrid accounting systems with the representation of both physical and monetary flows. Originally, the hybridisation method, which enhances the interface control of economic and technical systems, has been developed for energy goods in tonne of oil equivalent (toe) unit. Compared to previous work at CIRED, the procedure is carried out on a higher level of disaggregation for energy sectors. In addition, we extend the method to steel and cement sectors (in tons). It gives thus an opportunity to isolate in the initial description these "subsectors" often hidden into metal and non-metallic mineral aggregates in the original Input-Ouput table (IOT) from national accounts. Through

the hybridisation method, we gather the most relevant information available on physical balances, and on price statistics which can be heterogeneous across agents (households, different firms). We then implement resulting expenses into the national economic framework. At the end of the procedure, the hybrid IOT allows to describe up to twenty-nine sectors.
Different hybridisation techniques have different impacts on key empirical features that are important for policy evaluation, and we portray that benchmark IOTs can be significantly contrasted in the representation of energy systems. In Chapter 2, we analyse the sensitivity of results in a standard computable general equilibrium (CGE) model context. More precisely, we implement an aggregated two-sector static CGE model describing an open-economy which is calibrated alternatively on a benchmark of three IOTs to reveal the incidence of data treatments on energy policy implications.

The first motivation for building a hybrid IOTs is to go beyond the well-known limits of bottom-up and top-down approaches for the studies of environmental issues by re-establishing an articulation between technical systems and the global economy. Such an approach is described in Chapter 3 with the IMACLIM model. The chapter first explains our initiative during this thesis to develop a flexible platform that is common to all national versions of the model. Then, it provides the modelling features for the France version - IMACLIM-S FRANCE used in the further analyses. The model is calibrated on the hybrid accounting framework resulting from Chapter 1.

Chapter 4 and Chapter 5 provide first empirical analyses using the IMACLIM-S FRANCE model developed.
Chapter 4 first disentangles the interplay between key parameters for the analysis of a carbon tax impact. We start with a compact representation of the economy by calibrating the model on the hybrid IOT aggregated into three sectors (two energy sectors and the rest of the economy). The idea is to control the robustness of the main mechanisms of the model before embarking higher details. In a second step, we appreciate the incidence of the "granularity" level on results. In particular, we explore how different levels of sectoral aggregation, at calibration, impact results for the implementation of a same carbon policy.
In Chapter 5, the thesis work converges in the sense that, thanks to the hybridisation effort, it clarifies the interplay between wages settings and the degree of exposure. In the absence of sectoral bases on trade elasticities from the literature consistent with the IMACLIM representation of external trade, the chapter proposes a protocol to assess sectoral elasticities values and overcome this issue. It also introduces differentiated wages settings between sectors to capture their specificities regarding their exposure to international trade. Finally, it confirms the interest of keeping a representation of the heterogeneities of the overall economy. Through the method exposed, we aim to provide a tool capable to support the dialogue on sectoral policies in spite of the controversy about some key parameters.

Carbon constraint is expected to have positive effects on territorial emissions. But it may lead to an increase in emissions in international trade. In this thesis, we ran out of time to pursue such an analysis. However, in this perspective, Chapter 6 proposes a method, at the base year, to evaluate various emission inventories of CO_2, such as "consumption-based" emissions, and emissions embodied in imports. Thus, the chapter provides original insights on the drivers of emissions in France.

Beyond the supervision of Jean-Charles Hourcade, this thesis has benefited from collaborations. Particularly, Chapter 2 is a joint work with Emmanuel Combet, Frédéric Ghersi and Julien Lefèvre. In addition, the work has been part of the Imaclim modelling team at CIRED. Therefore, the new version of Imaclim-S France developed for this thesis has been elaborated while keeping in mind the emerging collaborations, with other institutions, for regional climate policy studies.

This thesis was carried out thanks to the co-financing of the French Environment and Energy Management Agency (ADEME) and Electricity of France Research & Development group (EDF R&D).

Chapter 1

Hybridisation procedures

Much compared and commented since the Second Assessment Report of Intergovernmental Panel on Climate Change (IPCC) (Hourcade et al., 1996), both bottom-up and top-down approaches to Energy-Economy-Environment (E3) modelling have known limits. On the one hand, engineering analyses focused on the representation of technologies do not account for the feedback loops between the energy system and the rest of the economy; on the other hand, traditional economic modelling is ill-equipped to embark even abstract descriptions of the inertias and flexibilities of the complex technical systems underlying energy consumptions. In the last decade, the E3 modelling community has increasingly tended to overtake these limits by developing "hybrid" models (Hourcade et al., 2006; Lefèvre, 2016). Notwithstanding their precise modelling choices, hybrid models should by nature rely on benchmark databases that provide information on the economic flows in monetary value and in physical units, notably for energy goods - the necessary condition to control the interface between economic and technical systems.

Especially for historical reasons, economic statistics are not consistent with physical statics. Indeed the balances have been produced within separated institutions. As a consequence, tables that consistently accommodate monetary and physical flows are still rarely available from official statistical agencies. We notice though that the ongoing developments of satellite accounts to the System of National Accounts (SNA) are promising (United Nations et al., 2003). In addition of hybrid flow accounts, the underlying price system must also be provided, and should be incorporated in any dataset, as key item necessary for the calibration of hybrid models. However, most energy-economy modelers are regretfully elusive about how they build such datasets from the raw data, i.e. the series of trade-offs and assumptions that they unavoidably make to reach consistency or fill statistical gaps. The leeway in these trade-offs and assumptions potentially leads to benchmark databases with different descriptions of the energy content of the economy. Paramount benchmark elements like the value of energy flows, the share of firms and households in physical energy consumption, and the different energy purchasing prices faced by agents, may vary, and therefore, may impact the evaluation of economy-wide consequences of energy and climate policies.

This chapter focuses on the techniques of data hybridisation as methods to reconstruct missing data and build consistent energy-economy databases with energy flows measured in hybrid units: as physical volumes on the one hand and monetary flows on the other, the two related by the price system. More precisely it analyses the impacts of such techniques on the empirical description of an initial state of the economy used to calibrate all hybrid computable general equilibrium (CGE) models of one region.
Most of discussions mainly focus on the various methods used for modelling technical change or embarking information on technologies in those models, because innovations in this area constitute the primary motivation for developing hybrid CGE models. Thus, studies often ignore the importance of having robust data. But, we will show that making explicit the procedure of data treatment is essential to better identify the empirical uncertainties associated with the choice of data and their processing. More specifically, we will show that the key point to insure consistent data is to manage the heterogeneities of information. We will detail a data hybridisation method that addresses important shortcomings of existing techniques by extending to supplementary data its conciliation of unmodified quantity statistics and national accounts data. In particular, the method allows accounting for the heterogeneity of the purchasing price faced by domestic economic agents for a given homogenous energy aggregate, beyond the impacts of differentiated taxations - net-of-taxes prices are indeed assumed homogenous across consumers in most CGE models, in contradiction with energy statistics, which report large differences.Prices differences would have important impacts on the way the price system translates economic interdependence and operates price-signal policies.

This chapter addresses such issues. In section 1.1, we start by reviewing the documented efforts to combine energy statistics with national accounts, and we present our original protocol to build a hybrid energy-economy Input-Ouput table (IOT) at a regional scale. The section 1.2 illustrates this protocol with 2010 data for France. For the sake of concision, we only present in the text a simplified version of the hybrid IOT, with high level of aggregation. Then, section 1.3 analyses changes induced by the procedure in the initial descrption. We confront our own method's outcome for energy sectors with a representative alternative hybrid IOT together with the original IOT of French national accounts (cf. sub-section 1.3.1). The comparative analysis illustrates the diversity of possible empirical material for hybrid CGE models. Finally, the procedure is applied to steel & iron, and cement quantities, and isolate those sectors originally aggregated in respectively metals sectors and non-metallic minerals sectors (cf. sub-section 1.3.2). Such material can be arguably differently relevant towards energy and climate policy assessment. Section 1.4 concludes.

1.1 Review of documented approaches

Originally, standard CGE models, although based on the Arrow-Debreu paradigm (Arrow and Debreu, 1954) -i.e. on a dual representation of the quantity and value flows of goods and services in the economy- are exclusively built on monetary data drawn from national accounts, commonly synthesised in the form of a Social Accounting Matrix (SAM). Benchmark quantities are not described in physical units but are deduced from value flows based on an exogenous cost shares. Freely fixed, as only relative price variations matter to the standard macroeconomic approaches, these prices are often normalised to 1 for the sheer sake of simplicity - which amounts to treating the million - or billion-currency output values as many levels of quasi-quantities. The need for physical information on underlying material flows, such as greenhouse gas (GHG) emissions or physical energy consumption, to carry out E3 analysis have led to develop hybrid accounts.

Hybrid accounting systems depart from the standard accounts by collecting and processing additional data on volumes and prices of goods from various sources and by reconciling them with the monetary flows registered in the IOTs of national accounts. To reach consistency in the hybrid description, all hybridisation procedures must reconcile data following two basic accounting principles. *First*, both physical and money descriptions must respect the conservation principle: the balances of resources and uses, both in quantities and values. *Second*, physical and money flows are linked by the system of prices: the economic values associated to the production, trade and consumption of each of the energy agregate described is the product of an aggregate volume and a price consistent with tax and margin systems. Beyond these two principles, the method of data hybridisation is not standardised.

The second accounting principle imposes that only one of three indicators (*volumes*, *prices* and *money flows*) can be adapted under the process of making them consistent for any economic operation described. Thus, a typology of the different procedures can be proposed by defining (i) the choice of which statistics from the raw data sources are kept unchanged (*"fixed" indicators*) and which indicator is modified to meet the accounting constraints (*"adjusted" indicator*); (ii) the technical procedure pinpointing the adjustments made to the indicators selected for adjustment.

Different methodologies to build energy-economy hybrid databases for E3 model calibration are documented in the literature. The different approaches available are regrouped in Table 1.1 and are characterised according to the typology previously framed. It details for each method the raw data sources, the data that are not altered (fixed indicators), and the data that are modified in the process (adjusted indicators).

The bulk of efforts to build and document energy-economy hybrid databases for E3 model calibration has been carried out in the context of the Global Trade Analysis Project (GTAP). The

Hybrid database	Scope and data sources (values/quantities)	Fixed indicators	Adjusted indicators	Used by model
Gtap-Eds	Multi-country (GTAP / IEA)	E volumes, traded E prices, traded	E volumes, domestic E and non-E prices, domestic I-O values E value added	Most global CGE models such as: Eppa (Paltsev et al., 2005) Gemini-E3 (Bernard and Vielle, 2007)
Gtap-Eg	Multi-country (GTAP / IEA)	E volumes, all Most E prices	I-O values E value-added	Gtap-Eg model
Imaclim	One country (national accounts / energy statistics - IEA)	E volumes, all E prices, all Total GDP	E and non-E sectors I-O values and value-added	Imaclim-S (Combet et al., 2010)

Table 1.1 – Four examples of hybridisation procedures

gtap has produced different generations of hybrid databases referred as Gtap Energy Data Sets (Gtap-Eds): Gtap 4 (Malcolm and Truong, 1999) and (Complainville and Van Der Mensbrugghe, 1998), Gtap 5 (Burniaux and Truong, 2002), Gtap 6 (Mcdougall and Lee, 2006). There also exists specific databases like Gtap-Eg (Rutherford and Paltsev, 2000) built for specific modelling purposes. One strength of GTAP databases is to provide harmonised national accounts for a large number of countries or regions and to insure the consistency of bilateral trade in monetary flows. This feature imposes specific accounting constraints in the hybridisation procedure compared to the single region case and should be taken into account when assessing the resulting hybrid IOT at a given regional level. Gtap-E Data Sets cross the general gtap accounts with International Energy Agency (IEA) energy balances and various data on prices, margins and taxes. The databases integrate the richness of the information available notably on the variety of user-specific energy purchasing prices at regional scale. Nevertheless the consistency of energy trade flows takes precedence in the hybridisation procedure to the detriment of regional input-output monetary flows. As a result, domestic input-output flows are adjusted with input-output algorithms, the cross entropy methods (Robinson et al., 2001), so that most initial statistics are altered in the process: energy volumes, energy and non energy prices, input-output values and value-added. A closer look to earlier versions of Gtap-Eds shows that the order of magnitude of final alterations can be significant for key sectors, and, regions (Sands et al.)[1]. This drawback is arguably quite detrimental for energy-policy

[1]For instance, Sands et al. reports important alterations for coal and power sectors in China in Gtap-Eds 5 compared to original statistics. Even though coal is the main energy provider in China, especially for electricity production, the hybrid database shows a coal price 58% lower, and coal consumption (in *Mtoe*) for power generation 37% higher compared to original statistics.

analysis at the single region scale if the algorithms used to compute domestic IOTs prevent to keep control of key domestic energy statistics. The data treatments in GTAP-EG are somehow different and preserve IEA energy volumes and most of the prices and adjust input-output values and energy value-added.

The SECOND GENERATION MODEL (SGM) procedure (Sands and Fawcett, 2005) was developed to overcome some of the flaws of GTAP approach at regional scale with a simpler method for the sake of transparency and clarity. The authors argue that it is in practice always possible in a multi-region database to dissociate the balance of bilateral trade flows from domestic balance of energy flows. As a consequence the SGM procedure, which details domestic data treatments, can be included in multi-region context as it is the case with the SGM model itself or the PET model of International Institute for Applied Systems Analysis (IIASA) (Fuchs et al., 2009). The main objective of SGM approach is to adhere strictly to energy balances so that energy volumes are fixed indicators of the procedure. Second, it aims at preserving the value-added of energy and non-energy branches as they appear in national accounts so that energy prices and input-output values have to be adjusted to guarantee the accounting principles. To do so, the method imposes: (i)on the one hand, the matrix of volumes uses (in physical units for energy sectors and in money metric –"quasi-quantities"- for non-energy sectors), and (ii) on the other hand, the vector of sectors' value-added. Then, it simply computes the vector of average net-of-taxes prices of sectors that rebalances resources and uses in money values: the resolution of a system of n linear equations of n unknowns in a word. This procedure keeps unaltered the economic value of energy flows and the aggregate Gross Domestic Product (GDP), but it does not use the information available about energy prices. In addition, it uses the values of energy flows reported by national accounts, which, as we will see below may overestimate the energy bills paid by economic agents.

The data hybridisation method developed for the IMACLIM modelling framework aims at overcoming the shortcomings of existing methods by improving the integration of energy statistics in general equilibrium frameworks. Next section details this procedure at country scale.

1.2 The IMACLIM procedure

The IMACLIM method follows two guiding rules. First, the correction of statistical gaps is carried out in such a way that both the total size of the economy (measured by GDP) and the data on energy quantities and prices coming from national energy statistics are preserved and fully used. Thus, contrary to SGM approach, the value-added of energy production is deduced from energy price data and not the other way around taken from national accounts to derive energy prices. Second, net-of-taxes purchasing price heterogeneities faced by the different economic agents (sectors and households) and reflected in energy statistics are introduced. Therefore, the resulting description of the energy content of national economic activities may be more relevant because it uses a nomenclature consistent with technical system and accurate by aggregating information from specialised data sources at the aggregation level chosen in the model (production sectors and final consumers).

In subsection 1.2.1 and subsection 1.2.2, we illustrate the general approach and the different steps of the procedure by relying on the energy flows only. However, within the framework of this thesis, the procedure has been extended to other physical flows. In subsection 1.2.1 and sub-section 1.2.2. However, these explanations can be transposed to other quantities flows. Last subsection 1.2.3 gives detailed sectoral results of the procedure for the French economy at year 2010.

1.2.1 General framework

First, we introduce the overall framework of the IMACLIM hybridisation procedure by setting out its main characteristics for its implementation.

Main steps

From a methodological point of view, the procedure can be summarised in two main steps (Figure 1.1) that we explain here succinctly. More details are given on these steps in the following sub-section. First, we explain succinctly the two main steps of the method. More details are given on these in the following sub-section

The **first step** consists in reorganising the physical datasets - that are the energy balance in million tonnes of oil equivalent (Mtoe) and energy prices in euros per Mtoe (€/*Mtoe*) - into input-output formats compatible with that of national accounts. As regards consumptions, this is not only a question of reallocating the physical energy flows of the energy balance to production sectors or households, but it is rather translating the knowledge of energy flows in national account terms. This means sorting out flows which in fact correspond to an economic transaction between national accounting agents, or even combining some of them to compute such flows (e.g. directly assigning to their accounting sectors the fuel consumptions of electricity auto-producers).

The real singularities of the IMACLIM procedure come up in the **second step** where the trade-offs to adjust indicators are made to guarantee the accounting balances. It starts with the reconstitution of energy expenses at the disaggregated level by the term-by-term product of volume and price tables. It then goes on with substituting this table of energy expenditures

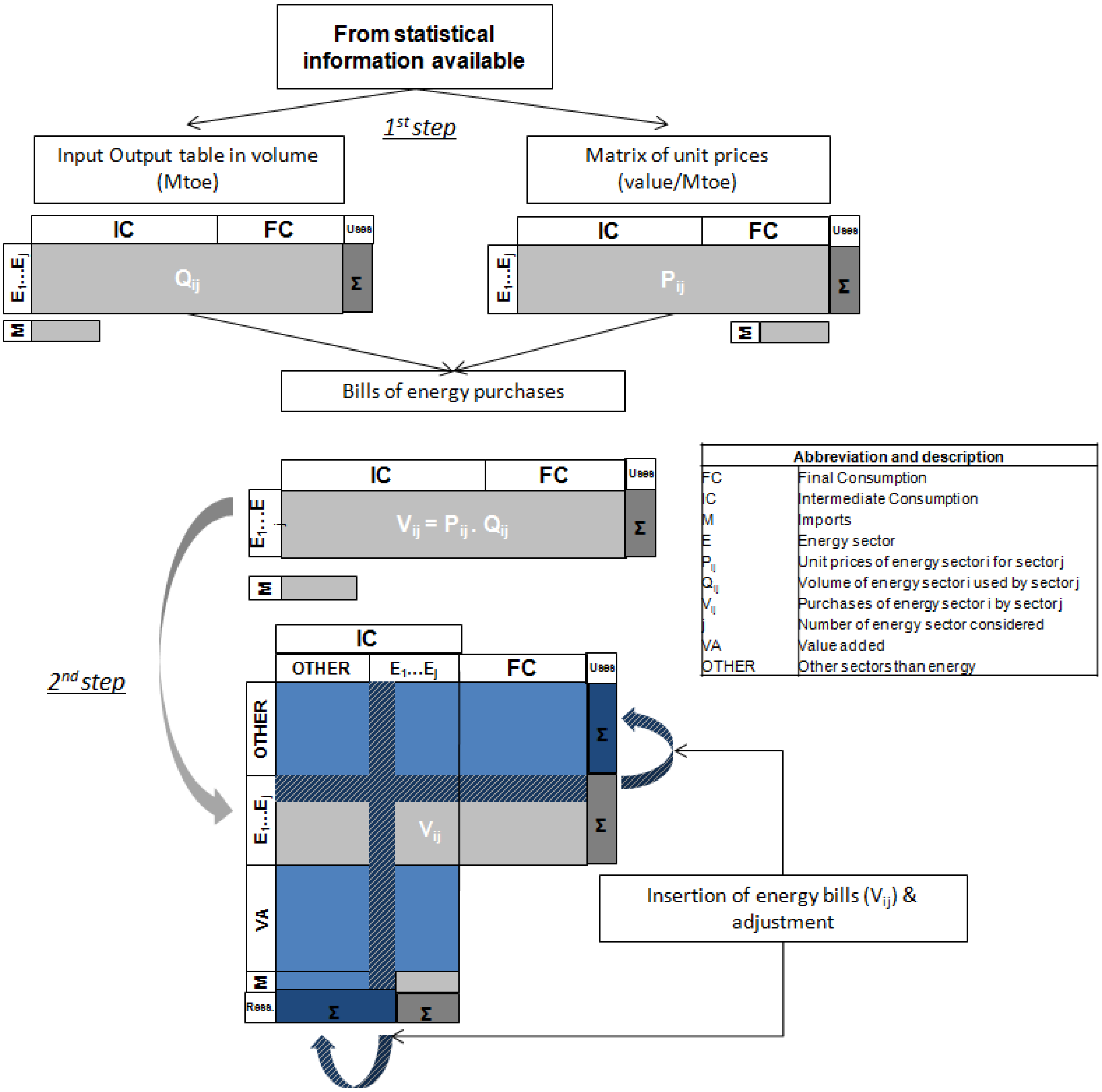


Figure 1.1 – Overview of the IMACLIM hybridisation procedure

to that pre-existing in the system of national accounts in order to fully enforce energy statistics within the hybrid IOT. Other components of the system are further adjusted to maintain the accounting identities, without modifying the total value-added of domestic production. This is done : (i) for the energy sectors, by adjusting all non-energy expenses (including value-added) pro rata the adjustment induced on total energy expenses, (ii) for all producing sectors and households, by compensating the difference between the recomputed energy expenditures and the original economic statistics through an adjustment of the expenses on the most aggregated non-energy good—a composite remainder of not specifically described economic activities, usually encompassing all service activities in E3 models. The underlying logic is to focus on the flows we are interested in, and put the rest in a large sector where the error reallocation will be unimportant given the large size of the sector.

Main feature

From a conceptual point of view, an important innovative feature of the IMACLIM procedure is the introduction of net-of-taxes purchasing price heterogeneities faced by economic agents. This feature is motivated by observing a wide gap in the unit energy prices faced by firms and households in energy prices statistics. To give just one example, in 2010 for France, the average net of value added tax purchaser's price of electricity commodity was 105 €/MWh for households versus 72 €/MWh for producing sectors i.e. 45% higher. A closer scrutiny of price data available, for both net-of-taxes and all-taxes included, confirms that this gap is not caused by taxation alone or transport and trade margins [2]. Indeed, it reflects contrasted pricing policies by enterprises. It unquestionably translates extra costs incurred for the fragmented distribution to individual households ("retail element" of the cost), be they administrative or technical in nature. But, corporate data undisclose and do not allow a meaningful distribution of these extra costs over the cost structure of energy production.

This is why we introduce a set of "pricing margins" that aggregate, for each economic user category, the deviations of the producers's price faced by each economic agent from the average producer's price emerging from the cost structure. A user-specific margin rate τ_{SMij} linked to the purchase of energy good i by user j can be introduced to link the user-specific producers' price to the average producer's price of energy good i :

$$p_{ij} = p_i \cdot \left(1 + \tau_{SMij}\right)$$

By construction the aggregate margins are compensated, and the balance of each energy sector (or the energy aggregate in our numerical example below) is not modified.

[2]Transport margins are small globally -1.5% of domestic electricity bill - and trade margins are null for electricity.

1.2.2 Procedure illustration

This subsection describes precisely the two steps mentioned above. For the sake of simplicity we illustrate the method with only two aggregated energy types: primary energy and final energy. Although the method has been carried out -for energy flows- on 16 energy sectors.

Step 1: Elaborating supply-use tables in physical units for energy

Because tables of resources and uses of energy flows and prices are not available from statistical institutes in a standardised manner, they must be built through the collection of different data sources.

	2010 - Million ton oil-equivalent, Mtoe	**Primary energy**	**Final energy**	**Non-valuables energies**	**Total**
R1	Production	1	121	13	*135*
R2	Imports	68	94	0	*162*
R3	Exports	-0	-33	0	*-33*
R4	Marine & Aviation bunkers	0	0	0	*0*
R5	**Total Primary Energy Supply**	**69**	**182**	**13**	***265***
R6	Transformations	-69	-17	-0	*-86*
R7	Energy industry own use	0	-10	0	*-10*
R8	Losses	0	-4	0	*-4*
R9	**Total Final Consumption**	**0**	**151**	**13**	***164***
R10	Iron and steel	0	4	0	*4*
R11	Non ferrous metals	0	1	0	*1*
R12	Non metallic minerals	0	4	0	*4*
R13	Construction	0	1	0	*1*
R14	Chemical and petrochemical	0	6	0	*6*
R15	Paper, pulp and print	0	2	1	*2*
R16	Mining and quarrying	0	0	0	*0*
R17	Transport equipement	0	1	0	*1*
R18	Other industries	0	9	1	*11*
R19	Transport	0	48	0	*48*
R20	Residential	0	36	8	*45*
R21	Agriculture and forestry	0	4	0	*4*
R22	Fishing	0	0	0	*0*
R23	Other sectors	0	27	3	*30*
R24	Non-energy uses	0	8	0	*8*

Source : IEA, 2010

Table 1.2 – Simplified structure of the IEA energy balance

Starting from IEA energy balance, statistical gaps and stock changes are first distributed between primary supply and consumptions (transformations or final consumption). Then, we isolate in marine and aviation bunkers, the consumption corresponding to national company to return those volume of energy in the sector of transport. The amounts of remaining energy are deducted from exports. After those pre-treatments, we can identify (Table 1.2) domestic production (R1 [3]), international trade (R3-4), transformation processes and the distribution of final consumption across activities (R10-24).

Difficulties of the transformation from the energy balance to a supply-use format are twofold. On the one hand, the energy balance does not distinguish for some productive sectors what is related with intermediate consumption, and what is related with household consumption of final demand. Indeed, it does not include information whether energy consumption serves to produce goods or directly the final consumer's needs (for mobility, heating, etc.). This question arises essentially for transport (R19) and residential (which mixes residential and tertiary-R20), and the decomposition for these two activities is dependent upon the availability of complementary datasets (e.g., transport and households' surveys). On the other hand, energy flows must be explicitly reconstituted to exclude the elements of the balance that do not correspond to commercial energy uses (e.g., non-energy uses, renewable energies, transformation by auto-production of secondary heat or electricity).

In practice, the elaboration of physical accounting systems can be divided in four sub-steps:

Sub-step 1.1 : disaggregating the description of certain products or uses. This step requires additional information from external statistical sources to define the split of quantities reported in an aggregate manner in the balance (in the absence of information, ad-hoc assumptions must be made). In the case of France, an important feature is, for example, to distinguish fuels used for households' mobility of those used for transport sectors. To this aim, the description of refined products in the energy balance must be complemented by more precise information on the details of uses. Table 1.3 illustrates the disaggregation of the transport sector (R19-20) using external sources of information.

Sub-step 1.2 : delineating the domain of analysis. In practice, this comes down to isolating the crucial components of the balance for a specific study. This means suppressing the rows and columns that correspond to activities outside the core analysis without introducing disequilibria in the balance. For example, the withdrawal of renewables and wastes is not problematic because it is a rather independent production process and it is then sufficient to add the volume of electricity produced from these sources . On the contrary, suppressing non-energy uses requires an equivalent decrease of resources.

Sub-step 1.3 : aggregating and allocating quantities of the energy balance in Table 1.3 according to the nomenclature of the final input-output matrix. This imposes to adopt a level of aggregation compatible with the nomenclature of national accounts, which comes down to

[3]We note Rn to point the row n of the table, and Rn-m for rows from n to m.

	2010 - Million ton oil-equivalent, Mtoe	Primary energy	Final energy	Non-valuables energies	Total
R1	Production	1	121	13	135
R2	Imports	68	94	0	162
R3	Exports	-0	-33	0	-33
R4	Marine & Aviation bunkers	0	0	0	0
R5	**Total Primary Energy Supply**	**69**	**182**	**13**	**265**
R6	Transformations	-69	-17	-0	-86
R7	Energy industry own use	0	-10	0	-10
R8	Losses	0	-4	0	-4
R9	**Total Final Consumption**	**0**	**151**	**13**	**164**
R10	Iron and steel	0	4	0	4
R11	Non ferrous metals	0	1	0	1
R12	Non metallic minerals	0	4	0	4
R13	Construction	0	1	0	1
R14	Chemical and petrochemical	0	6	0	6
R15	Paper, pulp and print	0	2	1	2
R16	Mining and quarrying	0	0	0	0
R17	Transport equipement	0	1	0	1
R18	Other industries	0	9	1	11
R19	**Transport - Households**	0	24	0	24
R20	**Transport - Sectors**	0	24	0	24
R21	Residential	0	36	8	45
R22	Agricuture and forestry	0	4	0	4
R23	Fishing	0	0	0	0
R24	Other sectors	0	27	3	30
R25	Non-energy uses	1	12	0	13

Source : IEA; Odyssee Enerdata - 2010

Table 1.3 – Energy balance after sub-step 1.1

aggregating columns and rows consistently with the level of description adopted in the input-output matrix. In our illustrative example, the columns have not to be modified because they directly correspond to the level of disaggregation of energy in national accounts; but, concerning rows, this thesis being focused on industries and households, intermediate consumption by tertiary activities can thus be aggregated with the consumption of other sectors.

Sub-steps 1.2 and 1.3 cannot be completely systematised because they involve a number of trade-offs depending on available datasets, the context and the question under consideration. The most important choices concern:

- ***How to assign final energy use.*** When surveys on consumption per use are missing, it becomes necessary to use information from similar economies where these data exist (e.g. Odyssee, Eurostat, or Enerdata database for transport sector) or to deduct the diffracting coefficients from national accounts by adapting the Leontief technique (Moll et al., 2007).
- ***How to establish input-output description consistent with the level of aggregation.*** Volumes of energy must be allocated in accordance with the concepts of supply and use tables (Resources, Uses and Intermediate Consumption). The way to do this assignment

depends on the level of aggregation used. In the example of France, only cross-sectoral exchanges associated with refining are described (disaggregated industry), other processing methods are not detailed (aggregated sector) .

- ***How to assign own use of energy.*** Most of the time, the amount of own used energy is not linked to any economic transaction, but must be recognised because it accounts for the estimation of technical coefficients, CO_2 emissions, and the opportunity cost they represent during the introduction of the carbon price (because losses and own uses reduce the net efficiency of the transformation). In particular, it seems consistent to identify own uses with distribution losses for coal, gas and electricity, and to transformation processes for refineries.
- ***How to describe the processes of co-productions.*** The relationship between co-productions is not described in the symmetrical IOTs, which conventionally postulates a separation of the conditions of goods' production. This assumption is not acceptable for some sectors (for example, in studies of agricultural production systems) and flows of co-production must then be described as well as the technical fundamentals which link the productions. In the example of France, this question remains of second order: in the circuit of commercial energies, only a small amount of refined products and industrial gases are by-products of other production processes (petrochemicals and inorganic chemistry) and we treat them as domestic resources into refined products and gas.

From sub-steps 1.1 to 1.3, we are finally able to get the IOT in physical unit, represented in Table 1.4. For the sake of simplicity, for next explanations, and next illustrations, non-energy sectors have been aggregated into one composite sector. However, this work has been carried out keeping all following sectors isolated from the composite sector : steel and iron, non ferrous metals, minerals, buildings construction, chemical and pharmaceutical, paper, mining, transport equipment, transport services, agri-forestry, fishing, food industry

2010 - Million ton oil-equivalent, Mtoe	Intermediate consumption			Final consumption			*Total uses*	Production	Import
	Composite	Primary energy	Final energy	Final demand	GFCF*	Export			
Primary energy	-	-	70.2	-	-	0.1	*70.3*	2.4	67.9
Final energy	86.6	0.04	18.9	60.0	-	32.8	*198.5*	109.1	89.4

* Gross fixed capital formation

Table 1.4 – Energy Input-output table

Sub-step 1.4 : computing the energy expenses and resources of the economy in monetary values. It simply consists in multiplying on a one-to-one basis the IOTs in quantities and prices to obtain a table in monetary units which corresponds to energy bills at the desired level of aggregation (Table 1.5). This table is fully consistent with the statistics on the diversity of prices, energy consumption, carbon content, etc.

2010 - Million of euros	Intermediate consumption			Final consumption			*Total uses*
	Composite	Primary energy	Final energy	Final demand	GFCF*	Export	
Primary energy	-	-	29 986.0	-	-	43.8	*30 030*
Final energy	59 386.9	18.9	4 224.3	72 288.6	-	16 612.1	*152 531*
Imports		29 535.0	28 305.8				

* Gross fixed capital formation

Table 1.5 – Balance of energy bills

Step 2: Aligning monetary and physical matrices

Once the IOT that describes the economic circuit of energy flows in quantity, value and price have been built, it remains to integrate it into the national accounts IOT without changing the important indicators for empirical analysis. This is the actual hybridisation step (Figure 1.1) that can be analysed in two stages: a set of manipulations on the rows of the table (1 - adjustment of uses) to insert the monetary sub-table resulting from step 1 and inform the energy expenses of the economy; and a set of manipulations on the columns (2 - adjustment of resources) to provide the description of the content of energy expenses: the cost structure of one litre of fuel purchased, one kWh, etc.. These columns describe the fixed and variable costs of industries that supply, process and distribute energy to consumers.

The result is a modified IOT in which the value added of energy flows is isolated from those corresponding to non-energy products from "energy branches" aggregated in the composite sector. This rearrangement in the nomenclature maintains the total value added of the economy as well as its sub-totals (wage bill, gross operating surplus, etc.), total imports and totals of final uses (Households' consumption, exports) while specifying the description of energy circulation.

To carry out this step 2 in the case of France, we start from the IOT obtained from National Accounts (Table 1.6).

Millions of euros	Intermediate consumption			Final consumption			Total uses
	Composite	Primary energy	Final energy	Final demand	GFCF	Exports	
Composite	1 576 798	263	27 077	1 532 623	376 721	444 564	3 958 046
Primary energy	1 698	0	39 270	-	-	1 255	42 224
Final energy	78 302	11	49 340	80 350	-	14 334	222 338
Value added	1 710 991	264	30 160				4 222 607
Total production	*3 367 789*	*538*	*145 847*				
Imports	448 519	41 539	22 606				
Taxes	141 738	147	53 885				
Total resources	3 958 046	42 224	222 338	4 222 607			

Table 1.6 – Input-Output tables in National Accounts

Sub-step 2.1 : adjustments of uses. Starting from the IOT (Table 1.6), we replace the values of energy branches (R2, R3 in orange) by the values of reconstructed energy bills from Table 1.5. Differences are added to uses and imports of composite (all R1 and R6-C1, in dark blue). These operations do not affect the total value of uses, but change those of different products. Therefore, the supply-use balances are broken for individual sectors.

	Millions of euros	Intermediate consumption			Final consumption			Total uses
		Composite	Primary energy	Final energy	Final demand	GFCF	Exports	
R1	Composite	1 668 256	434	10 454	1 540 684	376 721	443 497	4 040 047
R2	Primary energy	-	-	29 986	-	-	44	30 030
R3	Final energy	59 387	19	4 224	72 289	-	16 612	152 531
R4	Value added	1 710 991	264	30 160				4 222 607
R5	*Total production*	*3 438 634*	*717*	*74 824*				
R6	Imports	454 823	29 535	28 306				
R7	Taxes	141 738	147	53 885				
R8	Total resources	4 035 195	30 398	157 014	4 222 607			
	Resources - Uses	-4 852	368	4 484				
		C1	C2	C3	C4	C5	C6	

In this example, the intermediate consumption of the composite good for the production of energy (first row, second or third column: R1-C3(2)) is estimated in order to keep the input ratio Composite/Energy for energy products given by the IOTnational accounts (R1-C3(2) / [R2-C3(2) + R3-C3(2)]). The balance of inputs is assigned to the composite consumption good for the production of composite (R1-C1).

Table 1.7 – Input-Output table after adjustments of uses

	Millions of euros	Intermediate consumption			Final consumption			Total uses
		Composite	Primary energy	Final energy	Final demand	GFCF	Exports	
R1	Composite	1 668 256	434	10 454	1 540 684	376 721	443 497	4 040 047
R2	Primary energy	-	-	29 986	-	-	44	30 030
R3	Final energy	59 387	19	4 224	72 289	-	16 612	152 531
R4	Value added	1 715 843	-104	25 676				4 222 607
R5	*Total production*	*3 443 486*	*348*	*70 340*				
R6	Imports	454 823	29 535	28 306				
R7	Taxes	141 738	147	53 885				
R8	Total resources	4 040 047	30 030	152 531	4 222 607			
	Resources - Uses	0	0	0				
		C1	C2	C3	C4	C5	C6	

Table 1.8 – Input-Output table after adjustments of resources

Sub-step 2.2 : adjustment of resources. Balances between uses and resources are restored by manipulating the cost structure of industries (columns of the IOT). Values of imports and intermediate consumption are given by the energy statistics and other cost components - value added, margins, taxes on products - are adjusted to restore equality of resources with uses (Table 1.8). Since, in our example, energy taxation is known (R7-C1/C2), the adjustment is made by value added (R4). Finally, in the case of France, the margin rate is modulated according to buyers, which helps to distinguish the purchaser prices of energy products. After this last step, all accounting identities of the hybrid description are satisfied.

It is useful to keep in mind some principles to guide the choice of adjusting resources. We can offer a procedure to select the set of assumptions to be used to isolate the cost structures of two products (Figure 1.2) with the objective of mobilising the maximum statistical information available on intermediate consumption and unit costs of each input, labour, consumption of fixed capital and operating margin.

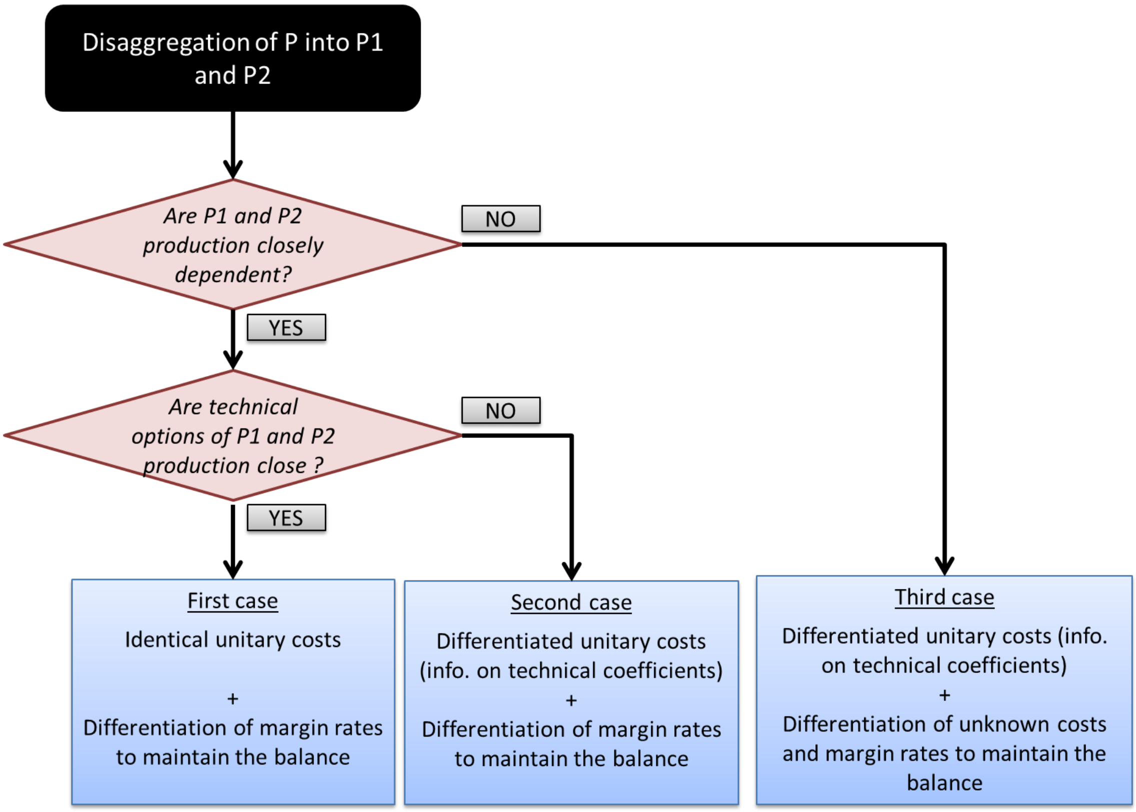


Figure 1.2 – Methodology for disaggregating cost structures and margin rates

We can then guide the search for information by discussing the conditions of production:

1 ***Productions P1 and P2 are the result of separate units.*** Therefore, the level of dependence is low. It is then likely that the information on one or the other of the structures of this cost is available. This is the case of industries specialised and concentrated, like the nuclear industry that can be isolated from other energy industries.

2 ***Productions P1 and P2 are products within the same units but with different processes.*** Information on technical coefficients (the unit quantities of inputs, capital, and labour) can be used to distinguish costs. This is the case, for example, for refined petroleum products which are derived from a combination of different methods of physico-chemical separation implemented in refineries.

3 ***The production unit and the processes are similar.*** Therefore, it is justified to retain the assumption of the same cost structure. Information is used either on unit costs or on the technical coefficients, but for both productions. Associated with the assumption of returns to scale and / or factor prices, this information can help reconstructing a structure of unitary costs for aggregates (since the total quantities produced are known). This case

corresponds, for example, to the distinction between diesel and heating oil, two products actually identical in physical term but used either for transportation or for heating.

1.2.3 Application on France 2010

The IMACLIM hybridisation procedure, has been carried out for fifteen energy sectors. Thus, we describe the quantities flows for the following sectors: crude oil-LNG-feedstocks, natural gas, coking coal, bituminous coal, coke oven coke, other coal products, gasoline, LPG, jet fuel, diesel and heating oil, heavy fuel oil, other petroleum products, biomass & waste, biofuels, electricity, heat/geothermal/solar thermal.
The hybridisation work on energy has been done for an economy with twelve industrial sectors: steel & iron, non-ferrous metals, non-metallic minerals, building constructions, chemical and pharmaceutical, paper, mining, transport equipments, transport services, agriculture and forestry, fishing, food industry. A composite sector aggregates remaining sectors (mainly services sectors).

One challenge is to better deal with competitiveness issues, and thus it is important to extend the procedure to some key sectors - the energy-intensive and trade-exposed (EITE) sectors- , and to well describe their quantities and prices. Thus, we apply the hybridisation method to two most predominant EITE sectors above all in terms of emissions: steel & iron sector, and cement sector. This additional hybridisation work has made it possible to isolate these sectors when they were initially aggregated to other sectors. Indeed, in the National accounts, iron and steel is included in metals sector, and cement in non-ferrous minerals sectors, while these aggregates are very heterogeneous.
The procedure for hybridising those sectors is mostly the same than for energy sectors, as explained below [4]. Data sources are available in Appendix A.

Finally, we obtain an IOT in monetary values with 29 sectors consistent with an IOT in quantities for seventeen sectors: sixteen energy sectors and two industrial sectors. For those sectors, IOTs in monetary values and in quantities are linked by a consistent system of price. Compared to the initial national accounts table, hybridisation procedure involves some changes in the picture of the economy. We address such analyses in section 1.3.

[4]Because steel & iron sector and cement sector do not have quantities balance statistics as for energy flows , we make some additional assumptions to ventilate production in quantities across intermediate and final consumption. In most cases, we keep the same structure as the aggregated form.

1.3 Impacts on French description

This section analyses what is the gain of the data work effort, and compares the resulting IOTs of hybridisation procedures with the initial description of the economy from national accounts. Subsection 1.3.1 addresses macroeconomic consequences of hybridisation procedures for energy quantities while subsection 1.3.2 looks at sectoral impacts.

1.3.1 Macroeconomic comparisons between input-output tables

As a case study, we compare in details the macroeconomic characteristics of SGM and Imaclim hybrid IOTs for France (2010) together with original national accounts in order to illustrate the results of contrasted hybridisation processes. For this purpose, we have reproduced the SGM method at a disaggregated level consisting of sixteen sectors including four energy sectors. By sticking to the law of unique price for energy goods, the SGM method is a good benchmark of usual hybridisation methods with the additional advantage to exhibit a simple and clear data treatment.

For pedagogy reasons, we first focus on macroeconomics, and thus we re-aggregate multi sectoral IOTs to the level of two sectors distinguishing: an aggregated energy sector, and a composite sector of the rest of the economy. Figure 1.3 presents the three IOTs after this aggregation.

We portray the striking macro differences through two sets of indicators related to:

- The size of the energy sector within the total economy (Table 1.9)
- The breakdown of total energy expenses and consumption between firms (productive sectors) and households (Table 1.10)

First of all, data hybridisation decreases substantially the share of energy in the economy (Table 1.9): the share of energy uses moves from 6.3% in national accounts to 5.4% for SGM and 4.3% for Imaclim - that is 31% less . The average energy price decreases accordingly. For SGM , without a substantive ajustment of the level of auto-consumption of the energy sector, the share of energy would be close to that of national accounts. As a contrast, in Imaclim the adjustments of energy expenses target all sectors and 24% of initial energy value-added has been allocated to the composite sector.

Second, the breakdown of energy expenses and consumptions between firms and households is modified by data hybridisation. Households get a bigger share of total energy expense moving from 32% to 36% for SGM and 44% for Imaclim - that is 35% more. Interestingly,

National accounts

2010 - Billion euros	COMPOSITE	ENERGY	C	G	I	X	Total uses
COMPOSITE	1 564	40	1 011	522	377	445	3 958
ENERGY	80	89	80	-	-	16	265
VA	1 711	30					
M	449	64					
VAT	120	15					
EXCISE IC	-	-					
EXCISE IF	-	-					
EXCISE	34	26					
Total supply	3 958	265					

Abbreviation			
C	Consumption	Excise E FC	Excise on energy interm. Consumption
G	Government	Excise E IC	Excise on energy final Consumption
I	Investment	Excise oth.	other excise
X	Exports	SMC	Specific margin for composite
VA	Value added	SME	Specific margin for energy
M	Imports	SMFC	Specific margin for FC
VAT	Value added taxes	SMG	Specific margin for G
		SMI	Specific margin for I
		SMX	Specific margin for X

IMACLIM

2010 - Billion euros	COMPOSITE	ENERGY	C	G	I	X	Total uses
COMPOSITE	1 652	28	1 019	522	377	443	4 040
ENERGY	59	34	72	-	-	17	183
VA	1 718	23					
M	455	58					
SMC	-	9					
SME	-	-17					
SMFC	-	9					
SMG	-	-					
SMI	-	-					
SMX	-	-1					
VAT	121	15					
EXCISE IC	-	7					
EXCISE IF	-	16					
EXCISE	35	2					
Total supply	4 040	183					

SGM

2010 - Billion euros	COMPOSITE	ENERGY	C	G	I	X	Total uses
COMPOSITE	1 576	41	1 015	522	377	445	3 974
ENERGY	84	52	77	-	-	16	228
VA	1 711	30					
M	449	64					
VAT	120	15					
EXCISE IC	-	-					
EXCISE IF	-	-					
EXCISE	34	26					
Total supply	3 974	228					

Energy Volumes IMACLIM and SGM

2010 - Mtoe	COMPOSITE	ENERGY	C	G	I	X	Total uses
ENERGIE	87	89	60	-	-	33	269
Y		111					
M		157					
Total supply		269					

Figure 1.3 – Two sectors level (Energy - Composite) Input-Output tables for National Accounts, SGM and IMACLIM

the share of energy consumption in volume evolves in the other direction[5]. Accordingly, the energy price ratios households / firms increase even more than energy expenses shares and moves from 1.24 to 1.65 and 2.26.

As gaps are substantive, it is required to investigate their origin so as to select the most appropriate data treatment towards the most relevant representation of energy goods circuit within the economy for climate and energy policy analysis. To do so, it is needed to look at the issues at the levels of aggregation where the hybridisation procedures operate: a disaggregated energy system constituted of several distinct energy sectors. Beyond the unavoidable non measurable statistical gaps linked to data collection and process by different organisations, one manageable source of discrepancy stems from differences of *nomenclature* related to energy flows in the different statistical systems. Nomenclature issues pertain: (i) on the one hand, to energy goods definition, and (ii) on the other hand, to the nature of flows.
With regard to the first issue, in national accounts, the energy sector includes, besides fuel production, a large number of other non-energy activities with high value-added (e.g., petroleum products). So, the sector, as reported by national account, is thus much larger than direct fuel production, though it is only the latter that will be affected by a given energy policy. In the context of a carbon tax for example the relative carbon burden (ratio between carbon

[5]For national accounts, energy volumes are derived from energy expenses by assuming a unique net-of-taxes price index of the agregated energy good. For hybrid IOTs, energy volumes are taken from energy statistics and are identical for the two hybrid IOTs because they both strictly stick to energy balances.

2010 France	National accounts [a]	SGM [b]	IMACLIM [c]	Gap SGM	Gap IMACLIM
Total energy uses (inc. exports), million €	265	228	183	-14%	-31%
Share of energy uses in total uses	6.3%	5.4%	4.3%	-13%	-31%
Average energy purchaser's price, € per toe	984	848	679	-14%	-31%

[a]Source: Institut national de la statistique et des études économiques (INSEE)
[b]Source: authors calculations - combination of IEA, INSEE and ENERDATA data
[c]Source: authors calculations - combination of IEA, INSEE and ENERDATA data

Table 1.9 – Macroeconomic differences of energy system in hybrid Input-Output table

2010 France	national accounts [a]	SGM [b]	IMACLIM [c]	Gap SGM	Gap IMACLIM
Share of firms in energy expenses (exc. exports)	68%	64%	56%	-6%	-17%
Share of households in energy expenses (exc. exports)	32%	36%	44%	12%	35%
Share of firms in energy consumption in volume (exc. exports)	72%	75%	75%	3%	3%
Share of households in energy consumption in volume (exc. exports)	28%	25%	25%	-9%	-9%
Energy purchasing prices ratios households/firms	1.24	1.65	2.26	-	-
Share of firms energy expenses in output	4.8%	3.9%	2.7%	-19%	-44%
Share of households energy expenses in expensed income	7.4%	7.0%	6.6%	-5%	-10%

[a]Source: INSEE
[b]Source: authors calculations - combination of IEA, INSEE and ENERDATA data
[c]Source: authors calculations - combination of IEA, INSEE and ENERDATA data

Table 1.10 – Breakdown of energy between firms and households in hybrid Input-Output tables

price and initial price of related energy good) will vary in a substantive manner. All the more than branches are generally not as disaggregated as products. In many case a unique branch "petroleum refineries" is distinguished. As a consequence, the relevant energy flows are mixed with other non-energy products or services in national accounts. The nomenclature gap may hinge on national accounts nomenclature precision and products disaggregation. The issue is common for petroleum products and sometimes for electricity. Energy statistics and bottom-up data collection make it possible to select the energy aggregates and related flows that are relevant for energy policy analysis within a broader macroeconomic framework.

The second nomenclature issue concerns the nature of flows and particularly the status of auto-consumptions. Indeed, a source of discrepancy specific to the energy sector is the trading of energy commodities, which developed in France in the wake of the markets liberalisations impulsed by the European Union. In the national accounts sector of electricity and gas distribution self-consumption, which can safely be assimilated to trading, amounts to 45 billion €. This is a significant share of the observed 82 billion€ discrepancy. We assume that the sector as reported by national accounts is thus much larger than direct energy expenses built by Imaclim hybridisation procedure because it amounts to count several economic transactions for the same underlying volume of energy. For all energy policy purposes other than those focused on energy markets organisation, indistinctly treating this trading as any other physical consumption cannot but flaw analysis. In SGM, estimating an average price for each energy good makes it possible to erase such trading effects and base own energy expenses on volumes of own-uses and losses. Nevertheless the procedure imposes that this self-energy consumption is valued at the average energy price what is likely unrealistic in some cases.

After identifying nomenclature gaps, it remains in theory the sole statistical uncertainty on figures. Through the procedure, the choices made should incorporate the entire information available and the most reliable data. In fact, there is every reason to believe that specialised energy statistics on prices and volumes are the most reliable, and often the only available for the nomenclature system chosen which seeks to delimit precisely the economic cycle of energy goods within the entire economy. Thus, any other specific hypothesis, that goes beyond nomenclature and data source considerations, refers to a particular model for the IOT. A specific model is likely to induce unjustified biases in the final hybrid IOT by contradicting available information (either from economic or energy statistics). This applies particularly to the model of unique net-of-taxes energy price.

Contrasted pricing policies are commonplace for energy goods. In addition of the French case mentioned earlier, US statistics also report that for year 2007, net-of-taxes electricity producer's price for households was double the price invoiced to industry. However, national accounts, in the same way as energy statistics, do capture the heterogeneities of energy prices by recording the true energy sales reported by companies and invoiced to the different economic sectors and agents. Thus, the energy expenses included in the original IOT reflect those heterogeneities even if there is no specific information available in national accounts on the specific extra-costs related - distinct from taxes and margins. That's why the unique price assumption for energy goods in fact contradicts available information.

Most if not all data hybridisation methods still enforce the law of unique price including Gtap Energy Data Sets. Even if Gtap methods admit the availability of data on user-specific net-of-taxes and margins prices, the hybridisation processes end up by enforcing a unique average producer's price for each energy goods (Mcdougall and Lee, 2006). User-specific purchaser's prices differ by sole user-specific tax rates. This is related to the modelling constraints of CGE models. Indeed, in the standard framework, there cannot be different prices for the same good. User-specific prices are typically not compatible with the zero profit condition and marginal cost pricing without further modelling treatments. Solutions exist like further disaggregating goods or creating multi-output sectors by means of specific functional form such as Constant Elasticity of Transformation (CET) functions. Nonetheless, we suspect that, in this case, modelling constraints bring trade-offs for benchmark data preparation. The consequence may be a significant bias on empirical description compared to available data (from both national accounts and energy statistics) and on the breakdown of energy expenses between economic agents. This cannot but impact policy analysis (cf. Chapter 2).

1.3.2 Sectoral distribution

After global consideration, this section observes the impacts of the IMACLIM hybridisation procedure on sectors described in the inital description compared to the national accounts IOT.

Energy cost shares

First, we portray differences between national accounts and the IMACLIM IOTs trough the breakdown of the share of energy expenses into production for each firms.

Because the "granularity" of the national accounts IOT is not as extensive as our hybrid IOT, we re-aggregate the metals sector and the non-metallic minerals sector in order to compare the two IOTs at the same level. Thus, Figure 1.4 displays the energy cost share in production for twelves sectors [6].

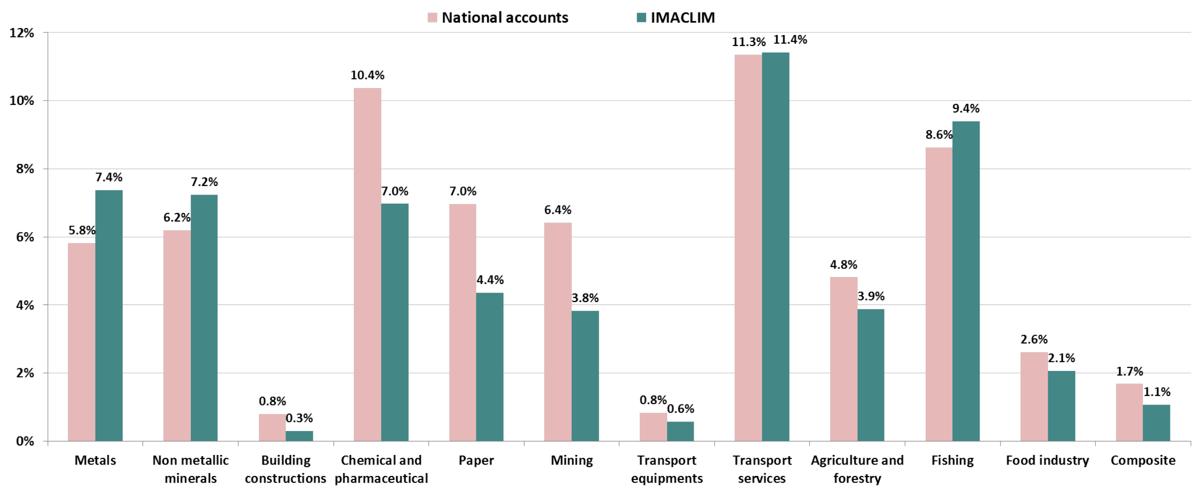


Figure 1.4 – Energy cost share across sectors

At macro level, we see in sub-sections 1.3.1 that hybridisation process tends to descrease the share of energy expenses in all firms for overall production compared to national accounts. At the sectoral level, it appears that the diagnosis is not uniform.

[6]The energy sector is not shown in Figure 1.4 because the impacts of the IMACLIM hybridisation procedure on the energy sector has already been commented on section 1.3.1.

The energy cost share of the two hybridised sectors has increased with the hybridisation procedure. The energy cost share of non-metallic minerals sectors is 17% high. Initially to 6.2%, it goes up to 7.2% in the Imaclim IOT. The difference is even higher for the metals sectors with a gap 27% between National accounts IOT and Imaclim IOTs, with energy cost shares moving from 5.8% to 7.4%.

For most industrial sectors, the share of energy cost is lower in the Imaclim IOT. The energy cost share for chemical and pharmaceutical production unit reaches 10.4% in national accounts, and it represents 7% in Imaclim IOT. There is −33% gap between the two IOTs. Same magnitudes of gap are observed for paper sector, mining sector, and transport equipment sector. The gap is even more substantial for the building constructions sector, even if in that case, energy represents a small share in production costs. Indeed, for national accounts energy cost share in production is 0.8% and after hybridising, it goes down to 0.3%, which bring the gap up to −63%.

As said in subsection 1.3.1, these discrepancies stem from inconsistent nomenclature between physical statistics and economics statistics. For instance, within a macroeconomic framework, energy expenses embark, in industries such as pharmaceutical and chemical sectors, a large part of energy expenses for non-energy uses that are then under climate policies constraints, which is unlikely. By re-including the non-energy uses into the production structure of chemical and pharmaceutical industry, we obtain a 10.8% energy cost share which is close to the share from national accounts.

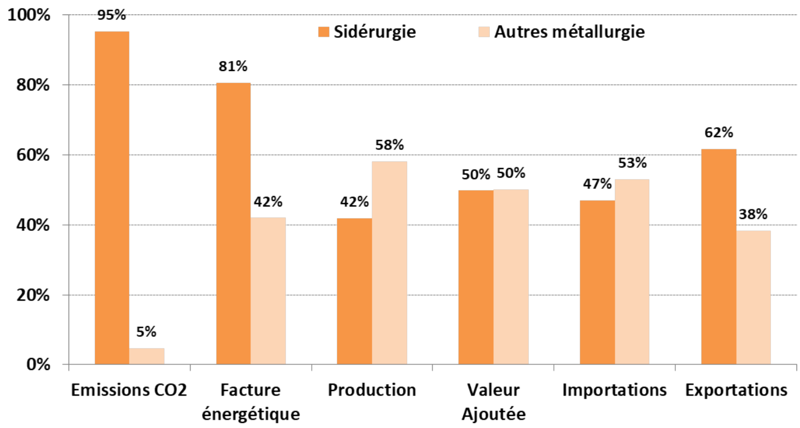
Metals sectors and non-metallic minerals sectors heterogeneities

Hybridisation procedure highlights specific sectoral descriptions which are sometimes not provided by national accounts. Hence, we show heterogeneities for major indicators within two key sectors originally aggregated in national accounts and revealed by hybridising: the metals sector and the non-metallic minerals sector.

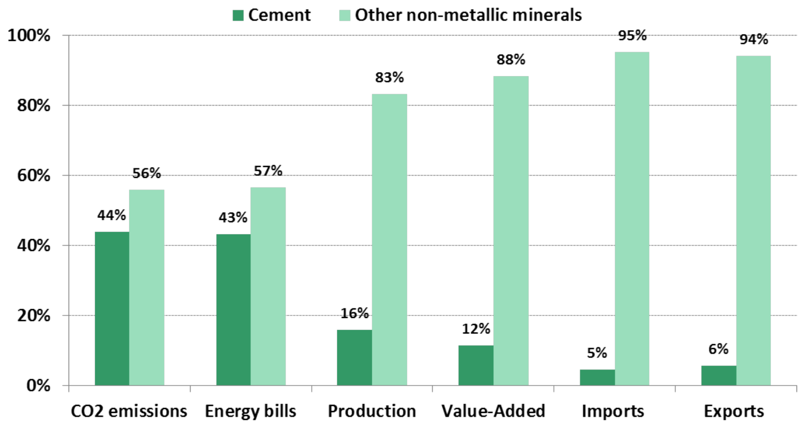
Figure 1.5 draws the breakdown of those two sectors by distinguishing:

- for the metal sector: steel & iron sector and the rest of the aggregate metal sector which corresponds to the non-ferrous metals sectors
- for the non-metallic mineral sector: cement sector and the rest of the aggregate mineral sector which corresponds to the other minerals sectors

Within the metals sector (see Figure 1.5a), steel & and iron sector accounts for less than half of the production, in value, of the metallurgical sector, with a share of 42%. However, it mainly drives the energy bills of the overall sector which accounts for 81%, and thus, represents almost all the CO_2 emissions whose share reaches 95%. This is due to coking in iron production



(a) Metals sector



(b) Non-metallic minerals sector

Figure 1.5 – Heterogeneities in metals and minerals sectors

process which are highly energy intensive. Further, steel & iron exports, in value, are bigger than the non-ferrous metals exports and accounts for 62%. Conversely, steel & iron represent 47% of metal sector imports.
Within the non-metallic minerals sectors (see Figure 1.5b), heterogeneities are even more striking. In this case, the breakdown of energy bills and CO_2 emissions between cement and the rest of the non-metallic minerals sectors is quite balanced, with a share of, respectivly, 43% and 44% for cement sector. However, those shares appear to be significant compared to the production, value-added and above all the external trade share of cement within the aggregate minerals sector. Production and value-added share of cement represent 16% and 12% in the non-metallic minerals sector. The imports and exports share of cement amount only to 5% and 6%. These are low shares but it is not a surprising distribution. Cement is confronted with high transport costs and therefore little intended for external trade.

Those sectoral heterogeneities originally hidden in the initial description of national ac-

counts are important to reveal with data hybridisation processing effort.
First, not taking into account these differences by keeping average values for aggregated sectors could be misleading when implementing carbon tax reform. As the weight of the energy in production differs significantly across sectors, the impacts on production, consumption and ultimately on international trade must contrast by nature (cf. Chapter 4). Moreover, the breakdown of those sector gives the opportunity to affect different trade elasticities in a modelling framework for environmental policies analysis. Indeed, the sensitivity of transport costs of these products is in essence not comparable, and it is misleading to give the same parameterisation to all of its subsectors.
Considered as a whole, the metallurgy and the non-metallic minerals sectors are assumed to be EITE sectors, which have strong negotiating power for any attempts to implement an ambitious environmental policy. However, by segmenting these sectors trough hybridisation work, we show that only few "sub-sectors" of the aggregate sectors induce high energy consumption, which also have specific pattern to trade. It is important to capture those aspects into the modelling exercises, as its change the debate around competitiveness issues and carbon leakage. Finally, taking into account all these differences can help to reduce the negative aspects of the application of carbon tax through objectives comprising equity, competitiveness for EITE sectors and better environmental efficiency when exploring countrywide reforms for France.

1.4 Conclusion

To conclude, the discussion around data hybridisation procedures could be argued to be purely technical if in practice the three sources of information (for values, prices and volumes) were more or less spontaneously consistent and data hybridisation processes would result in similar IOTs. However, as empirical results show, it may not be the case by large amounts. The technique proposed in this chapter has been originally developed for energy flows, and it has been extended to the description of two material flows: tons of cement and tons of steel. It could be extended to other material flows -like surfaces (m^2) or distances (passenger-km, ton-km)- and, obviously to other countries or years. Thus, our method represents an opportunity for the development of new generations of hybrid CGE models useful for sustainable development analysis.
Compared with the other hybridisation techniques, our solution replaces the nomenclature of material flows in the original Input-Ouput (IO) matrix from national accounts by the nomenclature used in material balances and physical statistics. The gap transfer to a large composite sector allows for keeping unchanged the whole size of the economy, as recorded in national accounts, while including without alteration the quantitative information about material flows, prices and quantities that come from specialised statistics.

We have attempted to demonstrate that enforcing energy statistics within a macroeconomic framework as the Imaclim method does, gives a more accurate picture of the energy system for economy-wide energy or climate policy analysis. Of course our hybridisation procedure has its limits. First, the adequacy of the method hangs on the quality and disaggregation of price data. Notwithstanding, we advocate working on explicit, improvable price x quantity disaggregation rather than keeping on using non-disambiguated national accounting aggregates. Secondly, the method is highly data- and time-intensive, even for countries with a developed statistical apparatus like France. It is therefore by essence a national method, or a method applicable to integrated regional ensembles for which aggregate statistics, especially price statistics, are available.

The Imaclim hybrid IOT build is at the heart of the work carried out in this thesis. As statistical gaps are important, the energy policy implications are expected to be substantial depending on the IOTs used for model calibration. The incidence of hybridisation for policy analysis in a standard CGE model is addressed in Chapter 2. Chapter 3 describes the hybrid Imaclim-S France model which is based on the hybrid IOT. Chapter 4 shows the sectoral aggregation bias in the analysis, which can be enhanced through our hybridisation method. Chapter 6 proposes a method based on the hybrid IOT to assess different CO_2 emissions inventories for France.

Chapter 2

Incidence of hybridisation for economic analysis : essay on conventional CGE

As mentioned in Chapter 1, computable general equilibrium (CGE) modelers are very elusive on the data hybridisation processes used to create the benchmark SAMs for CGE model calibration. The consequence is that no sensitivity analysis of modelling results to benchmark data really exists. The bulk of effort targets sensitivity to sole model structure and parameters (see Manresa and Sancho (2005), Sancho (2010)). Nonetheless we have portrayed that, in practice, benchmark Input-Ouput tables (IOTs) can be significantly contrasted in the representation of energy systems (see Chapter 1-Section 1.3) so that there is a need to appreciate the induced sensitivity of results in a CGE model context.

Thus, we complement in this chapter the analysis of the hybridisation procedure by revealing the impacts of the data treatments on energy policy evaluations. For this purpose, we implement an aggregated two-sector static CGE model describing one open-economy. Then, the model is calibrated alternatively on a benchmark of three IOTs. Except for some cases detailed after, this model is entirely based on well-known standard neoclassical assumptions and practices that have been used in CGE modelling to represent substitutions and macroeconomic behaviours.
A growing literature questions the suitability of such approaches to energy policy analysis, especially for non-marginal technical changes and over the long run (Hourcade et al., 2006). Nevertheless, we retain a standard framework to isolate the specific issue of upstream data processing from the other methodological innovation of the more relevant hybrid approaches - in particular the use of engineering expertise to model future technical change possibilities in place of postulated aggregate production and utility function parameterised with econometrically estimated elasticities.

Chapter is organised as follow. Section 2.1 presents the CGE model developed for the specific analysis. In Section 2.2, we explore how the hybridisation procedure, and the differences in the empirical description it entails, impacts the evaluation of the welfare costs of a simple tax-based climate policy. The contrasted results offer an illustration of the consequences of hybridising benchmark data. Therefore, we contribute to bridge a gap for studying the sensitivity of energy policy results to the benchmark Social Accounting Matrix (SAM). Analyses are based in the case of France (2010) considering three IOTs -introduced and compared in Chapter 1.3.1- which are representative of the range of conceivable hybrid IOTs.

2.1 A CGE framework

2.1.1 Main features

Overall interactions

We build standard CGE model based on a "*KLEM*" structure matching the level of aggregation of the benchmark input-output data used: it disaggregates two primary factors of production, capital (*K*) and labour (*L*) and, considering the focus of our study, two goods only, one energy aggregate (*E*) and one remainder of economic activity, or composite good (*M* for materials in the "*KLEM*" acronym, although we will retain this letter to designate imports in the following).

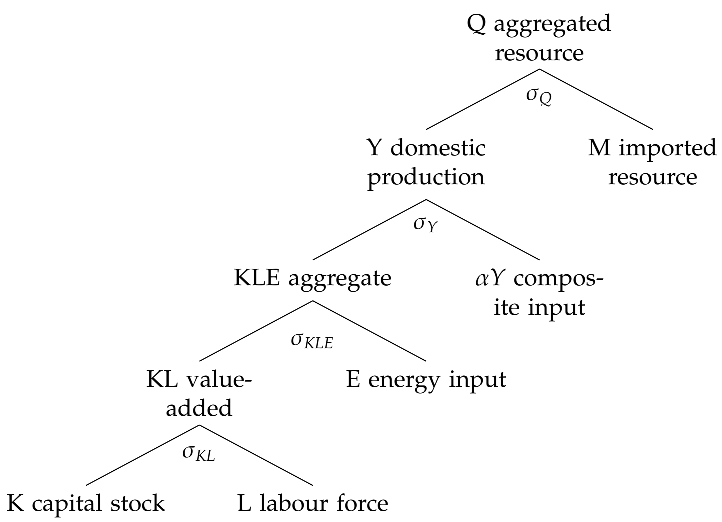


Figure 2.1 – Nested production structure of a "KLEM" model

Production of both goods is represented as a nested structure of primary and secondary factor consumptions that combine following Constant Elasticity of Substitution (CES) functions

Elasticity	Notation (cf. Appendix C)	Value, composite production	Value,energy production
Substitution of capital K to labour L	σ_{KL}	0.4200[a]	0.4501[b]
Substitution of value-added KL to energy E	σ_{KLE}	0.3518[c]	0.2374[d]
Substitution of KLE aggregate to non-energy secondary inputs αY	σ_Y	0.6678[e]	0.2378[f]
Substitution of domestic variety Y to imported variety M	σ_Q	2.0000[g]	3.7610[h]

[a]The elasticity computed by Van Der Werf (2008) for the aggregate French economy on time-series analysis.

[b]The average of the elasticities computed by Okagawa and Ban (2008) for the Mining and the Electricity, gas and water sectors weighted by the contribution of these sectors in the KL aggregate.

[c]The elasticity computed by Van Der Werf (2008) for the aggregate French economy on time-series analysis.

[d]The average of the elasticities computed by Okagawa and Ban (2008) for the Mining and the Electricity, gas and water sectors weighted by the contribution of these sectors in the KLE aggregate.

[e]The average of the elasticities computed by Okagawa and Ban (2008) for several activity sectors weighted by the contributions of these sectors to non-energy output of France 2010.

[f]The average of the elasticities computed by Okagawa and Ban (2008) for the Mining and the Electricity, gas and water sectors weighted by the contribution of these sectors in the KLEM aggregate.

[g]Inspired by the Armington elasticities of the non-energy sectors of the GTAP model (Hertel et al., 2008).

[h]The average of the corresponding elasticities of the GTAP model for 6 energy goods weighted by the contribution of these goods to the sum of domestic production and imports of energy goods in 2010 France.

Table 2.1 – Substitution elasticities of a "KLEM" model of France

(Figure 2.1). At the bottom of the structure, acknowledging recommendations of Van Der Werf (2008) and Okagawa and Ban (2008)[1], capital K and labour L trade off to produce a value-added (KL) aggregate, which then trades off with energy E to produce a KLE aggregate. This in turn is combined with non-energy secondary inputs to produce domestic output Y. Beyond domestic production, Y itself aggregates with imports M to constitute total resource Q.
The four elasticities characterising these trade-offs for each of the two represented sectors are drawn from the literature (Table 2.1).

Final demand of the two goods is disaggregated in three categories: household consumption (C), consumption of public administrations (G) and investment (I). Households devote to consumption a constant share rC of their income R, the sum of primary factors payments and social transfers. They trade off energy to composite consumption to maximise their welfare, which is a CES function of both consumptions. The elasticity of this trade-off is calibrated to

[1]Both authors demonstrate the higher relevance of the retained "KL-E" structure compared to other possible nested combinations of the K, L and E factors.

accommodate 0.6579 own-price elasticity of their energy consumptions, as inferred by weighting the GTAP model elasticities for housing utilities and transport and communications (Hertel et al., 2008) with the budget shares of domestic and private transportation energy consumptions in total household energy expenses. Public consumption G and aggregate investment I are for the composite good only. The former is specified as a constant share of Gross Domestic Product (GDP), the latter as a constant share of income. The maintained pre-existing tax rates, together with the explored excise taxes on energy consumptions (cf. infra), provide public income. Social transfers to households mechanically balance the public budget.

Remarks on the approach

We must immediately stress that we only resort to such a simple "KLEM" abstraction to set our analysis in a common-knowledge, fully controlled modelling background. Indeed, we recommend great caution in the interpretation of the absolute results of such a model. We have elsewhere criticised the inadequacy of CES functions to faithfully represent the inertias inherent to the complex engineering systems embodied in energy production and consumption (Ghersi and Hourcade, 2006). Moreover, to implement such functions we have to resort to ill-adapted elasticity estimates, of various sources of uncertain compatibility, and crudely adjust them (cf. notes to Table 2.1). We also apply them to the modelling of energy consumption constraints probably far beyond the range of their validity - fundamentally limited to the immediate vicinity of the price and quantity fluctuations observed in the time-series or cross-sectional data from which they were estimated. The reader should bear in mind, though, that this is indeed what many modelling studies do when they estimate drastic carbon policies as Factor 4 or Factor 5 (75% or 80% cuts of greenhouse gas (GHG) emissions) objectives. Also, our purpose is indeed to illustrate the impact of three different benchmarking practices by comparing their policy analysis consequences, not the policy analyses themselves.

We choose to implement a compact two-sectors CGE model instead of a customary applied model of middle size (10 to 30 sectors including 5 energy sectors for example) to be able to control the relationships between model results and the macro characteristics of benchmark energy sectors[2], and avoid the "black box" effect (Wing and No, 2004). In fact our exercice could be seen as an extension of a simple theoretical CES production function "*KLEM*" model that adds the main characteristics of an applied CGE model: IO structure, institutionnal sectors, trade, etc.
Obviously, the choice of compact CGE format masks some difficulties. As we noticed earlier, agregating the energy sector of the hybrid IOTs blinds mechanically price heterogeneities for the aggregated energy good around an average price even for Second Generation Model (SGM) IOT and this is a pure aggregation effect.Conversely, IMACLIM IOT accounts for the combina-

[2]The benchmark has been portrayed in section 1.3.1.

tion of contrasted pricing policies for individual energy goods and the aggregation effect whilst national accounts IOT keeps the assumption of unique price.
The idea is that we basically want to keep both benchmark energy cost shares and energy consumption breakdown in physical terms for analysis at the macro level so as to respect the characteristics of disaggregated benchmark data. To do so, we make a twist to the standard CGE framework, for IMACLIM and SGM IOTs, by implementing a set of "aggregation" margins (different in nature from "pricing margins" at the disaggregated level) held constant in simulation to differentiate the user prices around the average price (cf. Chapter 1).

2.1.2 Modelling equations and structure

We successively detail the production of the aggregate energy and composite resources, final consumption and investment, international trade, price formations and market clearings. Variable names indexed with a "0" designate the specific values calibrated on 2010 benchmark data; they thus indicate parameters of the equation system. Whenever required, good-specific variables are indexed by E for the energy good, by C for the composite good[3].

Production of the aggregate resource

The input trade-offs of each production (energy and the composite good) are represented as nested structures of Constant Elasticity of Substitution functions (cf. Figure 2.1). At each tier of these structures, standard cost minimisation defines the consumption of any input A traded off with another input B (capital K and labour L, value-added KL and energy E, KLE aggregate and composite input αY or domestic output Y and imported variety M) to produce some aggregate AB (value-added KL, KLE aggregate, domestic output Y or total resource Q) as:

$$A = \left(\frac{\alpha_{AB}}{p_A}\right)^{\sigma_{AB}} \cdot \left(\alpha_{AB}^{\sigma_{AB}} p_A^{1-\sigma_{AB}} + \beta_{AB}^{\sigma_{AB}} p_B^{1-\sigma_{AB}}\right)^{\frac{\sigma_{AB}}{1-\sigma_{AB}}} \cdot AB \tag{2.1}$$

with σ_{AB} the central elasticity parameter (cf. values reported Table 2.1); α_{AB} and β_{AB} coefficients calibrated on benchmark 2010 data; p_A and p_B the purchaser prices of good A and B.

[3]More detailed on notation are given in Appendix C.

Final consumption and investment

The consumed income of households R is the sum of primary factor payments and taxes, i.e. Gross Domestic Product (GDP), net of public expenses $p_G G$, investment $p_I I$ and the trade balance $p_X X - p_M M$:

$$R = GDP - \left(\sum_i p_{G_i} G_i + \sum_i p_{I_i} I_i + \sum_i p_{X_i} X_i - \sum_i p_{M_i} M_i \right) \tag{2.2}$$

Households' utility is a constant elasticity of substitution function of their consumptions of the energy and composite goods, H_E and H_C. Facing prices $p_H i$ and elasticity σ_u, utility maximisation induces:

$$H_i = \left(\frac{\alpha_U}{p_{H_i}} \right)^{\sigma_U} \cdot \left(\alpha_U^{\sigma_U} p_{H_E}^{1-\sigma_U} + \beta_U^{\sigma_U} p_{H_C}^{1-\sigma_U} \right)^{\frac{\sigma_U}{1-\sigma_U}} \cdot R \tag{2.3}$$

Public spending G_i is a constant share s_{G_i} of GDP (traditionally nil for energy goods i.e. $s_{G_E} = 0$)

$$p_{G_i} G_i = s_{G_i} GDP \tag{2.4}$$

Investment has a constant ratio s_{I_i} to consumed income, amounting to a constant savings rate (of course $s_{I_E} = 0$):

$$p_{I_i} I_i = s_{I_i} R \tag{2.5}$$

International trade

Following the Armington specification of international trade (Armington, 1969), the trade-off between domestic production Y and imports M is settled by a CES function—the upper tier of the production function of aggregate resource introduced above. Y and M thus follow the general form of (1). Exports X_i are defined as elastic to terms-of-trade:

$$X_i = X_{i_0} \left(\frac{p_{X_i}}{p_{M_i}} \frac{p_{M_{i_0}}}{p_{X_{i_0}}} \right)^{\sigma_{X_i}} \tag{2.6}$$

For lack of a better assumption both σ_{X_i} are set to 1.

Market clearings and accounting identities

Market balance for each good i equates total resource Q_i to the sum of intermediate consumptions $\alpha_{ij} Y_j$, household consumption H_i, the consumption of public administration G_i, the consumption for investment I_i and the exports X_i:

$$Q_i = \sum_j \alpha_{ij} Y_j + H_i + G_i + I_i + X_i \tag{2.7}$$

Labour and capital demand by the two productions i sum up to total exogenous labour supply L and capital endowment K (through the adjustment of wage w and rent p_K):

$$\sum_i L_i = L \tag{2.8}$$

$$\sum_i K_i = K \tag{2.9}$$

Producer and Purchaser Prices

The cost of labour p_L is equal to the net wage w plus payroll taxes levied at a constant rate τ_{CS}:

$$p_L = (1 + \tau_{CS})\, w \tag{2.10}$$

The price p_{AB} of any CES aggregate AB (value-added KL, KLE aggregate, domestic output Y, total resource Q) is the standard function of prices p_A and p_B:

$$p_A = \left(\alpha_{AB}^{\sigma_{AB}} p_A^{1-\sigma_{AB}} + \beta_{AB}^{\sigma_{AB}} p_B^{1-\sigma_{AB}}\right)^{\frac{1}{1-\sigma_{AB}}} \tag{2.11}$$

An exception, p_Y adds to this generic form a constant ad valorem output tax $\tau_Y p_Y$.

International prices p_{M_i} are fixed (the international composite good is the numéraire of the model; the price of imported energy relative to that of the international composite good is constant). The purchaser's price of good i consumed in the production of good j (p_{ij}), by households (p_{H_i}), by public administrations (p_{G_i}), in investment (p_{I_i}) or by exports (p_{X_i}) is the sum of: its resource price p_{Q_i}; a constant, agent-specific, ad valorem margin τ_{SM}; an exogenous, agent-specific excise tax t; an exogenous, agent-specific ad valorem sales tax τ:

$$p_{ij} = \left(p_{Q_i}\left(1 + \tau_{SM_{ij}}\right) + t_{ij}\right)\left(1 + \tau_{ij}\right) \tag{2.12}$$

$$\forall A \in [H, G, I, X]\, p_{Ai} = \left(p_{Q_i}\left(1 + \tau_{SM_{Ai}}\right) + t_{Ai}\right)(1 + \tau_{Ai}) \tag{2.13}$$

All tax and excise rates are calibrated on benchmark data (see subsection 2.2.1). Calibrating on non-hybridised matrices mechanically induces nil values for all τ_{SM}, i.e. prices are only differentiated by explicit tax differences across agents. The energy quotas simulated in section 2.2 use the t excises (on firms or household consumptions only, or on both agents simultaneously) as variables to comply with consumption cuts targets.

Accounting aggregates

GDP is the sum of factor payments and taxes T:

$$GDP = \sum_i wL_i + \sum_i p_K K_i + T \tag{2.14}$$

while T is the sum of taxes levied of labour, productions and consumptions:

$$T = \sum_i \tau_{CS} wL_i + \sum_i \tau_{Y_i} p_{Y_i} Y_i + \sum_i \sum_j \frac{\tau_{ij}}{1+\tau_{ij}} p_{ij} \alpha ij Y_j + \sum_i \sum_j t_{ij} \alpha ij Y_j + \sum_{A=H,G,I,X} \sum_i \frac{\tau_{Ai}}{1+\tau_{Ai}} p_{Ai} A_i \tag{2.15}$$

2.2 Model experiments and results

2.2.1 Data and numerical experiments

Data calibration

At this stage, we alternatively calibrate the CGE on three IOTs aggregated into two sectors, giving thus three models ready for simulation:

- ***NH model***: non-hybrid IOT based on national accounts (see Table 2.2)
- ***H1 model***: hybrid IOT based on SGM hybridisation procedure (see Table 2.3)
- ***H2 model***: hybrid IOT based on IMACLIM hybridisation procedure (see Table 2.4)

France 2010 - Million of euros		Intermediate consumption		Final consumption				Total uses
		Composite	**Energy**	**C**	**G**	**I**	**X**	
Intermediate consumption	**Composite**	1 563 850	40 288	1 010 980	521 643	376 721	444 564	**3 958 046**
	Energy	80 001	88 622	80 350	-	-	15 589	**264 561**
Value-added	**Labour net**	732 458	8 010					
	Labour taxes	401 063	4 386					
	Ouput taxes	55 339	1 967					
	Capital	522 131	16 061					
Imports	**M**	448 519	64 145					
Margins	**SMC**	-	-					
	SME	-	-					
	SMFC	-	-					
	SMG	-	-					
	SMI	-	-					
	SMX	-	-					
Taxes	**VAT**	120 266	15 313					
	Excise E IC	-	-					
	Excise E FC	-	-					
	Excise Oth.	34 420	25 770					
Total supply		**3 958 046**	**264 561**					

2010 - Prices (€/quasi quantities)		**Composite**	**Energy**	**pC**	**pG**	**pI**	**pX**
Intermediate prices	**Composite**	1 010	1 010	1 078	1 078	1 078	1 000
	Energy	1 124	1 124	1 389	1 389	1 389	1 000

		Composite	Energy
Imports	**pM**	1 000	1 000
Outputs	**pY**	1 000	1 000

Table 2.2 – Non-hybrid IOT based on national accounts (*NH* model)

For the convenience of the reader, we give the IOTs in the body of this chapter. Their comparison has already been made in Chapter 1 and we refer the reader to section 1.3 for more detail.

Let's just highlight again that contrary to the national account *NH* model and the SGM *H*1 model, the IMACLIM *H*2 model provides heterogeneous prices faced by different agents. This a hybridisation procedure result (see Chapter 1). The SGM hybridisation technique keeps an identical net-of-tax energy price.
Let's mention first that the aggregation from 4 energy sectors to one unique energy sector IOT, generally cancels the law of unique price. In the aggregated SGM IOT, the bulk of auto-consumption by the unique energy sector is made of crude oil purchases at a relative low price (compared to electricity for example) so that the average purchaser's price is lower for the energy sector than for the composite sector and households that purchase a bigger share of

France 2010 - Million of euros		Intermediate consumption		Final consumption				Total uses
		Composite	Energy	C	G	I	X	
Intermediate consumption	**Composite**	1 575 516	40 636	1 014 997	521 542	376 517	444 564	**3 973 772**
	Energy	84 056	51 638	76 638	-	-	15 589	**227 921**
Value-added	**Labour net**	732 458	8 010					
	Labour taxes	401 063	4 386					
	Ouput taxes	55 339	1 967					
	Capital	522 131	16 061					
Imports	**M**	448 519	64 145					
Margins	**SMC**	-	-					
	SME	-	-					
	SMFC	-	-					
	SMG	-	-					
	SMI	-	-					
	SMX	-	-					
Taxes	**VAT**	120 270	15 309					
	Excise E IC	-	-					
	Excise E FC	-	-					
	Excise Oth.	34 420	25 770					
Total supply		**3 973 772**	**227 921**					

2010 - Prices (€/quasi quantities)		Composite	Energy	pC	pG	pI	pX
Intermediate prices	**Composite**	1 010	1 010	1 078	1 078	1 078	1 000
	Energy	990	990	1 245	1 245	1 245	473

		Composite	Energy
Imports	**pM**	1 000	408
Outputs	**pY**	1 000	1 548

Table 2.3 – Hybrid IOT based on on SGM hybridisation procedure ($H1$ model)

France 2010 - Million of euros		Intermediate consumption		Final consumption				Total uses
		Composite	Energy	C	G	I	X	
Intermediate consumption	Composite	1 651 628	27 516	1 019 041	521 643	376 721	443 497	**4 040 047**
	Energy	59 387	34 229	72 289	-	-	16 656	**182 561**
Value-added	Labour net	734 346	6 122					
	Labour taxes	402 097	3 352					
	Ouput taxes	55 836	1 470					
	Capital	526 016	12 176					
Imports	M	454 823	57 841					
Margins	SMC	-	9 279					
	SME	-	-17 346					
	SMFC	-	8 913					
	SMG	-	-					
	SMI	-	-					
	SMX	-	-846					
Taxes	VAT	120 847	14 732					
	Excise E IC	-	7 199					
	Excise E FC	-	16 378					
	Excise Oth.	35 067	1 546					
Total supply		**4 040 047**	**182 561**					

2010 - Prices (€/quasi quantities)		Composite	Energy	pC	pG	pI	pX
Intermediate prices	Composite	1 010	1 010	1 078	1 078	1 078	1 000
	Energy	686	384	1 204	1 204	1 204	505

		Composite	Energy
Imports	pM	1 000	368
Outputs	pY	1 000	761

Table 2.4 – Hybrid IOT based on on IMACLIM hybridisation procedure (*H*2 model)

expensive energy like electricity. This is a pure aggregation effect that generally does not erase the initial bias of unique price. SGM method admittedly corrects the biases linked to energy auto-consumption like trading effects. However, Table 2.3 shows that the law of unique price at the disaggregated level induces a global transfer of energy expenses to the composite sector for households compared to both national accounts IOT (Table 2.2), and Imaclim IOT (Table 2.4).

Differently, the same law of unique price induces a bias in national accounts IOT when estimating the breakdown of energy consumptions in volume this time. Starting from energy expenses, the hypothesis of unique price, generally normalised to one, makes it possible to derive money-weighed energy volumes that are assumed to be in proportional relationship with real physical volumes so that total energy demand equals that of energy balance. However the reality of price heterogeneity and of higher energy prices for households induces in practice a wrong transfer of energy consumption from productive sectors to households compared to energy balance. Again the unique price assumption is linked to the constraints of standard CGE model.

Numerical experiments

Now, we explore the welfare costs of energy consumption cuts induced by an excise tax on energy consumptions.

We have seen that there could be links between the assumptions made for data hybridisation and the modelling features of CGE models, especially through the law of unique price. So the issue is to explore to what extent a CGE framework can cope with contrasted pricing policies and we have mentionned in Section 1.3.1 several existing solutions to do it. In addition, as at least one benchmark IOT differentiates energy prices, we will implement here one solution to cope with this feature. Nonetheless this otherwise crucial issue is out of the scope of the present chapter and refers to fundamental questions of split between quantity and prices, mass conservation, technical constraints management, market imperfections specification (among others) in applied general equilibrium contexts elsewhere explored and presented in Chapter 3. Rather, our goal is more simply to look at the possible dispersion of results related to the variability of benchmark energy cost-shares and consumption breakdown as it exists in hybrid IOTs.

We consider three different sets of energy policies depending on the targeted groups of economic agents: (i) the set of *uniform policies* targets firms an households indistinctly with a uniform excise tax; (ii) *firms policies* target firms only, with a specific excise tax on intermediate energy consumption; (iii) *households policies* target households only, by means of a specific final demand excise tax. Contrary to standard approaches that uses *ad valorem* taxes, we use a real excise taxes system, that adds to the already existing excise system, and that targets real energy volumes. This feature is crucial in a context of differentiated energy prices. As stated in section 2, the generated tax proceeds accrue to the public budget, which is in turn balanced by transfers to households once public expenditures have been financed. For each policy set, we explore the full range of energy cuts for the targeted group(s) - from 0% untill 99% because by construction, CES functions forbid modelling 100% cuts.

In relation to the characteristics of the benchmark IOTs portrayed in section 1.3.1, we seek to organise the results along two dimensions:

- The impact of benchmark global energy system size on welfare costs
- The impact of benchmark energy expenses and consumption breakdown between firms and households on the sharing of energy cuts efforts

2.2.2 Results and sensitivity tests

As put by Hogan and Manne (1977), at first order, the impact of energy cuts on the aggregated economic output depends on the initial share of the energy system in the economy and the elasticity of substitution between energy and the other factors. This is illustrated by the classical CES KLE model that represents the economy by means of a single production function that relates global output to the different factors including energy:

$$y = f(K, L, E) = \left(\alpha_K p_K^{\frac{\sigma-1}{\sigma}} + \alpha_L p_L^{\frac{\sigma-1}{\sigma}} + \alpha_E p_E^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}$$

with α_E the initial energy cost share and σ the elasticity of substitution.

For an elasticity of one, the relative impact on output is the multiplication of the energy cut by the cost share: a 10% energy cut will imply a 0.4% output decrease in an economy with an energy cost share of 4%. If the elasticity is lower (resp. higher) than one, the impact is higher (respectively lower). For complete energy cuts the outputs tends to zero. These results are valid for K and L held constant.

In our case, the model structures and elasticities values - ranging from 2.3 to 6.2 for energy input (cf. Table 2.1) are identical for NH, $H1$ and $H2$ models.
Figure 2.2 displays the welfare cost curve of *uniform policies* case of total energy cuts for the three models.

Models' results have very close response of welfare cost to energy cut with a CES-type convex profil. Logically, differences between NH, H1 and H2 models are null for a 0% and a

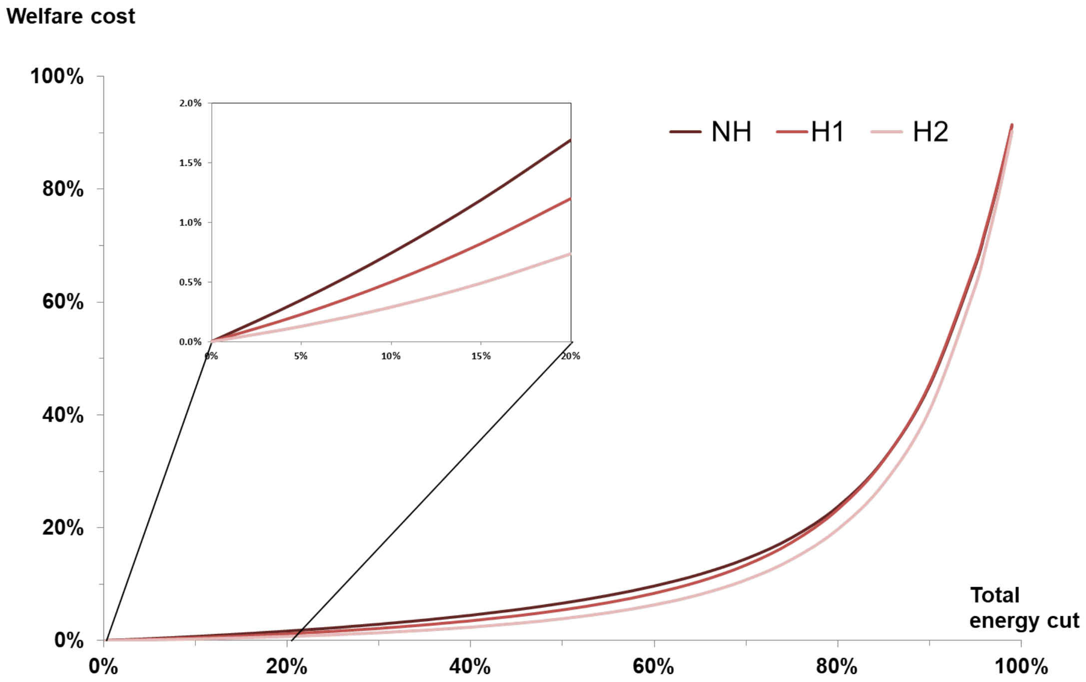
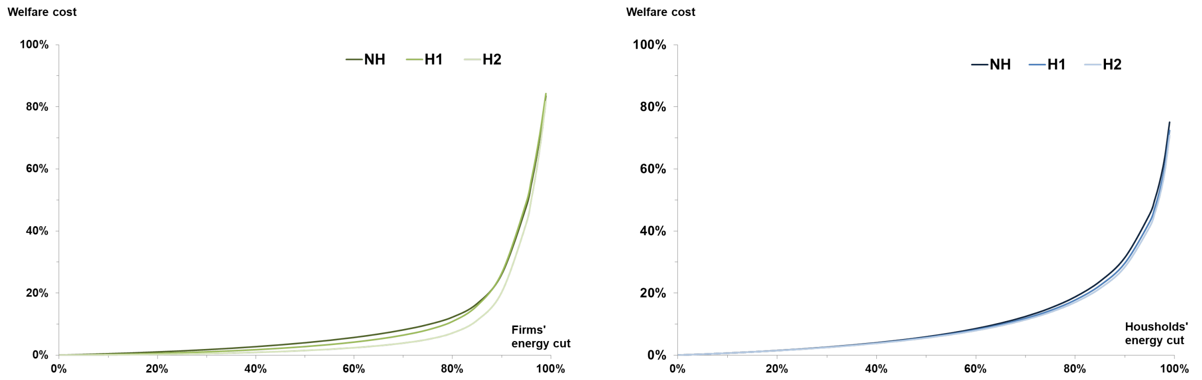


Figure 2.2 – Welfare cost of price-induced energy cuts for *uniform policies* set

100% energy cut, and higher in between. The hierarchy of welfare cost curves is identical and consistent with benchmark energy systems and the theoretical CES model. Indeed, welfare cost is all the lower than the benchmark energy cost share is low for the whole range of possible energy quotas.
At first sight, gap between models seems to have no interest. Nonetheless, as we will detail later, plotting the all scale of energy cut is misleading. By zooming between 0% and 20% of energy cut, which in fact correspond to the realistic policies, discrepancies arises. In particular if we compared to the range of CES cost curves that corresponds to the variability of benchmark energy cost shares of our models, we can observe that welfare costs are globally lower for our three models and the dispersion of costs is higher compared to the simple CES model. In the first place, the lower costs could be explained by the added flexibility of the CGE framework.

Looking at the results of alternative policies sets (*firms policies* and *households policies*) makes it possible to discriminate further the sources of discrepancies (Figure 2.3).

In each alternative, the hierarchy of costs certainly still holds, the higher the energy cost or expense share, the higher the welfare cost. The gap observed between each model is of intermediate size in the *uniform policy* case compared with the *households policy* and *firms policy* cases. As regard these later cases, the divergence in welfare cost estimates is much stronger for firms than it is for households. These results can be expected: propagation of production price has much effect on firms through multiplier effects while households are at the end of



(a) Firms policies (b) Households policies

Figure 2.3 – Welfare cost of price-induced energy cuts for *firms* and *households policies* sets

the production process. In addition, these results also echo (i) the direction and (ii) the relative sizes of the corrections of the energy expenses of both agents for $H1$ and $H2$ compared to NH. Indeed, in $H1$ and $H2$ cases, hybridisation decreases the energy expenses of both agents, but it cuts by respectively 19% and 44% the energy expenses of firms whilst it only adjusts those of households by 5% and 10% (cf. Table 1.9).

As we say just earlier, in absolute terms and for the all range of energy cut, differences between models seem low. By reporting results in relative terms, differences take another dimension. Figure 2.4 displays the ratios of welfare cost of NH and $H1$ on its of $H2$ in function of the level of energy cut in the three sets of policies. Results are thus much more striking.

For *households policies*, the welfare costs ratio never exceeds 1.04 and 1.11 respectively for $H1/H2$ and $NH/H2$. This result is consistent with the CES model. Indeed, the gap in benchmark households' energy expense shares is "directly" translated in gap of same magnitude for welfare costs.
Under *firms policies*, repercussions are much more contrasted. The marginal absolute magnitude of the estimation gap for the lower consumption cuts hides ever-increasing relative gaps as the target's ambition decreases. For a 10% cut of firms' consumptions the welfare cost estimated with $H1$ and NH, although small (respectively 0.45% and 0.23%), are 2.8 and 5.5 times that estimated with $H2$ (0.08%). Up to a 70% cut it is consistently more than 1.5 their counterpart in $H2$.
In the case of firms the impact on cost assessment thus largely exceeds the extent of the expense corrections. These results show that the deviations of our CGE model from the standard CES model are substantial. The gap must have to do with the more complex modelling features and behaviours of productive sectors, which includes feedback loops to the energy consumptions of input productions through the Input-Ouput (IO) matrix, and to the broader macroeconomic framework extending to the primary factors markets and international trade.

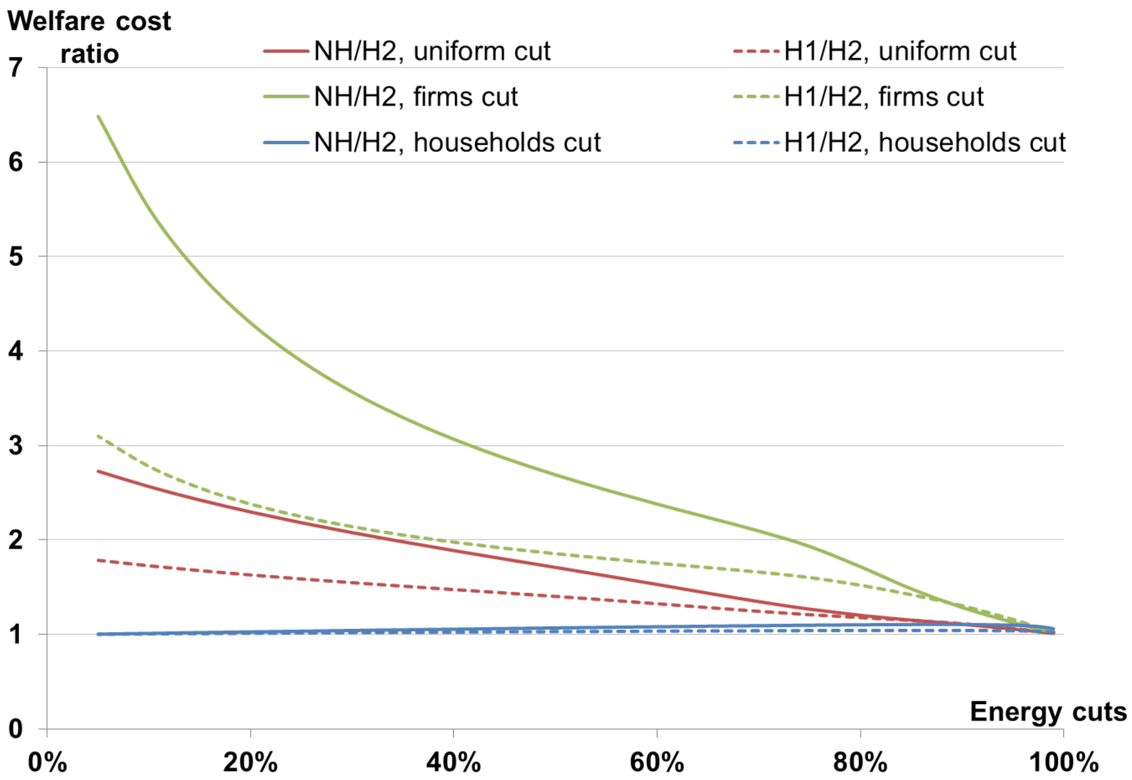


Figure 2.4 – Welfare cost ratios of *NH* and *H*1 on *H*2 for the three policies sets

During this thesis, we did not have time to give the full explanation to disentangle these mechanisms. However, the sensitivity analysis conducted for this exercise show that the mechanisms at play are depending on: (i) the elasticities of substitution, (ii) the initial repartition of intermediate consumption within the input-output matrix which induces a standard multiplier effect from final consumption to domestic production.

Figure 2.5 display the households' participation to the total energy cut effort for all models and range of cuts.

We observe unsurprisingly that the initial split of the global energy bill between households and productive sectors has a direct impact on the share of global energy cut effort between the two institutional sectors. Thus, in Imaclim the higher share of initial households energy bill implies a lower energy cut effort for medium global energy cut compared to SGM and Institut national de la statistique et des études économiques (INSEE). This has to be related to the links between initial cost or expense shares to the marginal product of energy (towards output or utility). Thus, in Imaclim *H*2 model, the higher share of initial households energy bill implies a lower energy cut effort for medium global energy cut compared to SGM *H*1 model and INSEE *NH* model. This has to be related to the links between initial cost or expense shares to the marginal product of energy (towards output or utility).

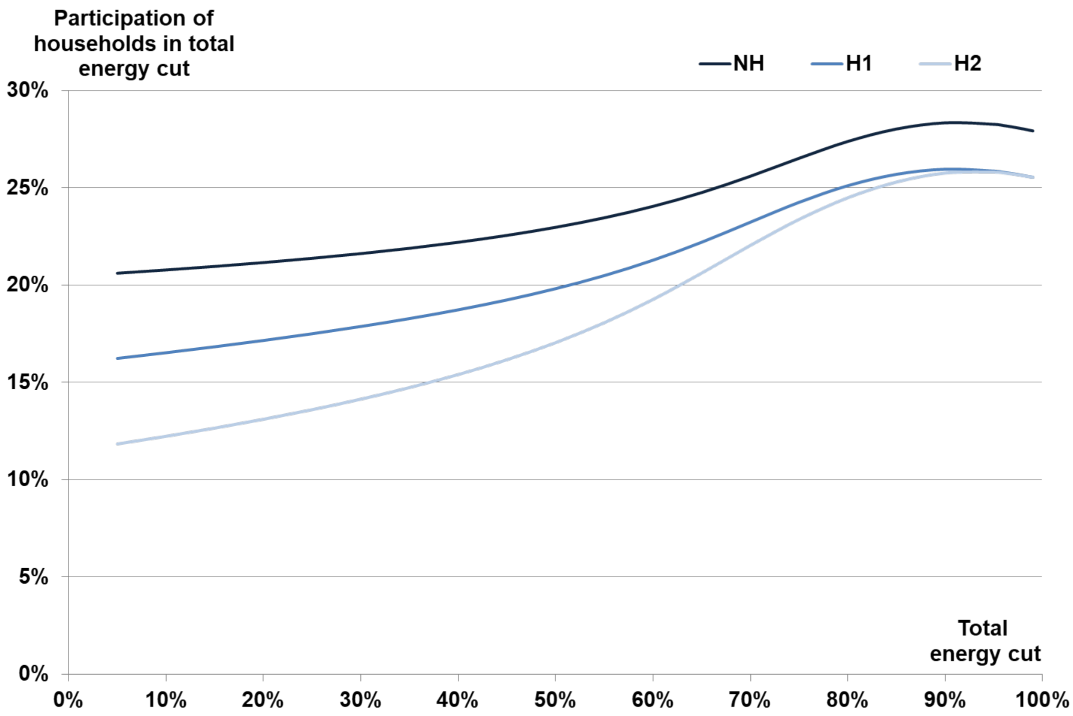


Figure 2.5 – Households' participation to total energy cut effort

In a nutshell, CGE simulations have shown that benchmark gaps for the economic size of the energy system translate into even larger gaps for welfare cost estimates of the same uniform energy saving policy. The maximal ratio of 1.45 for benchmark energy system sizes - already significant with actually +45% of energy size for *NH* compared to *H*2 - translates into a maximal ratio of 2.57 for welfare costs in the case of a total 10% energy cut. This is a qualitatively different appraisal for the same energy policy. Benchmark energy cost shares of productive sectors within the IO matrix are of paramount importance to explain the dispersion of the welfare costs. In addition, the gaps in the breakdown of benchmark energy bills and energy volumes consumed, between productive sectors and households, induce gaps at least as important for the assessment of energy cut effort sharing between the two institutional sectors. Finally, benchmark data hybridisation does matter for empirical energy policy assessment.

2.3 Conclusion

The chapter show that the non-marginal gap between empirical descriptions of the economy, arising by building hybrid SAM, has therefore a non-marginal impact on the policy evaluations of this economy. Particularly, the incidence of hybridisation exists with all types of CGE models, even at a high level of aggregation within "standard" neoclassical model like the one used in this chapter. Indeed, the hybridisation procedures used to reconcile energy data on price and quantities with IOTs coming from national accounts have direct impact on the description of empirical features that cannot but matter for energy policy evaluation: the economic size of energy flows, the relative share of energy bills paid by productive sectors and final consumers, the relative energy prices paid by economic agents and hence the relative energy consumption volumes of economic agents.

In absolute terms, the differences of welfare cost in response to any energy policy appear to be insignificant by using either standard CGE models, with a unique price, or hybrid CGE model with heterogeneous price by agents, but only at first sight. In relative terms, by comparing the welfare costs from standard model to the hybrid welfare cost, the gaps are in fact substantial. We then have point out that the gaps go in the same direction than the gaps between energy expenses in the empirical description, but that the magnitudes of the gaps significantly differ between policy cases. An excise tax supported by households only gives same order of discrepancy between the welfare cost and the households' energy expenses. It comes out that targeting only households, at the end the productive system, has not a multiplier effects through the input-output structure like they emerge by targeting only firms. Indeed, under firms policies, the relative gaps of welfare cost are much higher than the gaps of firms energy expenses.

We expect that gaps observed between models for policy implications would vary with the modelling assumptions about technical change and the macro functioning of the economy, as well as with the levels of aggregation of productive sectors and economic agents, and with the specific data at hand (year, country, and sources). In particular, the differences between the policy evaluations drawn from hybrid CGE models and "standard" neoclassical CGE models are of course magnified by the use of bottom-up models and engineering expertise in place of aggregate production functions calibrated on econometric estimations. Even if the impact of the modelling and aggregation choices has already begun to be discussed elsewhere, it has not been isolated from the impact of hybridisation techniques on the initial empirical description.

Still, the first motivation for elaborating hybrid social accounting matrices remains of course to embark in CGE frameworks the experts' information about future technical change and energy saving possibilities at different time horizons. Therefore, to continuing this research, it is natural to introduce a hybrid CGE model to evaluate the impact of different techniques and assumptions used to realise this dialogue between bottom-up engineering expertise and top-down macroeconomic modelling. Chapter 3 presents such a model.

Chapter 3

IMACLIM-S: a general equilibrium modelling framework

The Imaclim modelling approach has been developed at CIRED since the early 90s. At the core of the blueprint, the objective has been to build hybrid modelling architectures to articulate energy system and economy-wide representations to explore energy-climate-economy futures (Hourcade et al., 2006; Ghersi and Hourcade, 2006). Initially the Imaclim approach comes in several modelling platforms including a global multi-region recursive-dynamic version - Imaclim-R World (Sassi et al., 2010) and static national versions. A French version exists in either recursive-dynamic - Imaclim-R France (Bibas, 2015) - or in comparative statics - Imaclim-S France (Combet, 2013). Recently, other national versions have been developed for emerging economies like Brazil (Lefèvre, 2016), and South Africa (Schers et al., 2015). The core of each of these country scale models is similar. Behavioural and accounting equations are comparable although they embody certain particularities specific to the country's economy, and to the study that initially motivated the development of the model (competitiveness, equity, labour issues). Despite the common specifics, there are, so far, as many tools as Imaclim-S country versions.

Taking advantage of the needs of a flexible architecture for the studies conducted in this thesis for the French economy, a new rationalised tool has been developed. Section 3.1 describes the issues and benefits surrounding this new platform. In section 3.2, we give a general overview of the Imaclim-S France model version used to provide the analysis conducted this thesis by introducing the rationale and main features in a compact format in order to highlight major specificities. Section 3.3 details the complete modelling features and equations of the Imaclim-S France model.

3.1 A commun modular platform

Different versions of IMACLIM-S have developed up to now independently of one another leading to as many tools -with different quantitative software (EXCEL, SCILAB)- as well as versions (France, Brazil, South Africa). Even if an old version can always been used as a starting point for a new one, the development of IMACLIM-S requires intensive data-processing (hybridisation procedure) and is very time-consuming for establishing each system to solve.

To deal with the subjects of this thesis endeavour, the framework required flexibility for calibrating the model either on an extended sectoral description, or a compact representation. In addition, developments for new countries are to be launched (Saudi Arabia, China, India, South Africa) and any extension should be facilitated. For these reasons, a new rationalised platform has been developed using SCILAB, an open source software for numerical computation.

Main architecture
IMACLIM is a generic model that can be declined in various versions. Our first objective is to build a common architecture which supports all of these versions. Figure 3.1 illustrates this architecture of IMACLIM platform. Each version distinguishes itself from another by the economic and physical account tables that are put into equation for simulation. In practice, it is a country that defines the data structure, and so a new version (blue "blocks" in Figure 3.1). The tables' structure gives also the limit of the flexibility for a given version. Indeed, it gives the maximal number of variables and so of equations that can be solved for the version. Eventually, an IMACLIM version relies on common operations (hybridisation, calibration, resolution, etc.) that are identical and modular to adapt to its specificities (level of aggregation, variables for solving - "user choices" blocks in Figure 3.1). At the end, the idea is also to offer to the user the flexibility of choosing between a static resolution and a dynamic resolution as the core of the modelling is the same.

Flexibility for new version conception
The common platform has been developed surrounding a French version of IMACLIM-S . Thanks to the flexibility architecture, the version can be decomposed in many "sub-versions" according to the sectoral level chosen by the user for initial description. The limited extension for sectors is the hybrid Input-Ouput table (IOT) which gives the most disaggregated possible version of the model. Whatever the level of aggregation chosen, the hybridisation procedure has been automatised and specific margins are revaluated. The "aggregation" operation bloc reestimates all aggregated variables.
Households' disaggregation is also a matter of user's choice, as long as distribution key is available as data input. For the French version, households' disaggregation can go up to ten

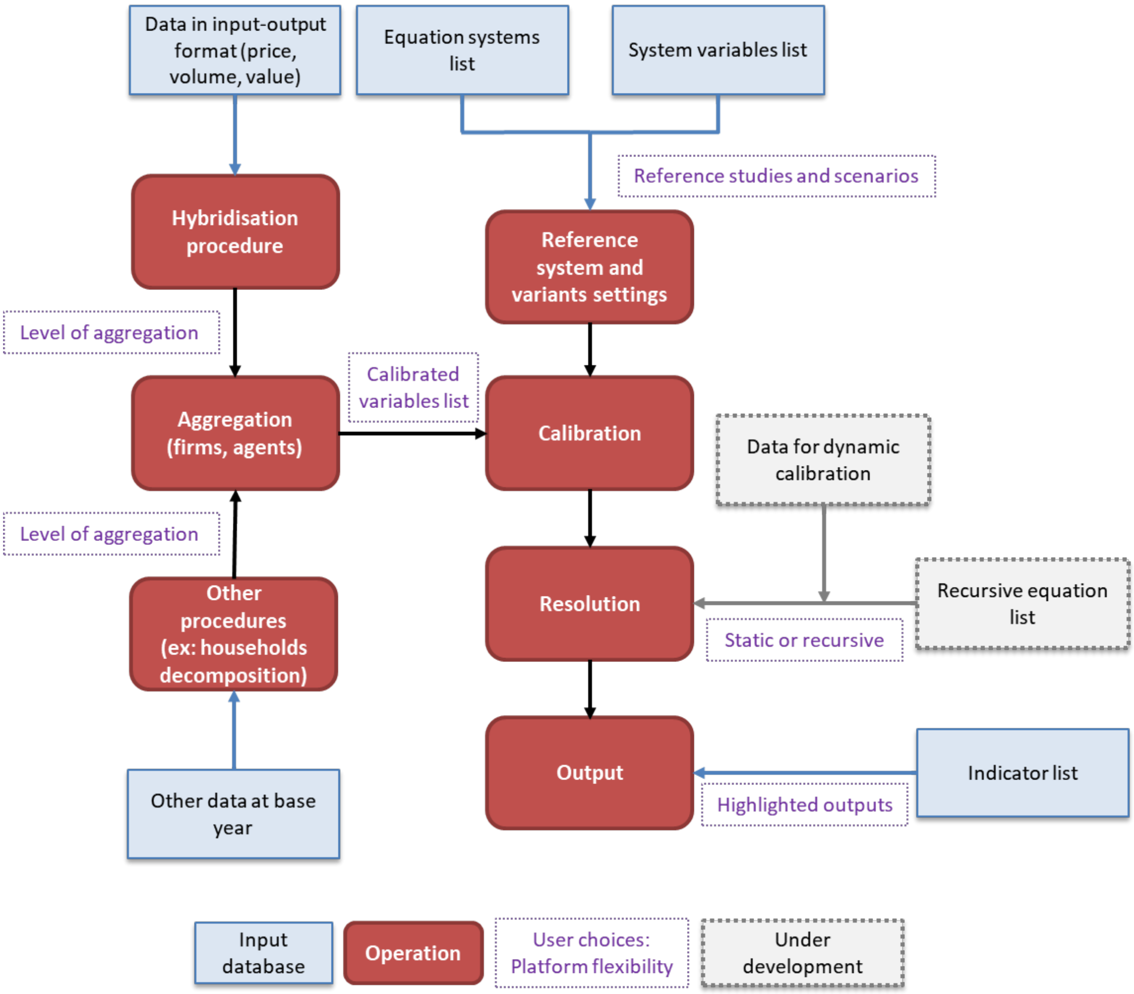


Figure 3.1 – Architecture overview of the Imaclim new platform

income classes. Calibration and resolution can be executed by defining calibrated parameters and the variables of the solving system.
A last notable flexibility is to be able to change the resolution system around different economic models that translate different "visions" and behaviours for the economy. On the one hand, behaviour equations can be substituted by another available in a common equation library to all versions. On the other hand, accounting equations are part of the common core of the architecture to all versions and cannot be substitute, they are always verified.
Table 3.1 synthesises the different 'blocks' of equations that characterise a version.

	Accounting equations	**Behavioural equations**
1- Institutional sectors	• Revenue = Expenses + AFC • Income composition • Expenditure composition	• Income/Activity selection *ex: tax structure* • Income composition • Selection of expenses *Current expenditure* *GFCF expenditure*
2- Productive systems	• Cost Structure • Production price structure	• Technical adjustments *Technical coefficients/modules* • Pricing choices *Margin on costs* • Investment decision *Volume demand*
3- Markets	• Use-Supply balance in quantities • Use-Supply balance in values • Purchase price structure *by type of buyer* • Current balance of payments • Offer / demand investment	• Wage formation *wage curve, etc.* • Employment distribution • Macroeconomic looping

Table 3.1 – Global composition of IMACLIM model

Let's now describe the model by relying on the Imaclim-S France version used in the rest of this thesis

3.2 General description of Imaclim-S France version

Imaclim-S comes in various country-versions specifically designed to build either counterfactuals simulations ('static' option) at a given date, or projections (by modelling economic growth) over the medium to long term, which are consistent with the energy-greenhouse gas (GHG) emissions-economy system. In particular, it can assess the macroeconomic implications of carbon-price or policies based on energy content. Imaclim-S departs from more standard neoclassical computable general equilibrium (CGE) models in several features.

First, as for standard CGE models, Imaclim-S is based on the representation of walrasian markets of goods and services with global income balance. In addition, like most hybrid CGE models, Imaclim-S has a dual quantity-economy accounting framework: economic flows *and* physical flows are balanced (see Chapter 1 for the methods and Chapter 2 for the consequences) and linked by a consistent price system. However, the description of the consumers' and producers' trade-offs, and the underlying technical systems depart from the neoclassical models. They are specifically designed to facilitate a calibration on bottom-up expertise in the energy field, with a view to guaranteeing technical realism to the simulations.

Second, Imaclim-S outputs are not necessarily located on equilibrated growth pathway. It computes accounting balances and walrasian markets of goods and services characterised by possible underemployment of production factors (labour) and imperfect markets (goods and factors). To do so, the model relies on a specific representation of capital and on other structural assumptions.

Finally, in this thesis, the Imaclim-S model is used for comparative static analysis (Samuelson, 1948) and generates energy-economy projections in a single time step. Alternative sets of parameters and policy packages gives different projections that are compared as counterfactual simulations (see Figure 3.2). We assume that the policy-induced transition is completed, after a series of technical and economic adjustments whose duration and scope are embedded in the behavioural functions retained for the time horizon under consideration. The transition process itself is however not described, but implicitly supposed to be smooth enough to prevent e.g. multiple equilibria, hysteresis effects, etc.

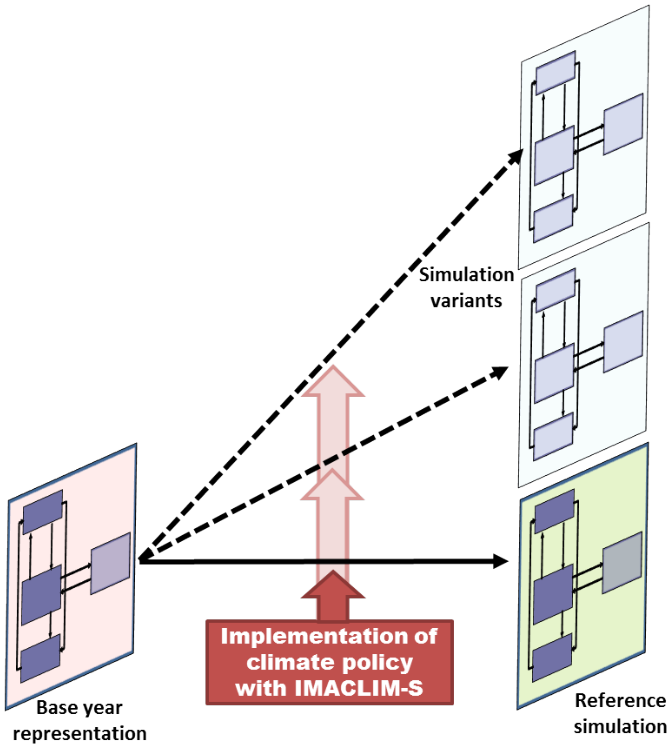


Figure 3.2 – Comparative statics with Imaclim-S

3.2.1 Overall interactions in Imaclim-S France

The Imaclim-S France is based on a standard IOT coupled with a consistent economic account table which synthetises the whole transactions for institutional sectors (firms, public administration, households[1], and the "rest of the world")[2] (see Figure 3.3). The model follows the Arrow-Debreu formulation of volumes and prices for goods and production factors, solves walrasian markets of goods, and insures the usual accounting identities in volumes and money flows for the different markets (goods and factors) and institutional sectors budgets.

The income flow associated with the flow of goods starts with the remuneration of production factors plus net payments from/to the rest of the world. It continues with distribution operations orchestrated by the public administration between the four categories of agents: taxes (payroll taxes, value-added tax, energy product tax, corporate tax, income tax, etc.) and transfers (unemployment benefits, pensions, etc.). Once they have made their consumption and investment choices, agents lend or borrow on financial markets depending on whether they

[1]Households can be decomposed into ten income groups. However, in the analysis performed in this thesis, we keep households aggregated as one single agent.

[2]Together, the IOT and the economic account table give all the elements to build the Social Accounting Matrix (SAM) which may be a more common representation in CGE community. The French national statistical agency (Institut national de la statistique et des études économiques (INSEE)) keeps IOT and economic account table separated. Thus, we decide to keep this representation for simplifying dialogues with French institutions

exhibit positive or negative savings. This affects their financial positions and the associated income flows (debt services, interest payments).

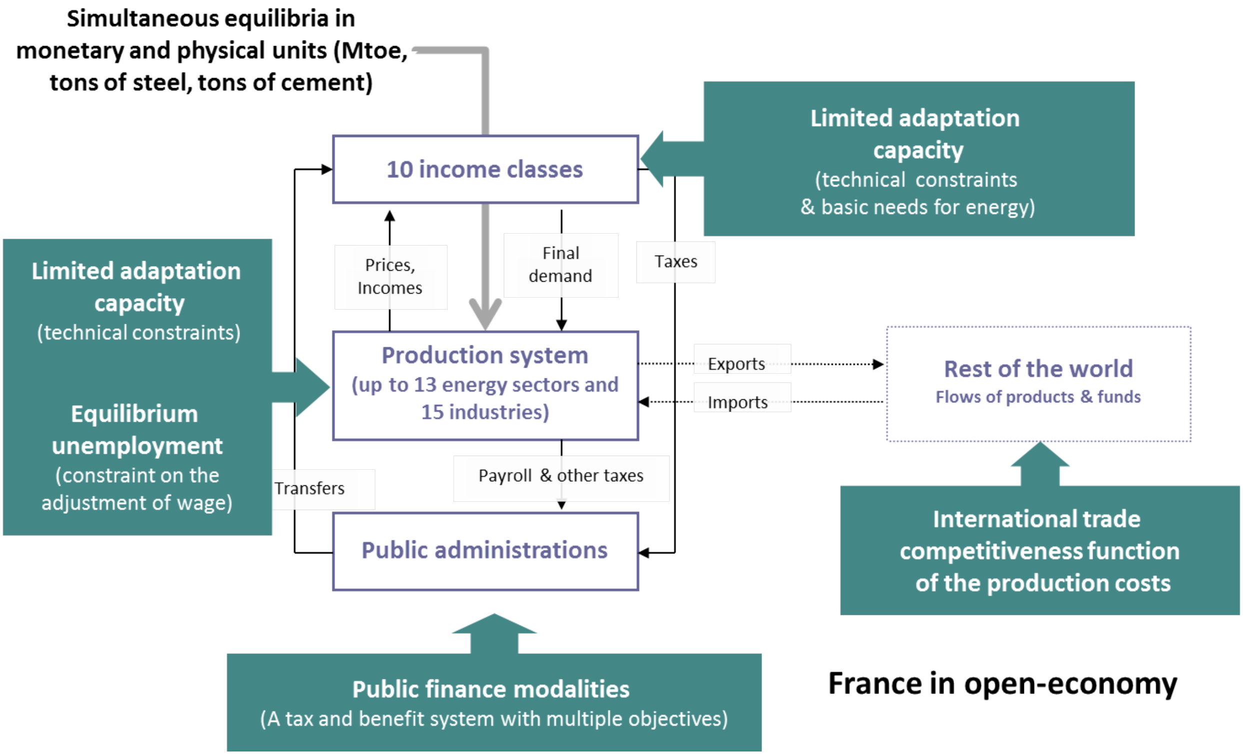


Figure 3.3 – Overview of the IMACLIM-S FRANCE model framework

The growth engine is basically exogenous and technical progress is implemented through factor augmenting coefficients. The model can accommodate different types of exogenous technical progress including Harrod, Hicks and Solow neutral technical progress.

The growth engine is the combination of several drivers:

- The total population and active population growth:

$$N = (1 + \delta_N)^t \cdot N_0 \tag{3.1}$$

$$NS = (1 + \delta_{NS})^t \cdot N_0 \tag{3.2}$$

- The implicit capital accumulation computed through a proportional link between total fixed capital consumption and the current level of total investment in capital good (see equation 3.70);
- A Harrod neutral exogenous technical progress on labour, implemented by means of a factor augmenting coefficient (see 3.3.4.2).

In the following analysis, we only run static analysis without implementing any demographic or economic drivers. However, the growth engine are part of the modelling framework built for the thesis. Even though, projection scenarios have been made for other projects, they are not reported into the thesis[3].

3.2.2 Compact description of the modelling framework

As Imaclim-S France departs from more standard - even hybrid - CGE models in specific features, it is required to characterise clearly the nature of the model and these specifics. We provide in this section a compact description of the model.

Imaclim-S France , a comparative statics model, boils down to a set of simultaneous equations:

$$\begin{cases} f_1(x_1, ..., x_n, z_1, ..., z_m) = 0 \\ f_2(x_1, ..., x_n, z_1, ..., z_m) = 0 \\ ... \\ f_n(x_1, ..., x_n, z_1, ..., z_m) = 0 \end{cases}$$

with :

- x_i, $i \in [1, v]$, a set of variables (as many as equations),
- z_i, $i \in [1, p]$, a set of parameters,
- f_i, $i \in [1, v]$, a set of functions, some of which are non linear in x_i.

The f_i constraints are of two quite different natures: one subset of equations describes accounting constraints that are necessarily verified to ensure that the accounting system is properly balanced; the other subset translates various behavioural constraints, written either in a simple linear manner (e.g. households consume a fixed proportion of their income) or in a more complex non-linear way (e.g. the trade-offs of the producers and the consumers). It is these behavioural constraints that ultimately reflect, in the flexible architecture of Imaclim-S France , a certain economic "vision".

A compact description of the Imaclim-S France is made of the following blocks of functions:

[3]The developed version of Imaclim-S France in this thesis has been used for ECOPA project - ANR project FACING SOCIETAL AND ENVIRONMENTAL CHANGES 2012 (SOC&ENV 2012) : Evolution of consumption patterns, economic convergence and carbon footprint of development. A comparison Brazil - France.

Domestic price formation	
Production price	$P_Y = P_{IC} \times \alpha + p_L \cdot l + P_K \cdot k + \overline{\tau_Y} \cdot P_Y + \overline{\Pi} \cdot P_Y$
Mean price	$P = [P_Y \cdot Y + P_M \cdot M]/[Y + M]$
Income generation and usage	
Investment	$R_{inv} = \sum P_I \cdot I$
Trade-offs	
Final consumption	$C = f_C(R_{CONS}, P)$
Input production	$\alpha = f_\alpha(P, \omega, P_K, \phi_L)$
Labour production	$l = f_l(P, \omega, P_K, \phi_L)$
Capital production	$k = f_k(P, \omega, P_K, \phi_L)$
Value-added breakdown	
Wage curve	$\omega = f_\omega(1 - \frac{L}{NS})$
Capital cost	$P_k = (\sum p_I \cdot I)\ I$
Mark-up pricing	$\Pi = \overline{\Pi}$
International trade	
Exports	$X = f_X(P_Y, P_M, X)$
Imports	$M = f_M(P_Y, P_M, Y)$
Accounting balances in volume	
Market of goods	$Y = Y \cdot \alpha + C + G + I + X - M$
Labour market	$L = \sum l \cdot Y$
Implicit capital balance	$I = \overline{\beta} \sum k \cdot Y$
Demographic and productivity drivers for projection	
Active population	$NS = (1 + \omega_{NS})^t \cdot N_0$
Technical progress on labour	$\phi_{L_i} \neq 0$

Table 3.2 – Short overview of IMACLIM-S FRANCE equations

3.3 Modelling economic features

This section gives the complete modelling economic equations and features of IMACLIM-S FRANCE . First, we present the accounting framework at the heart of the model in sub-section 3.3.1. Then, the equations are successively detailed and gathered as follows: (i) the accounting construction of the set of consumer prices, (ii) the accounting and behavioural equations that govern the four institutional sectors represented (households, firms, public administrations and the "rest of the world"), (iii) the market clearing conditions.

The equations distinguish three kinds of components: (i) the variables computed by the model, which represent the endogenous elements of the projected energy-economy picture at the time horizon studied, (ii) the parameters that are calibrated on the base year (iii) the other non calibrated parameters coming from external sources. All are listed and described in Appendix B.

In the equations, the calibrated parameters are identified with an over-line. A variable name with a '0' index designates the specific value taken by the variable in the reference equilibrium (i.e. the value calibrated on either the 2010 hybrid input-output or the 2010 economic account table).

Although most equations are written in an generalised n-goods format, when necessary good-specific variables are indexed by the subscripts detailed in table 3.3. Variables names are also consistent with the IOT (Table 3.3) and the national economic account table (Table 3.4).

3.3.1 The accounting framework

The IMACLIM-S FRANCE version used in this thesis, calibrated at year 2010, can distinguish up to 29 productive sectors. According to the objective of the studies, these sectors are aggregated to the level required. It includes two primary production factors: labour and capital.

All interactions are synthesised in a large accounting framework composed by two tables.

- The Input-Output table balances the uses and resources of products (see Table 3.3). Each sector produces one single good so that commodities and activities match and the IOT.
- The national economic accounts table details the primary and secondary distribution of income between representative economic agents (see 3.4). The model distinguishes four economic agents : *households* (H)[4], *corporate firms* (F), *public administrations* or *government* (G) and the *rest of the world* (ROW).

[4]Households can be disaggregated into ten classes of revenues

Imaclim-S France keeps detail on primary income distribution between each economic agents. Therefore households, firms and government have separated accounts in our model and may have different structural behaviours. This is an extention to traditional framework of CGE models that usually shortcut this aspect by assuming that households eventually own the total endowment of production factors. Households are the only agent to own labour factor.

Furthermore, through secondary income distribution, economic agents break down their income between goods consumption, investment, tax payments and transfers. The model considers a detailed system of taxes and transfers essentially between the triangle of domestic agents (households, firms and public administrations). This will be detailed in the following.

Owing to the split of accounts of institutional agents, Imaclim-S France also considers the breakdown of total Gross Fixed Capital Formation (GFCF) between agents. It further identifies for each agent the share of income that is not directly invested in GFCF, which is called self-financing capacity (*ACF*). The rest of the world classically interacts with domestic agents through trade of goods and capital balance.

The rest of this section details the equations of the model through different blocks: (i) price system and income generation, (ii) institutional sectors accounts, (iii) production and consumption trade-off, (iv) market balances, (v) growth engine, (vi) carbon tax policies.

The equations of the model are of two quite different natures: one subset of equations describes accounting constraints that are necessarily verified to ensure that the accounting system is properly balanced; the other subset translates various behavioural constraints, written either in a simple linear manner (e.g. households consume a fixed proportion of their income) or in a more complex non-linear way (e.g. the trade-offs of production and consumption). It is these behavioural constraints that ultimately reflect a certain *economic worldview*.

		Intermediate consumption ($IC_{val_{ij}}$)		**Final Consumption** (FC_{val_i})				**Uses** (Use_i)
		Hybrid sectors	***Non-hybrid sectors***	***Households*** (C_{val_i})	***Public administration*** (G_{val_i})	***Investment*** (I_{val_i})	***Exports*** (X_{val_i})	
Intermediate consumption ($IC_{val_{ij}}$)	***Hybrid sectors***	$p_{IC_{ij}} \cdot \alpha_{ij} \cdot Y_j$	$p_{IC_{ij}} \cdot \alpha_{ij} \cdot Y_j$	$p_{C_i} \cdot C_i$	$p_{G_i} \cdot G_i$	$p_{I_i} \cdot I_i$	$p_{X_i} \cdot X_i$	$\sum_j IC_{val_{ij}} + FC_{val_i}$
	Non-hybrid sectors	$p_{IC_{ij}} \cdot \alpha_{ij} \cdot Y_j$	$p_{IC_{ij}} \cdot \alpha_{ij} \cdot Y_j$					
Value-added (VA_j)	***Labour income***	$\omega_j \cdot l_j \cdot Y_j$	$\omega_j \cdot l_j \cdot Y_j$					
	Labour Tax	$\tau_{T_L} \cdot \omega_j \cdot l_j \cdot Y_j$	$\tau_{T_L} \cdot \omega_j \cdot l_j \cdot Y_j$					
	Capital income	$p_{K_j} \cdot k_j \cdot Y_j$	$p_{K_j} \cdot k_j \cdot Y_j$					
	Production Tax	$\tau_{T_{Y_i}} \cdot p_{Y_j} \cdot Y_j$	$\tau_{T_{Y_i}} \cdot p_{Y_j} \cdot Y_j$					
	Profit margin	$\pi_j \cdot p_{Y_j} \cdot Y_j$	$\pi_j \cdot p_{Y_j} \cdot Y_j$					
Production (Y_{val_j})		$p_{Y_j} \cdot Y_j$	$p_{Y_j} \cdot Y_j$					
Imports (M_{val_j})		$p_{M_j} \cdot M_j$	$p_{M_j} \cdot M_j$					
Margins ($Marg_j$)	***Trade margins***	$\tau_{CM_j} \cdot p_j \cdot (Y_j + M_j)$	$\tau_{CM_j} \cdot p_j \cdot (Y_j + M_j)$					
	Transport margins	$\tau_{TM_j} \cdot p_j \cdot (Y_j + M_j)$	$\tau_{TM_j} \cdot p_j \cdot (Y_j + M_j)$					
	Specific margins on IC ($SM_{IC_{ij}}$)	$\tau_{SM_{IC_{ij}}} \cdot p_j \cdot \alpha_{ji} \cdot Y_j$	0					
	SpeMarg on C (SM_{C_j})	$\tau_{SM_{C_j}} \cdot p_j \cdot C_j$	0					
	SpeMarg on G (SM_{G_j})	$\tau_{SM_{G_j}} \cdot p_j \cdot G_j$	0					
	SpeMarg (SM_{I_j})	$\tau_{SM_{I_j}} \cdot p_j \cdot I_j$	0					
	SpeMarg (SM_{X_j})	$\tau_{SM_{X_j}} \cdot p_j \cdot X_j$	0					
Taxes (T_j)	***Value-added tax***	$(\frac{\tau_{VAT_j}}{1-\tau_{VAT_j}}) \cdot FC_{val_j}$	$(\frac{\tau_{VAT_j}}{1-\tau_{VAT_j}}) \cdot FC_{val_j}$					
	Energy Tax IC	$t_{EnT_{IC_j}} \cdot \sum_i (\alpha_{ji} \cdot Y_i)$	$t_{EnT_{IC_j}} \cdot \sum_i (\alpha_{ji} \cdot Y_i)$					
	Energy Tax FC	$t_{EnT_{FC_j}} \cdot (C_j + G_j + I_j)$	$t_{EnT_{FC_j}} \cdot (C_j + G_j + I_j)$					
	Other indirect tax on products	$t_{OPT_j} \cdot (\sum_i \alpha_{ji} \cdot Y_i + C_j + G_j + I_j)$	$t_{OPT_j} \cdot (\sum_i \alpha_{ji} \cdot Y_i + C_j + G_j + I_j\ )$					
Supply (Sup_j)		$Y_{val_j} + M_{val_j} + Marg_j + T_j + T_j$	$Y_{val_j} + M_{val_j} + Marg_j + T_j + T_j$					

Table 3.3 – IMACLIM-S FRANCE Input-Output table (IOT)

	Firms (F)	**Public administration (G)**	**Households (H)**	**Rest of world (ROW)**
Trade balance	-	-	-	$\sum_i (p_{M_i} \cdot M_i - p_{X_i} \cdot X_i)$
Gross operating surplus (GOS)[5]	$\omega_{K_F} \cdot GOS$	$\omega_{K_G} \cdot GOS$	$\omega_{K_H} \cdot GOS$	-
Labour income	-	-	$\sum_j (\omega_j \cdot l_j \cdot Y_j)$	-
Labour tax (T_L)	-	$\tau_{T_L} \sum_j (\omega_j \cdot l_j \cdot Y_j)$	-	-
Production tax (T_Y)	-	$\sum_j \tau_{T_{Y_j}} \cdot p_{Y_j} \cdot Y_j$	-	-
Energy tax (T_{En})	-	$\sum_j [t_{EnT_{IC_j}} \cdot \sum_i (\alpha_{ji} \cdot Y_i) + t_{EnT_{FC_j}} \cdot (C_j + G_j + I_j)]$	-	-
Other indirect tax (T_{OP})	-	$\sum_j [t_{OPT_j} \cdot (\sum_i \alpha_{ji} \cdot Y_i + C_j + G_j + I_j)]$	-	-
Value-added tax (T_{VA})	-	$\sum_j [(\frac{\tau_{VAT_j}}{1-\tau_{VAT_j}}) \cdot FC_{val_j}]$	-	-
Property income	$-i_F \cdot D_F$	$-i_G \cdot D_G$	$-\sum_h (i_h \cdot D_h)$	$i_F \cdot D_F + i_G \cdot D_G + \sum_h (i_h \cdot D_h)$
Unemployment transfers (U)	-	$-\sum_h (\rho_{U_h} \cdot N_{U_h})$	$\sum_h (\rho_{U_h} \cdot N_{U_h})$	-
Pensions (P)	-	$-\sum_h (\rho_{P_h} \cdot N_{P_h})$	$\sum_h (\rho_{P_h} \cdot N_{P_h})$	-
Other social transfers (O)	-	$-\sum_h (\rho_{O_h} \cdot N_{O_h})$	$\sum_h (\rho_{O_h} \cdot N_{O_h})$	-
Other transfers (OT)	$\omega_{OT_F} \cdot OT$	$\omega_{OT_G} \cdot OT$	$\omega_{OT_H} \cdot OT$	$-(\omega_{OT_F} \cdot OT + \omega_{OT_G} \cdot OT + \omega_{OT_H} \cdot OT)$
Income tax (T_{I_H})	-	$\sum_h (\tau_{T_{I_h}} \cdot RBT_h)$	$-\sum_h (\tau_{T_{I_h}} \cdot RBT_h)$	-
Firm tax (T_F)	$-\tau_{T_F} \cdot GOS_F$	$\tau_{T_F} \cdot GOS_F$	-	-
Other direct tax (T_D)	-	$\sum_h (\tau_{T_{D_h}} \cdot CPI)$	$-\sum_h (\tau_{T_{D_{h_0}}} \cdot CPI)$	-
Gross disposable income (R)	$R_F = \sum$ row below	$R_G = \sum$ row below	$R_H = \sum$ row below	$R_{ROW} = \sum$ row below
Final consumption (FC_{val})	-	$\sum_i G_{val_i}$	$R_{CONS_H} = \sum_h (1 - \tau_{S_h}) \cdot R_h$	-
Gross fixed capital consumption ($GFCF$)	$GFCF_F = \frac{GFCF_{F_0}}{R_{F_0}} \cdot R_F$	$GFCF_G = \frac{GFCF_{G_0}}{GDP_0} \cdot GDP$	$GFCF_H = \sum_h (\frac{GFCF_{h_0}}{R_{h_0}} \cdot R_h)$	-
Expenses for final uses	$GFCF_F$	$\sum_i G_{val_i} + GFCF_G$	$R_{CONS_H} + GFCF_H$	-
Self-financing capacity (AFC)	$AFC_F = R_F - GFCF_F$	$AFC_G = R_G - [GFCF_G + \sum_i G_{val_i}]$	$AFC_H = \sum_h (\tau_{S_h} \cdot R_h - GFCF_h)$	$ACF_{ROW} = -(AFC_F + ACF_G + ACF_H)$
Net financial debt (D)	$D_F = D_{F_0} + \frac{t_{ref}}{2} \cdot (AFC_{F_0} - ACF_F)$	$D_G = D_{G_0} + \frac{t_{ref}}{2} \cdot (AFC_{G_0} - ACF_G)$	$D_H = D_{H_0} + \frac{t_{ref}}{2} \cdot (AFC_{H_0} - ACF_H)$	$D_{ROW} = -(D_F + D_G + D_H)$

Table 3.4 – IMACLIM-S FRANCE national economic accounts table

3.3.2 The price system and the income generation

Prices and income generation are first channels to impose structural constraints in the model as a first source of departure from a neoclassical CGE model. It includes (i) the representation of non-zero profits through mark-up pricing, (ii) the inclusion of specific margins for energy goods (in the way introduced earlier in Chapter 1), (iii) sector specific wages and (iv) a specific price for capital consumption.

3.3.2.1 The prices

Production prices
First of all, the producer's price of good-sector i (p_{Y_i}) is following the cost structure of the production of good i plus a pure profit component. Thus, p_{Y_i} is built as the sum of intermediate consumptions, labour costs, capital costs, a tax on production, and a rate of profit.

$$p_{Y_i} = \sum_{j=1}^{n} p_{IC_i} \cdot \alpha_{ij} + p_{L_i} \cdot l_i + p_{K_i} \cdot k_i + \overline{\tau_{Y_i}} \cdot p_{Y_i} + \overline{\pi_i} \cdot p_{Y_i} \tag{3.3}$$

Technical coefficients α, l, k are expressed in real terms. The ones for intermediary consumption of energy, steel and cement are respectively expressed in *ktoe*, tons of steel, or tons of cement, per unit of output.

The rate of profit $\overline{\pi}$, which corresponds in practice to the net operating surplus, is constant and calibrated at base year for all sectors in the reference version.
This mark-up pricing is used to translate both the specific structural conditions of the different market of goods and all costs that are not pure capital consumption costs (see section 3.3.4).

Import prices and ressource prices
The price of imported goods i (p_{M_i}) is goods-specific. The international composite goods are the *numéraire* of the model; its price ($p_{M_{COMP}}$) is assumed constant and equal to unity :

$$p_{M_{COMP}} = p_{M_{COMP_0}} = 1 \tag{3.4}$$

The prices of others goods evolve according to an exogenous rate $\delta_{p_{M_i}}$:

$$\forall\ i \neq COMP \quad p_{M_i} = \left(1 + \delta_{p_{M_i}}\right)^t \cdot p_{M_{i_0}} \tag{3.5}$$

$\delta_{p_{M_i}}$ parameters is used to simulate alternative world energy prices scenarios.

CGE models usually adopt the assumption of goods differentiation between domestic and imported goods and the implementation of an Armington specification (Armington, 1969).
It is fundamental in our modelling approach to maintain an explicit accounting of physical volumes. So, hybrid imported goods (energy, cement, and steel) are described in quantities, and we assumed that they are homogeneous with hybrid domestic goods.
Thus, the average price of the resource of good i (p_i),the weighted average of the production and import prices, does not create "hybrid" goods varieties for hybrid goods:

$$p_i = \frac{p_{Y_i} \cdot Y_i + p_{M_i} \cdot M_i}{Y_i + M_i} \tag{3.6}$$

Nevertheless, imported and domestic energy goods can coexist in the domestic market even with different prices (see subsection 3.3.4.3). For the sake of simplicity, non-energy goods are treated similarly.

Intermediate consumption prices
The purchaser's price of good i consumed for the production of good j ($p_{IC_{ij}}$) is equal to the resource price of good i plus trade and transport margins, specific margins, a domestic excise on oil products (energy product tax, EnT) , an aggregate of other excise taxes

$$p_{IC_{ij}} = p_i \cdot (1 + \tau_{CM_i} + \tau_{TM_i} + \overline{\tau_{SM_{IC_i}}}) + \overline{t_{EnT_{IC_i}}} + \overline{t_{OPT_i}} \tag{3.7}$$

A carbon tax rate $t_{carb_{IC}}$ is added to this price for carbon tax policy simulations(cf. sub-section 3.3.6).

Final consumption prices
The purcharser's price of good i for households (p_{C_i}), public administrations (p_{G_i}), investment (p_{I_i}), and the export price of good i (p_{X_i}), are constructed similarly. They only differ on whether they are subject to value-added tax (and thereafter, to the carbon tax) or not:

$$p_{C_i} = [p_i \cdot (1 + \tau_{CM_i} + \tau_{TM_i} + \overline{\tau_{SM_{C_i}}}) + \overline{t_{EnT_{FC_i}}} + \overline{t_{OPT_i}}] \cdot (1 + \overline{\tau_{VAT_i}}) \tag{3.8}$$
$$p_{G_i} = [p_i \cdot (1 + \tau_{CM_i} + \tau_{TM_i} + \overline{\tau_{SM_{G_i}}}) + \overline{t_{EnT_{FC_i}}} + \overline{t_{OPT_i}}] \cdot (1 + \overline{\tau_{VAT_i}}) \tag{3.9}$$
$$p_{I_i} = [p_i \cdot (1 + \tau_{CM_i} + \tau_{TM_i} + \overline{\tau_{SM_{I_i}}}) + \overline{t_{EnT_{FC_i}}} + \overline{t_{OPT_i}}] \cdot (1 + \overline{\tau_{VAT_i}}) \tag{3.10}$$
$$p_{X_i} = p_i \cdot (1 + \tau_{CM_i} + \tau_{TM_i} + \overline{\tau_{SM_{X_i}}}) + \overline{t_{EnT_{FC_i}}} + \overline{t_{OPT_i}} \tag{3.11}$$

A carbon tax rate $t_{carb_{FC}}$ is added to this price for carbon tax policy simulations(cf. sub-section 3.3.6).

Specific margins rates ($\overline{\tau_{SM_i}}$) are calibrated at base year and held constant to reflect the difference of tariffs (taxes excluded) of energy goods according to the different consuming agent/sector.

Trade margins rates (τ_{CM_i}) and transport margins rates (τ_{TM_i}), identical for all intermediate and final consumption of good i, are calibrated at base year and kept constant - except those on freight transport and trade activities (hereafter indexed COM and TRANS), which are simply adjusted, to have the two types of margins sum up to zero :

$$\sum_{j=1}^{n} \tau_{CM_{COM}} \cdot p_{COM} \cdot \alpha_{COM_j} + \tau_{CM_{COM}} \cdot p_{COM} \cdot (C_{COM} + G_{COM} + I_{COM} + X_{COM}) \\ + \sum_{i \neq COM}^{n} \sum_{j=1}^{n} \overline{\tau_{CM_i}} \cdot p_i \cdot \alpha_{ij} \cdot Y_j + \sum_{i \neq COM} \overline{\tau_{CM_i}} \cdot p_i \cdot (C_i + G_i + I_i + X_i) = 0 \tag{3.12}$$

and similarly :

$$\sum_{j=1}^{n} \tau_{TM_{TRANS}} \cdot p_{TRANS} \cdot \alpha_{TRANS_j} + \tau_{TM_{TRANS}} \cdot p_{TRANS} \cdot (C_{TRANS} + G_{TRANS} + I_{TRANS} + X_{TRANS}) \\ + \sum_{i \neq TRANS}^{n} \sum_{j=1}^{n} \overline{\tau_{TM_i}} \cdot p_i \cdot \alpha_{ij} \cdot Y_j + \sum_{i \neq TRANS} \overline{\tau_{TM_i}} \cdot p_i \cdot (C_i + G_i + I_i + X_i) = 0 \tag{3.13}$$

Imaclim-S France accounts for labour service in full-time equivalent jobs and thus deals with sector specific wages. labour costs (p_{L_i}) are further equal to the sector specific net wage (ω_i) plus payroll taxes that correspond to both employers and employees' social contributions in the case of France. These taxes are levied based on average sector specific rates (τ_{LT}) common to all productions and calibrated at base year:

$$p_{L_i} = (1 + \tau_{LT}) \cdot \omega_i \tag{3.14}$$

The wage ω_i is subject to variations that are dictated by the supply side of labour markets which relates it, by means of a wage curve, to the average rate of unemployment of the economy (see labour market balance in sub-section 3.3.5).

The cost of capital (p_K) is understood as the cost of the 'machine' capital (see the description of the production trade-offs in sub-section 3.3.4). It is obtained as the average price of investment goods (p_{I_i}):

$$p_K = \frac{\sum_{i=1}^{n} p_{I_i} \cdot I_i}{\sum_{i=1}^{n} I_i} \tag{3.15}$$

As mentioned earlier, it is a specific of our modelling approach where a standard CGE model compute a rate of return on capital.

3.3.2.2 The Gross Operating Surplus

Capital costs, profits (π_i) and specific margins (SM) determine the gross operating surplus (GOS) of the economy:

$$GOS = \sum_{i=1}^{n} \left(p_K \cdot k_i \cdot Y_i + \overline{\pi_i} \cdot p_{Y_i} \cdot Y_i \right) + SM \tag{3.16}$$

By construction, the specific margins on the different sales (SM) sum to zero in the base year equilibrium (this is a constraint of the energy-economy data hybridising process). However they do not in the future equilibrium, their constant rates being applied to varying prices. The total specific margin generated SM is then computed as:

$$SM = \sum_i \left(\sum_j \overline{\tau_{SM_{IC_{ij}}}} \cdot p_i \cdot \alpha_{ij} \cdot Y_j + \overline{\tau_{SM_{C_i}}} \cdot p_i \cdot C_i + \overline{\tau_{SM_{G_i}}} \cdot p_i \cdot G_i + \overline{\tau_{SM_{X_i}}} \cdot p_i \cdot X_i \right) \tag{3.17}$$

GOS is further broken down between institutional sectors as described in sub-section 3.3.3.

The consumer price index (CPI) is computed following Fisher, i.e. as the geometric mean of a Laspeyres index (variation of the cost of the present basket of goods from the present to the future set of relative prices) and a Paasche index (variation of the cost of the future basket of goods from the present to the future set of relative prices):

$$CPI = \sqrt{\frac{\sum_i (p_{C_i} \cdot C_{i_0}) \cdot \sum_i (p_{C_i} \cdot C_i)}{\sum_i (p_{C_{i_0}} \cdot C_{i_0}) \cdot \sum_i (p_{C_{i_0}} \cdot C_i}})} \tag{3.18}$$

3.3.3 Institutional agents accounts

The equations related to institutional agents and productive sectors basically reflect the constraints of accounting balance embodied in the IOTs and the economic accounting table.

Compared to most CGE models, IMACLIM-S FRANCE keeps the accounting logic of national accounts with the distinction between households, firms and public administration as different institutional agents. Again this results in a specific breakdown of capital income between institutional agents (as different legal entities that owns production factors) as well as the keeping track of their specific contribution to gross fixed capital formation (*GFCF*).

In a standard CGE model the representative household, endowed with all production factors, receives total factors income as a global transfer. Furthermore its total *GFCF* - effective total investment - is generally deduced from the difference between its total savings and the capital balance.

In this formulation, public administrations economic transactions are reduced to tax collection, social transfers and final services consumption.

3.3.3.1 Households

Households can be disaggregated into m classes (index $h, h \in [1, m]$) to take into account income structures and eventually behaviours and adaptation capacities that can vary significantly from one household class to the next[6]. In the following, h stands for a household class, and H stands for households as the sum of m household classes. In the developed version, households can be disaggregated up to ten classes.

The gross primary income, or revenue before tax, (RBT_h) of the representative household corresponds to the sum of the following terms:

- A share ω_{L_h} of the sum of aggregate endogenous net wage income $\omega_i\, l_i\, Y_i$;
- A share ω_{K_h} of the fraction of 'capital income' that goes to households, GOS_H;
- Social transfers as the sum of three aggregates : pensions ($\rho_{P_h} \cdot N_{P_h}$), unemployment benefits ($\rho_{U_h} \cdot N_{U_h}$) , and other social transfers ($\rho_{O_h} \cdot N_{O_h}$). The appellation ρ stands for a per capita income, and N_h for a target population;
- An exogenous share ω_{OT_h} of residual transfers OT_H , which corresponds to the sum of "other current transfers" and "capital transfers";

[6]Although equity issues are not the central concern of this thesis, the developed version can embark ten living-standards classes of households for simulations. This disaggregation is based on the households' budget survey by INSEE and is the result of previous work (Combet, 2013) which has been updated to 2010. Indeed, the development work of IMACLIM-S FRANCE was done with the will and the idea of obtaining a unique and flexible IMACLIM-S platform that can be easily adapted to different countries and subject of study (see 3.1).

- A 'debt service' $i_h \cdot D_h$, which is indeed negative and corresponds to property income - the overwhelming majority of classes being net creditors.

Hence,

$$RBT_h = \omega_{L_h} \sum_{i=1}^{n} \omega_i \cdot l_i \cdot Y_i + \overline{\omega_{K_h}} \cdot GOS_H + \rho_{P_h} \cdot \overline{N_{P_h}} + \rho_{U_h} \cdot N_{U_h} + \rho_{O_h} \cdot \overline{N_{O_h}} + \overline{\omega_{OT_h}} \cdot OT_H - i_h \cdot D_h \quad (3.19)$$

with in particular OT_H and GOS_H defined as constant shares ω_{OT_H} and ω_{K_H} of OT -Equation (3.54)- and GOS - Equation 3.16- :

$$OT_H = \overline{\omega_{OT_H}}\, OT \quad (3.20)$$

$$GOS_H = \overline{\omega_{K_H}}\, GOS \quad (3.21)$$

The gross disposable income R_h of class h is obtained by subtracting from RBT_h the income tax T_{I_h} levied at a constant average rate (Equation 3.37), and other direct taxes T_{D_h} that are indexed on CPI (Equation 3.38).

$$R_h = RBT_h - T_{I_h} - T_{D_h} \quad (3.22)$$

The income expensed in consumption goods of class h (R_{CONS_h}) is inferred from disposable income by subtracting savings. The savings rate τ_{S_h} is exogenous in the model.

$$R_{CONS_h} = (1 - \overline{\tau_{S_h}}) \cdot R_h \quad (3.23)$$

Furthermore the model specifies the share of households savings directly invested in gross capital formation ($GFCF_h$) as an exogenous value calibrated at base year:

$$\frac{GFCF_h}{R_h} = \frac{GFCF_{h_0}}{R_{h_0}} \quad (3.24)$$

The difference between savings and investment gives the self-financing capacity (AFC_h) of class h:

$$AFC_h = \overline{\tau_{S_h}} R_h - GFCF_h \quad (3.25)$$

The evolution of AFC_h between the no-policy and the policy-induced equilibrium can then be used to estimate the evolution of net debt (D_h). The computation is based on the simple assumption of a gradual wedge of AFC over the period of projection (t_{REF}).

$$D_h = D_{h_0} + \frac{t_{REF}}{2}\left(AFC_{h_0} - AFC_h\right) \tag{3.26}$$

3.3.3.2 Firms

Similar to households, the gross primary income before taxes (RBT_F) of firms (F) corresponds to the sum of the following terms:

- An exogenous share ω_{K_F} of capital income i.e. GOS (Equation 3.16);
- A 'debt service' (interests, dividends), which is strongly positive in the reference equilibrium (firms are net debtors): $i_F \cdot D_F$;
- An exogenous share ω_{OT_F} of global other transfers OT, which are assumed a constant share of GDP (Equation 3.54).

$$RBT_F = \overline{\omega_{K_F}} \cdot GOS - i_F \cdot D_F + \overline{\omega_{OT_F}} \cdot OT \tag{3.27}$$

The gross disposable income R_F of firms is obtained by subtracting from RBT_F total corporate tax payments T_F levied at a constant average rate (Equation 3.36):

$$R_F = RBT_F - T_F \tag{3.28}$$

Same as for households, the ratio of the gross fix capital formation of firms ($GFCF_F$) to their disposable income R_F is assumed constant:

$$\frac{GFCF_F}{R_F} = \frac{GFCF_{F_0}}{R_{F_0}} \tag{3.29}$$

The self-financing capacity AFC_F then arises from the difference between R_F and $GFCF_F$:

$$AFC_F = R_F - GFCF_F \tag{3.30}$$

The net debt of firms D_F is then calculated from their AFC_F on the same reasoning as that applied to households:

$$D_F = D_{F_0} + \frac{t_{REF}}{2}\left(AFC_{F_0} - AFC_F\right) \tag{3.31}$$

3.3.3.3 Public administration

Tax and social security contributions form the larger share of government (G) resources. In this model, we distinguish the revenues from: labour tax (T_L), taxes on production (T_Y), other taxes on products (T_{OP}), taxes on value-added (T_{VA}), taxes on households incomes taxes (T_{I_h}), taxes on firms profits (T_F), taxes on energy products (T_{En}), as follows:

$$T_L = \tau_{T_L} \sum_{i=1}^{n} w_i \cdot l_i \cdot Y_i \tag{3.32}$$

$$T_Y = \sum_{i=1}^{n} \overline{\tau_{T_{Y_i}}} \cdot p_{Y_i} \cdot Y_i \tag{3.33}$$

$$T_{OP} = \sum_{i=1}^{n} \sum_{j=1}^{n} \overline{t_{OPT_j}} \cdot \alpha_{ji} \cdot Y_i + \sum_{i=1}^{n} \overline{t_{OPT_i}} \cdot (C_i + G_i + I_i) \tag{3.34}$$

$$T_{VA} = \sum_{i=1}^{n} \frac{\overline{\tau_{VAT_i}}}{1 + \overline{\tau_{VAT_i}}} \cdot \left(p_{C_i} \cdot C_i + p_{G_i} \cdot G_i + p_{I_i} \cdot I_i\right) \tag{3.35}$$

$$T_F = \overline{\tau_{T_F}} \cdot GOS_F \tag{3.36}$$

$$T_{I_h} = \overline{\tau_{T_{I_h}}} \cdot RBT_h \tag{3.37}$$

$$T_{D_h} = CPI \cdot D_{T_{h_0}} \tag{3.38}$$

$$T_{En} = \sum_{i=1}^{n} \overline{t_{EnT_{IC_i}}} \cdot (\sum_{j=1}^{n} \alpha_{ij} \cdot Y_j) + \sum_{i=1}^{n} \overline{t_{EnT_{FC_i}}} \cdot (C_i + G_i + I_i) \tag{3.39}$$

Thus, the total taxe income (T) is given by the sum of taxes and social contributions:

$$T = T_L + T_Y + T_{OP} + T_{VA} + T_F + \sum_{h=1}^{m} T_{I_h} + \sum_{h=1}^{m} T_{D_h} + T_{En} + T_{carb} \tag{3.40}$$

where T_{carb} is the fiscal revenues from carbon tax policies (see sub-section 3.3.6).

Furthermore, the gross disposable income of public administrations R_G is the sum of the following terms:

- The total incomes from taxes and social contributions (T);
- An exogenous share ω_{K_G} of gross operating surplus (GOS);
- An exogenous share ω_{OT_G} of the global pool of "other transfers" (OT) ;
- A negative contribution from the public expenditures ($\sum p_G \cdot G$);
- A negative contribution linked to the social transfers for households : pensions (R_P), unemployment benefits (R_U), and other social transfers (R_O),

- A debt service ($i_G \cdot D_G$).

Hence,

$$R_G = T + \overline{\omega_{K_G}} \cdot GOS + \overline{\omega_{OT_G}} \cdot OT - \sum_{i=1}^{n} p_{G_i} \cdot G_i - R_P - R_U - R_O - i_G \cdot D_G \tag{3.41}$$

Public expenditures ($\sum p_G \cdot G$) are assumed to keep pace with national income, and therefore are constrained as a constant share of GDP:

$$\frac{\sum_{i=1}^{n} p_{G_i} G_i}{GDP} = \frac{\sum_{i=1}^{n} p_{G_{i_0}} G_{i_0}}{GDP_0} \tag{3.42}$$

Social transfers for pensions (R_P), unemployed (R_U), other transfers (R_O) are the sum across household classes of the transfers defined as components of their before-tax disposable income (Equation 3.19) :

$$R_P = \sum_{h=1}^{m} \overline{N_{P_h}}\, \rho_{P_h} \tag{3.43}$$

$$R_U = \sum_{h=1}^{m} N_{U_h}\, \rho_{U_h} \tag{3.44}$$

$$R_O = \sum_{h=1}^{m} \overline{N_h}\, \rho_{O_h} \tag{3.45}$$

Per capita transfers of retired (ρ_{P_h}) and "other transfers" (ρ_{O_h}) are indexed in GDP variation:

$$\rho_{P_h} = \frac{GDP}{GDP_0}\, \rho_{P_{h_0}} \rho_{O_h} = \frac{GDP}{GDP_0}\, \rho_{O_{h_0}} \tag{3.46}$$

Per capita transfers of unemployed (ρ_{U_h}) are indexed on the average net wage (Ω - see equation 3.66) :

$$\rho_{U_h} = \frac{\Omega}{\Omega_0}\, \rho_{U_{h_0}} \tag{3.47}$$

At last, the interest rate i_G of public debt evolves as do i_H and i_F.

Public investment($GFCF_G$) , same as public expenditures ($p_G \cdot G$), is supposed to mobilise a constant share of GDP:

$$\frac{GFCF_G}{GDP} = \frac{GFCF_{G_0}}{GDP_0} \tag{3.48}$$

The financial capacity of public administration (AFC_G) is given by:

$$AFC_G = R_G - [GFCF_G + \sum_{i=1}^{n} p_{G_i} \cdot G_i] \tag{3.49}$$

Finally, we determine the variation of the public debt:

$$D_G = D_{G_0} + \frac{t_{REF}}{2} (AFC_{G_0} - AFC_G) \tag{3.50}$$

3.3.3.4 The Rest of World

The closure of the model is made through the balance of capital flows between the three domestic institutional agents (H, F, and G) and the rest of the world (ROW):

$$AFC_{ROW} = -(AFC_H + AFC_F + AFC_G) \tag{3.51}$$

Hence, the evolution of its net financial debt is determined as:

$$D_{ROW} = D_{ROW_0} + \frac{t_{REF}}{2} (AFC_{ROW_0} - AFC_{ROW}) \tag{3.52}$$

The sum of Equation 3.51 and Equation 3.71 gives the savings-investment balance of the model.

According to Walras law, the last accounting balance, the balance of payments, which balances the rest-of-world budget (AFC_{ROW}), is given as a linear combination of the others equations of the model:

$$AFC_{ROW} = \sum_{i=1}^{n} p_{M_i} M_i - \sum_{i=1}^{n} p_{X_i} X_i + \sum_{K=H,F,G}^{n} i_K D_K - \sum_{K=H,F,G}^{n} OT_K \tag{3.53}$$

By construction the self-financing capacities (AFC) of the four agents clear (sum to zero), and accordingly the net positions, which are systematically built on the AFCs, change from a position in which they are strictly compensating each other to another such position. Indeed a zero condition on the sum of net positions could be substituted to Equation 3.52 without impacting the results of the model.

The hypothesis of a systematic 'compensation' by the ROW of the property incomes of national agents without any reference to its debt D_{ROW} may seem crude, but in fact only replicates the method of construction of the economic account table. Indeed, in the no-policy equilibrium the effective interest rate of the ROW (ratio of net debt to its property income), which ultimately results from a myriad of debit and credit positions and from the corresponding capital flows, is negative, so unworkable for modelling purposes.

At last, as previously mentioned other transfers (OT) are defined as a fixed share of GDP :

$$\frac{OT}{GDP} = \frac{OT_0}{GDP_0} \tag{3.54}$$

3.3.4 Production and consumption choices

3.3.4.1 Households consumption choices

In this version of IMACLIM-S FRANCE model, household demand is characterised by different sectors. We distinguish energy commodities and the other sectors .

For energy sectors, final demand is derived from a utility function of the Stone-Geary form , or Linear expenditure system (LES):

$$U = \prod_i \left(C_i - C_{i_{min}}\right)^{\overline{\alpha_i}}$$

However, the implied fixed budgets are beyond the scope of the basic needs what have been considered too restrictive. In addition, the use of a constant utility function is questionable. For these reasons, the energy consumptions of household class h has been defined - without resorting to any explicit utility function- as the sum of a exogenous basic needs ($\beta_{i_h} \cdot C_{i_h}$), and a consumption in excess of these needs that varies according to some income elasticity (σ_{CR_i}), and some price-elasticity (σ_{CP_i}).

Hence, energy demand for household class h is computed as follows:

$$for\ i \in [energy\ sectors], \quad C_{i_h} = \beta_{i_h} \cdot C_{i_{h_0}} + \left(1 - \beta_{i_h}\right) \cdot \left(\frac{p_{C_i}}{CPI} \cdot \frac{1}{p_{C_{i_0}}}\right)^{\sigma_{CP_i}} \cdot \left(\frac{R_h}{CPI} \cdot \frac{1}{R_{h_0}}\right)^{\sigma_{CR_i}} \cdot C_{i_{h_0}} \tag{3.55}$$

where β_{i_h} represents the share of the reference consumption of class h that corresponds to a basic need, and with prices indexed in the same way as the consumptions.

The demand of all non-energy goods of class h is the balance between the class's consumed income and the energy demand:

$$for\ i \notin [energy\ sectors], \quad \sum_i C_{i_h} = R_{CONS_h} - \sum_{j \in [energy\ sectors]} p_{C_j} \cdot C_j \tag{3.56}$$

Finally, the demand for each non-energy sector of class h is then simply defined as an exogenous distribution share ($\omega_{NE_{h_i}}$) of the total demand of these sectors:

$$for\ i \notin [energy\ sectors], \quad C_{i_h} = \overline{\omega_{NE_{h_i}}} \cdot \sum_i C_{i_h} \tag{3.57}$$

where $\overline{\omega_{NE_{h_i}}}$ is calibrated at base year and represents the share of non-energy sector i in household budget net of energy expenses of class h (Equation 3.56).

3.3.4.2 Production choices

The formulations of the unitary consumptions of secondary factors (α_{ij}), of labour (l_i) and of capital (k_i) are composed of:

- *a fixed share* corresponding to a floor value of consumption,
- *a variable share* of consumption above the floor value.

This structure of production choices is inspired from Ghersi and Hourcade (2006). Under the formulation, the idea is to introduce technical asymptotes constraining the unit consumptions of factors above some floor values (*fixed shared*). Then, the production choices are ruled by the relative prices of each production factors. In fact, the unit consumptions of production inputs and factors are substitutable (*variable shares*) according to a Constant Elasticity of Substitution (CES) specification with an elasticity of σ (the coefficients of which are calibrated at base year). The existence of a fixed share of each of these consumptions implies that the elasticities of substitution of *total* unit consumptions (sum of the fix and variable shares) are not fixed, but decrease as the consumptions approach their asymptotes. In the meantime, asymptotes make it possible to calibrate specific elasticities of substitution for the different inputs and factors. This provides a convenient way to create simple reduced-forms of bottom-up models.

Thus, α_{ij}, l_i and of k_i are computed as follows:

$$\alpha_{ji} = \beta_{IC_{ji}}\, \alpha_{ji_0} + \left(\frac{\lambda_{ji}}{p_{IC_{ji}}}\right)^{\sigma} \left(\sum_{j=1}^{n} \lambda_{ji}{}^{\sigma}\, p_{IC_{ji}}{}^{1-\sigma} + \lambda_{L_i}{}^{\sigma} \frac{p_{L_i}}{\left(1+\phi_{L_i}\right)^t}{}^{1-\sigma} + \lambda_{K_i}{}^{\sigma}\, p_{K_i}{}^{1-\sigma} \right)^{-\frac{1}{\rho}} \tag{3.58}$$

$$l_i = \frac{1}{\left(1+\phi_{L_i}\right)^t} \left[\beta_{L_i}\, l_{i_0} + \left(\frac{\lambda_{L_i}}{p_{L_i}}\right)^{\sigma} \left(\sum_{j=1}^{n} \lambda_{ji}{}^{\sigma}\, p_{IC_{ji}}{}^{1-\sigma} + \lambda_{L_i}{}^{\sigma} \frac{p_{L_i}}{\left(1+\phi_{L_i}\right)^t}{}^{1-\sigma} + \lambda_{K_i}{}^{\sigma}\, p_{K_i}{}^{1-\sigma} \right)^{-\frac{1}{\rho}} \right] \tag{3.59}$$

$$k_i = \beta_{K_i}\, k_{i_0} + \left(\frac{\lambda_{K_i}}{p_{K_i}}\right)^{\sigma} \left(\sum_{j=1}^{n} \lambda_{ji}{}^{\sigma}\, p_{IC_{ji}}{}^{1-\sigma} + \lambda_{L_i}{}^{\sigma} \frac{p_{L_i}}{\left(1+\phi_{L_i}\right)^t}{}^{1-\sigma} + \lambda_{K_i}{}^{\sigma}\, p_{K_i}{}^{1-\sigma} \right)^{-\frac{1}{\rho}} \tag{3.60}$$

where for convenience:

$$\rho = \frac{\sigma - 1}{\sigma}$$

This sum can nevertheless be modified to take into account the combination of exogenous labour productivity improvements ϕ_{L_i}, implemented as factor augmenting productivity gains. This multiplier makes it possible to drive changes in production patterns in order to mimic specific energy and economic scenarios.

In addition, we must underline again that the "cost of capital" (p_K) entering the production trade-offs is *stricto sensu* the price of "machine capital", which is equal to a simple weighted sum of the investment prices of immobilised goods (equation 3.15). Thus, we do not work on the economic productivity of capital, which corresponds to the ratio of net operating surplus and the invested capital, but it does not matter for the issues deal by the thesis.

3.3.4.3 International trade

The competition on international markets relies first of all on relative prices. The ratio of imports to domestic production on the one hand, and the "absolute" exported quantities on the other hand, are elastic to the terms of trade, according to constant, product-specific elasticities:

$$\frac{M_i}{Y_i} = \frac{M_{i_0}}{Y_{i_0}} \left(\frac{p_{M_{i_0}}}{p_{Y_{i_0}}} \frac{p_{Y_i}}{p_{Mi}} \right)^{\sigma_{M_{p_i}}} \tag{3.61}$$

$$\frac{X_i}{X_{i_0}} = \left(\frac{p_{X_{i_0}}}{p_{M_{i_0}}} \frac{p_{M_i}}{p_{X_i}} \right)^{\sigma_{X_{p_i}}} \tag{3.62}$$

The different treatment of imports and exports merely reflects the assumption that, notwithstanding the evolution of the terms of trade, import volumes rise in proportion to economic activity (domestic production), while exports do not (global demand is assumed constant). It implies, however, that improved terms of trade do not necessarily mean an improvement in the trade balance, depending on the concomitant variations of activity.

3.3.5 Market balances

3.3.5.1 Goods markets

Goods market clearing is a simple accounting balance between resources (production and imports) and uses (households and public administrations' consumption, investment, exports). Thanks to the process of hybridisation, this equation is written in *Mtoe* for energy goods and consistent with the 2010 French energy balance of the International Energy Agency (IEA) (notwithstanding that the G and I of these goods are nil by definition). It is also written in *tons* for cement and steel sectors.

$$\forall i \in \{1,...,n\} \qquad Y_i + M_i = \sum_{j=1}^{n} \alpha_{ij} \cdot Y_j + C_i + G_i + I_i + X_i \tag{3.63}$$

3.3.5.2 Labour market

The labour market results from the interplay of labour demand from the production systems, equal to the sum of their factor demands ($l_i\, Y_i$), and of labour supply from households. The labour endowment of households (L) is assumed constant (calibrated on the total full-time equivalent of the active population at base year). As part of key structural assumption, the model allows a strictly positive unemployment rate u and the market clearing condition writes:

$$(1-u)\,\overline{L} = \sum_{i=1}^{n} l_i \cdot Y_i \tag{3.64}$$

The unemployment level depends on a so-called "wage curve" (Blanchflower and Oswald, 2005) which synthesises the forces that drive wage formation. Such an empirical curve can be interpreted as the result of wage bargain between employers and employees or as an aggregate labour supply curve.
Rather than explicitly describe labour supply behaviour, the model infers changes in u, following a sectoral wage curve, which describes an empirical correlation between the wage of sector i (ω_i) and the unemployment rate (u), characterised by an constant elasticity ($\sigma_{\omega_{u_i}}$) :

$$\omega_i = \omega_{i0} \cdot \left[\frac{u}{u_0}\right]^{\sigma_{\omega_{u_i}}} \cdot \left[\beta_{w_{CPI_i}} \cdot CPI + (1 - \beta_{w_{CPI_i}})\right] \tag{3.65}$$

The indexation parameter $\beta_{w_{CPI_i}}$ gives a flexibility to describe a wage curve based either on nominal wage ($\beta_{w_{CPI_i}} = 0$) or real wage ($\beta_{w_{CPI_i}} = 1$). For all values included between 0 and 1, we assume that only a share of wage can be bargain based on real wage.
The underlying intuition is that any increase in unemployment creates a downward pressure on wages, which is indeed interpretable in terms of either bargaining power, or efficiency wage. According to the openess of the sector at the international scale and its mobility, the bargain lies between real wage and nominal wage.

The average wage (Ω) is defined by:

$$\Omega = \frac{\sum_{i=1}^{n} \omega_i \cdot l_i \cdot Y_i}{\sum_{i=1}^{n} l_i \cdot Y_i} \tag{3.66}$$

Changes in employment corresponding to the evolution of u are then split between the household classes according to their specific unemployment u_h :

$$u_h = u_{h_0} \frac{u}{u_0} \tag{3.67}$$

Hence N_{U_h} the number of unemployed in each class follows:

$$N_{U_h} = u_h \overline{L_h} \tag{3.68}$$

N_{L_h} the number of employed in class h (defined as $L_h - N_{U_h}$) allows moreover to determine the share ω_{L_h} of total labour income that accrues to class h:

$$\omega_{L_h} = \frac{\frac{N_{L_h}}{N_{L_{h_0}}} \omega_{L_{h_0}}}{\sum_{h=1}^{m} \frac{N_{L_h}}{N_{L_{h_0}}} \omega_{L_{h_0}}} \tag{3.69}$$

3.3.5.3 Investment and capital flows

Contrary to standard CGE models, Imaclim-S France does not represent explicit capital markets, which is admissible given the nature of static exercises conducted. The capital-investment balance is "demand-driven". As previously highlighted, productive sectors arbitrate capital consumption according to prices of equipment, and not according to the return on capital.
Then, the capital immobilised in all productions is supposed homogeneous, and all its components vary as the total consumption of fixed capital:

$$\frac{I_i}{\sum_{j=1}^{n} k_j \cdot Y_j} = \overline{\beta_i} = \frac{I_{i_0}}{\sum_{j=1}^{n} k_{j_0} \cdot Y_{j_0}} \tag{3.70}$$

In the meantime the assumption is made of a single investment good in the economy as a weighted sum of different goods calibrated at base year.

Furthermore, the investment supply adapts to the demand. Capital formation from firms completes households and public contribution to satisfy that demand, and, balance investment flows.

$$GFCF_H + GFCF_F + GFCF_G = \sum_{i=1}^{n} p_{I_i} \cdot I_i \tag{3.71}$$

Eventually, the investment balance, together with households saving rate and public expenses, imposes the external or trade balance which is endogenous in the model.

3.3.6 Carbon tax policies

The model is specifically designed to study carbon tax policies in the medium to long run by generating policy-constrained projections. In the model, implementing a carbon tax amounts to adding a shock on energy prices proportional to their carbon content at the time horizon studied. Within our one-step projection framework, the underlying assumption is that a phase-in carbon tax is applied in the economy starting, in 2010, with a small level to reach the ultimate carbon tax level at the time t_{ref} studied. Accordingly, the model represents the result of technico-economic adjustments and market interactions at t_{ref} as the end of a smooth pathway which undergoes a rising carbon tax.

The implementation of carbon prices[7] ($t_{carb_{IC}}$ and t_{carb_C}) increase intermediate consumption prices (Equation 3.7) and purchaser's price for households (Equation 3.8) in proportion of the emission factor of the energy good i consummed by sector j ($\gamma_{IC_{ij}}$), and households (γ_{C_i}). Thus, the policy constrained price system is the following :

$$p_{IC_{ij}} = p_i \cdot (1 + \tau_{CM_i} + \tau_{TM_i} + \overline{\tau_{SMIC_i}}) + \overline{t_{EnT_{IC_i}}} + \overline{t_{OPT_i}} + \boldsymbol{t_{carb_{IC}}} \cdot \overline{\boldsymbol{\gamma_{IC_{ij}}}} \tag{3.72}$$

$$p_{C_i} = [p_i \cdot (1 + \tau_{CM_i} + \tau_{TM_i} + \overline{\tau_{SM_{C_i}}}) + \overline{t_{EnT_{FC_i}}} + \overline{t_{OPT_i}} + \boldsymbol{t_{carb_C}} \cdot \overline{\boldsymbol{\gamma_{C_i}}}] \cdot (1 + \overline{\tau_{VAT_i}}) \tag{3.73}$$

Thus, total carbon revenues (T_{carb}) are the sum of carbon taxes levied on households and the different sectors:

$$T_{carb} = \sum_{i}^{n} (\sum_{j}^{n} t_{carb_{IC}} \cdot \overline{\gamma_{IC_{ji}}} \cdot \alpha_{ji} \cdot Y_i) + \sum_{i}^{n} t_{carb_C} \cdot \overline{\gamma_{C_i}} \cdot C_i \tag{3.74}$$

In the present model version, IMACLIM-S FRANCE can simulate different uses of the carbon tax revenues, that can be split in three categories. The carbon tax revenues is either used:

[7] The framework can accommodate sector specific carbon prices.

- to only feed public budget, or
- to directly compensate domestic agents: firms and/or households, or
- to reduce existing other taxes rates.

The last two categories can be combined : a share of the carbon tax revenues may be directly returned to domestic agents, and the remained part is then used to reduce other taxes rates.

Direct compensations can be computed by the following options:

- **Lump-sum transfer to households**
  A share (δ_{LS_H}) of the carbon tax revenues are directly transferred to households while maintaining neutral policy budget:

$$LS_H = \delta_{LS_H} \cdot T_{carb} \text{ with } \delta_{LS_F} \in [0,1] \tag{3.75}$$

- **Lump-sum transfer to firms**
  A share (δ_{LS_F}) of the carbon tax revenues are directly transferred to firms while maintaining neutral policy budget:

$$LS_F = \delta_{LS_F} \cdot T_{carb} \text{ with } \delta_{LS_F} \in [0,1] \tag{3.76}$$

The shares δ_{LS_H} and δ_{LS_F} can be fixed exogenously as a parameters or can correspond to a proportion of variables, endogenously. For no direct transfers to agents, the shares are set up to zero.

Carbon tax revenues can be used to alleviate different existing taxation. In this thesis, we focus on a standard case:

Reduction of the labour tax
The labour tax alleviation can set up under different constraints.

- All carbon tax revenues (net of direct compensation if applied) are used to reduce the labour taxation while maintaining neutral policy budget. Thus, under this recycling option, the sector specific rates of labour taxes $\overline{\tau_{T_L}}$ is alleviated by the same coefficient

Δ_{T_L}:

$$T_{carb} - LS_H - LS_F = \Delta_{T_L} \sum_i^n \omega_i \cdot l_i \cdot Y_i \tag{3.77}$$

$$\text{with } \overline{\tau_{T_L}} = \tau_{T_L} + \Delta_{T_L} \tag{3.78}$$

- The level of labour tax reduction is determined while imposing a specific budget constraint. Thus, the cut Δ_{T_L} is endogenously calculated to satisfy the budget condition.

  In the analysis reported in this thesis (see Chapter 4 and Chapter 5), unless otherwise specified, carbon tax are recycled into labour tax reduction while maintaining the government financial capacity constant to GDP variation:

$$\frac{AFG_G}{GDP} = \frac{AFG_{G_0}}{GDP_0} \tag{3.79}$$

3.4 Transition

This chapter presents the new IMACLIM-S platform for country scale analyses. By relying on the heritage of CIRED and offering better flexibilities for further developments, the countrywide model gives new perspective to study socio-economic implications of environmental reforms. The platform has been developed on the basis of the French economy. Thus, the features presented are prone of the French specificities and the insights we want to highlight in this thesis. The IMACLIM-S FRANCE model is at the core of the empirical studies carry out in the two next chapters.

Chapter 4

Interactions between key parameters and incidence of sectoral granularity

The Intended Nationally Determined Contributions (INDCs) announced during the COP21 in Paris suggest moving towards with domestic climate policy implementation. However, tensions between countries, households and economic industries still represent a barrier that must be lifted. Beyond equity issues at the regional or international scale, globalisation drives concerns about asymmetry of carbon constraints. In particular, preservation of the competitiveness of energy-intensive and trade-exposed industries and the risk of carbon leakage in the case of asymmetric action often come up in the debate. Although the value-added of these industries represents a small fraction of the industrialised countries' GDP, their production remains highly strategic, and the power of industrial lobbies has proven to be decisive regarding any attempt to implement ambitious environmental taxation or quantitative control of greenhouse gas emissions.

To protect these industries and increase the environmental efficiency of a unilateral climate policy, different policy design has been proposed. Compensation mechanisms or border tax adjustments (BTA) are often considered (Böhringer et al., 2012), but raise international objections. Beside consequences for international cooperation, this kind of policy also drives compatibility issues with World Trade Organization (WTO) (Trachtman, 2016). Thus, unilateral carbon tax reform is easier to set up, and, the way to use the tax revenues represents a great potential of action to appropriately balance macroeconomic, equity and competitiveness concerns (Bovenberg et al., 2008). Numerous studies, based on either partial equilibrium models or computable general equilibrium (CGE) models, examined the impact of alternative policy design on competitiveness and leakage issues. One the one hand, partial equilibrium models bring high details on some keys energy-intensive and trade-exposed (EITE) sectors (in particular cement and steel sectors) and use relevant empirical information to analyse specific competitiveness constraints facing by those sectors. On the other hand, CGE models often embark poor details on EITE sectors, as by representing the economic system in a more aggregated way. Recently, some efforts have been be made to disaggregate EITE sectors in CGE models. These attempts have shown that taking into account this higher level of "granularity" changes significantly the evaluation of the distributional effects of climate policies (Alexeeva-Talebi et al., 2012; Caron, 2012).

To go further with these efforts and embark relevant sectoral details for designing policies articulating both competitiveness and environmental issues, we take benefit from the hybridisation procedure exposed at Chapter 1. Not only the method combines physical with monetary input-output data from national accounts within a consistent "hybrid" accounting system, but it also provides a mean of extracting some sectors -in this case the steel and cement sectors- from their initial aggregates in the original Input-Ouput table (IOT) - respectively the metallic sector and the non-metallic mineral sector. Thus, our procedure goes beyond previous disaggregation techniques only based on economic data (Böhringer et al., 2012). In other words, the hybridisation procedure gives the opportunity to build coherent input-output tables whose "granularity" - in the case of energy-intensive sectors - is relevant enough for studying the sectoral distributive effects of carbon policy.

Under this background, the chapter aims to highlight interactions between keys parameters for modelling and sectoral representation for carbon policy evaluation. It is done by following two steps.
First, we discuss main mechanisms occurring after implementing a carbon policy with a compact Imaclim-S France model. Thus, Section 4.1 disentangles the interplay between key parameters and modelling choices, as wage curve and trade elasticities, within an aggregated representation of the economy, and, without paying attention at first to sectoral interdependency. It also validates the new version of the Imaclim-S France model for France (Combet, 2013). At a highly aggregated sectoral level, we find similar mechanisms observed in previous version leading to a double-dividend with a unilateral carbon tax.
Second, we explore to what extend the level of sectoral "granularity" has an impact on carbon policy evaluation. Section 4.2 analyses the sensitivity to results by embarking different level of sectoral representation into the modelling framework. The effort undertaken to develop a new numerical platform for Imaclim (see Chapter 3) offers flexibility to investigate this issue. Indeed, it makes it possible to easily calibrate the model on different aggregation profiles, from the hybrid input-output table in its most disaggregated representation (29 sectors for the France data).

This chapter discusses the mechanisms at play between various economical modelling choices, but it does not discuss the values given to key parameters. We are aware that these values are central for the carbon tax analysis and the economic outcomes. However, there are controversies on their meaning, and the range of value is often uncertain, above all when it comes to embark heterogeneity across sectors. This topic is left aside in this chapter, by assuming some homogenous values, but it will be deeply discussed in Chapter 5.

4.1 An aggregated FRANCE model as a starting point

At first, IMACLIM-S FRANCE model is calibrated on an aggregated sectoral representation. We focus only on feedback loops of the economy from an environmental tax reform to highlight conditions for a global positive effect, before looking at distributional effects. So, the aggregate model is used more for exploratory experiments than realistic scenarios.
The fast computational progresses have enabled the development of extended models which are often wrongly opposing to stylised models. Extended models can be accused of a lack of transparency and are seen as "black box" whose interactions are impossible to discern, and results difficult to understand and comments. Conversely, stylised models gives an opportunity to reveal economics implications of a politics even at a country scale (Henriet et al., 2014), but they do not rely on physical reality. In addition, beside traceability advantage, stylised models hide discrepancies on policy impacts and thus may lead to questionable results (Pottier et al., 2014; Acemoglu et al., 2011).

Therefore, this section aims to start with a compact model, stylised enough but still with consistent physical representation for understanding the logic at play for carbon tax evaluation. Thus, we test certain control parameters by freeing themselves from the effects of intra-sector interaction on the overall economy. These first studies represent also an opportunity to test our aggregated version of IMACLIM-S FRANCE model to validate it by observing the main mechanisms described in Combet (2013)'s thesis. His work has shown that carbon tax impacts not only depend on how tax revenues are recycled, but also on how the labour market is modelled, and the degree of openness given to the French economy.

The use of highly aggregated indicators to analyse the impact of climate policy neglects the importance of sectoral distribution and raises questions on the necessity of keeping enough details in modelling the economic system for revealing carbon policy consequences. This will be dealt in Section 4.2.

France, 2010 in billions of euro[a]	Corporations	Government	Households	Rest Of World
Trade Balance	0.0	0.0	0.0	52.5
GOS	406.6	57.9	153.8	0.0
Labour Income	0.0	0.0	740.5	0.0
Labour Tax	0.0	325.3	0.0	0.0
Production Tax	0.0	57.3	0.0	0.0
Energy Tax	0.0	23.6	0.0	0.0
Other Indirect Tax	0.0	36.6	0.0	0.0
VA Tax	0.0	135.6	0.0	0.0
Property income	-68.8	-31.4	123.1	-22.9
Unemployment transfers	0.0	-42.6	42.6	0.0
Pensions	0.0	-278.5	278.5	0.0
Other social transfers	0.0	-94.2	94.2	0.0
Other Transfers	-90.5	58.1	24.9	7.6
Income Tax	0.0	142.6	-142.6	0.0
Firm Tax	-36.7	36.7	0.0	0.0
Other Direct Tax	0.0	21.6	-21.6	0.0
Gross disposable income	210.6	448.6	1293.4	37.1
FC	0.0	521.6	1091.3	0.0
GFCF	200.1	64.3	112.3	0.0
Expenses for final uses	200.1	585.9	1203.6	0.0
Self-financing capacity	10.5	-137.4	89.7	37.1
Net Financial Debt	1911.3	1067.6	-2624.2	-354.7

[a]Source: Institut national de la statistique et des études économiques (INSEE) and author calculations

Table 4.1 – Economic account table of Imaclim-S France model

4.1.1 Data and numerical experiments

4.1.1.1 Data calibration

For the following experiments, the original hybrid IOT is aggregated into three sectors: the primary energy sector (*PrimEn*), other energy sectors (*FinEn*), and the rest of the economy (*AllComp*). Table D.1, in Appendix D, gives the sectoral correspondences with the developed hybrid IOT (see A.2) .

The integrated economic accounts (Table 4.1) synthetises the whole transactions for institutional agents (firms, public administration, households, and the "rest of the world"). It describes the composition of disposable income, and gives situation on savings, net lending, etc., for each agent. This table does not depend on the sectoral level on which Imaclim-S France model is calibrated. Thus, it remains valid for all sectorial description variants of the model used in this thesis.

The aggregated hybrid IOT in monetary value is given in Table 4.2. We note that households and non-energy firms (aggregated into *AllComp*) mostly consume final energy: that is why we keep two energy sectors. Moreover, despite the sectoral aggregation, the recalculated specific margins reveal heterogeneity in the cost of energy between the various economic agents. Corresponding energy prices are given in Table 4.3. The reader may observe that energy is sold at a higher price for final consumption, which is not without incidence for carbon policy implementation.

France, 2010 in billions of euro		**Intermediate consumption**			**Final consumption**				**Uses**
		PrimEn	***FinEn***	***AllComp***	***C***	***G***	***I***	***X***	
Intermediate consumption	***PrimEn***	0.9	32.5	8.7	10.6	0	0	0.6	53.2
	FinEn	0	0.8	50.7	61.7	0	0	16.1	129.3
	AllComp	3.6	16.1	1659.5	1019	521.6	376.7	443.5	4040
Value-added	***Labour income***	1.3	4.8	734.3					
	Labour Tax	0.6	2.1	322.6					
	Capital income	1.5	5	263.1					
	Production Tax	0.3	1.2	55.8					
	Profit margin	1.3	5	342.4					
Imports	***M value***	40.7	17.1	454.8					
Margins	***Trade margins***	0.2	5.4	-5.6					
	Transp margins	0.3	2	-2.3					
	SpeMarg PrimEner	-0.6	0	0					
	SpeMarg FinEn	-0.2	-0.5	0					
	SpeMarg AllComp	-1.1	1.9	0					
	SpeMarg C	2.5	2.4	0					
	SpeMarg G	0	0	0					
	SpeMarg I	0	0	0					
	SpeMarg X	-0.5	-3.8	0					
Taxes	***VA Tax***	2	12.7	120.8					
	Energy Tax IC	0.3	6.9	0					
	Energy Tax FC	0	16.4	0					
	ClimPolCompensbySect	0	0	0					
	OtherIndirTax	0.3	1.3	35.1					
	Carbon Tax	0	0	0					
Supply		53.2	129.3	4040					

Table 4.2 – Input-Output table (IOT) for three-sector IMACLIM-S FRANCE model

Energy prices are given in Table 4.3. The reader may observe that energy is sold at a higher price for final consumption, which is not without incidence for carbon policy implementation.

France, 2010 €/toe	**Intermediate consumption**			**Final consumption**			
	PrimEn	***FinEn***	***AllComp***	***C***	***G***	***I***	***X***
PrimEn	246.2	407.0	363.7	710.0	504.2	504.2	212.0
FinEn	580.0	487.0	808.7	1 367.1	1 300.7	1 300.7	532.3

Table 4.3 – Energy prices for three-sector IMACLIM-S FRANCE model

Physical tables are given in Table 4.4. The table shows "real" quantities of energy (in kilo tonne of oil equivalent (ktoe)) consumed by each agents with an IOT representation. We notice the weight of primary energy imports and the high share of firms and households in final energy consumptions. Labour are given in full-time equivalent (FTE) for each of the three sectors. Physical data are consistent with monetary values and prices.

France, 2010 ktoe	**Intermediate consumption**			**Final consumption**			
	PrimEn	***FinEn***	***AllComp***	***C***	***G***	***I***	***X***
PrimEn	3 540.1	79 845.7	23 970.3	14 881.0	0.0	0.0	2 787.4
FinEn	49.1	1 714.0	62 655.8	45 150.9	0.0	0.0	30 177.9

France 2010, Full time equivalent	***PrimEn***	***FinEn***	
Labour	21.6	86.2	26693.0

Table 4.4 – Energy quantities and labour for three-sector IMACLIM-S FRANCE model

Table 4.5 gives the corresponding CO_2 emissions[1], from energy sectors. It gives only emissions from energy combustion.

France, 2010 $MtCO$_2$	**PrimEn**	**FinEn**	**AllComp**	**C**	Total
PrimEn	15.2	60.8	68.6	35.7	
FinEn	0	3.9	110.1	91.2	
AllComp	0	0	0	0	
Total	15.2	64.7	178.7	126.9	385.5

Table 4.5 – CO_2 emissions for three-sector IMACLIM-S FRANCE model

More details on basic year prices as well as socio-demographic data are available in Appendix D (Table D.8 and Table D.7).

4.1.1.2 Numerical experiments

We proceed to comparative static exercises which amount to distort the 'image' of the no-policy economy by an external shock: the carbon tax. Thus, we implement a unilateral carbon tax of 500€ per ton of CO_2 levied on the CO_2 content of all transactions, that means for all purchases from firms and households. We voluntarily choose a high level of taxation to accentuate price effects and to highlight economic adjustments to such a reform.

Table 4.6 shows the main parameters for the reference simulations. These reference cases analyse the impacts of the carbon policy according to the way of using carbon tax revenues: additional revenues for government, or revenues returned to firms. Then, we study the impact of the carbon tax - whose revenues are recycled into labour tax reduction- by differentiating

[1]The CO_2 table results in the aggregation of the extended CO_2 IOT from hybridisation procedure -see Table A.3 in Appendix A.

Variable[a]			**PrimEn**	**FinEn**	**AllComp**
$t_{CARB_{IC}}$	€$/tCO_2$	PrimEn	500	500	500
		FinEn	500	500	500
		AllComp	500	500	500
t_{CARB_C}	€$/tCO_2$		500	500	500
$\beta_{IC_{ji}}$		PrimEn	0.8	0.8	0.8
		FinEn	0.8	0.8	0.8
		AllComp	0.8	0.8	0.8
β_{K_i}			0.8	0.8	0.8
β_{L_i}			0.8	0.8	0.8
β_{i_h}			0.5	0.5	Nan
σ			1.2	1.2	1.2
$\sigma_{M_{p_i}}$			0	0.5	1
$\sigma_{X_{p_i}}$			0	0	1
σ_{CP_i}			-0.03	-0.39	Nan
σ_{CR_i}			0.8	0.8	0.8
σ_{w_u}			-0.1	-0.1	-0.1
$\beta_{w_{CPI}}$			0	0	0
t_{REF}			1		

[a] At this stage, we give assumed values to elasticities keeping in mind that they are questionable.

Table 4.6 – Reference parameters

successively: the way to model labour market, the degree of openness given to the economy, and the decarbonisation potential given to households and firms.

4.1.2 The confirmation of well-established results

4.1.2.1 Carbon tax revenues: recycling options

To begin, we focus on two simulation cases. First, we analyse an implementation of carbon tax without any redistribution of the revenues generated by this tax (*REF_NR*). As any strong feedback effects of public debt variation are modelled, this option isolates the consequences of higher energy prices from those of returning revenues to domestic agents. Secondly, we simulate a classical recycling option in the "double-dividend literature": a carbon tax which revenues are used to decrease existing labour tax (*REF*). In France, as in most European countries, the best option from a macroeconomic point of view is to use the revenue to finance a reduction of labour tax rates (Goulder, 2013). More precisely in this second case, the tax revenues contributes to the public budget, which evolves like *GDP*. Similarly, the public debt ratio is maintained constant to the *GDP* ratio. In order to respect this constraint on public administration, part of tax revenues is recycled to finance a reduction of existing labour tax rates.

As exposed in Chapter 3, the unemployment level depends on a "wage curve" (Blanchflower and Oswald, 2005) which synthesises the forces that drive wage formation. In this study case, wages are indexed to international prices - which are constant in the IMACLIM-S FRANCE model.

Table 4.7 summarises the incidence of the carbon tax on some major indicators according to strategy for recycling revenues.

Variation in percentage (%)	Carbon tax rate at 500 €/tCO2 No recycling of tax revenues REF_NR	 Labour tax reduction REF
Real GDP (Laspeyres)	-9.38	4.61
Imports/Domestic production ratio	1.48	1.37
Imports of Non Energy goods in volume	-7.23	4.11
Exports of Non Energy goods in volume	-2.24	0.14
Total Employment	-8.07	6.26
Unemployment rate (% points)	0.07	-0.06
Net-of-tax wages	-5.69	9.98
Labour Intensity (Laspeyres)	1.80	2.05
Labour tax rate (% points)	0.00	-0.25
Energy Input Price (Laspeyres)	164.83	164.10
Energy Intensity (Laspeyres)	-15.38	-4.99
Energy cost share for composite sector	137.00	142.33
Production Price (Laspeyres)	3.96	1.21
Production Price Non Energy goods (Laspeyres)	2.66	-0.11
Real Households consumption (Laspeyres)	-16.21	3.54
Energy in Households consumption	-1.02	-0.63
Non Energy goods in Households consumption	-15.19	4.18
Public Deficits	-41.12	9.39
Total Emissions	-21.27	-12.56

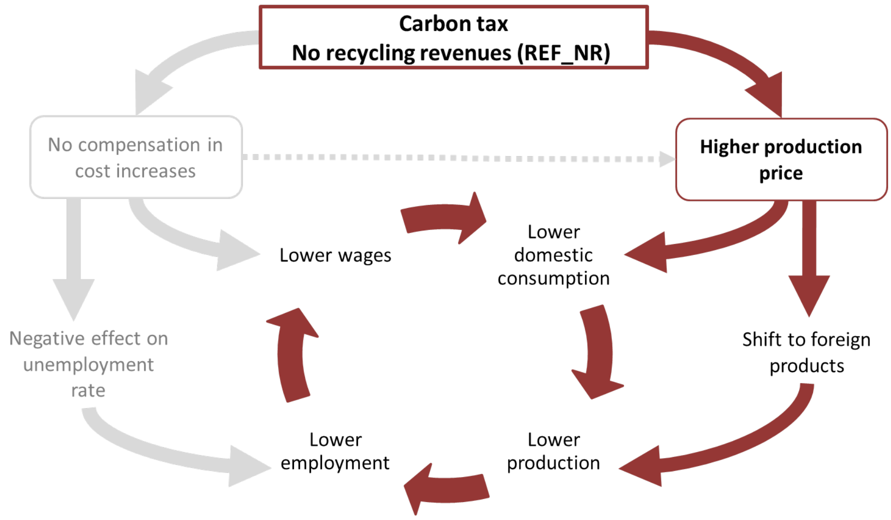
Table 4.7 – Carbon tax impact with different recycling options of tax revenue

First of all, macroeconomic outcomes are sensitive to the recycling option used for carbon tax revenues. The macroeconomic cost of the environmental tax reform in terms of *GDP* and employment is positive when the carbon tax revenue is used to finance a reduction of the labour tax (+4.6% for real *GDP*, and +6.3% for employment). In contrast, the economic activity and the level of employment are significantly impacted without any recycled process (−9.4% for real *GDP*, and −8% for employment). This is a classic result from the double dividend literature (Bovenberg, 1999; Goulder, 1994, 2013). When the revenue of a carbon tax is not returned to domestic agents, the reform harms the whole economy by increasing the firm production cost and reducing purchasing power of households.

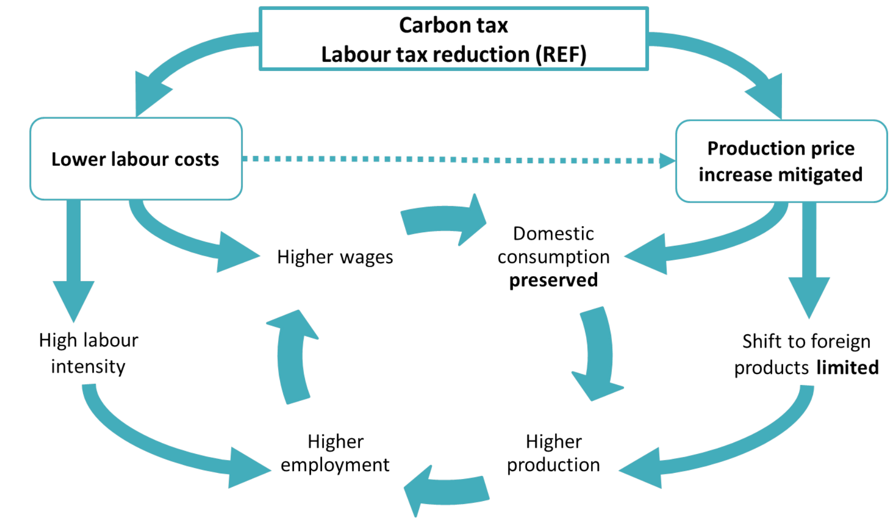
Main mechanisms occurring in these simulations are illustrated in Figure 4.1[2].

[2]Figure 4.1 is an adaptation of Combet (2013).

Figure 4.1a shows the direct effect of a carbon tax which harms the whole economy by spreading via increase of prices which negatively impacts both demand and supply. Carbon tax provokes a vicious circle and, alone, doesn't leave possibilities for co-benefit. The simulation with recycling revenues (*REF*) into labour tax reduction reveals the emergence of a double dividend (see 4.1b) with an environmental and an economic gain preserving its competitiveness.



(a) A vicious circle without uses of carbon tax revenues



(b) A potential virtious circle by reducing labour tax

Figure 4.1 – Vicious circle versus virtuous circle

The production price (p_Y) is in fact the entry point for disentangling the mechanisms induced by the introduction of a carbon tax.

Without recycled revenue, production prices are greatly affected (+2.7% for the composite sector). Therefore, both domestic and external demand shrink, contributing in *GDP* depression. In addition, domestic consumption shifts to foreign products and the proportion of imported goods increases (+1.5%). This reduces *GDP* even more. Technical substitutions and structural change induce a decrease in energy intensity of domestic productions (−15.4%). However, this is not enough to outweigh the increase in energy prices for firms (+164.9%), and energy cost share greatly increases (+137% for the composite sector). Furthermore, through the wage curve equation, workers face lower net-of-tax wages (−5.7%) because the higher unemployment rate (+0.07 in % points) decreases their bargaining power. However, this does not offset the higher production cost which is spreading within the economy, and still harms international trade.

When carbon tax revenues are recycled, price increases are mitigated by a lower level of labour taxation, and composite production price even decreases (−0.1%). However, as sectors are less negatively affected, energy intensity decreases less (−5% instead of −15.4% without recycled revenues), and therefore the increase of energy cost shares are even more significant (+142.3% instead of +137% without recycled revenues for the composite sector). Nevertheless, this negative effect is outweighed by the positive effect of lower labour costs. On the one hand, recycled revenues reduce the relative cost of labour compared to energy. As a result, the labour intensity of production also progress more (+2%) and total employment is preserved (+6.3%). On the other hand, the higher net-of-tax wages demanded by workers (+10%) is compensated by lower labour taxes (−0.2%*points*). As a result, both wage incomes and households' demand are supported. Thus, consumption increases and contributes to *GDP* growth (+4.6%). In addition, the decrease in production cost limits the shift of domestic consumption to foreign products, and the proportion of imported goods increases (+1.4%) but less than the $REF_N R$ simulation.

Depending on the strength of interactions, the net effect of carbon tax may differ in magnitude, and, the outputs may have opposite variations to results. In the following, we propose to keep only the simulation with recycling revenues as a virtuous reference simulation and observe the sensitivity of the results to variations in some parameters that matter for dealing with competitiveness issues.

4.1.2.2 Influence of the wage curve

We aim to highlight the importance of assumptions on labour market modelling for the impact of carbon tax. The labour market is represented by a wage-unemployment curve summarising the bargaining power of wage at an unemployment rate. In our reference parameters, the wage reaction of sectors is indexed on international price. Nevertheless, this can be done on real wage, i.e. indexed on consumer prices.

Thus, we propose to study the effects of the indexation level of the wage curve on consumer prices for the composite sector. We simulate two different settings: wages indexed by half on consumer prices (*W_HALF*), and, wages fully indexed to consumer prices (*W_CPI*). Technically, we change the $\beta_{w_{CPI}}$ parameter from 0 (as in reference simulation) to 1 (indexation on consumer prices). The changes of setting for those simulations are shown in Table 4.8. Main simulation outputs are represented in Figure 4.2. For a complete table of results, we refer the reader to Table D.2 in Appendix D.

Simulation Name	**Changing parameters**	**PrimEn**	**FinEn**	**AllComp**
W_HALF	$\beta_{w_{CPI}}$	0	0	0.5
W_CPI	$\beta_{w_{CPI}}$	0	0	1

Table 4.8 – Parameters for different wage curve indexation

By indexing half of the wages on the consumer price (*W_HALF*), we observe a double dividend, although less pronounced than our central simulation: GDP grows (+3.1%), resulting in increases of employment (+4.5%) and household consumption (+2.5%).
Indeed, contrary to the reference case, lower labour costs do not offset the increase in energy costs, and the composite production price increases slightly (+1.53%). This is explained by more important increase in wages (+11.2%), whose negotiation is partly based on the real wage.
The increase in the production price affects both households demand (+2.5% instead of +3.5% in the reference case) and foreign trade: exports are falling (−1.3%), and the share of imported goods in domestic production increases more. As domestic consumption is lower, supply adapts. This explains the smaller decline in the unemployment rate (−0.04%*points*) compared to the reference.

Full indexation of wages to the consumer price (*W_CPI*) causes a significant decline of the economy: *GDP* falls (−0.2%) and employment and households consumption slightly increase (respectively +0.9% and +0.4%).
This negative outputs are explained by significant higher production price (+5.2%): labour cost reductions are fully counteracted by wage increase (+13.7%). Through the wage curve indexed on domestic prices, workers bargain a retention their purchasing power.
As a result of rising production costs, competitiveness is negatively impacted: exports are decreasing (−4.3%) and the share of imports in production is increasing (+1.5%). Thus, losses in competitiveness prevent a significant decrease in the unemployment rate (−0.01%*points*).

This exercise highlights how the way of implementing the wage curve leads to different results in terms of gain or loss of competitiveness and consumption. This depends on the net effect, on the price of production, of a reduction in the tax on labour combined with an increase in wages and energy prices.

Now that we have above results, we analyse the impact of the decarbonisation potential of household on the outcomes, as it is linked to the level of labour tax reduction.

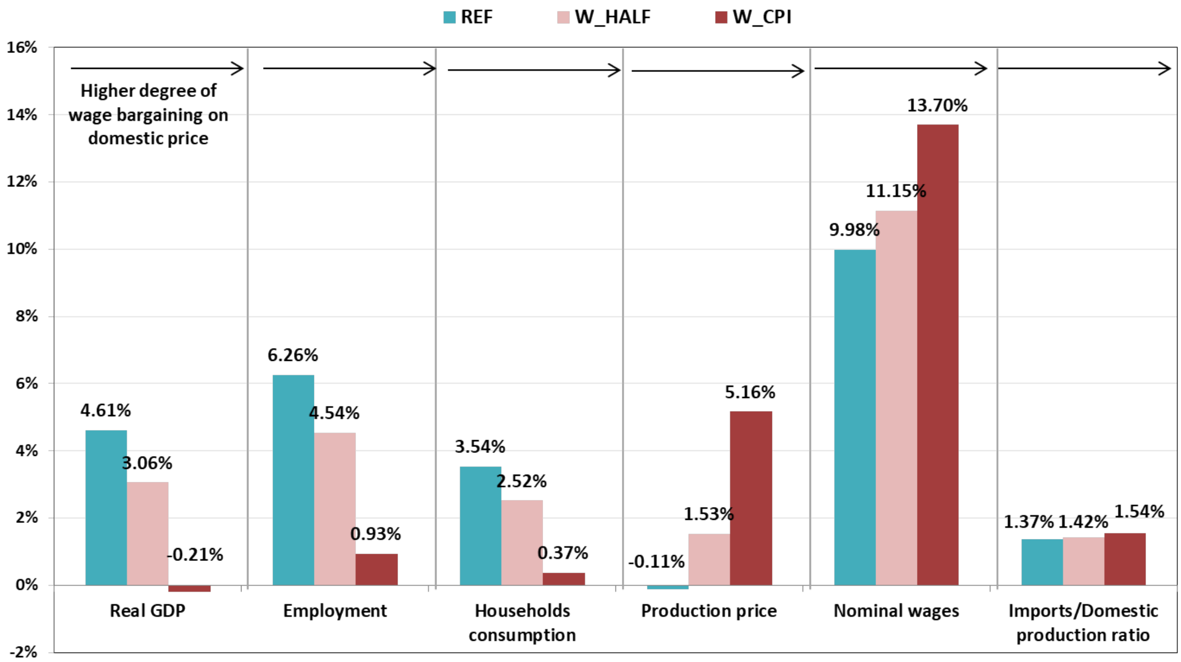


Figure 4.2 – Carbon tax impact with different options for wage curve indexation

4.1.2.3 Influence of the decarbonisation potential

The purchasing power of households is crucial for determining the national demand. But it deeply depends on the increase of the energy bills, and on their capacities to substitute their energy consumptions to low-carbon goods. So, we propose to test the sensitivity of results to the decarbonisation potential of households. To do so, we run two simulations around the reference case: one with a decarbonisation potential halved (*DCH_L*), another with a decarbonisation potential doubled (*DCH_H*). The table 4.9 gives the changes of parameters.

Simulation Name	Changing parameters	PrimEn	FinEn	AllComp
DCH_L	β_{i_h}	1	1	N/A
	σ_{CP_i}	-0.015	-0.195	N/A
DCH_H	β_{i_h}	0.25	0.25	N/A
	σ_{CP_i}	-0.06	-0.78	N/A

Table 4.9 – Parameters for different decarbonisation potential of households

Main simulation outputs are represented in Figure 4.3. For a complete table of results, we refer the reader to Table D.3 in Appendix D.

With higher decarbonisation potential, we observe a growth in *GDP* but which is lower than the reference (+3.9% instead of +4.6%) . The same applies for employment (+5.9% instead

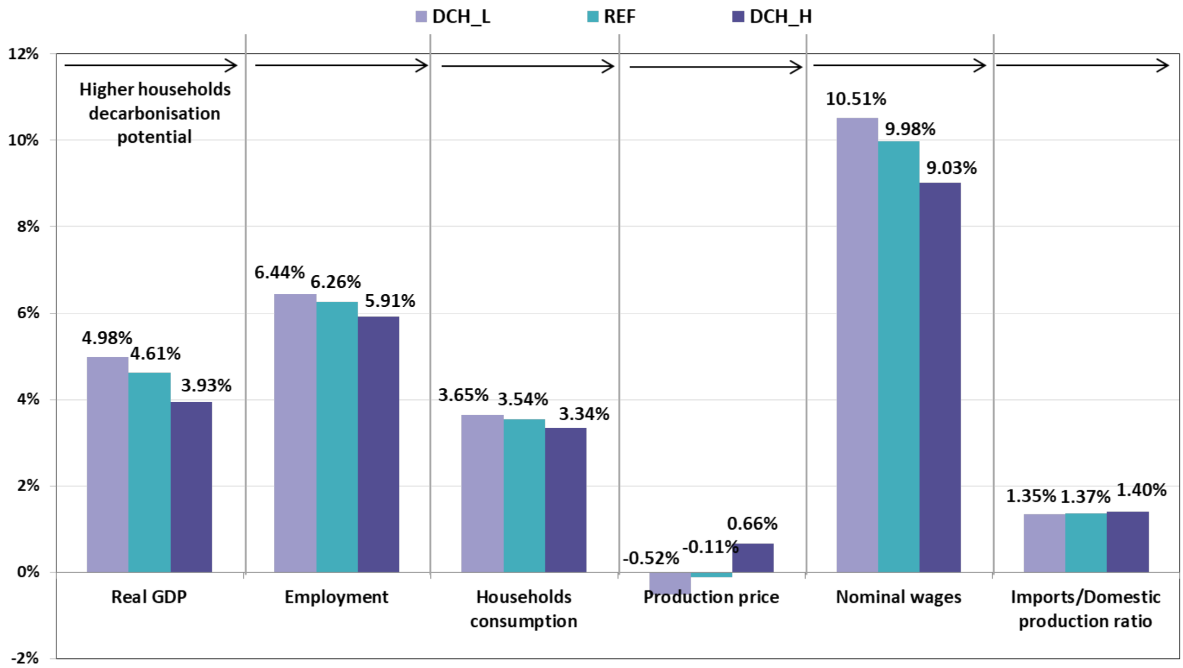


Figure 4.3 – Carbon tax impact with different decarbonisation potential for households

of +6.3%). Indeed, production price of composite sector increases (+0.7%) which negatively impacts exports (−0.6%), and imports rise.
By facing carbon tax, households, compared to firms, have a disadvantage and have more incentive to substitute their consumption to non-energy goods. That is why giving them more flexibility to decarbonise their consumption reduces the amount of fiscal revenues that can be returned to firms. Thus, labour tax rate decreases less than the reference case (−0.23%*points* instead of −0.25%), and net effect of carbon tax leads to a growth of production price, and competitiveness loss.

The opposite mechanism occurs by reducing the decarbonisation potential of household consumption. The *GDP* growth is higher (+5%), as well as the level of employment (+6.5%). In fact, households do not substitute their consumption of energy goods, which guarantees more revenues for a reduction in labour tax (−0.26%*points*) and so lower production price (−0.5% for the composite sector). As we have already underlined, production price decrease is a key for competitiveness gain: exports increase more and imports increase less compared to the reference case.

This exercise highlights here a paradox: a quick erosion of the tax base through high potential of decarbonisation could break the virtuous circle.

4.1.2.4 Influence of the degree of exposure of the economy

If the decarbonisation potential of households does not significantly change the macroeconomic impact,it seems more intuitive and direct to understand to what extent the degree of openness given to the economy can change the analysis of a carbon tax impact.

We propose to test the sensitivity of the outputs to the parameters that reflect this openness: the imports and exports elasticities to the terms of trade. Compared to the reference, we run two tests with respectively higher (*TRD_H*) and lower elasticities (*TRD_L*) for the composite sector.
We remind that it is only for numerical experiment, and that the values used for those elasticities do not pretend to be realistic. Table 4.10 gives the changes of parameters.

Simulation Name	**Changing parameters**	**PrimEn**	**FinEn**	**AllComp**
TRD_L	$\sigma_{M_{p_i}}$	0	0.5	0.5
	$\sigma_{X_{p_i}}$	0	0	0.5
TRD_H	$\sigma_{M_{p_i}}$	0	0.5	1.5
	$\sigma_{X_{p_i}}$	0	0	2

Table 4.10 – Parameters for sensitivity test on trade elasticities

Main simulation outputs are represented in Figure 4.4. For a complete table of results, we refer the reader to Table D.4 in Appendix D.

Under these conditions of settings, the simulation with more openness of the French economy (*TRD_H*) gives better *GDP* growth than the reference simulation (+4.7%). Employment also increases more (+6.3%) which leads to higher wages (+10%) and a lower reduction of production price for the composite sector (−0.04%). Nevertheless, exports grew even more (+0.2%) because the higher reaction of trade to the external price variation. Moreover, thanks to higher wages, purchasing power is strengthened, and stimulates both domestic and external demand.

On the contrary, when the economy is more closed to external trade, *GDP* growth is lower than the reference simulation (+4.5%). Employment increases less (+6.1%) which leads to lower increase of wages (+9.6%) and a higher reduction of production price for the composite sector (−0.4%). This more substantial reduction gives higher exportations even if there are less sensitive to external price variation. However, this is not enough to offset the lower purchasing power that leads to lower domestic demand.

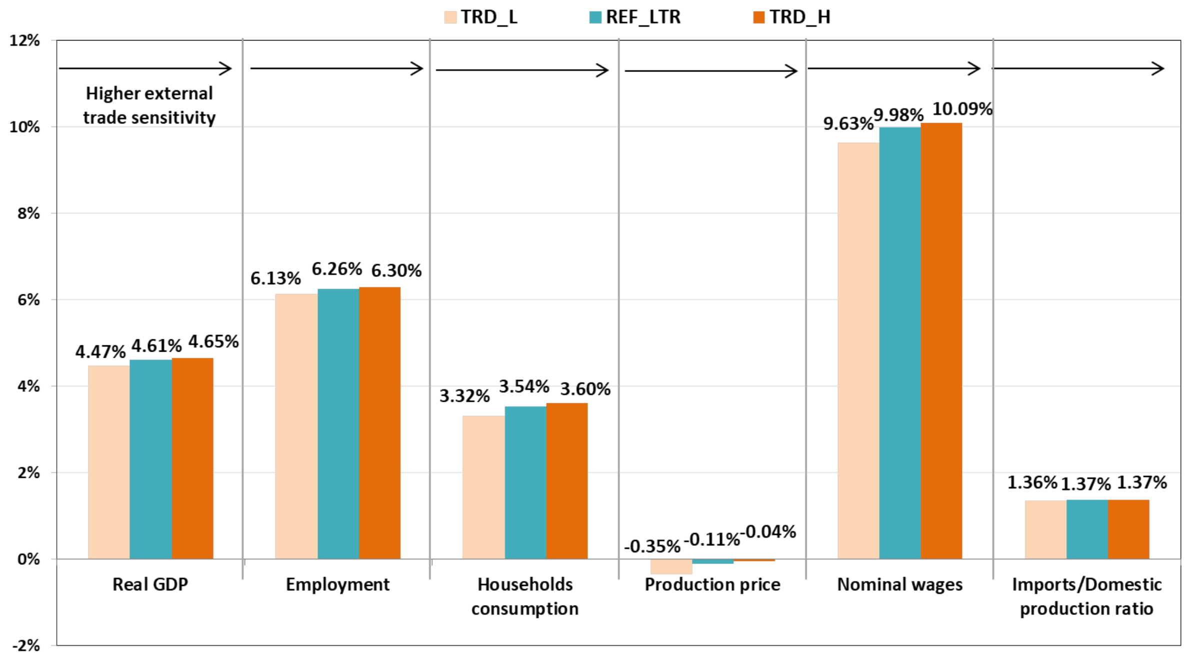


Figure 4.4 – Carbon tax impact with different trade elasticities

4.1.2.5 Interplay between the degree of openness and the wage curve

We have just observed that the sensitivity of the results to the elasticities of external trade is not very significant: the amplitude of results changes but leads to a double dividend.

In fact, in all previous tests, the way the wage curve is modelled appears to be the most sensitive since it has led to both positive and negative outcomes - by indexing the wage curve to the consumer price for the composite sector (*W_CPI*).
However, a wage curve indexed on domestic price coupled with an economy open to international competition seems inconsistent fora realistic economic representation. Thus, we propose to test the sensitivity of the results by combining a lower openness of the economy together with the wage curve indexed to the consumer price for the composite sector (*TRD_L + CPI*).

Table 4.11 gives the parameter settings of this simulation.

Simulation Name	Changing parameters	PrimEn	FinEn	AllComp
TRD_L+CPI	$\sigma_{M_{p_i}}$	0	0.5	0.5
	$\sigma_{X_{p_i}}$	0	0	0.5
	$\beta_{w_{CPI}}$	0	0	1

Table 4.11 – Parameters for sensitivity test on trade elasticitiess with wage curve indexed on consumer price

We compare main outputs in Figure 4.5 with outputs obtained for the simulation that keeps reference values for trade elasticities but whose wage curve is indexed on consumer prices (*W_CPI*). Again, full results are available in Table D.5 in Appendix D.

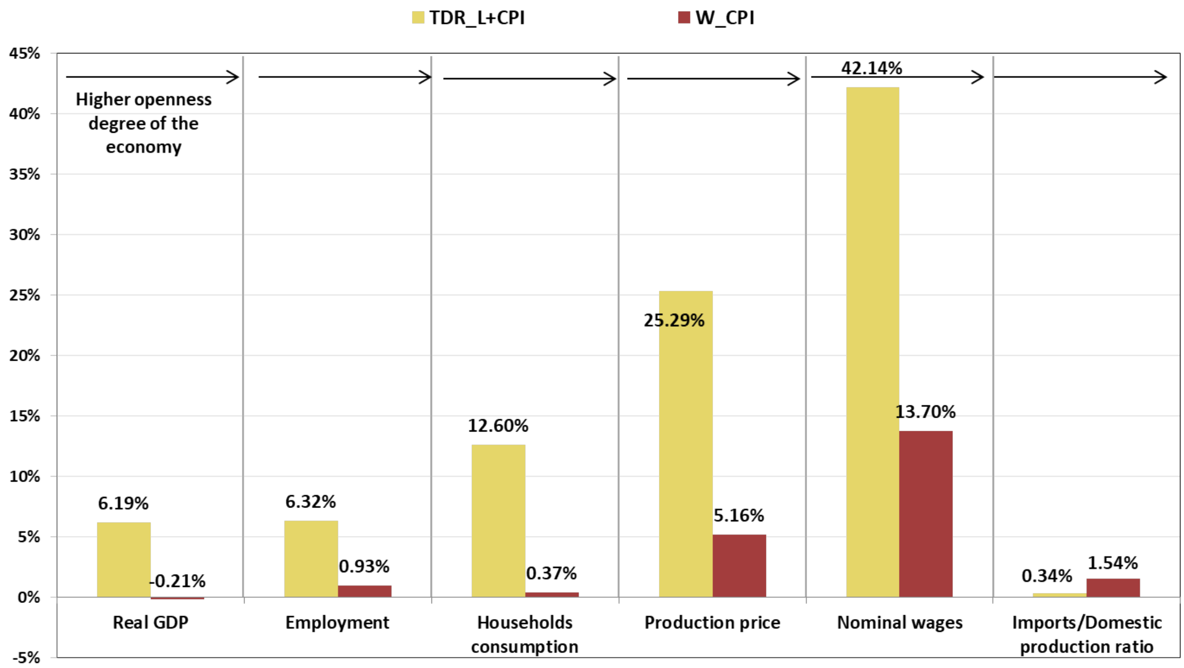


Figure 4.5 – Carbon tax impact with low trade elasticities and wage curve indexed on consumer price

In a closed economy, the increase of production price (+25.3% for the composite sector), although very substantial, does not cause enough competitiveness losses (−9.5% of exports for the composite sector) to offset the positive effect of the recovery of household consumption (12.6%) allowed by higher wages. As a result, GDP grows (+6.2%). The important increase in consumption stimulates domestic production, and employment (+6.3%) which induces a decrease of unemployment rate (−0.06%*points*) and leads to even higher wages (+42.1%). As a result, the imports to domestic production ratio is barely rising (+0.3%), less than for an open economy , although imports increase more significantly (+18.8%) to satisfy the domestic demand.

Finally, we notice that the elasticities of international trade, which capture the degree of openness of the economy, can be fundamental in the outputs according to the indexation given to wages.

We remind that, until now, we run only numerical experiments on a highly aggregated representation of the economy. Thus, these experiments do not pretend to embark realistic values of parametrisation. However, we show the sensitivity to the results of combinations translating different visions on external competition (wages, or international market). In the end, we reveal that the bargaining power of wages and the degree of openness of an economy go hand in hand. Still, their convenient representations depend on the sectoral level description of the modelling framework.

4.2 Consequences of a gain in granularity

Since not all industries are subject to the same exposure to international trade, it seems essential to take into account a greater sectoral heterogeneity.

4.2.1 Data calibration

The IMACLIM-S FRANCE model is calibrated on different level of aggregation detailed in Table 4.12.

Sectoral correspondance between aggregation profiles		
AGG_3Sec	**AGG_MetMinEn**	**AGG_IndEner**
Primary Energy	Crude oil	Crude oil
	Gas	Gas
	Coal	Coal
Final Energy	Fuel Products	Fuel Products
	Electricty	Electricty
	Heat Geo Sol Th	Heat Geo Sol Th
Rest of the economy (AllComp)	Metals	Steel Iron
		Non Ferrous Metals
	Non-metallic minerals	Cement
		Other Minerals
	Other Industries	Other Industries
	Agriculture	Agriculture
	Composite	Composite

Table 4.12 – Three level of aggregation for calibration

The three-sectoral representation (*AGG_3Sec*) is defined as in section 4.1 with two-energetic sectors and the rest of the economy aggregated into a unique composite sector. The IOTs, in both quantities and monetary flows, correspond to tables in previous section (see Table 4.2, Table 4.4, Table 4.5, and Table 4.3).

The two other level of representation gives better detail on both energy and industry sectors. In order to not multiply the distributional effects between sectors and highlight benefits from hybridisation procedure, these two levels of aggregation are almost similar except for the metallic, and the non-metallic mineral sectors. The most disaggregated profile (*AGG_IndEner*) isolates from these aggregate sectors the iron and steel, and the cement sectors which are described in both physical quantities and monetary values. Indeed, thanks to the hybridisation work, Imaclim-S France model can be calibrated on sectors that are originally taken as a whole. This gives an opportunity to study heterogeneity of impacts and distributional effects. We compare results from this calibration to results from a more aggregated representation for these energy-intensive sectors (*AGG_MetMinEn*). Otherwise, the two aggregation profiles offer the same details on energy sectors by distinguishing: crude oil, gas, coal, fuel products, electricity, and heat/solar/geo-thermic sources.

For more concisenesses, we give only the IOT tables for the most disaggregated profile (*AGG_IndEner*). The tables IOT for the profile that considers metals and non-metallic minerals (*AGG_MetMinEn*) are given in Appendix D (see Table D.9 to Table D.14). These tables re-aggregate metals and non-metallic minerals into heterogeneous sectors whose quantities are then "pseudo-quantities".

The integrated economic accounts remain the same for each aggregation profiles and given in Table 4.1.

France, 2010 in billion of euro		Intermediate consumption													Final consumption				Uses
		Crude oil	*Natural gas*	*Coal*	*Fuel Products*	*Electricty*	*HeatGeoSol Th*	*Steel Iron*	*Non Ferrous Metals*	*Cement*	*Other Minerals*	*Other Industries*	*Agriculture*	*Composite*	*C*	*G*	*I*	*X*	
Intermediate consumption	*Crude oil*	0.0	0.0	0.0	29.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	29.2
	Natural gas	0.0	0.0	0.0	0.3	1.4	0.8	0.3	0.1	0.1	0.4	1.8	0.1	4.3	10.4	0.0	0.0	0.5	20.5
	Coal	0.0	0.0	0.9	0.0	0.8	0.0	1.4	0.0	0.1	0.0	0.1	0.0	0.0	0.1	0.0	0.0	0.1	3.5
	Fuel Products	0.0	0.0	0.0	0.0	0.5	0.1	0.0	0.1	0.4	0.3	17.0	2.4	11.3	41.9	0.0	0.0	13.8	87.8
	Electricty	0.0	0.0	0.0	0.2	0.0	0.1	0.4	0.3	0.2	0.2	3.4	0.3	12.8	19.7	0.0	0.0	2.2	39.8
	HeatGeoSol Th	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	1.4	0.1	0.0	0.0	0.0	1.7
	Steel Iron	0.0	0.0	0.0	0.0	0.0	0.0	0.9	0.6	0.0	0.2	2.4	0.0	11.3	0.2	0.0	0.1	12.5	28.2
	Non Ferrous Metals	0.0	0.0	0.0	0.1	0.0	0.0	5.7	1.0	0.0	0.3	3.6	0.0	16.9	0.3	0.0	0.1	7.8	35.8
	Cement	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9	0.5	0.5	0.0	2.4	0.4	0.0	0.0	0.3	5.0
	Other Minerals	0.0	0.0	0.0	0.0	0.2	0.0	0.3	0.1	0.4	2.7	4.3	0.3	20.1	3.6	0.0	0.0	4.5	36.4
	Other Industries	0.0	0.7	0.0	0.6	2.6	0.1	0.6	3.1	0.2	2.0	118.0	13.8	122.0	249.0	29.1	70.2	204.4	816.2
	Agriculture	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	35.0	13.8	5.6	32.4	0.0	1.3	13.4	101.4
	Composite	0.2	2.4	0.1	4.0	8.4	0.2	2.5	12.7	0.7	6.8	183.8	10.4	1053.2	733.3	492.6	305.0	200.6	3016.9
Value-added	*Labour income*	0.0	1.3	0.0	0.3	4.4	0.1	1.3	1.3	0.2	3.0	62.5	11.3	654.7					
	Labour Tax	0.0	0.6	0.0	0.1	1.9	0.0	0.6	0.6	0.1	1.3	27.5	5.0	287.6					
	Capital income	0.1	1.3	0.0	0.2	4.7	0.1	0.6	0.7	0.2	0.6	27.2	11.1	222.6					
	Production Tax	0.0	0.3	0.0	0.2	1.0	0.0	0.2	0.4	0.2	0.2	5.8	-6.4	55.5					
	Profit margin	0.1	1.2	0.0	0.6	4.3	0.1	0.4	0.2	0.1	0.9	6.6	5.9	328.3					
Imports	*M value*	28.8	9.8	2.2	16.1	1.0	0.0	11.0	12.4	0.3	6.4	170.1	9.6	245.2					
Margins	*Trade margins*	0.0	0.0	0.2	5.4	0.0	0.0	1.4	1.7	0.8	8.4	135.9	21.7	-175.4					
	Transp margins	0.0	0.3	0.0	1.0	0.9	0.0	0.4	0.5	0.1	1.6	-16.1	1.8	9.3					
	SpeMarg Crude oil	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0					
	SpeMarg Natural gas	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0					
	SpeMarg Coal	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0					
	SpeMarg FuelProd	0.0	-0.1	0.0	0.0	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0					
	SpeMarg Electricty	0.0	-0.5	-0.4	-0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0					
	SpeMarg HeatGeoSol Th	0.0	-0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0					
	SpeMarg Steel Iron	0.0	-0.1	0.4	0.0	-0.2	0.0	-5.0	0.0	0.0	0.0	0.0	0.0	0.0					
	SpeMarg NonFerrousMetals	0.0	0.0	0.0	0.0	-0.2	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0					
	SpeMarg Cement	0.0	0.0	0.0	-0.1	-0.1	0.0	0.0	0.0	-1.2	0.0	0.0	0.0	0.0					
	SpeMarg Oth. Min	0.0	-0.1	0.0	-0.1	-0.1	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.0					
	SpeMarg Oth. Indus	0.0	-0.3	0.0	0.8	-1.5	0.0	0.8	0.0	0.1	0.0	0.0	0.0	0.0					
	SpeMarg Agriculture	0.0	0.0	0.0	-0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0					
	SpeMarg Composite	0.0	-0.3	0.0	1.8	1.1	0.0	3.7	0.0	0.7	0.0	0.0	0.0	0.0					
	SpeMarg C	0.0	2.3	0.0	0.3	2.2	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0					
	SpeMarg G	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0					
	SpeMarg I	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0					
	SpeMarg X	0.0	-0.6	0.0	-2.0	-1.1	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.0					
Taxes	*VA Tax*	0.0	2.0	0.0	5.9	6.8	0.0	0.0	0.0	0.0	0.7	32.0	1.8	86.3					
	Energy Tax IC	0.0	0.3	0.0	6.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0					
	Energy Tax FC	0.0	0.0	0.0	16.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0					
	ClimPolCompensbySect	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0					
	OtherIndirTax	0.0	0.2	0.0	0.5	0.8	0.0	0.0	0.0	0.0	0.0	-5.2	-1.3	41.5					
	Carbon Tax	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0					
Supply		29.2	20.5	3.5	87.8	39.8	1.7	28.2	35.8	5.0	36.4	816.2	101.4	3016.9					

Table 4.13 – Disaggregated (*AGG_IndEner*) Input-Output table (IOT)

France, 2010 ktoe, ktons	Intermediate consumption													Final consumption				Production	Imports
	Crude oil	*Natural gas*	*Coal*	*Fuel Products*	*Electricty*	*HeatGeoSol Th*	*Steel Iron*	*Non Ferrous Metals*	*Cement*	*Other Minerals*	*Other Industries*	*Agriculture*	*Composite*	*C*	*G*	*I*	*X*	*Y*	*M*
Crude oil	0.0	0.0	0.0	66 967.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.8	2 406.3	64 614.3
Natural gas	9.8	0.0	1.8	841.2	4 190.7	2 510.9	795.6	215.8	305.8	1 226.3	4 693.3	210.5	10 570.0	14 396.4	0.0	0.0	2 556.5	636.2	41 888.4
Coal	0.0	0.0	3 528.4	0.0	5 324.3	10.9	4 635.6	0.8	301.7	173.7	650.8	0.0	190.2	484.6	0.0	0.0	178.1	3 389.3	12 089.9
Fuel Products	0.0	0.0	0.0	0.0	1 087.8	173.0	55.4	203.9	661.3	457.8	20 246.2	3 336.8	11 799.3	31 451.9	0.0	0.0	25 861.7	58 184.8	37 150.3
Electricty	27.0	17.1	5.0	272.2	0.0	181.0	855.4	625.2	307.8	460.3	6 280.5	294.8	14 753.5	13 602.1	0.0	0.0	4 316.2	40 430.5	1 567.5
HeatGeoSol Th	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	264.0	6.4	2 047.4	96.8	0.0	0.0	0.0	2 414.7	0.0
Steel Iron	0.0	4.6	19.2	37.0	16.0	0.3	9 662.8	701.3	15.5	226.1	2 622.3	11.8	12 386.8	183.0	0.0	65.8	20 297.7	30 363.2	15 887.1
Cement	0.0	28.7	1.1	8.9	100.5	2.1	162.9	39.4	14 706.0	2 406.0	2 607.5	177.8	12 235.0	2 183.0	0.0	0.0	1 311.0	32 899.0	3 071.0
Labour - Full time equivalent	0.3	23.2	0.5	4.2	81.1	1.7	38.5	39.9	5.0	99.2	1214.3	249.4	23464.7						

Table 4.14 – Physical quantities and labour for disaggregated (*AGG_IndEner*) calibration

France, 2010 MtCO2	Crude oil	Natural gas	Coal	Fuel Products	Electricty	HeatGeoSol Th	Steel Iron	Non Ferrous Metals	Cement	Other Minerals	Other Industries	Agriculture	Composite	C	Total
Crude oil	0	0	0	20.2	0	0	0	0	0	0	0	0	0	0	
Natural gas	0	0	0	2	9.8	5.9	1.9	0.5	0.7	2.9	11	0.5	24.8	33.8	
Coal	0	0	15.2	0	22.9	0	21	0	1.2	0.7	2.6	0	0.8	1.9	
Fuel Products	0	0	0	0	3.3	0.5	0.2	0.6	2	1.4	60.8	9.9	35.2	91.2	
Electricty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
HeatGeoSol Th	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Total	0	0	15.2	22.2	36	6.4	23.1	1.1	3.9	5	74.4	10.4	60.8	126.9	385.4

Table 4.15 – CO_2 emissions for disaggregated (*AGG_IndEner*) calibration

France, 2010 €/toe, €/ton	Intermediate consumption													Final consumption			
	Crude oil	*Natural gas*	*Coal*	*Fuel Products*	*Electricty*	*HeatGeoSol Th*	*Steel Iron*	*Non Ferrous Metals*	*Cement*	*Other Minerals*	*Other Industries*	*Agriculture*	*Composite*	*C*	*G*	*I*	*X*
Crude oil	436.4	436.4	436.4	436.4	436.4	436.4	436.4	436.4	436.4	436.4	436.4	436.4	436.4	436.4	436.4	436.4	458.2
Natural gas	329.0	438.8	329.0	329.0	329.0	329.0	329.0	329.0	329.0	329.0	380.4	476.0	408.0	724.9	529.9	529.9	200.8
Coal	226.4	226.4	245.9	226.4	148.3	171.9	308.2	171.9	171.9	258.7	185.3	226.4	199.9	265.8	269.9	269.9	299.7
Fuel Products	799.1	799.1	799.1	799.1	442.0	526.1	891.0	677.5	631.4	584.4	838.6	715.6	955.4	1 332.6	1 323.0	1 323.0	534.7
Electricty	580.0	580.0	580.0	580.0	788.3	580.0	504.0	504.0	504.0	504.0	544.7	865.0	865.0	1 451.0	1 204.7	1 204.7	518.2
HeatGeoSol Th	681.7	681.7	681.7	681.7	681.7	681.7	681.7	681.7	681.7	681.7	683.7	683.7	683.7	768.6	827.3	827.3	674.6
Steel Iron	609.9	911.8	911.8	911.8	911.8	911.8	90.0	911.8	911.8	911.8	911.8	911.8	911.8	911.8	740.3	911.8	616.3
Non Ferrous Metals	1 065.0	1 065.0	1 065.0	1 065.0	1 065.0	1 065.0	1 065.0	1 065.0	1 065.0	1 065.0	1 065.0	1 065.0	1 065.0	1 144.4	1 144.4	1 144.4	1 064.5
Cement	138.4	194.9	194.9	194.9	194.9	194.9	194.9	194.9	58.0	194.9	194.9	194.9	194.9	194.9	152.8	152.8	211.9
Other Minerals	1 388.7	1 388.7	1 388.7	1 388.7	1 388.7	1 388.7	1 388.7	1 388.7	1 388.7	1 388.7	1 388.7	1 388.7	1 388.7	1 702.5	1 702.5	1 702.5	1 386.9
Other Industries	1 168.4	1 168.4	1 168.4	1 168.4	1 168.4	1 168.4	1 168.4	1 168.4	1 168.4	1 168.4	1 168.4	1 168.4	1 168.4	1 286.6	1 286.6	1 286.6	1 178.9
Agriculture	1 282.9	1 282.9	1 282.9	1 282.9	1 282.9	1 282.9	1 282.9	1 282.9	1 282.9	1 282.9	1 282.9	1 282.9	1 282.9	1 354.6	1 354.6	1 354.6	1 302.7
Composite	960.3	960.3	960.3	960.3	960.3	960.3	960.3	960.3	960.3	960.3	960.3	960.3	960.3	1 017.6	1 017.6	1 017.6	945.7

Table 4.16 – Intermediate and final prices for disaggregated (*AGG_IndEner*) calibration

4.2.2 Simulation protocol

The model is calibrated on each level of aggregation described in Table 4.12.
For each calibration, we run comparative statics simulations by implementing a carbon tax at 100€ per tonne of CO_2. Common to all reforms, the tax is assumed unilateral, without border adjustment measures for now, imposed on the carbon content of all fossil fuel sales. It is supposed to have grown smoothly, leading to 'counterfactual 2010 France' adjusted to the twenty-year reform.

We assume a wage curve indexed on consumer prices for all sectors[3]. For a given calibration, the simulations only differ on the way that carbon tax revenues are recycled. We focus on two cases.
First, we analyse an implementation of carbon tax without any redistribution of the revenues generated by this tax. Revenues are used to finance the public debt. This option helps better isolating the consequences of higher energy prices from those of returning revenues to domestic agents.
Secondly, we simulate a classical recycling option in the "double-dividend literature" : a carbon tax which revenues are used to decrease existing labour tax[4].
Finally, we run a sensitivity analysis for the trade elasticities by calibrating the model either on the most aggregate profile at three sectors, or the most disaggregate profile. Indeed, because indexing wage curve on consumer prices seems relevant in a close economy, we reduce trade elasticities and observe the impact of a carbon tax recycled into labour tax reduction. We analyse the impact differences for each calibration.

Identical settings of parameters are given to each calibration. In this study, we do not comment the values given to these parameters, which are often either missing or uncertain data. Before estimating more documented values (see Chapter 5), we limit ourselves to identifying the principal mechanisms of the model and the effects by calibrating on matrices of different sizes. The values of the parameters are given in Table 4.17 for model with three sectors (*AGG_3Sec*), in Table 4.18 for the most disaggregated model (*AGG_IndEner*). We refer to Appendix D, Table D.14, for parameter values of the model which aggregates cement to the rest of mineral sector, and steel to the rest of metallic sector (*AGG_MetMinEn*).

[3] In previous sectors, we run simulations with a wage curve indexed on consumer prices but only for non-energetic sectors. Here, we set the same wage curve for all sectors to not multiply heterogeneous bahaviour across sectors.

[4] Additional revenues from carbon tax are not directly recycled into labour tax cut. The part of these revenues that actually are used to reduce existing labour tax is defined by respecting a constraint on public debt: government net lending is maintained constant to GDP.

Variable		Three sector model (AGG_3Sec)	PrimEn	FinEn	AllComp
$t_{CARB_{IC}}$	€$/tCO_2$	PrimEn	100	100	100
		FinEn	100	100	100
		AllComp	100	100	100
t_{CARB_C}	€$/tCO_2$		100	100	100
$\beta_{IC_{ji}}$		PrimEn	0.8	0.8	0.8
		FinEn	0.8	0.8	0.8
		AllComp	0.8	0.8	0.8
β_{K_i}			0.8	0.8	0.8
β_{L_i}			0.8	0.8	0.8
β_{i_h}			0.5	0.5	N/A
σ			1.2	1.2	1.2
$\sigma_{M_{p_i}}$			0	0.5	1
$\sigma_{X_{p_i}}$			0	0	1
σ_{CP_i}			-0.03	-0.39	N/A
σ_{CR_i}			0.8	0.8	0.8
σ_{w_u}			-0.1	-0.1	-0.1
$\beta_{w_{CPI}}$			1	1	1

Table 4.17 – Initial simulation parameters for compact model (*AGG_3Sec*) calibration

Variable			Crude oil	Gas	Coal	Fuel Products	Electricty	Heat Geo Sol Th	Steel Iron	Non Ferrous Metals	Cement	Other Minerals	Other Industries	Agriculture	Composite
			Thirteen sector model (AGG_IndEner)												
$t_{CARB_{IC}}$	€/tCO_2	Crude oil	100	100	100	100	100	100	100	100	100	100	100	100	100
		Gas	100	100	100	100	100	100	100	100	100	100	100	100	100
		Coal	100	100	100	100	100	100	100	100	100	100	100	100	100
		Fuel Products	100	100	100	100	100	100	100	100	100	100	100	100	100
		Electricty	100	100	100	100	100	100	100	100	100	100	100	100	100
		Heat Geo Sol Th	100	100	100	100	100	100	100	100	100	100	100	100	100
		Steel Iron	100	100	100	100	100	100	100	100	100	100	100	100	100
		Non Ferrous Metals	100	100	100	100	100	100	100	100	100	100	100	100	100
		Cement	100	100	100	100	100	100	100	100	100	100	100	100	100
		Other Minerals	100	100	100	100	100	100	100	100	100	100	100	100	100
		Other Industries	100	100	100	100	100	100	100	100	100	100	100	100	100
		Agriculture	100	100	100	100	100	100	100	100	100	100	100	100	100
		Composite	100	100	100	100	100	100	100	100	100	100	100	100	100
t_{CARB_C}	€/tCO_2		100	100	100	100	100	100	100	100	100	100	100	100	100
$\beta_{IC_{ji}}$		Crude oil	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Gas	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Coal	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Fuel Products	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Electricty	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Heat Geo Sol Th	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Steel Iron	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Non Ferrous Metals	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Cement	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Other Minerals	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Other Industries	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Agriculture	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Composite	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
β_{K_i}			0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
β_{L_i}			0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
β_{i_h}			0.5	0.5	0.5	0.5	0.5	0.5	N/A	N/A	N/A	N/A	N/A	N/A	N/A
σ			1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
$\sigma_{M_{P_i}}$			0	0	0	0.5	0.5	0.5	1	1	1	1	1	1	1
$\sigma_{X_{P_i}}$			0	0	0	0	0	0	1	1	1	1	1	1	1
σ_{CP_i}			-0.03	-0	-0	-0.39	-0.03	-0.03	N/A	N/A	N/A	N/A	N/A	N/A	N/A
σ_{CR_i}			0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
σ_{w_u}			-0.1	-0	-0	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
$\beta_{w_{CPI}}$			1	1	1	1	1	1	1	1	1	1	1	1	1

Table 4.18 – Initial simulation parameters for disaggregated (*AGG_IndEner*) calibration

4.2.3 Significant impacts on results of the sectoral granularity

4.2.3.1 Carbon tax revenues: recycling options

Macroeconomic results
Key macroeconomic results are given in Figure 4.6a for the non-recycled carbon tax simulation, and in Figure 4.6b for the carbon tax revenues recycled in labour tax reduction. Full macroeconomic results are available in Appendix D at Table D.16 and Table D.17.

Two main remarks emerge from these results.
Firstly, macroeconomic outcomes are sensitive to the recycling option used for carbon tax revenues regardless the initial sectoral description for calibration.
Secondly, macroeconomic outcomes are hardly sensitive to the initial sectoral "granularity" description. This appears to be also in line with studies focusing on the macroeconomic and distributive effects of border tax adjustments (Caron, 2012; Böhringer et al., 2012). The level of industrial aggregation has only second order effects on the variations of aggregate components.

To argue the first point, we analyse the results from the model calibrated on the higher sectoral description (*AGG_IndEner* column of Table 4.6b and Table 4.6a). Despite a higher level of sectoral description at calibration, same mechanisms occur than the ones observed in Section 4.1.2.1.
The economic activity and the level of employment are much more impacted without any recycled process(−3.3% instead of −0.02% for real *GDP*, and −3% instead of +0.4% for employment). This is a classic result from the double dividend literature: when the revenue of a carbon tax is not returned to domestic agents, the reform harms the whole economy by increasing the firm production cost and reducing purchasing power of households. This leads to higher costs for comparable emissions reductions (−10.8% to −8.9% reductions). Without recycled revenue, production price (2.5% for non energy goods). Therefore, both domestic and external demand shrink, contributing in a *GDP* depression (−2% for the contribution of household consumption to *GDP*, −0.6% for investment, and −0.6% for exports). In addition, domestic consumption shifts to foreign products and the proportion of imported goods increases (+0.3%) but in volume, imports decreases (−0.9% for non-energy goods). Technical substitutions and structural change induce a decrease in energy intensity of domestic productions (−6.2%). However, this is not enough to outweigh the increase in energy prices for firms (+13.4%), and energy cost share greatly increases (26.2%). Furthermore, through the wage curve equation, workers tend to maintain their purchasing power by demanding higher net-of-tax wages (+1.1%). Thus, part of energy tax is shifted to the firms, which harms the production costs and international trade.

On the contrary, when carbon tax revenues are recycled, production price increase is mitigated by a lower level of labour taxation (+1.6% for non-energy goods). However, as energy intensive sectors are less negatively affected, the energy intensity remains higher (−3.9% instead of −6.2% without recycled revenues), and therefore energy cost share increases more (+26.6%). But this negative effect is outweighed by the positive effect of lower labour costs. On the one hand, the higher net-of-tax wages demanded by workers (+3.4%) is compensated by lower labour taxes (−0.05%). As a result, both wage incomes and households'demand are sustained, and the lower increase in production costs limits the negative consequences on the real trade balance. The decrease in exports and the increase in imports less contribute to a drop of effective demand and *GDP* (−0.4% instead of −0.6% for exports). On the other hand, recycled revenues reduce the relative cost of labour compared to energy. As a result, the labour intensity of production also progress more (+0.3%) and total employment is preserved (+0.4%).

To comment the second remark, we compare results for different sectoral calibration of an identical carbon tax reform. As noted before, for the given tax, disaggregating sectors has only second order effects on macroeconomic magnitudes. The sectoral disaggregation leads to slightly different impacts for each reform cases. In the two cases, the most aggregated model (*AGG_3Sec*) gives the highest *GDP* variation in absolute terms and the lowest reduction of CO_2 emissions. We observed that for the non-recycled revenues simulations, results across models are close, especially for the two extreme cases of sectoral description (the most aggregated and disaggregated model).
However, for the revenues recycled in labour tax reduction, the initial sectoral description has more substantial effects on results, and changes the sign of the *GDP* growth: +0.2% for the most aggregated model (*AGG_3Sec*) and −0.02% for the most disaggregated model (*AGG_IndEner*). In these simulations, even though carbon tax revenues are used to contain an increase in production prices through labour tax reduction, the indexation of wage curve on domestic price does not make it possible to avoid these increases.
In the *AGG_3Sec* model, the mean CO_2 emission intensities leads to higher production price increase for aggregated energy goods compared to the *AGG_IndEner* model, and greater revenues from carbon tax. Thus, we note lower labour tax rates and lower increases in production prices compared to disaggregated models. As a consequence, in the three-sector model, the international trade is less depressed and households consumptions are preserved enough to sustain *GDP* growth.
In the *AGG_IndEner* model, we argue that the EITE sectors suffer the tax and generate revenues but they do not benefit from redistribution. Thus, the recycling option exacerbates discrepancies between sectors. We will discuss this issue with more detail latter.

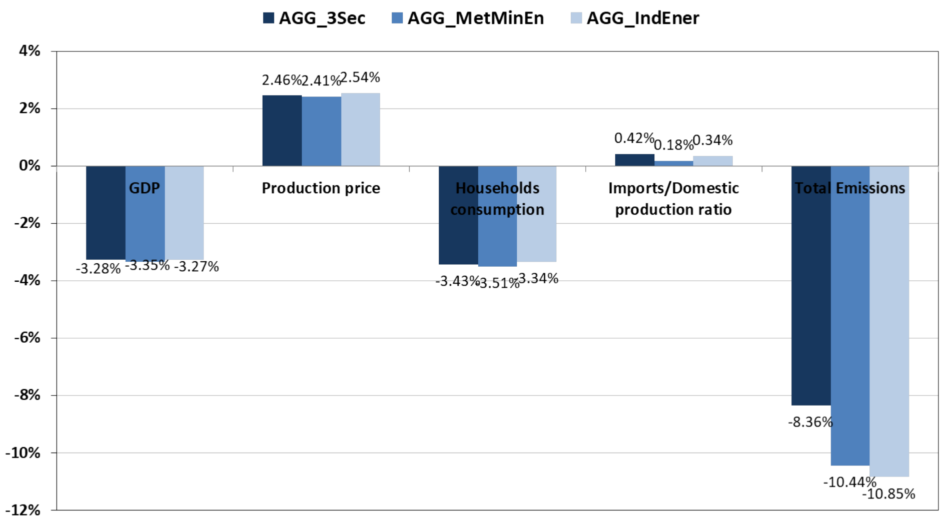
In the following, we will see that whatever the recycling options for the carbon tax, aggregates results hide an important heterogeneity among production sectors.

Distribution of impacts among sectors
The burden of a carbon policy is not the same for all sectors. Beyond the macroeconomic effects, describing heterogeneous sectors in the modelling framework gives insights to understand which ones of them suffer the reform, and where problems of competitiveness and unemployment exist. For the two carbon tax recycling options, we compare sectoral results from the two more detailed models (*AGG_MetMinEn* and *AGG_IndEner*) which only differ by the description given to two energy-intensive sectors: the metallic sector and the non-metallic mineral sector.
Table 4.19 and Table 4.20 represent main results of the four simulations : either on disaggregated or aggregated input-output table, with a carbon tax implementation which revenues are recycled or not.

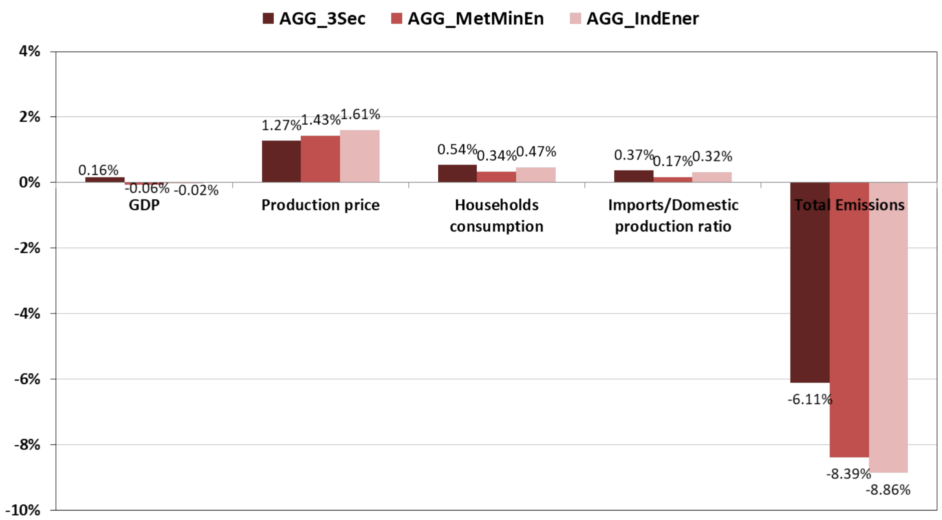
Firstly, we look at policy simulations whatever the initial description for calibration: so we rely, for now, on results of the most disaggregated model (*AGG_IndEner*). In line with macroeconomic results, it appears that recycling tax revenues into a reduction of labour tax rate preserve all industries. Globally, production prices of all firms increase less and production, as well as exports, fall less compared to a policy without recycled revenues. Taking the example of the *other industries* sector, we note that its production price increase by +3.0% for the recycled-revenues simulation against +3.9%, without return carbon tax revenues to firm. Thus, its production faced less decrease from −4.5% without returning revenues to −1.7% by recycling carbon tax revenues. As production price increases more without recycled revenues, exports fall down more, from −2.8% compared to −2.2% for the recycled-revenues simulation.

Secondly, we focus now on the sectoral description of each model, whatever the carbon tax reform. Straightforwardly, we observe that the distribution of the tax effects is different across sectors. Some sectors are much more impacted by an implementation of a carbon tax than others: production prices increase more and often lead to a greater decline in production.
For both simulation cases, we note that sectors, with same granularity description at calibrating the two models, are comparably impacted by a carbon tax. As example, for the non-recycled revenues simulation, the electricity production price increases by +16.6% in the most detailed model (*AGG_IndEner*), and by +16.5% in the model which represents metallic sector and non-metallic mineral sector as their whole (*AGG_MetMinEn*). Thus, production decreases by −4.6% for both models, and imports increases by +3%.
Notwithstanding, disaggregation reveals high level of heterogeneity within sectors, like for metallurgy and non-metallic mineral sectors. Steel and cement sectors are much more impacted by a carbon tax policy implementation than the rest of their corresponding aggregate sectors. As steel and cement sectors are much more energy intensive, their production prices increase a lot compared to the rest of their rest of metals and minerals sectors. Indeed, in the recycled-revenues case, production prices of steel and cement sectors rise up to respectively +21.8% and +17.2%, while the rest of those sectors only faces respectively +2.3% and +4.7% of increase.

This is very understandable especially for steel, as its energy cost share in production growth up significantly to +11.3%*points* while for the rest of the metallic sector, energy cost share only increases by +0.5%*points*. This is less pronounced for the non-metallic mineral sectors, although cement energy cost share increases by 5.8%*points* while the energy cost share of the other mineral sector increases by 2.0%*points*. Behaviours are also very different in analysing trade intensity and the import penetration rate, and it even goes in opposite directions. Keeping those sectors aggregated introduces a consequent bias. As example, trade intensity decreases for steel industry (−1.4%) while trade intensity of the rest of the metallurgy increases (+0.5%) for the recycled-revenues policy simulation. This decrease of trade intensity for steel sector can be explained. Production in value increases (production price increases more than production in quantities decreases), as well as imports plus exports in value increases. However, production in value increases more than the terms of trade. As consequence, trade intensity rate falls down. If we keep metal sector as a whole, trade intensity goes down (−1.2%). Cement trade intensity decreases (−3.7%) much more than the rest of the minerals sectors (−0.9%). By considering the mineral sector as one entire sector in the simulation, we hide this difference (−1.12%). The negative growth rate import penetration rate for steel (−2.3%), and cement (−0.6%) is due to a higher increase for domestic demand in value compared to the imports increase in value. Once more, keeping aggregate those sectors hides very different effects across their "sub-sectors" and reveals significant aggregation bias.



(a) Carbon tax impacts without recycling revenues for different sectoral aggregation levels at calibration



(b) Carbon tax impacts with revenue recycled into labour tax reduction for different sectoral aggregation levels at calibration

Figure 4.6 – Cross sensitivity analysis between granularity and recycling options of the carbon tax impacts at 100 €/tCO_2

Comparaison after carbon tax implementation without recycling

100€/tCO2	Production Price		Prodution (volume)		Import (volume)		Export (volume)		Energy cost share in production		Trade Intensity		Import Penetration rate	
Unit	*variaton (%)*		*variaton (%)*		*variaton (%)*		*variaton (%)*		*points %*		*variaton (%)*		*variaton (%)*	
Aggregation profil	***IndEner***	***MetMinEn***	***IndEner***	***MetMinEn***	***IndEner***	***MetMinEn***	***IndEner***	***MetMinEn***	***IndEner***	***MetMinEn***	***IndEner***	***MetMinEn***	***IndEner***	***MetMinEn***
Crude oil	3.05	2.92	-6.97	-7.02	-6.97	-7.02	0.00	0.00	0.71	0.71	-2.95	-2.83	-0.04	-0.04
Gas	1.91	1.77	-8.18	-8.14	-8.18	-8.14	0.00	0.00	0.01	0.01	-1.39	-1.27	-0.58	-0.52
Coal	179.33	179.31	-23.82	-21.44	-23.82	-21.44	0.00	0.00	10.27	10.27	-63.24	-63.30	-37.57	-37.61
Fuel Products	6.72	6.70	-6.90	-6.95	-3.83	-3.88	0.00	0.00	0.50	0.51	0.59	0.62	-0.03	0.00
Electricty	16.58	16.45	-4.62	-4.58	2.98	2.97	0.00	0.00	8.00	8.02	0.61	0.60	-6.83	-6.79
Heat Geo Sol Th	44.50	44.41	-9.46	-9.55	-45.58	-45.65	Nan	Nan	6.70	6.72	Nan	Nan	Nan	Nan
Steel & Iron	22.41	-	-17.26	-	1.28	-	-12.02	-	11.24	-	-0.67	-	-1.13	-
Other metals	3.09	-	-5.95	-	-3.04	-	-1.89	-	0.53	-	1.21	-	0.96	-
Metals Aggregated results*	***10.90***	***11.65***	***-10.94***	***-9.82***	***-1.02***	***0.69***	***-8.26***	***-6.37***	***71.3***	***5.86***	***0.70***	***-0.32***	***0.73***	***-0.35***
Cement	17.81	-	-10.20	-	5.79	-	-13.83	-	5.7	-	-2.59	-	-0.40	-
Other Minerals	5.53	-	-5.45	-	-0.22	-	-3.95	-	2.0	-	0.09	-	0.05	-
Non metallic minerals Aggregated results*	***7.47***	***6.91***	***-6.26***	***-6.13***	***0.06***	***0.35***	***-4.55***	***-5.02***	***38.2***	***2.86***	***-0.71***	***-0.15***	***-0.65***	***-0.07***
Other Industries	3.85	3.73	-4.53	-4.58	-0.85	-1.02	-2.75	-2.67	1.16	1.16	0.47	0.56	0.38	0.46
Agriculture	3.83	3.71	-4.79	-4.86	-1.14	-1.33	-3.24	-3.14	1.14	1.15	0.68	0.79	0.24	0.28
Composite	2.12	1.99	-3.08	-3.17	-1.02	-1.25	-1.90	-1.77	0.23	0.23	0.47	0.57	0.07	0.09

**aggregated results have been calculated using fisher price index and fisher quantity index for detailed model*

Table 4.19 – Cross sectoral comparaison of key indicators with a non-recycled carbon tax

Comparaison after carbon tax implementation recycled into labour tax

100€/tCO2	**Production Price**		**Prodution**		**Import**		**Export**		**Energy cost share in production**		**Trade Intensity**		**Import Penetration rate**	
Unit	*variaton (%)*		*variaton (%)*		*variaton (%)*		*variaton (%)*		*points %*		*variaton (%)*		*variaton (%)*	
Aggregation profil	***IndEner***	***MetMinEn***	***IndEner***	***MetMinEn***	***IndEner***	***MetMinEn***	***IndEner***	***MetMinEn***	***IndEner***	***MetMinEn***	***IndEner***	***MetMinEn***	***IndEner***	***MetMinEn***
Crude oil	2.19	2.02	-5.50	-5.53	-5.50	-5.53	0.00	0.00	0.72	0.73	-2.14	-1.97	-0.03	-0.03
Gas	1.00	0.82	-6.13	-6.04	-6.13	-6.04	0.00	0.00	0.01	0.01	-0.64	-0.47	-0.25	-0.17
Coal	179.02	178.98	-22.21	-19.57	-22.21	-19.57	0.00	0.00	10.31	10.31	-63.24	-63.29	-37.56	-37.60
Fuel Products	6.58	6.55	-5.41	-5.43	-2.34	-2.38	0.00	0.00	0.57	0.59	-0.12	-0.10	-0.59	-0.57
Electricty	15.73	15.56	-2.42	-2.34	4.98	4.98	0.00	0.00	8.10	8.12	-0.88	-0.91	-6.67	-6.61
Heat Geo Sol Th	43.92	43.80	-6.55	-6.60	-43.95	-44.00	Nan	Nan	6.79	6.80	Nan	Nan	Nan	Nan
Steel & Iron	21.77	-	-15.70	-	2.65	-	-11.74	-	11.33	-	-1.37	-	-2.29	-
Other metals	2.29	-	-3.40	-	-1.19	-	-1.41	-	0.53	-	0.47	-	0.37	-
Metals Aggregated results*	***10.14***	***10.89***	***-8.83***	***-7.52***	***0.61***	***2.56***	***-7.91***	***-5.99***	***71.5***	***5.92***	***-0.09***	***-1.16***	***-0.13***	***-0.35***
Cement	17.17	-	-7.33	-	8.58	-	-13.40	-	5.8	-	-3.74	-	-0.58	-
Other Minerals	4.70	-	-2.46	-	2.13	-	-3.38	-	2.0	-	-0.86	-	-0.44	-
Non metallic minerals Aggregated results*	***6.67***	***6.07***	***-3.28***	***-3.11***	***2.43***	***2.77***	***-4.00***	***-4.44***	***38.2***	***2.90***	***-1.70***	***-1.12***	***-1.11***	***-0.51***
Other Industries	3.04	2.88	-1.73	-1.74	1.26	1.10	-2.19	-2.07	1.19	1.19	-0.68	-0.59	-0.54	-0.47
Agriculture	3.01	2.84	-1.78	-1.80	1.17	0.99	-2.56	-2.42	1.17	1.18	-0.68	-0.57	-0.24	-0.21
Composite	1.16	0.98	0.25	0.21	1.42	1.19	-1.06	-0.89	0.23	0.23	-0.63	-0.53	-0.10	-0.08

**aggregated results have been calculated using fisher price index and fisher quantity index for detailed model*

Table 4.20 – Cross sectoral comparaison of key indicators with a recycled carbon tax in labour tax reduction

4.2.3.2 Trade elasticities sensitivity

We have shown that recycling options of carbon tax revenues involve the same mechanisms for different level of sectoral description at model calibration, although magnitude of results is not the same between models. In this last part, we compare the sensitivity of trade elasticities to results according to the sectoral description at calibration in order to validate equivalent behaviours. We aim to ensure that the interactions lead to the same macroeconomic results.

For this exercise, we focus on two models; the most aggregated (*AGG_3Sec*) and the most disaggregated (*AGG_IndEner*). In this section, wage curve is modelled by indexing wages on consumer prices. As we have already explained, this representation is taking more sense in a closed-economy. Thus, we run two tests, one for each model, by halving trade elasticities, of both imports and exports. Carbon tax is at the same rate of 100€ per tCO_2 and revenues are recycled into labour tax reduction.
Changed parameters for these simulations are given in Table 4.21 for the aggregate model (*AGG_3Sec*), and, in Table 4.22 for the disaggregated model (*AGG_IndEner*).

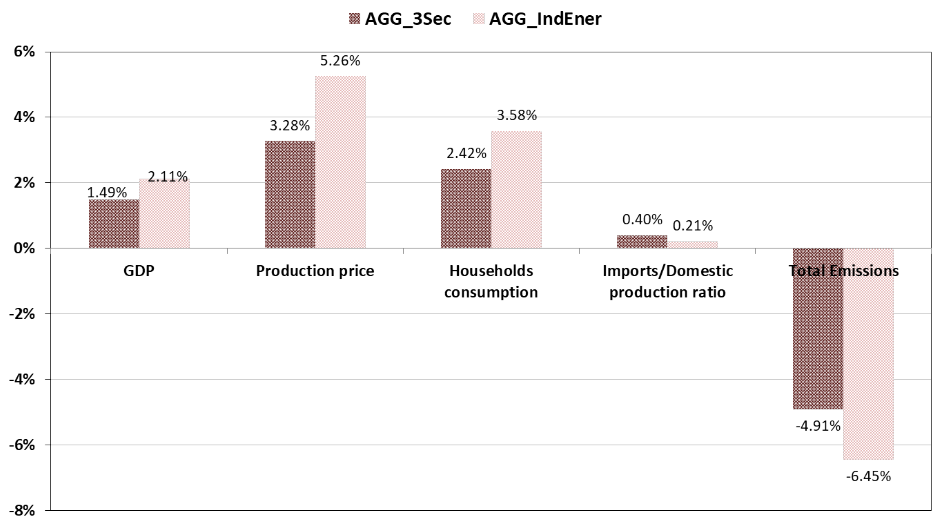
Parameters- AGG_3Sec	$\sigma_{M_{p_i}}$	$\sigma_{X_{p_i}}$
PrimEnergy	0	0
FinEnergy	0.5	0
AllComp	0.5	0.5

Table 4.21 – Changing parameters of disaggregated model for trade elasticities sensitivity analysis

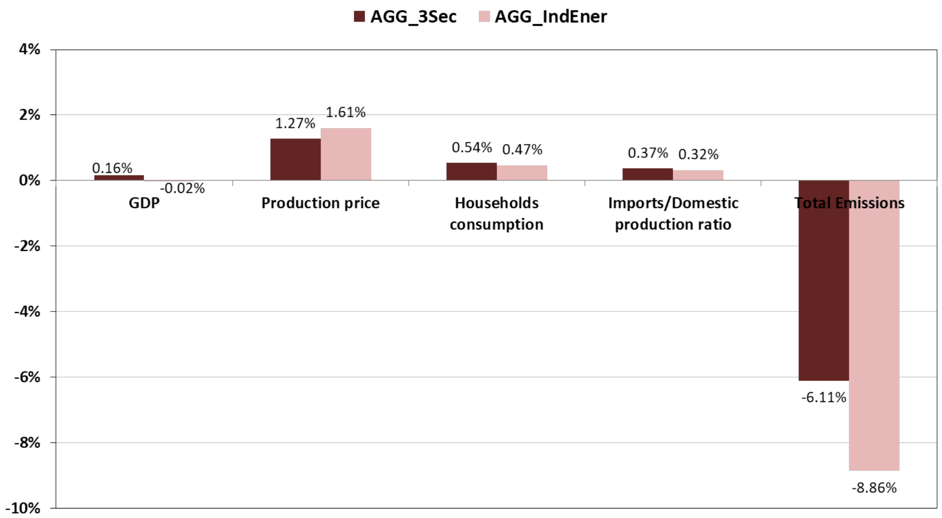
Parameters- AGG_IndEner	$\sigma_{M_{p_i}}$	$\sigma_{X_{p_i}}$
Crude_oil	0	0
Natural_gas	0	0
Coal	0	0
FuelProd	0.5	0
Electricty	0.5	0
HeatGeoSol_Th	0.5	0
Steel_Iron	0.5	0.5
NonFerrousMetals	0.5	0.5
Cement	0.5	0.5
OthMin	0.5	0.5
OthIndus	0.5	0.5
Agriculture	0.5	0.5
Composite	0.5	0.5

Table 4.22 – Changing parameters of disaggregated model for trade elasticities sensitivity analysis

In Figure 4.7a, we compare the outcomes with low trade elasticities (Figure 4.7b) with the outcomes of the earlier simulation (Figure 4.7b) of recycled-revenues. Full macroeconomic results are given in Table D.18



(a) Low trade elasticities



(b) Reference trade elasticities

Figure 4.7 – Cross sensitivity analysis between granularity and degree of exposure for the carbon tax impacts at 100 €/tCO_2

Two main remarks emerge from results. First, the aggregation level of the model does not change the positive effect of a carbon tax for a closed economy, where wages are set by national prices. Secondly, depending on the parameter value, the model that transmits higher consequences from the carbon tax more is not always the same.

As observed in early analysis at section 4.1.2.4, we note a positive effect of the carbon tax for a wage indexation on the consumer price, coupled with a closed economy (through low trade

elasticities), whatever the calibration. The mechanisms appear to be similar and independent from the sectoral description.
We illustrate them by relying on the disaggregated model results (*AGG_IndEner*). The production price increase (+5.5%) does not sufficiently affect the commercial balance to counterweight positive effect of a higher consumption from households (+3.5%). Such an increase in consumption encourages domestic production and employment (+2.4%), and thus, leads to higher wages (+8.8%). Finally, *GDP* growth is stimulated (+2.11%), and import to domestic ratio less increases than in a situation of an open economy (+0.2% against +0.3%).
Such an incidence loop is identical with the model calibrated on an aggregated three-sector economy (*AGG_3Sec*), as same mechanisms are observed by closing the economy through lower trade elasticities.

However, the amplitudes are not the same: the impacts of the carbon tax are higher (in absolute term) in the aggregated model with "reference" trade elasticities, while in a closed economy, the magnitude of impact is lower in the aggregated model compared to the disaggregated model.
The reason lies in multiplier effects caused by an extended IOT (Su et al., 2010; Kymn, 1990). In this thesis, we do not go into the analytic demonstration of this result. We consider that higher sectoral details do not change the order of the effects for a same simulation.

The discussion around disaggregating IOTs could be argued to be purely informative if in practice the different sectoral level of calibration had led to consistent aggregated results. However, as practical results demonstrate, it is not the case, and the gaps may vary from simulation characteristics. We still observe same macroeconomic mechanisms for a given policy which allows us to validate our disaggregated IMACLIM-S FRANCE model with an initial description of thirteen sectors.
In addition, disaggregation highlights sectoral heterogeneities hidden in the initial description, and thus in simulations. Thus, thanks to the previous data work through the hybridisation procedure (see Chapter 1), we embark specific representations for energy-intensive sectors. It gives significant opportunity to provide insights on interaction between environment, political, competitiveness issues. Indeed, a unilateral carbon policy weighs on energy-intensive sectors at first. Competitiveness issues would then come up only if concerning energy-intensive sectors had also a high trade exposure. But in fact, energy-intensive sectors are not always the one whose international trade is significant (important transport costs). The disaggregation is a mean to differentiate, into the modelling, sectors which are really exposed to competitiveness from those which are protected and cannot be outsourced.

4.3 Conclusion

In this chapter, we have shown that the Imaclim-S France model calibrated at 2010 reproduces well the mechanisms observed both by previous version of Imaclim-S and literature when implementing a unilateral carbon tax at aggregated scale. Macroeconomic outcomes of a carbon tax are very sensitive to policy design, in this case the recycling revenues strategy. On the one hand, tax revenues recycled into lower taxes on labour provokes a virtuous circle with growth, increased employment and an environmental benefit. On the other hand, when these returns have not returned to firms, the whole economy is depressed. Moreover, we observed that these classical results are sensitive to the initial parameters (wage curve, and international trade). Some parameters are crucial in obtaining –or not- the double dividend, but models are often elusive on the values given to some of them. This chapter have only shown the sensitivity to the parameters, without assessing or discussing the "real" values that would make sense.

Outcomes are few sensitive to the level of sectorial description on which the model is calibrated. This result is consistent with previous studies focused on BTA, as Caron (2012). Still, taking into account of certain sectors in the modelling is also a real stake that we have achieved thanks to the work of hybridisation. Indeed, the distribution of outcomes among sectors are important, especially within the production of metals and minerals. Thus, aggregation hides important disparities and losses for segments of those sectors, which are both highly energy-intensive and exposed to international trade. Nevertheless, this level of granularity is not captured in most macroeconomic and multi-sectoral models. Lowering the labour tax with the carbon tax revenue preserve most of economic activities, and leads to better macroeconomic outcomes. However, it is not enough to avoid important profitability losses for major industrial stakeholders. Some accompanying measures are expected to preserve these industries and to reconcile competitiveness issues with macroeconomic efficiency. Generally, this chapter have also shown that a larger sectoral detail at calibration does not change the mechanisms of the model even if it changes the amplitude of the results. The gap is depends on the policy design, and, is difficult to anticipate due to the spread of price increases and the feedback mechanisms in the Leontief matrix.

Some limits of analysis conducted in this chapter deserve to be highlighted explicitly. The simulations do not rely on actual values for some crucial parameters, in particular: (i) the substitution possibilities away from fossil energies, (ii) the wage-setting behaviours, (iii) the sensitivity of international trade to production costs and prices (exports and imports). A deeper literature review should be provided for assessing value to these parameters that may influence cost rankings of the alternative policy options. To be relevant to decision-making support to stakeholders, it is necessary to be accurate on those parameters and reveal values that reflect the economy as a whole, as well as sectoral heterogeneities. Obviously, we also expect that the interplays between these parameters as well as a heterogenous representation among sectors would influence the mechanisms observed in previous excercices. This issue will be addressed in subsequent studies in Chapter 5.

Finally, other trade-offs are to be considered to rightly evaluate the costs and benefits of these alternative options. In particular, other important national objectives have been neglected: the distribution issues among individuals and equity concerns, the public finance objectives. The scope of the trade-offs to be considered in the use of the carbon tax revenue is larger. Some portion of the proceeds can be allocated to vulnerable households, and the fiscal envelop available for compensations depend on the budgetary rules followed by the government. All these considerations influence the cost rankings of policy options (Goulder, 2013).

Chapter 5

Disentangling the interplay between trade elasticities and the wage curve

In Chapter 4, we have stressed the main mechanisms in Imaclim-S France triggered by the introduction a carbon tax and the sensitivity of results to parameters variations. We highlight that wages curve and degree of trade exposure overall interactions lead to contrasted results according to the original parametrisation. A high level of indexation between wages and consumers prices brings positive outcomes for an economy with low international trade, and, negative outcomes for an economy with high international trade. This is indeed a linked issue: wages adjustments much depend on the degree of openness of the economy at study, and also on both its internal and external demand.

So far, we have conducted sensitivity tests, but the discussion around the original value given to wage curve indexation parameter and the trade elasticities has been dropped. Thus, Chapter 5 raises the question of what would be the right values for these parameters and which would be their interactions.
The assessment of the trade elasticities is controversial, and there is poor information at sectoral level. Notwithstanding, our intuition is that some advances can be achieved for climate policy analysis thanks to the gain in sectoral granularity allowed by the hybridisation effort. Indeed, if the implementation of sectoral behaviours has been neglected, we assume they are crucial to understand the dynamic of industrial structural changes through the interaction between the degree of exposure and the formation of wages for the various sectors segments of the value chain.

Over the recent years, the literature insisted on the link between the production fragmentation reflected by the global value chain and the dynamic of wages formation in industrialised countries.

The basic statement is that for some segments of the production, the low skill workers from developing countries have a competitive advantage compared to low skill worker from developed countries. This advantage introduces competition on wages which tend to reduce the bargaining power of workers on their wages in industrial area. There is then a shift for qualified jobs demand with higher wages which it a source of increasing inequalities in advanced economies (Timmer et al., 2014).
Frocrain and Giraud (2016) make a step further by emphasising the existence of two jobs categories. A first category corresponds to *sedentary jobs* which cannot be reallocated elsewhere because they will always be required locally (archetypal e.g.: hairdresser). A second category corresponds to *nomad jobs* which are exposed to international markets because they can be outsourced in foreign country. Workers from *sedentary jobs* have better means to bargain higher wages while wages of workers from *nomad jobs* depend on the international wage competition. Finally, the increase of domestic final demand might not result to higher employment within the country.

In this thesis, we do not go into this potential important distinction (degree of the exposure of activities vs. degree of the exposure of jobs). We assume a univocal definition between both of these two dichotomies. This hypothesis could be relaxed in further works but it will however suffice for helping to show out the conditions under which a low carbon transition, by relying on targeted activities, can drive structural changes on the French economy apt to make it less depend upon the wage competition.

The primary aim of this chapter is to provide better control, under a climate policy constraint, of the articulation between trade elasticities and the wage curve by differentiating sectors depending upon the degree of inward and outward orientation. We underline again that the data hybridisation work, through the disaggregation of the mineral and metallic sectors, is an essential perquisite to properly achieve this objective.
Section 5.1 discusses the complexity of trade elasticities assessment, and, describes the methodology used to assess the elasticities of imports and the elasticities of exports with differentiation among sectors. It analyses the incidences of this heterogeneous information on carbon policy evaluation. Section 5.2 proposes a documented approach for parameterising the wage curve with a different sectoral indexation of salaries according to their mobility and exposure to international trade. We explore to what extend this heterogeneous representation of wage interacts with sectoral trade elasticities to influence the carbon tax impacts. Section 5.3 summarises the major lessons of the chapter.

5.1 The trade elasticities "puzzle"

Feeding a hybrid computable general equilibrium (CGE) model like Imaclim , with reasonable assumptions on trade elasticities, confront the modellers to what Fontagné et al. (2017) call *the international elasticity puzzle*. They understand that empirical estimates of trade elasticities did not gather any consensus. This is due to the fact that trade elasticities are constantly evolving and they are sensitive to the global context.
Indeed, the trade elasticities are very country specific. This is well understandable. An energy shock, for example, generates very different structural changes in various countries (Waisman et al., 2012). In the same type of example, the creation of euro with no harmonisation of fiscal policy and welfare policy logically generates a trend to polarise the industries in some regions (Aglietta and Brand, 2013; Krugman, 2001). In addition, over the three past decades a repetition of external shocks occurred (e.g: three oils shocks, creation of euro, financial crisis, etc.) making difficult to assume a constant context for calculating elasticities reasonably robust.

The difficulty is even worth for elasticities given at the sectoral level. Nevertheless, the major obstacle might be embarking trade elasticities necessarily calculated in a partial equilibrium basis into a CGE framework which. This problem had been tackled by Sonnenschein, Mantel and Debreu whose works has remained into the denomination of the Sonnenschein-Mantel-Debreu theorem[1]. This issue will be confirmed below in this section. The attempt is rather to clarify how to make the best use of existing information even though it could be qualified as weak and controversial.

To do so, we first conduct numerical experiment (Sub-section 5.1.1) on the basis of the apparent trade elasticities from the literature without any discussion on their values, and we discuss the paradoxical outcomes. In a second step (Sub-section 5.1.2), we discuss more in depth how to interpret the apparent trade elasticities, and how to incorporate them in a consistent manner in the dual accounting system of the Imaclim-S France model.

5.1.1 Numerical experiments based on literature review trade elasticities

At first, we try to gather French specific information from econometric studies in order to calibrate the Imaclim-S France model. Indeed, the structural differences lead to unequal sensitivities of exchange-rate variation between countries (Hervé, 2001).

The paper of Ducoudré and Heyer (2014) proposes a complete literature review of trade elasticities assessment models for France. We note that the material gathered from econometric studies is unbalanced between the export elasticities and the imports elasticities. Taken from

[1]See (Rizvi, 2006) for a synthesis.

the paper, Figure 5.1 illustrates the large range of values given to price elasticities of exports in French macro-econometric models. The discrepancy in results already implies that sensitivity tests are really necessary. The review gives us an important first material on exports elasticities, but it raises a twofold problem.
First, although an average value of export price-elasticity around 0.6, the range of values is large from almost zero to 1.1. Looking only at the most recent studies does not reduce this gap to a same category of elasticities (values assessed at 0.6 and 1.1). Thus, it seems unwise to simply rely on an average value. Second, the review does not provide sectoral differentiation, which is one of the sector specific impacts of the social reform in France, and their aggregate consequences.
Same problems stand for the elasticities of imports.

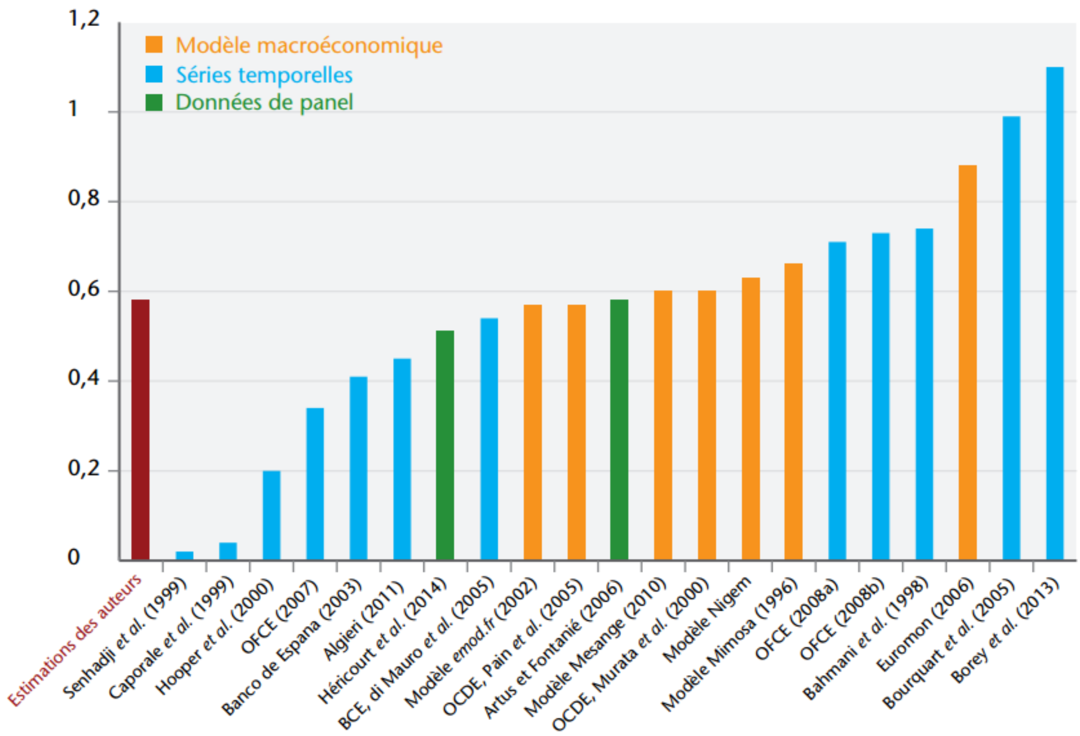


Figure 5.1 – A litterature review from Ducoudré and Heyer (2014) for price elasticities of exports for France

Indeed, the aim is to capture sectoral specificities. But gathering recent sectoral studies on trade elasticities evaluation appears to be even more complicated, even leaving aside the requirement for studies at the level of France. Erkel-Rousse and Mirza (2002) and Fouquin et al. (2001) works are the only ones available with sectoral description we found. The authors propose sectoral information for both exports elasticities and imports elasticities.
Facing the lack of more recent studies, we have relied on these works to calibrate the Imaclim-S France -"*AGG_IndEner*"- model at the level of thirteen sectors[2].

[2]Defined in Chapter 4: Crude oil, Gas, Coal, Fuel Products, Electricty, Heat/Solar thermic, Steel & Iron, Non

This choice makes sense only if the here-below exercise is view as a first step of a scientific learning process in which sensitivity test around the first values retained are conducted. So, this set of values is used for pinpointing where the lack of better information matters. It is also used under a protocol that allows for progressively incorporating any new information, including from sectoral studies, into the modelling framework.

5.1.1.1 Settings of Imaclim-S France on apparent elasticities

We develop a numerical protocol to derive a consistent set of elasticities assumptions that represent the existing knowledge both on sectoral elasticities and the global value of elasticities. The same logic will be followed at each step further of the analysis by retaining the most aggregated value as the most robust one for lack of anything better.

We set up our most disaggregated version of the hybrid Input-Ouput table (IOT)[3] with 29 sectors to then adapt elasticities according to the sectoral aggregation profile for modelling. As just mentioned, setting the trade elasticities relying from Erkel-Rousse and Mirza (2002) and Fouquin et al. (2001) works[4] is not straightforward. Indeed, there are differences between their sectoral granularities and the one of Imaclim-S .
If the two sectoral nomenclatures match: in that case, we keep the value from the literature. If not, we distinguish two cases.

- **First case:** no information is available even at a more aggregated level. Tnen, we assume a value for elasticities that can easily be changed through dialogues with sectoral experts leading to possibly better assumption.
- **Second case:** we do have information for more aggregated sectors than those described in Imaclim (e.g. we have information on metallurgic sectors but we need details on the steel and iron branch and the non-ferrous metal sector).
  In that case, we select sub-sectoral values because we think that is possible to have control on them including through reasonable sensitivity analyses. Then, the ultimate calibration constraint is that the remaining sub-sector has an elasticity which allows for recovering the apparent elasticity of the re-aggregated sector.

We have assessed the imports and exports elasticities at the most disaggregated level of our hybrid IOT (see Table E.1 in Appendix E) by ensuring that the overall elasticities of France are consistent with those given in Ducoudré and Heyer (2014).

Ferrous Metals, Cement, Other Minerals, Other Industries, Agriculture, Composite.
[3]See Table A.4 in Appendix A.
[4]Hereafter referred to as the literature.

Subsequently, from this disaggregated representation, we deduce aggregated elasticities for calibrate the IMACLIM-S FRANCE aggregated at the level of thirteen sectors (*AGG_IndEner*) used in the rest of this chapter[5].

Resulting trade elasticities values are given in Table 5.1. We keep these values for all the exercises conducted in this sub-section.

Trade elasticities	$\sigma_{M_{p_i}}$	$\sigma_{X_{p_i}}$
Crude oil	0.00	0.00
Natural gas	0.00	0.00
Coal	0.00	0.00
Fuel Products	2.00	2.00
Electricty	0.10	0.10
HeatGeoSol Th	0.00	0.00
Steel Iron	0.10	0.10
Non Ferrous Metals	0.95	0.75
Cement	0.10	0.10
Other Minerals	0.89	0.81
Other Industries	0.75	0.35
Agriculture	1.01	0.24
Composite	0.77	0.16
Global level	0.74	0.58

Table 5.1 – Sectoral details on trade elasticities

For a lack of any better option, we also select the overall elasticities from the French literature as a binding to sectoral information. Obviously the consistency is not straightforward, and so this is an important problem for converting the elasticities. This issues will be deeply discussed after.

5.1.1.2 Experiments results using literature elasticity values

We simulate comparative statics experiments by implementing a carbon tax at 500€ per tonne of CO_2, and using the elasticities of Table 5.1 for setting the model. We simulate a classical recycling option by using a share of carbon tax revenues to decrease existing labour tax. Because the discuss on the public budget policy is out of the scope in this thesis, even if it matters for the analysis of climate policy impact (Combet, 2013), we simply maintain a constraint on public debt: government net lending is constant to *GDP* growth. We assume constant government consumption in proportion to *GDP* (simulation noted as "1.*CGC*"). Under these conditions, we test three variants for the economic system description.

We compute a set of analyses by starting from a wage curve indexed on international prices

[5]The IOTs and comments on which we calibrate IMACLIM-S FRANCE are available in Chapter 4: Table 4.13 for monetary IOT, Table 4.14 for quantity IOTs, and Table 4.16 for prices.

(noted as "*INT*"), to a wage curve indexed on consumer prices (noted as "*CPI*") for non-energetic sectors (see Table 5.2 for the changes in parameters). We also compute an intermediate case in which only half of the wages are indexed on consumer prices.
We refer to Appendix E at Table E.2 for all other reference parameters.

	Variants of wage curve indexation		
$\beta_{w_{CPI}}$	**'SIMU'_INT**	**'SIMU'_HALF**	**'SIMU'_CPI**
Crude oil	0	0	0
Natural gas	0	0	0
Coal	0	0	0
Fuel Products	0	0	0
Electricty	0	0	0
HeatGeoSol Th	0	0	0
Steel Iron	0	0.5	1
Non Ferrous Metals	0	0.5	1
Cement	0	0.5	1
Other Minerals	0	0.5	1
Other Industries	0	0.5	1
Agriculture	0	0.5	1
Composite	0	0.5	1

Table 5.2 – Parameters for simulation variants on wage curve indexation

In Chapter 4 at Section 4.1.2.2, we observe that a wage curve indexed on consumer prices depresses the economy compared to wage curve indexed on the international prices. We portray the basic mechanism occurring in the case of wages indexed on consumer price by representing main interactions in Figure 5.2.

In the below simulations, the aim is to analyse the effect of the elasticities on the overall interactions for each variants. Figure 5.3 shows the impact of the carbon tax on key macro indicators for the different variants on wage curve modelling[6].

The straightforward conclusion of these simulations is that we do not found the vicious circle in the simulation case with wage bargaining based on consumer price (1.*CGC_CPI*).

By comparing the outcomes with the base case on compact model (cf. Chapter 4, Section 4.1.2.2), the results look surprising.
On the one hand, *GDP* grows for the variant with wage curve based on the consumer price (+6.16%), instead of a *GDP* loss in the base case. On the other hand, we note also a gain in *GDP* (+6.81%) with wage bargaining on international price together with an increase of production price (+8.65%). However, in the base case, it was the decrease of production price which explained the overall balance.

[6]We refer the reader to Appendix E for detailed full results. Table E.3 provides complete macro-economic results, and tables E.4 - E.5 and E.6 give sectoral distribution of the carbon tax impacts for each variant of wage curve indexation.

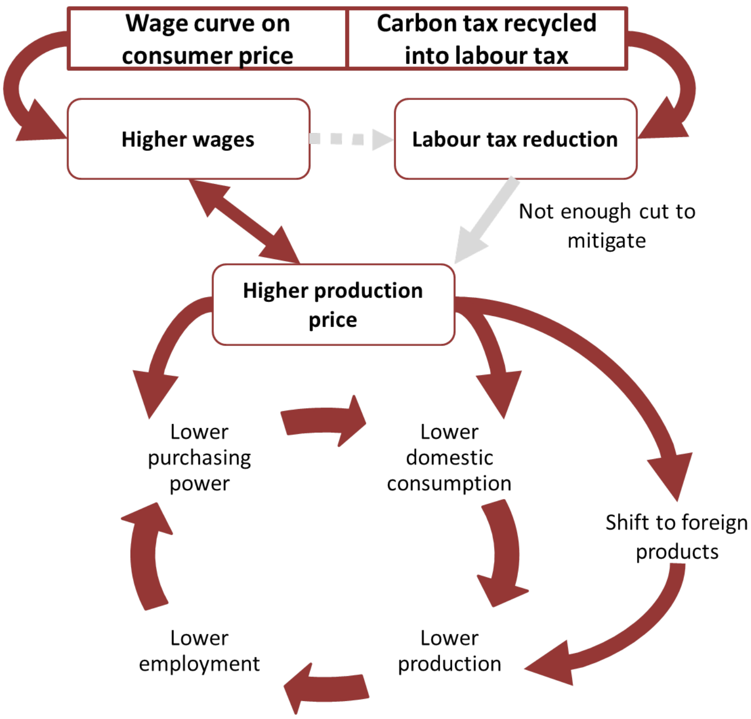


Figure 5.2 – A vicious circle by bargaining wages on domestic prices

For the simulation 1.*CGC_CPI* with wage curve based on the consumer price, the positive sign of *GDP* is at first striking.Actually, this apparent paradox is due the low values retained for the trade elasticities (which are discussed further). Thus it is totally conforms to the sensitivity test on trade elasticities (cf. Chapter 4, Section 4.1.2.5).

With the wage curve based on the consumer price, workers tend to maintain their purchasing power which is depressed by the increase of energy prices. The logical consequence is that the salaries increase more than if the wages bargaining is function to the international price (from +19.6% for 1.*CGC_INT* simulation to +43.7% for "1.*CGC_CPI*" simulation).
In no variants of wage curve modelling, labour tax cuts contain the increase of energy costs. Consequently, production prices increase substantially from +8.6% in the "1.*CGC_INT*" simulation and up to +28.4% in the "1.*CGC_CPI*" simulation. In some way, the fact that trade elasticities are low allows a gain for increasing *GDP* and employment, even for the simulation 1.*CGC_INT*.

Such an increase of production price should involve consequent competitiveness losses which could harm the entire economy. But, the penalty on trade balance is lower than the gain on domestic activities and households consumption grow significantly, from +8.2% for "1.*CGC_INT*" simulation to +13.5% for "1.*CGC_CPI*" simulation. Households have higher wages to consume both domestic and import goods to meet their demand.
This does not mean that there is no negative outcome at all. Indeed, there is a degradation of

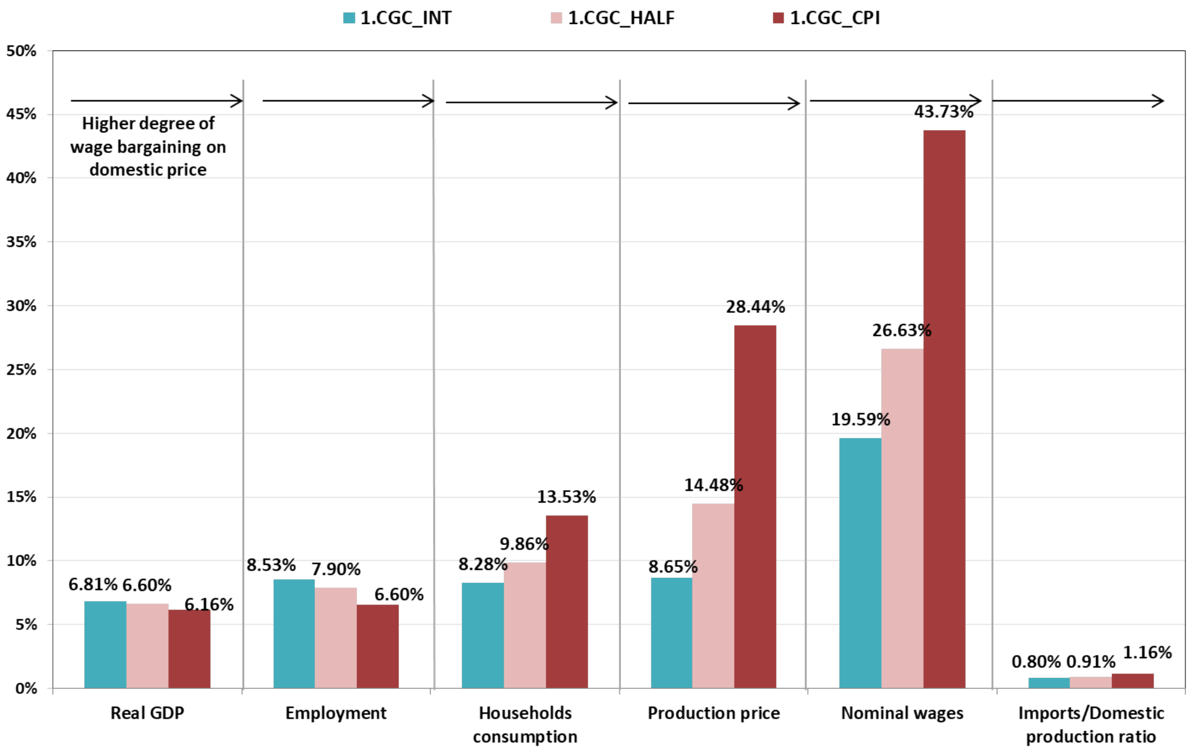


Figure 5.3 – Impact of a 500€/tCO_2 carbon tax on key indicators for different wage curve indexation with constant public consumption

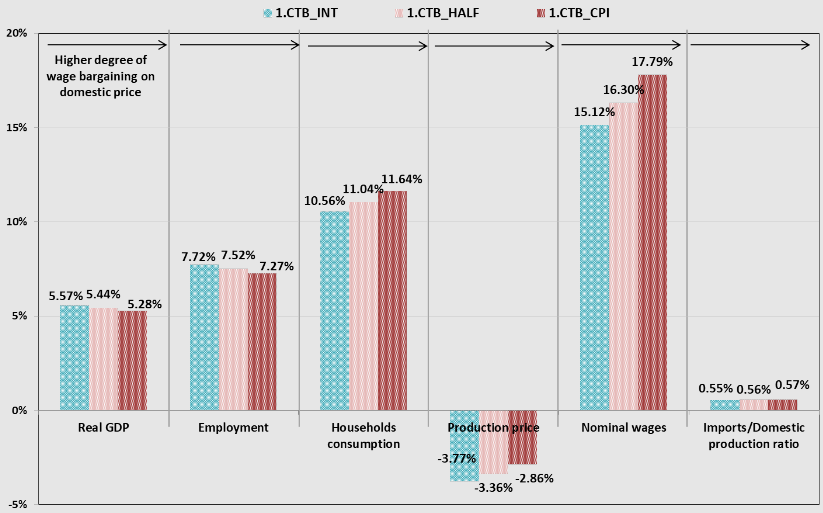
the trade balance. Its degradation is worst with wage curve indexed on domestic price. This is due to the higher production price increase. Imports increase substantially to satisfy this higher demand (from +10% for "1.*CGC_INT*" simulation to +24.6% for "1.*CGC_CPI*" simulation), and so does the public deficit (from +20.07% for "1.*CGC_INT*" simulation to +42.7% for "1.*CGC_CPI*" simulation), which is both unrealistic and unsustainable.
In the following box, we explore to what extent a constraint on trade balance changes the analysis for a same simulation plan.

By setting aside the debt problem and whatever the wage curve indexation, production price increases do not initiate a vicious circle, and instead, we obtain an unbreakable virtuous circle from carbon tax. Above results and the gap with previous exercises, beyond sectoral granularity, are obviously due to the low elasticities used to set the external trade in Imaclim-S France . We realise the ambiguity around their values which are very low, and indirectly protect the French economy from competitiveness issues and negative effects of a carbon tax. Thus, it raises the question of the realism of the trade elasticities taken from the literature and directly applied in Imaclim to volume flows. We clarify this question in next sub-section.

Introducing a trade balance constraint: example of a modelling illusion

We explore a constraint on trade balance in order to avoid a behaviour of "infinite" debt by means of high increase of imports as occurred in first set of stimulation, and so leading to a positive impact of the carbon tax[a].

The figure below shows the impact of the carbon tax on key macro indicators for the different variants on wage curve modelling.



Wages increase in each simulation variants from +15.1% for "INT" simulation to +17.8% by maintaining the purchasing power of workers ("*CPI*" simulation). However, production prices drop off in this set of simulations. Indeed, they decrease from −2.7% by indexing wages on consumer price to −3.8% for "INT" simulation, despite the consequent increase of wages. Lower production prices are the entry point to a virtuous circle and thus *GDP* grow in a range of +5.6% to +5.3% depending the indexation of the wages.

In fact, by looking closer to sectoral distribution effects[b], production prices mainly decrease for the *composite* sector while for other sectors they increase. Still, the *composite* sector represent a large part of export (70% at base year) and thus the overall economy benefit from this decrease.

Constant trade balance limits market transactions, and so consumption and supply. This is why, in this set of simulations, carbon tax revenues contain energy price increases by recycling carbon revenues into labour tax reduction. Through consumption limits, labour tax cuts are determined in order to obtain a level wages leading to production price decrease and initiating the virtuous circle for positive outcomes.

[a] We refer the reader to Appendix E for detailed full results. Table E.7 provides full macro-economic results, and tables E.8 - E.9 and E.10 give sectoral distribution of the carbon tax impacts for each variant of wage curve indexation.

[b] see Table E.8 to Table E.10 in Appendix E for results.

5.1.2 Numerical experiments based on a reinterpretation of the literature trade elasticities

Low trade elasticities of price, under carbon tax policy lead automatically to wage increase and *GDP* growth in IMACLIM . This could be explained by a simple example:

> Let's suppose that France exports 100 physical units in volume at the unitary price of 1, that is to say France has 100 € of revenues from exports. Let's say that a +10% price increase involve a −5% decrease of exports in volume. France would exports 95 physical units in volume at the unitary price of 1.1, generating so 104.5 € of revenues. In this case, the terms of trade improves but exports revenues increase for less production work in volume.

Since, such results is not realistic, we reconsider the low values gleaned from the literature for direct application to the representation in real volume of IMACLIM . We realise that the trade elasticities give any unanimity on the values that must be used according to the modelling framework used.
This is explained in Ruhl (2008) paper: on the opposite of some business model, static CGE models need high values of trade elasticities to *explain the growth in trade volumes that result from a change in tariffs*. He explain that the large range of Armington elasticity (below 1 and up to 15) is due to differences sources of price and quantity variations which focus on either transitory shocks or permanent changes.

In the rest of this chapter, we made the assumption that the ambiguity stands on the different notions of volume. Indeed, econometric exercises are based on volume that actually derived from chain index prices on the basis of sectoral statistics. While the IMACLIM model, through the hybridisation procedure and the dual accounting system is based on physical volume.
We thus assume that trade elasticities values proposed for a first test of simulation in Table 5.1 are not consistent with IMACLIM representation of external trade. We cannot enter in details into this discussion in this thesis, and we propose to reconcile the information by converting the elasticities in volume, in the econometric sense, into elasticities in volume in the IMACLIM sense.

5.1.2.1 Protocol of translation in the IMACLIM-S model terms

The question is now how to convert the elasticities in values into elasticities in volume. We introduce below the protocol followed. We start by explaining the process for export elasticities assessment, and then we pursue with the explanation of the procedure for import elasticities assessment.

Calculation of export elasticities in volume

To keep integrating differentiations of behaviour between sectors relying on most relevant available sources, we rely on the sectoral values gathered from the literature (Table 5.1).
We interpret that these export elasticities were for monetary flows. Thus, we propose to convert the figures in export elasticities of volume to fit with the IMACLIM-S FRANCE description of trade. To do so, we set up the following simple mathematical calculation.

We note $\sigma^{val}_{X_{p_i}}$ the export elasticities in value to the domestic price (in absolute value).
By definition, a +1% rise of price of sector "i" involves a export decrease of $\sigma^{val}_{X_{p_i}}$% in value :

$$X^{val}_{i_1} = X^{val}_{i_0} \cdot (1 - \sigma^{val}_{X_{p_i}}\%) \tag{5.1}$$

The dual accounting system provides the following equations :

$$X^{val}_{i_0} = X_{i_0} \cdot pX_{i_0} \tag{5.2}$$

$$X^{val}_{i_1} = X_{i_1} \cdot pX_{i_1} \tag{5.3}$$

with by definition : $pX_{i_1} = pX_{i_0} \cdot 1.01$

We decompose value terms into price and quantity multiplications in Equation 5.1. By reorganising the equation, we deduce an expression of X_{i_1}/X_{i_0}, and therefore elasticities in volume noted as $\sigma_{X_{p_i}}$:

$$\left[\frac{X_{i_1}}{X_{i_0}} - 1\right] \cdot 100 = -\frac{\sigma^{val}_{X_{p_i}} + 1}{1.01} \tag{5.4}$$

We then deduce elasticities of export volumes to a change in prices from Equation 5.5:

$$\sigma_{X_{p_i}} = -\left[\frac{\sigma^{val}_{X_{p_i}} + 1}{1.01}\right] \tag{5.5}$$

Calculation of import elasticities in volume

Because of a lack of any better information, we assess unique import elasticity in volume for the non-energetic sectors in France. Starting from the most relevant information for global import elasticity in value, we propose a method to reveal import elasticities in volume for sectors. We can derive a weak unique form of import elasticity because IMACLIM has differentiated prices. Again, this method leaves the possibility to easily integrate sectoral elasticities coming from technical experts if we can access such data. Through a global consistency control under a set of constraints, the elasticities of the other sectors are then adapted.

We assume an identic value of import elasticity for all non-energetic sectors. By definition, a +1% rise of domestic price involves an import decrease of $\sigma^{val}_{M_p}\%$ in value :

$$M^{val}_1 = M^{val}_0 \cdot (1 - \sigma^{val}_{M_p}\%) \tag{5.6}$$

The dual accounting system provides the following equations :

$$M^{val}_0 = \sum_i \left(M_{i_0} \cdot p_{i_0}\right) \tag{5.7}$$

$$M^{val}_1 = \sum_i \left(M_{i_1} \cdot p_{i_1}\right) \tag{5.8}$$

where M_{val} are expressed in domestic price.
The price p_{i_1} is assumed by computing a weighting of energy content after increasing energy prices of 1% without any retroaction.

By definition, the relation between M_{i_1} and M_{i_0} is given by :

$$M_{i_1} = M_{i_0} \cdot (1 - \sigma_{M_p}\%)$$

where σ_{M_p} is the import elasticities in volume.

We decompose global value terms into a sum of price and quantity multiplications in Equation 5.6, and we replace M_{i_1} by the expression above to get a relationship between σ_{M_p} and $\sigma^{val}_{M_p}$:

$$\frac{\sum_i p_{i_1} \cdot (1 - \sigma_{M_p}\%) \cdot M_{i_0}}{\sum_i p_{i_0} \cdot M_{i_0}} = \sigma^{val}_{M_p}\% \tag{5.9}$$

At this point, by a simple computation we assess the import elasticities in volume.

Based on these protocols for exports and imports, we deduce trade elasticities to set up IMACLIM-S FRANCE . The values are given in Table 5.3.

5.1.2.2 Experiments results using reassessed elasticity values

Running the same comparative statics simulations than sub-section 5.1.1, we assume constant public consumption in proportion to *GDP* (simulations noted as "2.*CGC*")[7]. Again, under

[7] We also run alternative simulations for a trade balance constrained (noted as "2.*CTB*") but we do not analyse them here. Detailed results are referred in Appendix E. Table E.16 provides full macro-economic results, and tables E.17 - E.18 and E.19 give sectoral distribution of the carbon tax impacts for each variant of wage curve indexation.

Trade elasticities	$\sigma_{M_{p_i}}$	$\sigma_{X_{p_i}}$
Crude oil	0.00	0.00
Natural gas	0.00	0.00
Coal	0.00	0.00
Fuel Products	0.50	0.00
Electricty	1.58	1.09
HeatGeoSol Th	1.58	0.99
Steel Iron	1.58	1.09
Non Ferrous Metals	1.58	1.73
Cement	1.58	1.09
Other Minerals	1.58	1.79
Other Industries	1.58	1.33
Agriculture	1.58	1.23
Composite	1.58	1.15

Table 5.3 – Sectoral assumptions on trade elasticities

these conditions, we test three variants for the economic system description.

Like in previous sub-section, we compute a set of analyses by starting from a wage curve indexed on international prices (noted as "*INT*"), to a wage curve indexed on consumer prices (noted as "*CPI*") for non-energetic sectors (see Table 5.2 for the changes in parameters). We also compute an intermediate case in which only half of the wages are indexed on consumer prices. We refer to Appendix E at Table E.11 for all other reference parameters.

For detailed full results, we refer the reader to Appendix E. Table E.12 provides full macro-economic results, and tables E.13 - E.14 and E.15 give sectoral distribution of the carbon tax impacts for each variant of wage curve indexation.

Figure 5.4 shows the impact of the carbon tax on key macro indicators for the different variants on wage curve modelling.

For a carbon tax at 500€$/tCO_2$ and wages indexed on international prices (2.*CGC_INT*), we observe a *GDP* growth (+2.97%). In addition, the energy prices increase incentive to reduce emissions (-20%) .
On the supply side, production price increases is mitigated by labour tax reduction (+0.79%), and by looking closer the results, production price of non-energy goods even decrease slightly (-0.45%).Thus, there is a net positive effect of lower labour cost with a tax cut of -0.23%*points*, that reduce the relative cost of labour compared to energy. As a result, labour intensity progresses (+1.75%) and total employment increases (+5.4%).
On the demand side, households ask for higher wages (+7.41%) thanks to the lower rate of unemployment and support both internal and external demand by increasing their consumption (+1.92%) leading to a *GDP* growth. In this case, we find classical results of double dividend as analysed in Chapter 4 for the aggregated model.

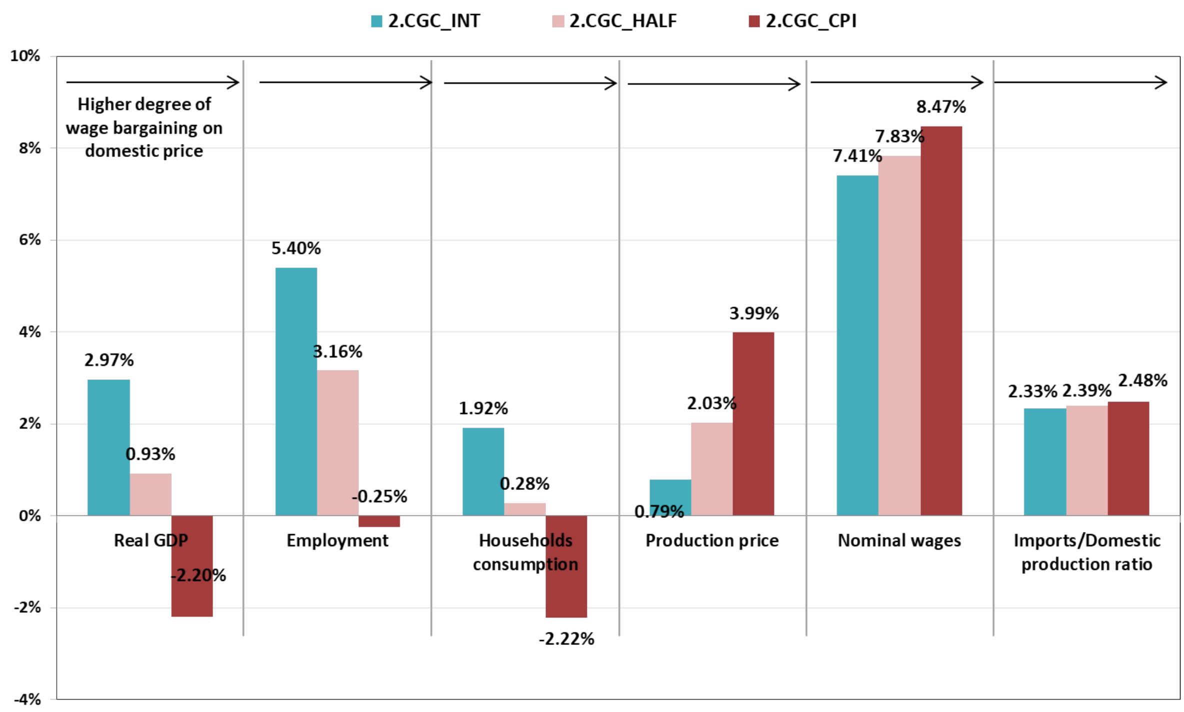


Figure 5.4 – Impact of a 500€/tCO_2 carbon tax on key indicators for different wage curve indexation with constant public consumption after reinterpreting trade elasticities

By indexing half of the wages on the consumer price (2.*CGC_HALF*), we observe the same mechanisms at work but less pronounced than in previous simulation.

Contrary to previous simulations, the entire economy is harmed by indexed wages on consumer prices (2.*CGC_CPI*): *GDP* declines (−2.20%), as well as employment (−0.25%) and households consumption (−2.22%).
Labour cost reduction is not sufficient to mitigate an increase in production price (+3.99%), and households ask for higher wages to try maintaining their purchasing power, which increase even more production price. Ultimately, they do not succeed to do so because the economy is constrained by international trade.
Because of higher production costs, the economy experiences competitiveness losses: exports are decreasing (−5.93%) and the share of imports in production is increasing (+2.48%). Finally, losses in competitiveness combined with lower households consumptions harm both external and domestic demand, and thus, employment decreases (−2.22%).

By calibrating Imaclim-S France model with this set of trade elasticities in real volume, and indexing a wage curve on consumer price, we find the same type of production price propagation previously observed and illustrated in Figure 5.2.

Under this parameterisation of trade elasticities with a reinterpretation of value drawn from the literature, we find results consistent with the main mechanisms. Notwithstanding, we relax one of the initial goals which was having a heterogeneous sectoral representation for external trade both for exports and imports. Indeed, if main mechanisms are consistent, there is no differentiation between sectors of the import to domestic production ratio sensitivity to a change in the terms of trade. We have made some progress by clarifying how to make the best use of the trade elasticities information, at both the global and the sectoral level. The weakness of the protocol however stands in the same elasticity of imports. So, we must underline that it is a first step of an incremental improvement process on trade elasticities.

The next step is to link the heterogeneity of the wage curve which represents the degree of bargaining power to the sectoral degree of exposure. The challenge is important because it gives an opportunity to demonstrate to what extent inwards activities can benefit from the low carbon transition. Doing so, we have to add into the modelling framework a distinction between jobs according to their exposure to international trade.

5.2 Linking sectoral wage settings and degree of exposure

This section aims to implement into the IMACLIM-S FRANCE modelling framework an additional sectoral specificity. Through a sectoral wage curve parametrisation, we propose to define a heterogeneities of jobs representations and their exposure to the competitiveness .

5.2.1 Parameterisation of the wage curve

Until now, we have modelled the bargaining power of wages to a change in unemployment ratio for non-energetic sectors considering three options: two extreme cases, with full indexation on consumer prices or full indexation on international price of wage, and an intermediate case, with wages half indexed on consumer price and half indexed on international prices. The reaction of wages was homogeneous for all non-energetic sectors, and we now relax this assumption by giving different bargain weight for sectors.

Each one of the sectors of the model used has to be clarified regarding their degree of trade intensity. Table 5.4 shows that the shares of trade in value-added or production are very heterogeneous among sectors.

For the *composite sector* which aggregates various kinds of productions, it is not straightforward to distinguish the share between low- international trade activities and trade-intensive activities. To better understand, the aggregated figures, it deserves to be looked at more precisely.

France 2010, Millions of €	Imports	Exports	Value-Added	Production
Steel and Iron	10 972	12 509	3 161	15 324
Non Ferrous Metals	12 401	7 786	3 186	21 204
Cement	310	278	782	3 736
Other Minerals	6 373	4 483	6 007	19 397
Construction	0	0	12 306	40 508
Chemical and petrochemical	62 069	74 547	20 002	85 110
Paper, pulp and print	9 223	6 413	4 451	17 673
Mining and quarrying	2 571	627	1 952	4 742
Transport equipement	66 458	81 526	18 053	121 547
Transport - Sectors	2 995	16 453	47 670	108 641
Industrie agro-alimentaire	1 368	519	762	2 104
Agriculture	11 178	29 320	73 784	174 522
Composite	238 859	201 680	1 308 234	2 450 323

Table 5.4 – Sectoral key indicators for trade exposure

The composite sector is essentially constituted by service industries and few manufacture industries as the textile industry. All the decomposition of this aggregate at the 88 sectoral level of the nomenclature "NAF Rev 2"[8] is available in Appendix E at Table E.20.
As synthesis in Table 5.5, sectors that have none external trade represent more than 68% of the composite value-added, whereas sectors that do have external trade, even no intensive, correspond to 24% of the composite value-added.

France, 2010	Value-Added (millions of €)	Share in 'composite' aggregate
Low-trade sectors in composite aggregate	855 646	68%
Trade-intensive sectors in composite aggregate	313 167	24%
Composite aggregate	1 308 234	-

Table 5.5 – International trade in 'composite' aggregate

We run comparative statics simulations under the same conditions than Section 5.1 by implementing a carbon tax at 500€ per ton of CO_2. Revenues are again recycled trough labour tax reduction while public debt is maintained constant (to *GDP* growth).
We take the values of elasticities estimated in the previous section (cf. Table 5.3).

We represent three categories of jobs: (i) the exposed jobs, (ii) the 'in-between' jobs, and (iii) the protected jobs. We assume that workers of trade exposed sectors have any lever to maintain their purchasing power through wages, and that workers of protected sectors adjust 80% of their wages to the consumer price index. The workers of 'in-between' sectors have 40% of their wages that follow the consumer price index. This distinction can be implemented via

[8] "NAF Rev 2" is the current French nomenclature of activities mainly designed to facilitate the organisation of economic and social information.

the $\beta_{\omega_{CPI}}$ vectoral parameter.
Table 5.6 sums up the assumptions made and remind their meanings for labour market modelling.

Classification assumptions for wage curve indexation

Sector classification	Bargaining power	Wage ponderation on domestic price*
Exposed	Low	0
Intermediate case	Middle	0.4
Protected	High	0.8

* using the $\beta_{\omega_{CPI}}$ parameter of the wage curve

Table 5.6 – Three levels for wage indexation

First, we simulate a reference case with heterogeneous wage curve according to the degree of exposure defined. We note $\beta_{\omega_{CPI_{ref}}}$ the reference parameter of the wage curve for indexation between domestic and international prices, and "*WG_REF*" the reference simulation (cf. Table 5.7, "*WG_REF*" column).
In view of previous observations, the composite sector appears to be mostly inward oriented, like cement sector, and we assume the associated labour is protected. We set up to it a $\delta_{\omega_{CPI}}$ value of 0.8. We assume that other-mineral sector and the steel sector are an intermediate case and that workers can adjust 40% of their wages to changes in domestic prices ($\delta_{\omega_{CPI}} = 0.4$). For all other non-energetic sectors, wages are based on international price.

We decrease the indexationt by step of -10% [9]. Implicitly, for each incremental step, we simulate a more exposed economy to the international trade in which workers have less negotiating power to align wages to the domestic price index. Thus, salaries are more prone to follow the international price but heterogeneities of wages indexation by sectors are kept same proportion. Although exposed sectors still have lower bargaining power than protected sectors, the gap is decreasing between sectors, and this might reveal sectoral wages incidence and their implications on the overall economy.
Similarly, we also increase the wage curve indexation homothetically of +10%. In this case, we simulate an economy more closed to term of trade changes while keeping heterogeneities protection of workers by sector.

Simulation plan with variants on parameters for wage curve indexation is resumed in Table 5.7. All parameters for the reference simulation are given in Appendix E at Table E.22.

We observe in what heterogeneities of wage curve indexation change the analysis of carbon policy.

[9]Simulation noted as $WG\_''X''$ corresponds to a $''X'' \cdot \beta_{\omega_{CPI_{ref}}}$ indexation of the wage curve.

	Variants for simulation on wage curve indexation										
$\beta_{w_{CPI}}$	WG_0.1	WG_0.2	WG_0.3	WG_0.4	WG_0.5	WG_0.6	WG_0.7	WG_0.8	WG_0.9	WG_REF	WG_1.1
Crude oil	0	0	0	0	0	0	0	0	0	0	0
Natural gas	0	0	0	0	0	0	0	0	0	0	0
Coal	0	0	0	0	0	0	0	0	0	0	0
Fuel Products	0	0	0	0	0	0	0	0	0	0	0
Electricty	0	0	0	0	0	0	0	0	0	0	0
HeatGeoSol Th	0	0	0	0	0	0	0	0	0	0	0
Steel Iron	0.04	0.08	0.12	0.16	0.2	0.24	0.28	0.32	0.36	0.4	0.44
Non Ferrous Metals	0	0	0	0	0	0	0	0	0	0	0
Cement	0.08	0.16	0.24	0.32	0.4	0.48	0.56	0.64	0.72	0.8	0.88
Other Minerals	0.04	0.08	0.12	0.16	0.2	0.24	0.28	0.32	0.36	0.4	0.44
Other Industries	0	0	0	0	0	0	0	0	0	0	0
Agriculture	0	0	0	0	0	0	0	0	0	0	0
Composite	0.08	0.16	0.24	0.32	0.4	0.48	0.56	0.64	0.72	0.8	0.88

Table 5.7 – Simulation plan for wage curve indexation

5.2.2 Simulation and results

Macroeconomics impacts of wage curve differentiations

Complete macroeconomic results are available in E at Table E.23. Figure 5.5 gives an overview of the carbon tax impact on key indicators for all variants.

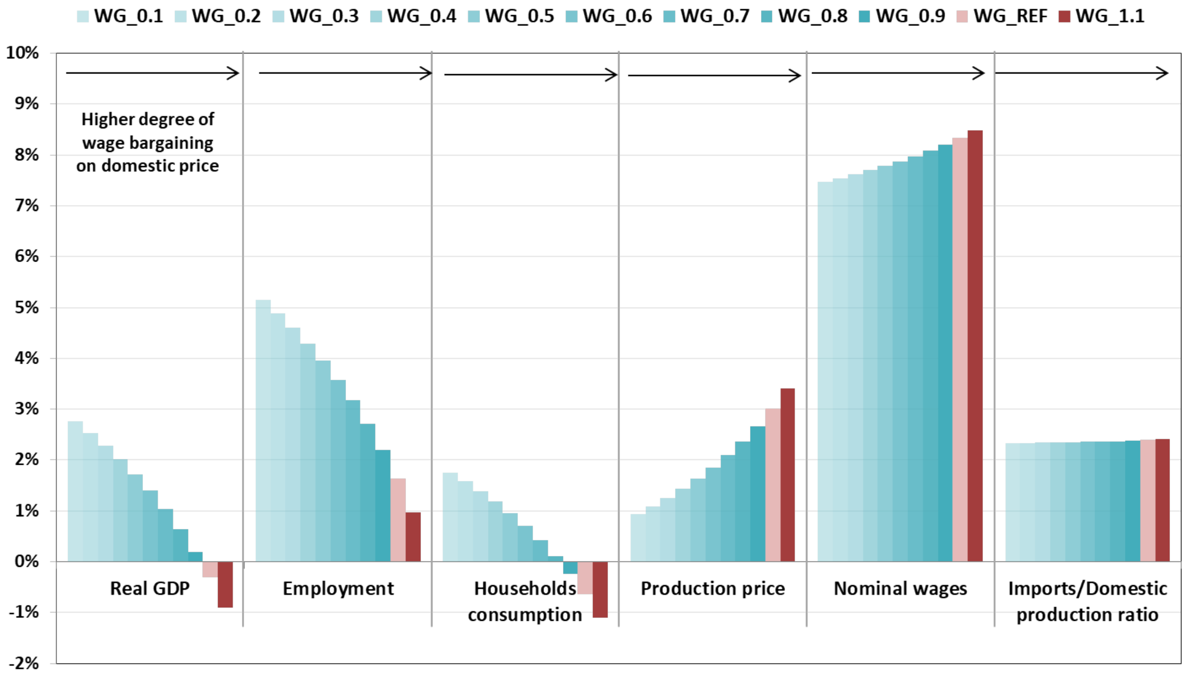


Figure 5.5 – Impact of a 500 €/tCO_2 carbon tax on key indicators for a large range of wage curve indexation

We first look at the reference simulation (*WG_REF*). By giving heterogeneous wage curve indexation according to the level of jobs exposure, we observe a low loss of *GPD* (−0.31%), but employment is preserved (+1.6%).

Labour cost reduction do not compensate the increase in energy costs and production prices increase (+3%). Indeed, mean wage increases (+8.3%) thanks to a negotiation power based on real wages for protected sectors.
Production price increase harms both households demand (−0.6%) and external trade: the import to domestic production ratio increases (2.4%).

By increasing by +10% the $\beta_{w_{CPI_{REF}}}$ parameter, we calibrate the wage curve to its highest level of indexation on consumer prices, while keeping same sectoral heterogeneity on international exposure (*WG*_1.1 simulation). In this case, we experiment a more significant decline of the economy: *GDP* falls (−0.9%), as well as households consumption (−1%), and employment slightly increases (+0.9%).This is consistent with the previous sensitivity tests and the mechanism pictured in Figure 5.2: each step toward an implicitly more closed economy by reinforcing wage curve indexation on domestic price leads to higher increase of wages, and higher increase of production price which harm the entire economy. Interestingly, by adopting sectoral heterogeneities on wage indexation, we find lower negative outcomes. In fact, compared to a homogenous wage curve with full indexation on consumer prices for all sectors, as simulated in previous section (see Figure 5.4 for results of 2.*CGC_CPI* simulation), the *GDP* loss reached −2.2%.

Conversely, by decreasing by only 10% the $\beta_{w_{CPI_{REF}}}$ parameter, we switch to positive outcome for the *GDP* (+0.23%), but households consumption slightly declines (−0.23%) although less than the reference scenario. Each step toward an implicitly more opened economy by reinforcing wage curve indexation on international price involves better outcomes; better growth, higher employment level and consumption.
By decreasing by 90% the $\beta_{w_{CPI_{REF}}}$ parameter, we calibrate the wage curve to its lowest level of indexation on consumer prices, while keeping same sectoral heterogeneity on trade exposure (*WG*_0.1 simulation). Results lead to a double dividend outcomes thanks to a production price decrease. However, they are not such positive than a wage curve based on nominal salaries for all sectors.

Another insight from the overall simulations is that results appear to be less disparate between an indexation on international price or on domestic price compared to previous simulations. This demonstrates the importance of better capturing of the sectoral heterogeneity of the economy to understand the macroeconomic impacts of policies. Obviously, the gain in sectoral granularity into the analysis helps to detect better the nature of the mechanisms at play.

Sectoral impacts of wage curve differentiations
For sectoral policy proposals, it is important to gives reliable information on distributional effect of the reform. Again, this can be achieved through hybridisation procedure (Chapter 1).

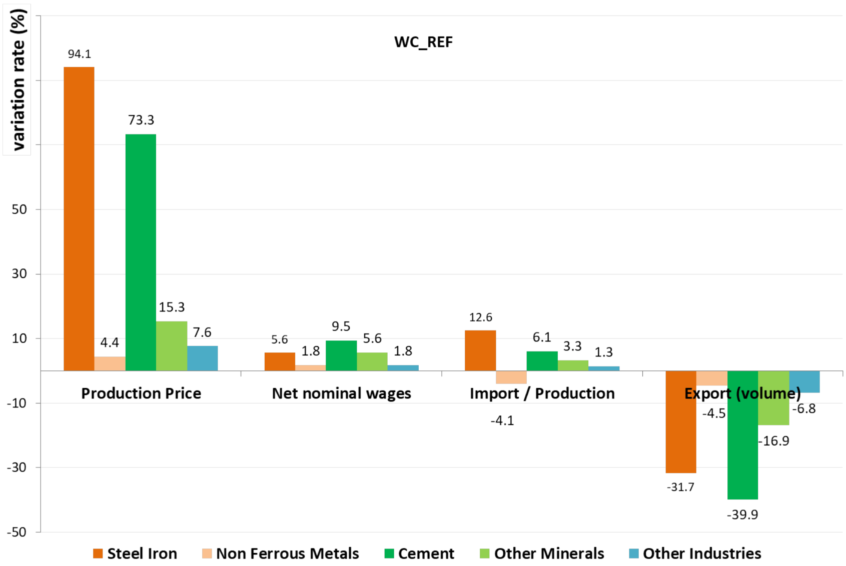
We focus only on key industrial sectors.

We analyse the impact of the carbon tax across sectors for the reference simulation (*WG_REF*) which is viewed here as the central case. We remind that in this simulation, production price increases, leading to a decrease of *GDP*.
Figure 5.6 illustrates an overview of the carbon tax impact on key indicators for industrial sectors[10].
We find unsurprisingly that production price increases for all the sectors, but with again, a significant disparity among them (see Figure 5.6a). On the one hand, steel and iron faces a +94% increase of production price, and cement production price increases by 74%. On the other hand, for all other industrial sectors, production price increases do not go beyond +15% (which is the increase for the other minerals sectors). These rates of increase may be notably higher than the results from partial equilibrium analysis which only captures the direct impact of the carbon price on the energy price, and ultimately on, the production cost.
Part of the disparity of these results is due to the variation of nominal wages, and the way it differs across sectors through heterogeneous behaviour of wages. As a protected sector, wages of cement sector increase (+9.47%) more than other industrial sectors to maintain the purchasing power altered by higher domestic prices. A counterpart is that higher wages lead to even higher production prices. On the contrary, exposed sectors, like non-ferrous metals sector, have lower increase of wages (+1.76%) because they are not bargained on domestic prices but on international prices.
Despite low export elasticities for cement and steel sectors, the exports are more harmed by the tax than other industrial sectors which is directly due to the high level of prices increase. This price increases also explains the higher import/production ratio for these sectors even though they still represent a small external trade share of the economy.
Obviously, such high level of price increases can be viewed as unrealistic given the shocks they represent at the sectoral level which then might trigger important economic shocks at the local level where the production is located. However, these shocks should be seriously considered because they capture important mechanisms at play. In fact, they raise a real problem of political tool, and give the opportunity to develop and explore a controlled sectoral policy tool with for example of specific abatement of the carbon tax (or free allocation under a cap and trade system). However, the key point to further analyse is to introduce the jobs distinction. Our analysis demonstrates indeed the critical multiplier role of the wage setting on the sectoral basis. Under the hypotheses made, it is likely that enterprises, even though they cannot be geographically reallocated, maximise the outsourcing for some segment or services mobilised in their production chain. We could not conduct this analysis in this thesis because it demands specific studies but it is possible to introduce these considerations. The enterprises might first reinforce the outsourcing of the production but the increasing of exposure might then change

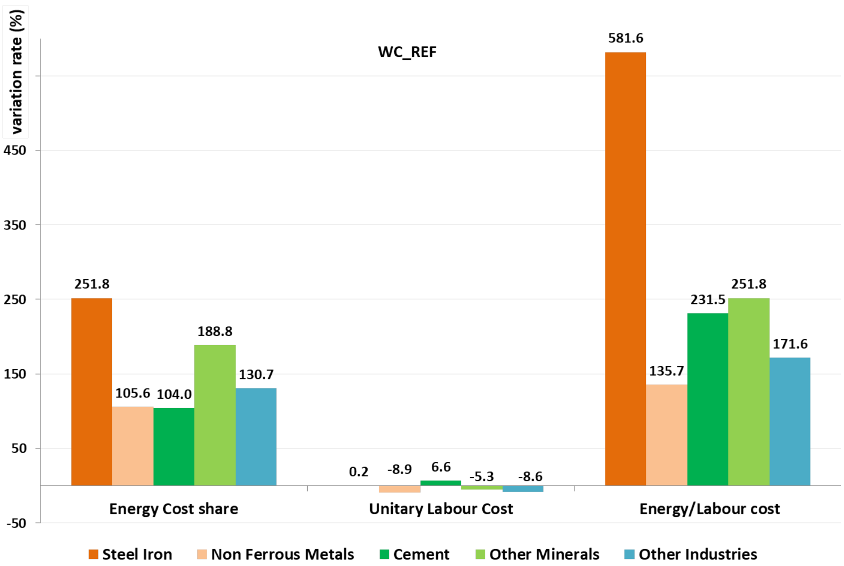
[10] We refer the reader to Appendix E at Table E.25 for detailed full results.

the relationship with the bargaining power of wage.

The good indicators of this paradox are illustrated given in Figure5.6b which represents the cost share variation of energy and labour. Carbon tax revenues make possible to reduce labour tax rate of $-0.2\%points$ and labour costs decrease for all sectors in spite of wages increases. We note particularly that labour intensity increases because of the higher energy prices, and, it increases even more for energy-intensive sectors like cement and steel sectors. As a results, for these sectors unitary labour cost increase (+0.2% for steel and +6.6% for cement) which might be unlikely.



(a) Prices, wages and trade

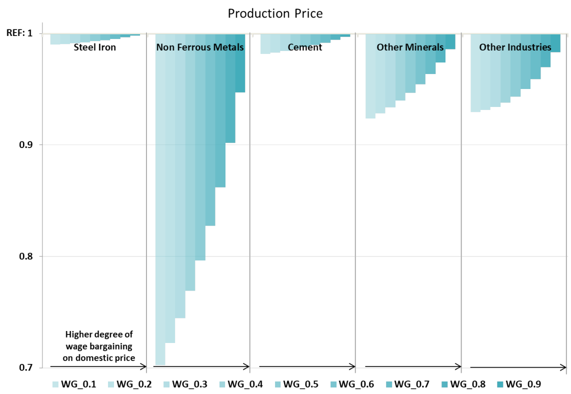


(b) Factor distribution

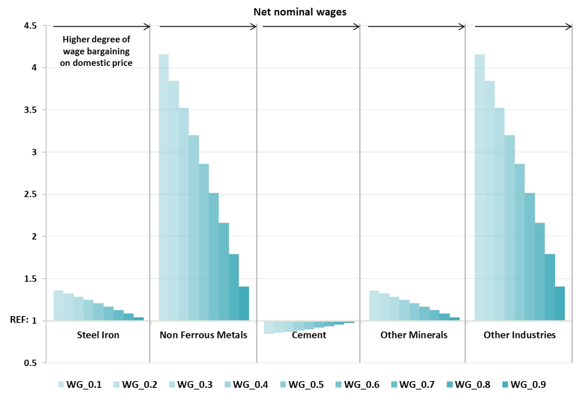
Figure 5.6 – Sectoral results on key indicators for the reference simulation

Finally, different wage behaviours matter for sectoral outcomes, and lead to discrepancies in sensitivity tests. In Figure 5.7, we picture results of simulations that provide lower indexation of wage curve by step of 10% from the reference setting for some key indicators. To compare variant experiments to the reference simulation, the representation normalise to 1 reference outcomes (*WG_REF*).

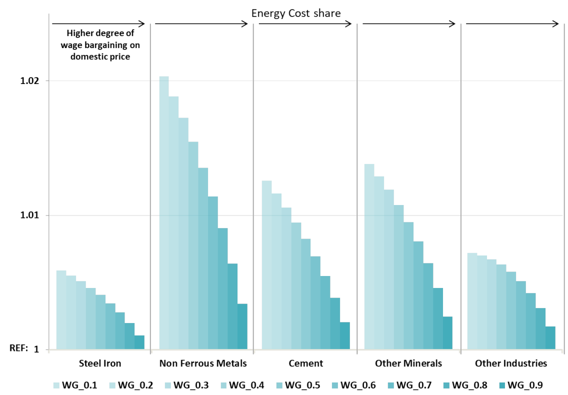
In line with macroeconomic results, we notice that production prices variation decrease by reducing the wage curve indexation for all sectors compared to the production price of the reference simulation (Figure 5.7a). However, some sectors are much more sensitive than others to this reduction. In particular the non-ferrous metal sector has a production price variation 30% lower in the *WG*_0.1 simulation compared to the reference simulation. Net nominal wages variation is also sensitive to the indexation for this sector (Figure 5.7b). Indeed, exposed sectors are not indexed on domestic price at all, and thus wages only depend on unemployment variation. By approaching international price for wage curve indexation, wages variations are 31% higher than the reference case for non-ferrous metal sector and other industries. On the contrary, protected sectors like cement sector are hardly sensitive to the wage curve indexation, and besides, have lower wages variation by reducing proportionally the indexation up to 90% for all sectors.
For all sectors, we observe that the reference heterogeneous indexation of the wage curve mitigate energy cost shares variations in production (Figure 5.7c). In fact, by representing a more open economy through wage indexation, the energy cost shares increase, compared to the reference simulation. The non-ferrous metal sector remains the most sensitive to the indexation variation, for the same reasons explained above.
Moreover, we notice contrasted outcomes for the variation of energy/labour cost ratio between exposed and protected sectors (Figure 5.7d). Giving to cement sector a "protected status", through the wage curve, limits the energy/labour cost variation which vary much more in *WG*_0.1 variant compared to the reference case. On the contrary, the energy/labour cost variation is lower in *WG*_0.1 case compared to the reference simulation for exposed sectors like non-ferrous metal and other industries sectors.
Ultimately, beyond disparities of distributional effects involved by different initial energy cost share, the implementation of a heterogeneous indexation for the wage curve leads to disparate sensitivity to results between sectors according their categories and their initial energy cost share.



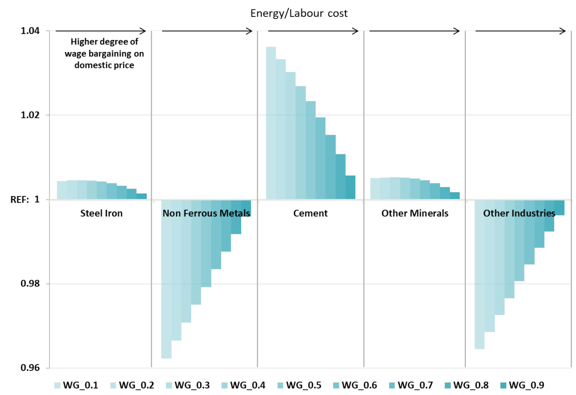
(a) Production price



(b) Net nominal wages



(c) Energy cost share



(d) Energy/Labour cost ratio

Figure 5.7 – Sectoral sensitivity to wage curve indexation on key indicators - normalised to the reference simulation

5.3 Conclusion

In this section, we have discussed the values given to some crucial parameters for the analysis of a unilateral carbon tax reform.

First, we show the complexities of calibrating sectoral values for trade elasticities. There are many studies for country-level elasticities assessment, but there is a lack in the literature for recent assessment of sectoral elasticities. Disaggregated models have been neglected at the expense of stylised models.
After gathering the most relevant information available on sectoral trade elasticities, we highlight an inconsistency between the meaning of elasticities into Imaclim-S France and the ones taking from the literature. This incompatibility leads to unexpected impacts of carbon tax implementation, and remind how important it is to pay careful attention to parameter values. Thus, we propose a method to adjust elasticities values from monetary terms to volume terms

which are required for the model. Thanks to this protocol, expected mechanisms, put forward in Chapter 4, are retrieved by implementing a carbon tax whose revenues are recycled for labour tax reduction. Doing so and because a lack of sectoral information, we had to set same import elasticities for all sectors described in IMACLIM-S FRANCE . Nevertheless, if sectoral trade elasticities of imports emerge from discussions with expert, the method can easily gather the further information while maintaining a country level of import elasticity consistent with literature.

Secondly, we implement heterogeneous sectoral wage curve in order to modelling mobility distinctions of jobs to any changes in the terms of trade. We propose a classification of three jobs categories, and we justified to which one of them each sector belongs. We show that embarking heterogeneous wage curve alleviates its sensitivity of indexation to results while taking into account concrete specificities for some sectors.
We highlight the distributional effects of carbon tax among sectors and the differences between energy intensive segments of production often aggregated with others goods (metallurgy and mineral sectors). We observe that the heterogeneous wage curve indexation changes the sectoral sensitivity to results and protected sectors benefits mostly from this differentiation. For all industrial sectors, implementing three distinct groups of wages representation at calibration preserve the increase of energy cost share compared to a wage curve close to international prices for all these sectors

Finally, through the development of a new extended version of IMACLIM-S FRANCE we reveal the importance of key parameters to analyse carbon policy effects at the country scale but still opened to the rest of the World. Indeed, the wage curve and the external trade parametrisation are central points to study any taxation reform because their representations directly influent on competitiveness of the country. Competitiveness is one of the first arguments said in order to avoid the implementation of any ambitious action against climate change, although its various meanings are been often ignored by the ones using it (Krugman, 1994). Competitiveness has not the same meaning at the national scale than at the sectoral scale. Anyway, the impacts on the national competitiveness obviously depend on the structure of the economy: the share of exposed sectors which burden the tax, and the share of the protected sectors which benefit from the tax. Thus, in this chapter, we embark this heterogeneity of "trade status" into the modelling framework, thank also to the hybridisation procedure which isolate the energy intensive sectors; cement and steel sectors. A next step is to differentiate the upstream fragments of production of these sectors into the modelling framework (cast iron and clinker. Indeed these upstream fragments are in fact the energy intensive part of the production but they represent only a small share of the value-added and they cannot be outsourced because of transport costs and capacity of investments.

The chapter is restricted the analysis of climate policy reforms to unilateral carbon tax levied on the CO_2 content of all transactions that means for all purchases from firms and households. To go further, it would be interesting to be able to implement other reforms. If climate policy is designed to have a positive effect on environment, the impact of the measure on energy-intensive and trade-exposed (EITE) sectors may reduce this positive effect and even turn it into a negative effect on environment because of carbon leakage. Indeed EITE sectors relocation in a globalised context leads to an increase of embodied emissions in imports. Depending on countries specificities, the global effectiveness of the measure may not be positive for the environment.

Understanding well the interactions between competitiveness issues and environmental concerns are necessary to be able to lift barrier for implementing climate policy. A starting point is to describe accurately the environmental state as an "initial picture", including what carbon content is hidden into imports, before disturbing it with climate measures. The next chapter describes a method developed for assessing emissions embodied in imports.

Chapter 6

Emissions embodied in international trade

Environmental progress achieved by a country depends on the scope given to the greenhouse gas (GHG) emissions inventory. In United Nations Framework Convention on Climate Change (UNFCCC) territorial-based inventories, the emissions embodied in international trade are not assessed while they represent a lever to control carbon leakage and understand competitiveness concerns.

The assessment of emissions incorporated in international trade remains unpopular for stakeholders because there are uncertainties about their use in policy actions, and because they also minimise the effort done for emission reductions. Beside political consideration, these estimates are not obvious. In the literature, different methods exist to evaluate alternative emissions inventories. However, methods are data-intensive and models mainly rely on existing global databases with balanced bilateral trade flows. The control of these databases and the articulation with country-scale prospective models remain difficult.

The aim of this chapter is to propose a single-region method to account for CO_2 emissions with different perspectives of inventories, moving them from a production-based to a consumption-based point of view. To do so, the method also assesses emissions embodied by its external trade while taking into consideration major specificity of partner countries. Furthermore, for each inventory, sectors that drive emissions, and thus that represent a lever for environmental efforts, are identified. The technique relies on hybrid national-scale data to then be articulated with a prospective general equilibrium model.

The procedure is applied as a study case to France (2010) which energy transition law now provides for territorial emissions reduction targets without increasing embodied emissions in its imports. The results show that the differences between French CO_2 emission inventories, taking or not into account emissions embodied in international trade, are not substantial. It also appears that if France had produced its own imports, it would have caused fewer CO_2 emissions. Finally, assessing different accounting systems of CO_2 emissions lead to different sectoral distributions although results are sensitive to the initial level of description.

The chapter is structured as follows. Section 6.1 addresses a review of existing approaches for accounting emissions with a consumption point of view. Section 6.2 proposes a method for a single country relying on hybrid work and that can further be articulated with a computable general equilibrium (CGE) model developed for France. Section 6.3 is an application of the method on France (2010) and discusses French emissions inventories from different point of views.

6.1 Review of main approaches

Since UNFCCC creation, signatory countries have to establish regular national inventories of emissions which are used for the commitment to GHG reductions under Kyoto Protocol. The geographic boundary of these inventories corresponds to *"general greenhouse gas emissions and removals taking place within national territory and offshore areas over which the country has jurisdiction"* (IPCC, 2006). Thus, there are ***territorial-based inventories*** that rely on technologies used within territories to quantify the amount of emissions.

However, it appears that such inventories give biased information on the responsibility of a country in global emissions. Indeed, countries satisfy their consumptions not only thanks to their production, but also thanks to their imports. Thus, a significant share of global emissions transit through the international trade embodied in the form of products or services - 26% of CO_2 global emissions in 2008 (Peters et al., 2011). In a globalisation context, this share tends to increase, and it becomes important to take into account the role of international trade in emissions to evaluate effectiveness of environmental measures and to design global sustainable actions. Thus, alternative emissions inventories, which connect production to consumption between regions, emerge from studies and are generally identified as ***consumption-based inventories*** or ***carbon footprint***. These inventories give new opportunities to well analyse the risk of carbon leakage and competitiveness issues under unilateral climate policies, but their estimates are not straightforward. Indeed, they are no direct quantification for those emissions which involve more complex calculations than the territorial-based inventories. A large number of analyses with slightly different methods account for consumption-based emissions (Sato, 2013). They rely mainly on two types of approaches: the "top-down" approach, and the "bottom-up" approach (see Figure 6.1).

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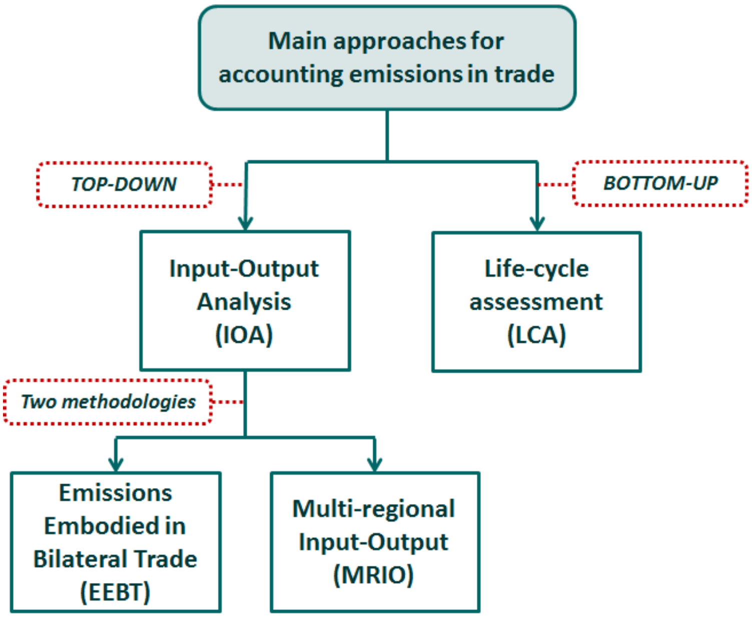


Figure 6.1 – Overview of the main approaches for accounting emissions in trade

The "bottom-up" approach

It essentially corresponds to the lifecycle assessment (LCA), which estimates the environmental "footprint" of products or services by accounting the carbon emitted during their production processes, their distributions, and also their uses and their recycling or destructions (Hertwich, 2005). LCA describes a wide scale of different products, and thus it embarks very specific technologies. The counterpart of this precise description is that LCA requires a large amount of input data. Furthermore, with LCA approach, it remains difficult to link economies between each other and thus to quantify the role of international trade in emissions.

Hence, this approach is not the main focus of the review since our aim is to focus on the role of imports in emissions for a given country in a global economic framework.

The "top-down" approach

It is mainly based in Input-Ouput analysis (IOA), which no more involves a product-specific description but gives an economic-compatible description since it relies on Input-Ouput table (IOT).

As a first step, this approach requires ***production-based inventories*** consistent with System of National Accounts (SNA) description, and that provide the assessment of emissions from monetary flows. To do so, each purchase of energy is associated with a quantity of emissions. Hence, these emissions are allocated to different economic sectors corresponding to the IOT nomenclature. In national emissions inventories under the UNFCCC, the assessment is more based on direct measures or energy statistics, and its nomenclature is then origin-emission-

oriented. Beyond nomenclatures differences, Peters and Hertwich (2008) emphasises that *"production-based inventory is related to, but different from the IPCC definition"*, and results in a conversion of "technological-based" inventories. Official statistic agencies have made some efforts to develop environmental extended IOTs compatible with the economic nomenclature, as for the European NAMEA accounts[1] (United Nations et al., 2003; Moll et al., 2007).
The second step of this approach consists in a reallocation of the production-based inventories to the ***consumption-based inventories*** by using the IOA technique, as illustrated in Figure 6.2. The consumption-based inventory is "conceptually" equivalent to the carbon footprint , since *"the consumption-based approach considers the environmental pressures arising from a product it can be considered as a generalisation of life-cycle assessment to the aggregated consumption of a country"* (Peters and Hertwich, 2008).

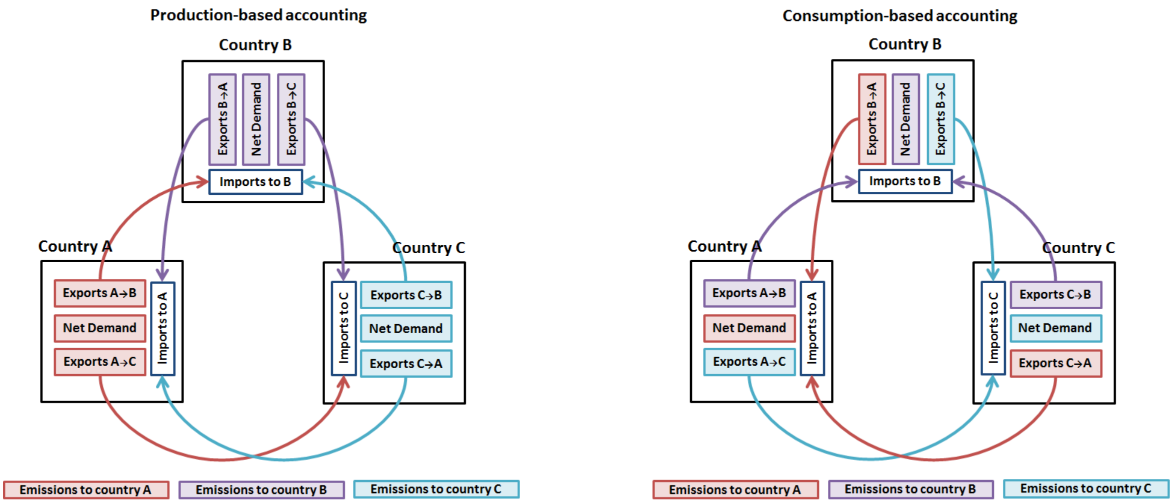


Figure 6.2 – Overview of the production-based and consumption-based accounting system for emissions

At this stage, the differences between methods are twofold and link by data requirements: (i) the geographical and sectoral scale used, and (i) the precise technique of IOAs conducted. Most studies are done at the global scale, and thus rely on global balanced database such as GTAP (Bureau and Mougeot, 2004), but they are limited by the sectoral level of the database used, whose granularity of industries may be inadequate depending on the purpose of the study (Caron, 2012). Regarding the technique of IOAs, there two main methodologies to assess consumption-based inventories, and so emissions embodied in trade:

- **The embodied emissions in bilateral trade (EEBT)** analysis describes all trade between each country represented within the modelling system. Distinct emission intensity factors are given to all international flows according to their origin and their specific production systems. It gives the emissions induced by the total domestic consumption (households,

[1]NAMEA is part of the European environmental accounting program conducted by Eurostat.

government, and investment), and also assesses the emissions embodied in imports and exports. The main assumption here is that international flows go directly to final consumption (households, government, and investment).

- **The multi-regional input-output (MRIO)** analysis is more complex but similar than the EEBT analysis. Indeed, in this case, international flows are split between final consumption and intermediate consumption. The international flows for intermediate consumption are then reprocessed to the production of goods wihtin another territory, and so the emissions intensity factors given to those flows are different. This approach captures all the feedback effects of imports that are re-exported - in theory (Sato, 2013).

Both of these approaches required global database well balanced for all international flows. However, for such database, control and uncertainties are difficult to assess. Weber (2008) mentioned that MRIO is a *"minefield"*. Sato (2013) discusses the lack of methodological transparency of those models.

Relying on what exists in terms of methods to set consumption-based inventories, we have to go a little beyond regarding some aspects, and relax other assumptions not necessary for our studies. Approaches described are based on historical dataset, and give descriptive analysis. Alone, they do not allow to understand the relationship between: (i) climate policy options, (ii) emission reductions depending on accounting methods, (iii) possible changes in production systems, and (iv) international trade and competitiveness issues. However each of its aspects are closely linked. Thus, next section proposes a single-region method relying on hybrid data work to embark the level of description needed for the aim of study, and then that can be articulated with prospective exercises at regional scale.

6.2 A method for a single region

As the study mainly focus on one region, we do not seek to quantify emissions through "closed-loop" models, like MRIO or EEBT models do. Such models require a significant amount of information harmonised at the global level. Even if global databases exist to easily build such a model, our aim is to develop a method that relies on the hybrid work of IOT, explained in section 1.2, to be consistent with the overall objectives of regional analysis and prospective studies.

Thereby, this section describes an IOA method around the hybrid IOT of France (see Chapter 1) to estimate emissions embodied in its imports while incorporating sufficient information on the main French trading partners. The procedure is drawn from the work of Pasquier (2010) which it calls himself a "multi-regional and unilateral" Input-Ouput (IO) method (Lenglart and

Pasquier, 2010). Besides domestic economic data, the method also requires extra information on technical coefficients of French partners as well as CO_2 intensity of their production. It also requires to identify the uses of imports within the French economy represented by the hybrid IOT. The large framework of the procedure and data sources are given in Figure 6.3. Thus, to allocate emissions to different components of the economy, we must follow some steps. First, we distinguish imported goods into uses of the hybrid IOT. We describe this in the sub-section 6.2.1. With the resulting input-output accounting system, we allocate national emissions to final demand. We explain this calculation in the sub-section 6.2.2. Finally, with assumptions on the French partners for imports, we formulate the embodied emissions in imports (sub-section 6.2.3).

The method proposed here is presented from a French perspective. However, as the hybridisation procedure, this method can be easily applied to other countries or regions. This is a simplified description of embodied emissions in trade or consumption but that remains sufficient in the studies we conduct.

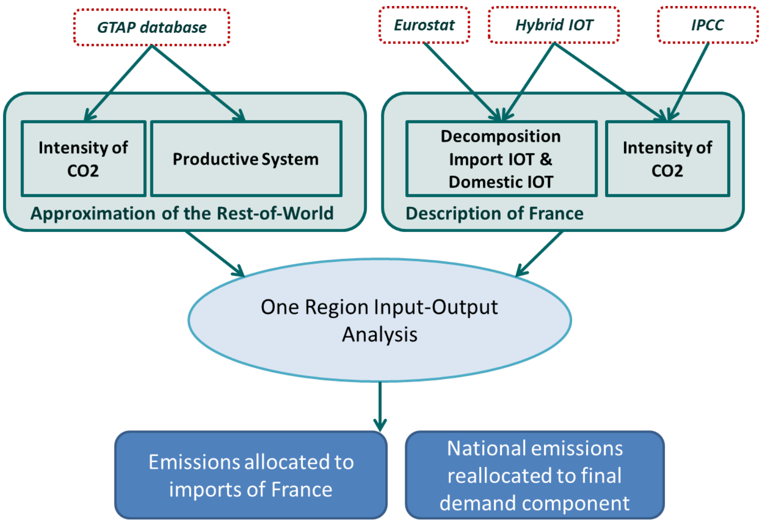


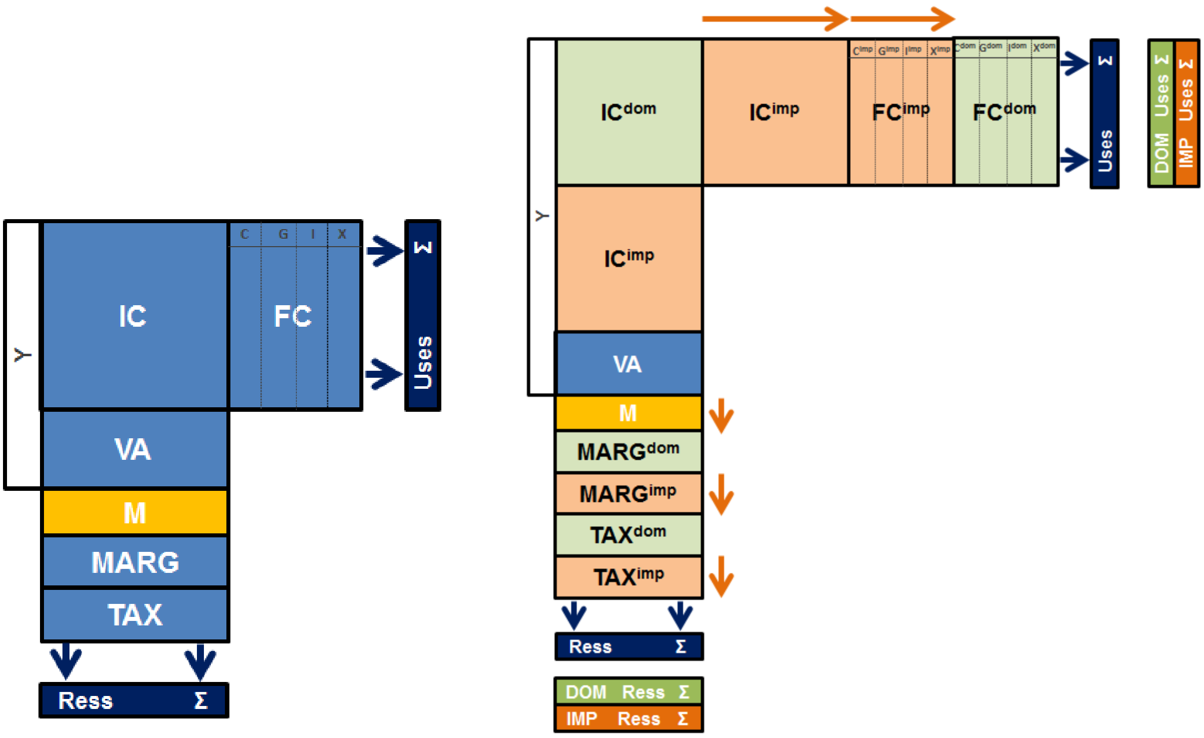
Figure 6.3 – General framework of the developed method

6.2.1 Description of the use of imports

The hybrid monetary IOT of Chapter 1 can be synthesised in the form of several matrix blocks as shown in Figure 6.4a.

IC is the square matrix of intermediate consumptions, whose size depends on the sectoral granularity describing the economy. The matrix *FC* is composed by the vectors of final consumption (households consumption *C*, government *G*, investment *I*, and exports *X*). *VA* is the matrix of the value-added components. Y is the outputs at basic price[2], and corresponds, for a given sector, to the sum of its intermediate consumptions and the value-added. M describes imports expressed in free on board (FOB) price. $MARG$ is a matrix composed by the trade margins CM vector, and the transport margins TM vector. The matrix TAX describes the fiscal revenues: from the tax on energy products T_{EnT} ($T_{EnT_{FC}}$ for the revenues from final consumption, and $T_{EnT_{IC}}$ for the revenues from intermediate consumption), the value-added tax T_{VAT}, and the excise taxes other than the energy product tax T_{OPT}. $MARG$ and TAX are revenues either from domestic production and imports.

In this global IOT framework, IC, FC, $MARG$, and TAX do not distinguish the origin of the transaction: domestic or imported. The imports M are represented without details on their uses in the economy. Thus, the first step is to decompose the IOT between import and domestic purchases as described in Figure 6.4b. The *imp* exponent is given to the purchases related to imports while the *dom* exponent is related to purchases from the domestic productions.



(a) Global Input-Output table (b) After decomposition of imports

Figure 6.4 – Components and notations of the Input-Output table

The decomposition process may respect two basic balances :

A) The import resources must balance the import uses.

[2]The basic price is the amount received by the producer less the taxes on the products and plus any subsidies on the products. The purchase price is the amount paid by the purchaser, including taxes and excluding subsidies.

B) Domestic and imported purchases must be consistent with the aggregated purchase given in IOT. For the sake of clarity, we sum-up this balance to a unique equation represented by the transaction Z which can either be IC, FC, $MARG$ or TAX.

Thus, these balances are formulated as follows:

$$A) \quad M + MARG^{imp} + TAX^{imp} = \sum_{row} IC^{imp} + \sum_{row} FC^{imp3} \tag{6.1}$$

$$B) \quad Z = Z^{dom} + Z^{imp} \tag{6.2}$$

Decomposition of intermediate and final consumption

In order to disaggregate flows in the hybrid IOT, we use additional information from Eurostat that provides symmetric input-output tables showing the use of imports. Thanks to this database, we assess for each goods purchases the proportion of imports in each one its uses - either for intermediate consumption ($\tau^{IC^{imp}}$) or final consumption ($\tau^{FC^{imp}}$)[4].

Then, the assessment of these rates is used to define intermediate and final consumption of imported goods in the hybrid IOT as follows:

$$IC^{imp} = \tau^{IC^{imp}} \cdot IC^5 \tag{6.3}$$

$$FC^{imp} = \tau^{FC^{imp}} \cdot FC \tag{6.4}$$

As Eurostat dataset are not available at purchase price, we do not have the information required on taxation or margins to distinguish the share related to imports. So, to disaggregate these components of the IOT, some assumptions are made.

Decomposition of margins and revenues from taxes on intermediate consumption

Regarding the margins components $MARG^{imp}$, transport and trade margins from imports (TM^{imp} and CM^{imp}) are assessed in proportion of the weight of imports within net resources

[3]In Chapter 6, the operator noted as $\sum_{row}$ returns the row sum of a matrix giving as a result a row vector. Symmetrically, in the following, the operator noted as $\sum_{col}$ returns the column sum of a matrix giving as a result a column vector.

[4]The Eurostat IOT are symmetric tables in the sense that they are product-by-product tables at basic prices. The hybrid IOT developed in Chapter 1 is at purchase prices since policy analyses carried out in this thesis require the description of tax revenues. Thus, to keep consistency, we convert domestic and imports tables from Eurostat at the purchase price (see Appendix F for more details). So, $IC_{Eurostat}$, $FC_{Eurostat}$, $IC^{imp}_{Eurostat}$ and $FC^{imp}_{Eurostat}$ are at purchase prices and are resulting from author's calculations, based on original IOT of Eurostat

[5]In Chapter 6, the operator noted as " · " means a multiplication, term by term, of two vectors or matrices, with at least a dimension equal.

(the amount of output Y and imports M). The same assumption is used to assess revenues of taxes on intermediate consumptions from imports :

$$Z^{imp} = Z \cdot [M \,/\, (M + Y)]^{6} \tag{6.5}$$

where Z can be either TM^{imp}, CM^{imp}, $T^{imp}_{EnT_{IC}}$, or T^{imp}_{OPT}.
Implicitly, we assume that the margins rate and the intermediate consumption tax rate are the same for imported and and domestically produced goods.

Decomposition of revenues from taxes on final consumption
Regarding revenues of taxes on final consumption from imports, we suppose that they are in proportion the weight of final consumption from imports within total final consumption. So, we formulate :

$$Z^{imp} = Z \cdot [(C^{imp} + G^{imp} + I^{imp} + X^{imp}) \,/\, (C + G + I + X)] \tag{6.6}$$

where Z can be either T^{imp}_{VAT} or $T^{imp}_{EnT_{FC}}$.

Adjustment for imports balance
However, the previous assumptions do not ensure the total market balance for imports described in Equation 6.1 at first try. Because there are differences between Eurostat IOT, that we convert at purchase prices, and the hybrid IOT we developed, we need to introduce a δ parameter to restore imports balance.

The δ parameter is an adjustment variable of the share of imports in intermediate and final consumption from Eurostat as follows:

$$\hat{\tau}^{IC^{imp}} = \delta \cdot \tau^{IC^{imp}}_{Eurostat} \text{ and } \hat{\tau}^{FC^{imp}} = \delta \cdot \tau^{FC^{imp}}_{Eurostat} \text{ with } \delta \in [0, 1] \,.$$

There is only a unique set of δ parameter that balances the ressources and uses of imports (Equation 6.1)[7]. Concretely, we adapt the information drawn from Eurostat to keep the aggregated information contained in the hybrid IOT.

[6]In Chapter 6, the operator noted as "/" means a division, term by term, of two vectors or matrices, with at least an equal dimension.
[7]The parameter δ is set at 1 at firs try. The values found for the δ parameter to balance imports are available in Appendix F.

Thereby, in describing all components, we get the following equality:

$$M + \underbrace{CM^{imp} + TM^{imp}}_{MARG^{imp}} + \underbrace{T^{imp}_{EnT_{IC}} + T^{imp}_{EnT_{FC}} + T^{imp}_{OPT} + T^{imp}_{VAT}}_{TAX^{imp}} = \sum_{row} IC^{imp} + \underbrace{C^{imp} + G^{imp} + I^{imp} + X^{imp}}_{FC^{imp}} \quad (6.7)$$

For the following, we set $\hat{M}$, the value of imports at purchase price as:

$$\hat{M} = M + CM^{imp} + TM^{imp} + T^{imp}_{EnT_{IC}} + T^{imp}_{EnT_{FC}} + T^{imp}_{OPT} + T^{imp}_{VAT}$$

Description of domestic and imports balances
Therefore, since domestic and imports uses are consistent (Equation 6.2), the "global" detailed balance of the hybrid IOT represented in Figure 6.4a can be decomposed as follows :

$$Y + M + \underbrace{CM + TM}_{MARG} + \underbrace{T_{VAT} + T_{EnT_{IC}} + T_{EnT_{FC}} + T_{OPT}}_{TAX} = \sum_{row} IC + \underbrace{C + G + I + X}_{FC} \Leftrightarrow \quad (6.8)$$

$$\hat{Y} + \hat{M} = \sum_{row} IC^{dom} + \sum_{row} IC^{imp} + C^{dom} + C^{imp} + G^{dom} + G^{imp} + I^{dom} + I^{imp} + X^{dom} + X^{imp} \quad (6.9)$$

where $\hat{Y}$ is the value of outputs at purchase price :

$$\hat{Y} = CM^{dom} + TM^{dom} + T^{dom}_{VAT} + T^{dom}_{EnT_{IC}} + T^{dom}_{EnT_{FC}} + T^{dom}_{OPT}$$

Finally, the balance of IOT get in the Equation 6.9 can be symplified by removing import balances given by the Equation 6.7. To summarise, we thus obtain two market balances, for domestic and import purchases, formulated as follows:

$$\hat{Y} = \sum_{row} IC^{dom} + C^{dom} + G^{dom} + I^{dom} + X^{dom} \quad (6.10)$$

$$\hat{M} = \sum_{row} IC^{imp} + C^{imp} + G^{imp} + I^{imp} + X^{imp} \quad (6.11)$$

In the Input-Output analysis literature, studies are based on tables at basic prices. For the following, we make the assumption that developing this analysis for a single country using matrices at purchase prices does not affect results substantially.

6.2.2 Reallocation of national emissions to final demand

Through the decomposition of the input-output table, we now allocate national emissions to final demand components by using the Leontief input-output technique. This is equivalent to conversion of a territorial-based emissions inventory to a production-based emissions inventory.

From the matrices of intermediate consumption (IC^{dom} and IC^{imp}) and the output $\hat{Y}$, the technical coefficients A^{dom} and A^{imp} are assessed:

$$A^{dom} = IC^{dom} \;/\; \hat{Y} \;\Leftrightarrow\; \sum_{row} IC^{dom} = A^{dom} \times \hat{Y} \tag{6.12}$$

$$A^{imp} = IC^{imp} \;/\; \hat{Y} \;\Leftrightarrow\; \sum_{row} IC^{imp} = A^{imp} \times \hat{Y} \tag{6.13}$$

These matrices identify the input proportions required to produce a unit of product. Thus, they represent direct interactions between industries.

Therefore, we can rearrange the Equation 6.11 and the Equation 6.10 as follows:

$$\hat{Y} = (I - A^{dom})^{-1} \times [C^{dom} + G^{dom} + I^{dom} + X^{dom}]^{8} \tag{6.14}$$

$$\hat{M} = A^{imp} \times (I - A^{dom})^{-1} \times [C^{dom} + G^{dom} + I^{dom} + X^{dom}] + [C^{imp} + G^{imp} + I^{imp} + X^{imp}] \tag{6.15}$$

where I is the identity matrix.

The $(I - A^{dom})^{-1}$ matrix represents the domestic Leontief matrix. It represents the total direct and indirect input requirements of any industry from an additional unit of final demand (Leontief, 1970)[9].

To reallocate emissions to final demand, emissions intensity (F) of each industry are required. This corresponds to the amount of CO_2 emitted by spending one euro of final consumption. This can directly be estimated using the hybrid energy IOT in tonne of oil equivalent (toe) and emission factors given in Intergovernmental Panel on Climate Change (IPCC) report (Gómez et al., 2006). First, the direct CO_2 emissions is estimated from energy inputs of each sector $CO2^{dir}_{sec}$. Then, emissions intensities are defined as follows :

$$F = CO2^{dir}_{sec} \;/\; \hat{Y} \tag{6.16}$$

Finally, the reallocation of national CO_2 emissions to final demand, for each industry, are deduced from Equation 6.14 :

$$CO2_{FC} = F \times (I - A^{dom})^{-1} \times [\, |C^{dom} + G^{dom} + I^{dom} + X^{dom}|\,]^{10} \tag{6.17}$$

[8] The exposant Z^{-1} designe the inversion of the matrix Z.

[9] The Leontief matrix can be developed as $(I + A + A^2 + A^3 + ... + A^{+\infty})$ to distinguish the direct and the indirect requirements.

$CO2_{FC}$ is a vector with all sectors described within the economy.

The reallocation can be also done for each component of final demand:

$$CO2_C = F \times (I - A^{dom})^{-1} \times |C^{dom}| \quad (6.18)$$
$$CO2_G = F \times (I - A^{dom})^{-1} \times |G^{dom}| \quad (6.19)$$
$$CO2_I = F \times (I - A^{dom})^{-1} \times |I^{dom}| \quad (6.20)$$
$$CO2_X = F \times (I - A^{dom})^{-1} \times |X^{dom}| \quad (6.21)$$

We have perfect decomposition, so we have: $CO2_{FC} = CO2_C + CO2_G + CO2_I + CO2_X$. With the aim to distinguish production-based emissions and consumption-based emissions, we also define the emissions allocated to final demand net of-exports :

$$CO2_{FC_{netX}} = CO2_C + CO2_G + CO2_I \quad (6.22)$$

6.2.3 Assessment of embodied emissions in imports

The previous sub-section gives domestic emissions induced by the production of one euro of domestic final demand. We now want to assess emissions embodied in imports. Those emissions should account for direct emissions in a foreign country r from energy consumption of industries, but also indirect emissions occurring in the upstream process of industries within the region r, induced by the demand of imports. Thus, this calculation requires additional information on trade partners.

At this stage, information on the rest of the world are required. For each French's trade partner r, we need the sectoral emission intensities (F_r), the technical coefficient matrix (A_r)[11], and the share of imports from region r by industry. Then, the emissions embodied in French imports can be estimated by the sum of emissions occurring in each region r to satisfy French imports :

$$CO2_M = \sum_r [(F_r \times (I - A_r)^{-1}) \times |\hat{M}_r|] \quad (6.23)$$

with

$$\hat{M} = \sum_r \hat{M}_r \Leftrightarrow \hat{M} = \hat{M} \cdot \sum_r \tau_{M_r} \quad (6.24)$$

[10]In Chapter 6, the operator noted as "|" means a diagonalisation of a vector.
[11] A_r is the matrix of technical coefficients for the region r without distinguishing the uses of imports.

where the vector τ_{M_r} represents the share of import from region r by industry ($\sum_r \tau_{M_r} = 1$).

So, the equation 6.23 can be arranged as follows:

$$CO2_M = \underbrace{\sum_r \left[(F_r \times (I - A_r)^{-1}) \times \tau_{M_r} \right]}_{COEF_{RoW}} \times |\hat{M}| \tag{6.25}$$

where the necessary data on the rest of the world are gathered in a global coefficient noted $COEF_{RoW}$.

Finally, by replacing the imports in Equation 6.25 by its expression given in Equation 6.15 , we asses foreign emissions induced by national demand:

$$CO2_M = COEF_{RoW} \times \Big[A^{imp} \times (I - A^{dom})^{-1} \times |(C^{dom} + G^{dom} + I^{dom} + X^{dom})| + |(C^{imp} + G^{imp} + I^{imp} + X^{imp})| \Big] \tag{6.26}$$

This equation can be decomposed in two components :

- The emissions embodied in imports used for intermediate consumptions:

$$CO2_M^{IC} = COEF_{RoW} \times \left[A^{imp} \times (I - A^{dom})^{-1} \times |(C^{dom} + G^{dom} + I^{dom} + X^{dom})| \right] \tag{6.27}$$

- The emissions embodied in imports for direct domestic final consumptions:

$$CO2_M^{FC} = COEF_{RoW} \times \left[|(C^{imp} + G^{imp} + I^{imp} + X^{imp})| \right] \tag{6.28}$$

We note that the emissions accounting in Equation 6.28 include emissions induced by imports that are used for exports (X^{imp}). However, these emissions are not necessary taken into account for the consumption-based inventories. They corresponds to emissions in foreign country for consumption in another foreign country. So, for not accounting these emissions, we define the emission embodied in imports, net of exports:

$$CO2_M^{FC_{netX}} = COEF_{RoW} \times \left[|(C^{imp} + G^{imp} + I^{imp})| \right] \tag{6.29}$$

Finally, we settle the 'avoided emissions' by imports. They are fictional CO_2 emissions that would have occurred within the territory, if imports had been produced locally. They are computed by using the domestic emissions intensities (F) and the Leontief matrix of France

$((I-A)^{-1})$:

$$CO2_M^{av} = F \times (I-A)^{-1} \times \Big[A^{imp} \times (I - A^{dom})^{-1} \times |(C^{dom} + G^{dom} + I^{dom} + X^{dom})| + |(C^{imp} + G^{imp} + I^{imp} + X^{imp})|\Big] \quad (6.30)$$

The procedure described here for accounting embodied emissions in imports is not strictly "closed". Indeed, we only assess emissions occurring in foreign countries for satisfying intermediate and final consumption of France, but we do not assess emissions occurring for French exports, that are used for intermediate consumption in the rest of the world, and then may be re-imported in France, like MRIO models do. The box below gives more details on the implicit assumption made here.

The assumption of a "quasi-closed economy" for the rest of world

The method defined differs from methods described in section 6.1. It is a kind of "half way" between EEBT and MRIO models regarding what it accounts for embodied emissions in trade.

Indeed, the EEBT method accounts for emissions occurring in one region A to produce trade flows to a region B (that is to say: export from region A to region B) . However, the method does not describe where the flows go within region B : if there are for intermediate or final consumption. This is not the case in the method developed. In fact, the imports from the rest of the world are decomposed between intermediate and final consumption flows inside the French economy. However, regarding French exports to the rest of the world, we do not distinguish the share that goes to intermediate consumption from the share that goes to final consumption.

The MRIO method fully describes these flows. By not making this distinction, it implicitly amounts to considering that all export flows from France to the rest of the world are used for final consumption, and therefore are never then "re-imported" into France.We assume implicitly that the world is a "nearly-closed" economy.

Analytically, compared to a MRIO model, this amounts to fix the technical coefficients of imports to almost zero for each region r we take into account : $A_r^{imp} \approx 0 \Rightarrow A_r \approx A_r^{dom}$.

This may be justified by the size of the French economy compared to the rest of the world: France is a small country. Pasquier (2010) calls this method a "unilateral multi-regional" approach: "multi-regional" because specificities of major French trading partners are taken into account, "unilateral" because specific data of a given region r which exports to France are taken into account, although the origin of the imports of this same region r is not described, and therefore its specificities either.

2010 France	Imports in billion of Euros [a]	Ratio
Germany	79051.8	17%
China	37435.3	8%
Belgium	35933.5	8%
Italy	34801.2	8%
Spain	28314	6%
United States	26672.1	6%
UK	19841.9	4%
Netherlands	19262.2	4%
Russia	12205.7	3%
Swiss	10857.7	2%
Japan	8918.6	2%
Poland	6971.7	2%
Ireland	5886.2	1%
Sweden	5695.6	1%
Norway	4908	1%
Rest of the world	120103.2	26%
Total	456858.7	100%

[a]Source: Eurostat database

Table 6.1 – Major French trade partners for imports

6.3 French CO_2 emissions inventories

The procedure described in section 6.2 is applied to the hybrid IOT developed in section 1.3.

To assess the rest of world coefficients $COEF_{RoW}$, we use the GTAP database using available specific information for the fifteen first French partner countries, and the rest of the world aggregated as one region. The fifteen countries has been identified thanks to Eurostat database and represent more than 70% of the total value of French imports in 2010. Values and ratios of French imports from those countries are given in Table 6.1.

Because the naming of different indicators, and scopes of emissions inventories may slightly change from one publication to another, we remind the following terms:

- **National direct emissions of CO_2**
  They correspond to the emissions from territorial fossil fuel combustion. It can be assessed by using the energy hybrid iot of Chapter 1.
  National direct emissions of CO_2 are decomposed into:
  - ***Direct emissions of households*** corresponding to final energy use, mainly for transports and residential consumptions ($CO2^{dir}_{HH}$).
  - ***Direct sectoral emissions*** corresponding to intermediate use of energy in production ($CO2^{dir}_{sec}$).

- **Production-based emissions of CO_2**
  The total amount of production-based emissions is equivalent to that of national direct emissions. However, sectoral distribution is not the same. Indeed, in that case, the total amount of direct sectoral emissions are reallocated to the final demand components (households, government, capital formation, and exports).
  Production-based emissions of CO_2 are decomposed into:
  - ***Direct emissions of households*** as defined above.
  - ***Emissions allocated to final demand*** correspond, for a given sector, to the emissions from the direct use of energy in proportion of its output that goes to final demand, and the 'indirect' emissions from other sectors' energy use that provide intermediate inputs ($CO2_{FC}$, Equation 6.17).

- **Consumption-based emissions of CO_2**
  This accounting system is decomposed into:
  - ***Direct emissions of households*** as defined above.
  - ***Emissions allocated to final demand net of exports*** correspond to emissions allocated to final demand, as define above, but without taking into account emissions allocated to exports ($CO2_{FC_{netX}}$, Equation 6.22).
  - ***Emissions embodied in imports*** account for emissions occurring in foreign countries to satisfy domestic demand.
    We distinguish emissions embodied in imports for intermediate uses ($CO2_M^{IC}$, Equation 6.27) and emissions embodied in imports for final demand of imports, net of exports($CO2_M^{FC_{netX}}$, Equation 6.29).
    Emissions embodied in imports are compared to fictional emissions if imports have been produced locally. It is a way to estimate the gain or loss of trade for the environment. We name these emissions as the ***'avoided emissions'***($CO2_M^{av}$, Equation 6.30).

6.3.1 Global results

National direct emissions of CO_2
The energy IOT (29 sectors) of Chapter 1 is combined with emission factors from the IPCC report (Gómez et al., 2006) to assess national direct emissions of CO_2. The evaluation, based on energy statistics, provides sectoral and households allocations of direct emissions corresponding to the economic classification. It is therefore consistent with 'official' inventory given by NAMEA accounts.

Thus, we first compare global direct emissions of CO_2 resulting from our own calculations with the estimates from the NAMEA accounts. Results are given in Table 6.2.

2010 France, $MtCO_2$	**Hybrid IOT**	**NAMEA**	**Statistical gap**
Direct sectoral emissions	258.6	254	1.7%
Direct emissions of households	127.0	130.3	-2.5%
Total	385.6	384.5	0.3%

Table 6.2 – National direct emissions of CO_2

Our own estimate of total national emissions gives satisfactory results with a national quantity of CO_2 emissions close to the quantity given by NAMEA accounts. The gap is of 0.7%. The breakdown between emissions from production (direct sectoral emissions) and household's emissions is less accurate but remains acceptable. The emissions from production estimates are slightly overestimated in our account (1.7%) compared to NAMEA while direct emissions of households are underestimated (-2.5%). The difference can be mainly explained by the assumption made for the disaggregation of energy consumption in transport between transport services and households.

CO_2 emissions allocated to final demand

As described in section 6.2, IOA allocates direct sectoral emissions from production (258.6 $MtCO_2$) to the components of final demand. Figure 6.5 shows the share of each component in monetary final demand, and the share of emissions allocated to each of these components in overall direct sectoral emissions.

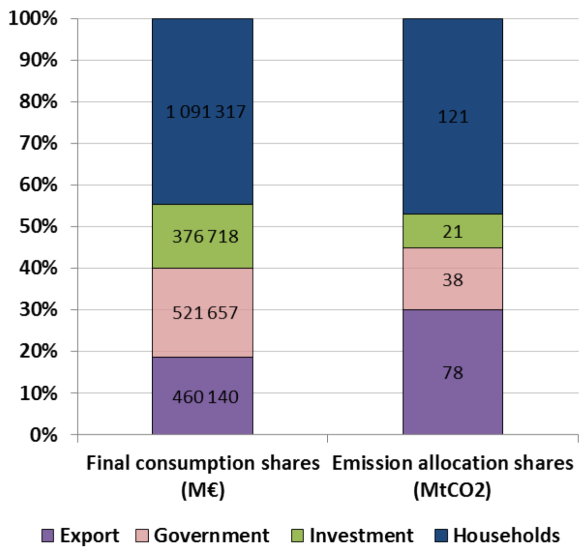


Figure 6.5 – Final demand and emissions shares

45% of the French final consumption corresponds to households demand. The share of emissions allocated to households consumption reaches a similar proportion (47%). With a share of 19%, exports are the third component of final demand. However, the share of emissions allocated to exports is more significant and represents 30% of the emissions from production. This may due to the fact that exports are driven by industries which are highly intensive in emissions but not so much valuable in the final demand.

Production-based emissions versus consumption-based emissions of CO_2

The total amount of national direct emissions (386 $MtCO_2$) described in Table 6.2 are equivalent to the production-based accounting system. We compare this amount of emissions with the consumption-based emission allocations.

By applying the method described in section 6.2, we estimate emissions embodied in imports (net of exports) at 202 $MtCO_2$. Then, we set up the consumption-based emission attributions. Figure 6.6 synthesises the two emissions budgets.

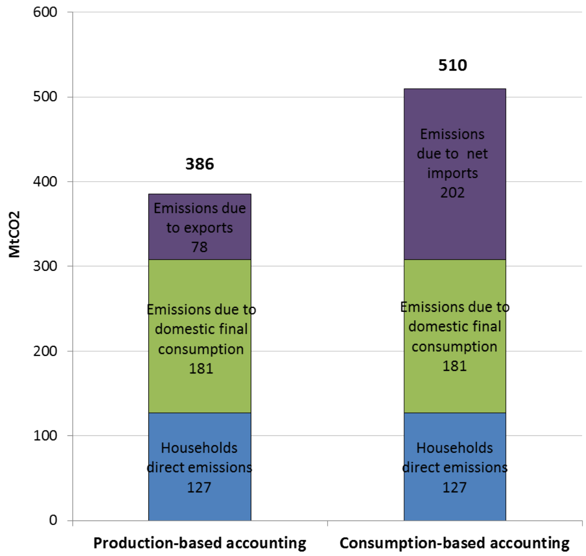


Figure 6.6 – Production-based vs. consumption-based emission allocations

It appears clearly that moving from the production-based inventory to the consumption-based inventory increases the French contribution to the global emissions. The total consumption-based emissions inventory of the country amounts to 510 $MtCO_2$. Compared to the 386 $MtCO_2$ emissions of the production-based budget, the gap is not marginal, and it corresponds to an increase of 32% of the French emission inventory. This result confirms that it is important to focus not only on direct emissions from territories but also on tracking emissions embodied in imported goods.

Furthermore, if the imported products would have been produced domestically, in France , we estimate that their production would have induced the emission of 135 $MtCO_2$[12] instead of 202 $MtCO_2$ of emissions embodied in imports. We could say that globalisation has generated additional 67 $MtCO_2$ emissions.

6.3.2 Sectoral distribution

After estimating emissions at the macro level, we explore now the contribution of the various productive sectors to those aggregated results. Indeed, in the context of climate policy analysis, it seems crucial to have a good picture of which activities would be impacted, what drives their emissions, and if they have a key role in carbon leakage and competitiveness issues. Thus, we now analyse the sectoral distribution of previous aggregated results.

Comparison of sectoral distribution between direct emissions and emissions allocated to global final demand

We observe how emissions allocated to final demand are distributed between sectors, without distinguishing the origin of final demand (households, public administration, investment, exports).

Figure 6.7 gives this sectoral distribution of emissions driven by final demand and compared it to the distribution of direct sectoral emissions[13].

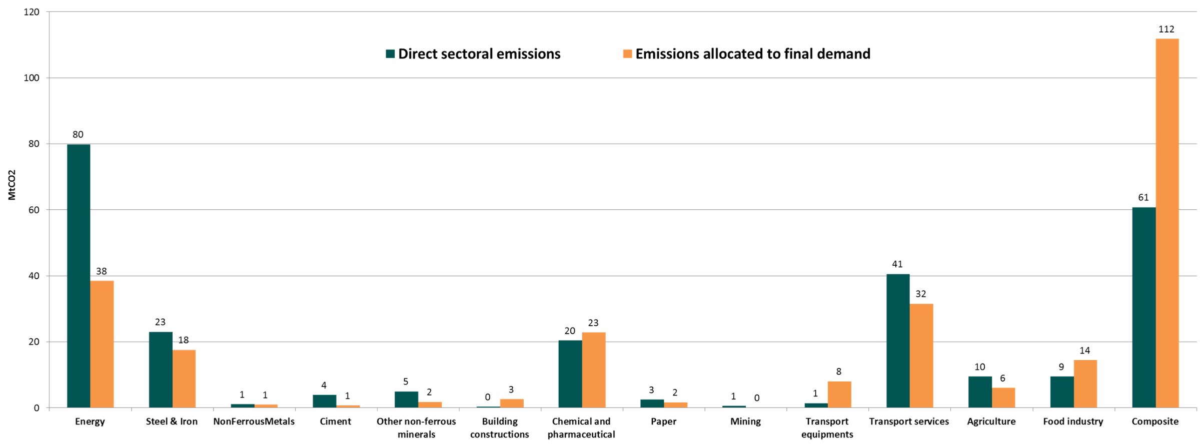


Figure 6.7 – Direct sectoral emissions vs. emissions allocated to final demand by sectors

The two accounting methods highlight some drastic differences in the allocation of emissions.

First, we see that for most energy-intensive and trade-exposed (EITE) sectors and the energy

[12]To assess this quantity of emission, we change in Equation 6.26 the $COEF_{RoW}$ by the French emission factors and the domestic Leontief matrix.

[13]The assessment provide a breakdown of the 29 sectors of the hybrid IOT. For the sake of clarity and readability, the results are aggregated to 14 sectors.

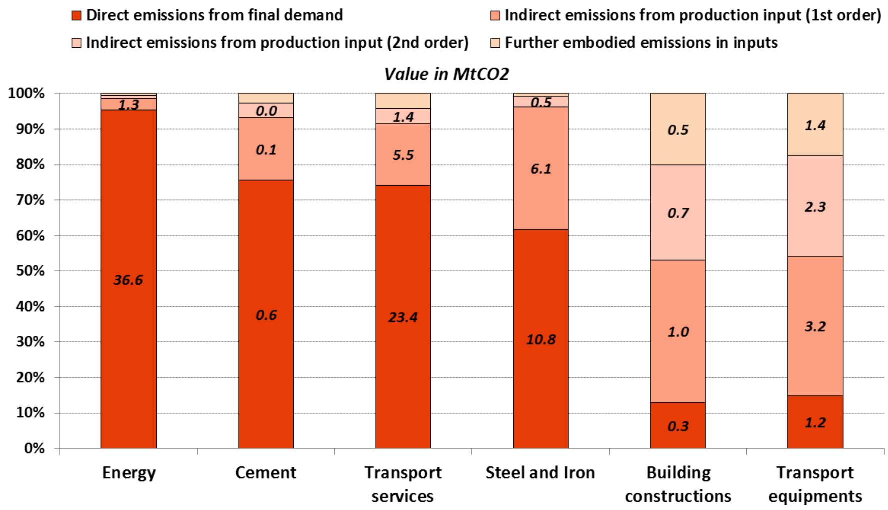


Figure 6.8 – Drivers of emissions allocated to final demand for some key sectors

sector, the allocation is lower for emissions induced by final demand than for direct production emissions:

- ***The energy sector:*** it emits 80 $MtCO_2$ for its production and represents 35% of total emissions from production (258$MtCO_2$). However, reallocating emissions to final demand reduces by almost half emissions from energy sector (38 $MtCO_2$). This is due to the fact that energy (including electricity) is very used as an intermediate goods. Thus, a major part of its emissions occurring during the production process are reallocated to the other sectors which use it, explaining the lower attribution observed. Among the 38 $MtCO_2$ allocated to final demand, a significant part (95%) are related to direct energy uses by final demand components, mainly households (see Figure 6.8). The inputs of energy sectors emitted 1.3 $MtCO_2$ to satisfy final energy demand. These *first order* indirect emissions from inputs correspond to the auto-consumption of the energy sectors.
Similar mechanism is observed for energy-intensive sectors.
- ***The cement sector:*** its production emits 4 $MtCO_2$ from energy consumption but the emissions allocated to its final demand barely amount 1 $MtCO_2$. As shown in Figure 6.8, most of these 1 $MtCO_2$ (78%) are directly induced by the final uses of the sector (households and exports - in comparable proportions). The inputs required to produce final demand only amounts 18%: as for the energy sector, these emissions are mainly due to the auto-consumption in cement production.
- ***The transport services sector:*** direct emissions from transport services amount to 41 $MtCO_2$, while their emissions attributed to final demand amount to 32 $MtCO_2$. Much of this latter figure (74%) is directly attributable to final uses of the sector (households and exports). The sector's inputs account for 5 $MtCO_2$ mainly due to the use of energy in intermediate consumption.

- ***The steel and iron sector:*** it emits 23 $MtCO_2$ for its French production but by allocating emissions to final demand, the sector is "responsible" for 18 $MtCO_2$. Among these 18 $MtCO_2$, about 11 $MtCO_2$ are directly due to final uses of steel (exportation), while the inputs required steel production induced 6 $MtCO_2$ - mainly because of the intermediate consumption of coke.

The opposite mechanism occurs for sectors that use many energy-intensive inputs in their production and are mainly intended for intermediate uses :

- ***The building construction sector:*** it uses many intensive-energy goods for its production, which tends to increase its allocation of emissions to final demand up to 3 $MtCO_2$ while direct emissions from the sector are very low. Indeed, only 13% of these 3 $MtCO_2$ are due to final demand of building construction (investment), but the inputs required for the sector to reach final demand represent 40%. This is due to the consumption of steel, cement, and other minerals in the production process of building construction.
- ***The transport equipments sector:*** it emits 1 $MtCO_2$ for its French production, but reallocate emissions to final demand increases its emission balance to 8 $MtCO_2$. Only 15% of the emissions allocated to final demand directly occurs for final uses, while the required inputs for transport equipments sectors are "responsible" of almost 40%, mainly because of the intermediate use of steel in the production process. But the manufacture of this steel input itself requires energy. Thus indirect "second-order" emissions (Figure 6.8) account for 28% of the emissions reallocated to transport equipments final demand.
  For these sectors, the convergence towards the emissions allocated to final demand is less immediate than for previously observed sectors because of their use in the economy and their required intermediate consumption.

The following box gives deeper analytical details on the difference between direct sectoral emissions and the allocation to final demand.

Analytical comparison between direct sectoral emissions ($CO2_{sec}^{dir}$) and emissions allocated to final demand ($CO2_{FC}$)

To understand the meaning of the positive or negative gaps for a given sector between its direct emissions, and the emissions allocated to its final demand, we draw analytically the differences between these two indicators. By developing the Leontief matrix (Equation 6.17) and introducing the definition of the emissions intensities (Equation 6.16), we have :

$$CO2_{FC} = \underbrace{(CO2_{sec}^{dir}/\hat{Y}) \times I \times |\sum_{col} FC^{dom}|}_{CO2_{FC}^{1^{st}}} + \underbrace{(CO2_{sec}^{dir}/\hat{Y}) \times [A + A^2 + ... + A^{+\infty}]|\sum_{col} FC^{dom}|}_{CO2_{FC}^{2^{nd}}}$$

$CO2_{FC}^{1^{st}}$ corresponds to direct sectoral emissions in proportion of its output that goes to final demand. $CO2_{FC}^{2^{nd}}$ accounts for the 'indirect' emissions from other sectors' energy use that provide intermediate inputs.
First, we compare $CO2_{sec}^{dir}$ with $CO2_{FC}^{1^{st}}$. So, we get :

$$CO2_{sec}^{dir} - CO2_{FC}^{1^{st}} = (CO2_{sec}^{dir}/\hat{Y}) \times |\sum_{col} IC^{dom}|$$

The gap corresponds to direct sectoral emissions in proportion of its output that goes to its intermediate uses. This a positive term, so this inequality is always verified :

$$CO2_{sec}^{dir} \geq CO2_{FC}^{1^{st}}$$

.
Thus, we give the following explanation to understand the sign of the difference between $CO2_{sec}^{dir}$ and $CO2_{FC}$:

- $\boldsymbol{CO2_{sec}^{dir} \geq CO2_{FC} \Leftrightarrow (CO2_{sec}^{dir}/\hat{Y}) \times |\sum_{col} IC^{dom}| \geq CO2_{FC}^{2^{nd}}}$
  Direct emissions of the sectors allocated to intermediate uses are higher than the emissions induced by the production of goods needed to produce those intermediate consumption.
- $\boldsymbol{CO2_{sec}^{dir} \leq CO2_{FC} \Leftrightarrow (CO2_{sec}^{dir}/\hat{Y}) \times |\sum_{col} IC^{dom}| \leq CO2_{FC}^{2^{nd}}}$
  Direct emissions of the sectors allocated to intermediate uses are lower than the emissions induced by the production of goods needed to produce those intermediate consumption.

Emissions allocated to each final demand components

Figure 6.9 provides further decomposition by distinguish final demand components[14].

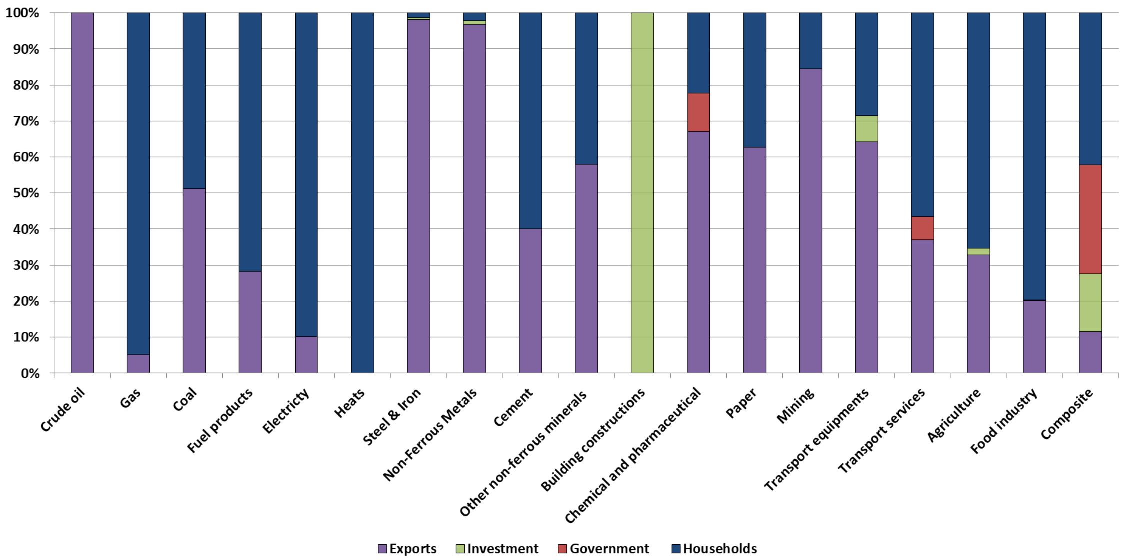


Figure 6.9 – Distribution between the components of final demand of allocated emissions

As we have seen at the macro level, it is household's consumption which drives emissions in France for a number of sectors. However, export demand is largely "responsible" of the emissions allocated to final demand for many sectors. These emissions will be imputed when accounting for consumption-based inventory. Furthermore, we see that final demand of energy-intensive sectors such as steel and iron, or non-ferrous-metals sectors have induced emissions mainly because of exports. This tends to reduce the footprint of France when accounting emissions with a consumption-based point of view. Cement does not have the same profile. Indeed, cement is not so much exported, because of transport costs, and the emissions allocated to final demand are mainly due to household demand. Some other sectors like the building construction sector mainly responds to investment, which then drives the allocated emissions.

Emissions embodied in international trade

Table 6.3 gives the sectoral emissions allocated to exports, and emissions embodied in imported goods. The net import balance of CO_2 of France is the sectoral difference between those two assessments.

We note that for many sectors, the CO_2 emissions allocated to exports offset the emissions embodied in imports. This reflects the intra-industry trade. Intra-industry trade means the import and export of similar products between countries. According to the Organisation for

[14]The assessment provide a breakdown of the 29 sectors of the hybrid IOT. For the sake of clarity and readability, the results of energy sectors are aggregated revealing 19 sectors in the figure.

2010 France, $MtCO_2$	Emissions allocated to export	Embodied emissions in net imports	Emissions "leakage"
Crude oil	0.002	0.001	-0.001
Gas	0.01	1.18	1.17
Coal	0.5	0.09	-0.42
Fuel products	4.32	14.08	9.76
Electricty	2.2	1.98	-0.23
Heats	0	0.04	0.04
Steel & Iron	17.22	2.01	-15.21
NonFerrousMetals	0.94	1.03	0.09
Cement	0.3	0.13	-0.17
Other non-ferrous minerals	1.06	1.23	0.17
Building constructions	0	2.85	2.85
Chemical and pharmaceutical	15.32	25.45	10.14
Paper	1.04	1.53	0.49
Mining	0.06	0.03	-0.02
Transport equipments	5.16	28.28	23.12
Transport services	11.67	5.47	-6.2
Agriculture	2.25	4.95	2.7
Food industry	2.76	12.43	9.68
Composite	12.93	98.9	85.98
Total	77.74	201.68	123.93

Table 6.3 – Emissions of CO_2 due to French international trade

2010 France	Export[a] (Millions of €)	Import[b] (Millions of €)	Trade balance (Millions of €)	Import penetration Rate[c](%)
Crude oil	13.8	28 740.3	-28 726.6	98.6
Gas	513.3	9 798.7	-9 285.3	57.0
Coal	32.1	2 148.3	-2 116.2	67.1
Fuel products	11 325.3	13 593.6	-2 268.2	42.4
Electricty	2 236.8	1 025.3	1 211.5	3.5
Heats	0.0	0.0	0.0	0.0
Steel & Iron	7 575.8	6 038.8	1 537.0	79.6
NonFerrousMetals	6 810.9	11 426.0	-4 615.1	48.0
Cement	265.3	297.3	-32.0	8.2
Other non-ferrous minerals	3 841.3	5 731.0	-1 889.7	29.9
Building constructions	0.0	0.0	0.0	0.0
Chemical and pharmaceutical	70 451.8	57 974.2	12 477.7	87.9
Paper	6 205.9	9 016.2	-2 810.3	45.1
Mining	411.1	2 355.1	-1 944.0	38.4
Transport equipments	77 281.7	62 213.4	15 068.3	62.4
Transport services	16 011.5	2 553.3	13 458.1	3.1
Agriculture	13 386.0	9 551.2	3 834.8	14.9
Food industry	24 876.0	26 736.1	-1 860.1	21.3
Composite	187 559.3	232 109.8	-44 550.5	8.6
Total	428 798.0	481 308.7	-52 510.7	14.4

[a]Domestically produced
[b]Net of re-exported imports
[c]Defined as the value of imports divided by the value of net-of-export demand

Table 6.4 – French international trade in value

France, tCO2/million €	Intensity Export	Intensity Import
Crude oil	111.4	0.0
Gas	22.4	120.9
Coal	15 708.3	40.7
Fuel products	381.8	1 035.9
Electricty	984.5	1 927.5
Heats	nan	nan
Steel & Iron	2 272.4	332.2
NonFerrousMetals	138.0	90.3
Cement	1 123.0	422.2
Other non-ferrous minerals	275.8	214.3
Building constructions	nan	nan
Chemical and pharmaceutical	217.4	439.0
Paper	168.3	170.1
Mining	143.7	14.7
Transport equipments	66.8	454.6
Transport services	729.1	2 143.7
Agriculture	168.2	518.7
Food industry	110.7	465.1
Composite	68.9	426.1
Total	181.3	419.0

Table 6.5 – Trade CO_2 intensities

Economic Co-operation and Development (OECD), such trade is becoming more pronounced in developed countries mainly between members countries of the European Union[15].

However, for some sectors, there is a significant gap between emissions allocated to exports and the emissions embodied in imports that make France a net importer of CO_2 (124 $MtCO_2$):

- ***The composite sector:*** it is largely responsible of the CO_2 net importer status of France (86 $MtCO_2$). This sector aggregates industries and services in the French economy that we have not described during the hybridisation procedure. It includes all services, but also some industries such as textiles and electronics industry which France is a net importer, and whose production must be CO_2 intensive abroad.
- ***The transport equipment sector:*** the gap of emissions from the transport equipment sector is also striking (23 $MtCO_2$). Nevertheless, Table 6.4 shows that export in value for this sector are quite higher than imports in monetary value, and the corresponding CO_2 emission-intensity (see Table 6.5) is important for imports. We assume that the most emission-intensive part in the value chain of this sector is produced abroad, and France exports quasi-finished products that are more valuable.

In contrast, for other sectors, France is net exporter of CO_2 :

- ***The cement sector:*** exports involve more emissions than imports (−88%) but in mone-

[15] From the book "Perspectives économiques de l'OCDE Volume 2002", Chapter 6.

tary value, exports are lower (see Table 6.4). The differences in emissions are due to a striking difference in emission intensity which is directly due to hybridisation procedure. The cement sector is originally aggregated with the other non-metallic minerals sector. The resulting aggregate sector, the non-metallic minerals, has a lower average emission intensity. Hybridisation makes it possible to isolate these intra-sector heterogeneity. The GTAP database used to calculate emissions embodied in imports does not provide the sectoral granularity that isolates the cement sector. It is therefore an average intensity that emerges.

- ***The steel & iron sector:*** exports involves more emissions than imports (−88%). Regarding monetary value, Table 6.4 shows that France also exports far more steel than it imports. This is a result of the hybridisation procedure (see 1) that revealed much higher exports in quantities. However, the magnitude of the balance in value (and quantities) does not explain the magnitude of balance in emissions. It is rather explained by the difference in emission intensity of this sector between imports and exports, which is in fact a consequence of the hybridisation procedure (see 6.5). Indeed, we attribute a significant portion of energy as intermediate consumption of the sector, especially for coke, which is the most polluting coal products, which increases the emission intensity of exports. However, regarding imports, the calculations of emissions intensity of the rest of-world are assessed from a energy product aggregate in GTAP database, and may be underestimated because of a coal average emission intensity. At that stage, it becomes difficult to comment on figures from a database that we do not control.

We emphasise here again the interest to build our own hybrid IOT, although this remains possible only at the regional scale. Indeed, applying the method at the global scale is a too data-intensive and time-consuming exercise. Nevertheless, we need to be careful by comparing these results because differences may come from the hybridisation procedure that has only been applied for domestic flows and not for imports, which are described only in monetary terms and whose sectoral granularity do not fit studied sectors here.

6.3.3 The role of aggregation

Relevant theoretical literature (Morimoto, 1970; Kymn, 1990), as well as applied literature Majeau-Bettez et al. (2016); Su et al. (2010), stress the aggregation bias issue for IOAs. Majeau-Bettez et al. (2016) argue that the heterogeneous aggregation does not keep the balance of the analysis and it introduces bias. Su et al. (2010) observe that *"studies are often conducted at a specific level [...] and the choice made to a large extent is dictated by economic and energy data availability"*. The paper studies the sector aggregation effect on result and assumes that *"approximating the "ideal" situation the hybrid data treatment approach produces better results than the uniformly distributed data*

Hybrid IOT	AGG_IndEner	AGG_4Sec	AGG_EnComp
Crude oil	Crude oil	Primary Energy	All Energies
Natural gas	Natural gas	Primary Energy	All Energies
Coking coal	Coal	Primary Energy	All Energies
Bituminous coal	Coal	Final Energy	All Energies
Coke	Coal	Primary Energy	All Energies
Other coal	Coal	Final Energy	All Energies
Gasoline	Fuel products	Final Energy	All Energies
LPG	Fuel products	Final Energy	All Energies
Jetfuel	Fuel products	Primary Energy	All Energies
Fuel	Fuel products	Final Energy	All Energies
Fuel oil	Fuel products	Final Energy	All Energies
Heavy fuel oil	Fuel products	Final Energy	All Energies
Other fuel products	Fuel products	Final Energy	All Energies
Electricty	Electricty	Final Energy	All Energies
Heat, Geothermal & Solar Th	Heat, Geothermal & Solar Th	Final Energy	All Energies
Steel & Iron	Steel & Iron	Industries & Agriculture	Rest of sectors
Non Ferrous Metals	Non Ferrous Metals	Industries & Agriculture	Rest of sectors
Cement	Cement	Industries & Agriculture	Rest of sectors
Other Minerals	Other Minerals	Industries & Agriculture	Rest of sectors
Buildings construction	Other Industries	Industries & Agriculture	Rest of sectors
Chemical & Pharmaceutical	Other Industries	Industries & Agriculture	Rest of sectors
Paper	Other Industries	Industries & Agriculture	Rest of sectors
Mining	Other Industries	Industries & Agriculture	Rest of sectors
Transport Equipment	Other Industries	Industries & Agriculture	Rest of sectors
Transport services	Other Industries	Industries & Agriculture	Rest of sectors
Agriculture & Forestry	Agriculture	Industries & Agriculture	Rest of sectors
Fishing	Agriculture	Industries & Agriculture	Rest of sectors
Food industry	Other Industries	Industries & Agriculture	Rest of sectors
Composite	Composite	Composite	Rest of sectors

Table 6.6 – Aggregation levels and correspondences with original hybrid IOT

treatment approach".

We analyse here the sensitivity of the results to the aggregation level.
In our previous results, the assessments are made on the hybrid IOT at its most disaggregated level (see Table 6.6). We compare these results to the three higher levels of aggregation described in Table 6.6. The first level (*AGG_IndEner*) consists in an aggregation of main energy products. The aggregation level noted *AGG_4Sec* distinguishes primary and final energy, the aggregation of all originally described sectors in the hybrid IOT, excluding composite, and the composite sector. The last level (*AGG_EnComp*) aggregates all energies on one hand, and all the rest of the economy on the other hand.

Using the three corresponding IOTs, we run the same calculations as before. We focus on two original results which are : (i) the embodied emissions in net imports, and, (ii) the 'avoided' emissions, if imports had been produced in France. The results are shown in Table 6.7 and seem at first sight to strongly depend on the level of aggregation for both indicators.

We first analyse the gaps between the different levels of aggregation for the assessment of

the 'avoided' emissions. These assessments give to imports the domestic production system as well as the domestic emission factors.
By aggregating coal and fuel products from the hybrid IOT (*AGG_IndEner*), the estimate of 'avoided' emissions is drastically different (312 $MtCO_2$) and increases by 131% compared to the estimate based on the original disaggregated hybrid IOT (135 $MtCO_2$). The aggregation into four sectors (*AGG_4Sec*) gives a result closer to the original case (191 $MtCO_2$) but with a gap even of 41%. By reducing the economy into two sectors (*AGG_EnComp*), the estimate of 'avoided' emissions is of the same order as the one that describes 29 sectors (135 $MtCO_2$).
At level *AGG_IndEner* of aggregation, we define an average domestic emission intensity which is very different than emission intensities of each coal types. In fact, some values of coal emission intensities are artefacts due to the production case of France. Specifically, emission intensities of coking coal and bituminous coal have been defined as zero since their French production is zero. The resulting 'avoided' emissions in France by importing coking and bituminous coal are then nil since the estimate is based on a zero domestic emission intensity factor. However, by aggregating coal products, it gives to each euro of imported coal (including thus coking and bituminous coal) a non-zero average emission intensity. This explains the higher estimate for the aggregation level *AGG_IndEner* and *AGG_4Sec*. By aggregating the economy into only two sectors, the energy sector and the rest *AGG_EnComp*, average domestic emissions intensities re-balance to give a close result of 'avoided' emissions to the result based on hybrid IOT.
At last, speaking of 'avoided' emissions can be misleading because the results strongly depend on the domestic productive structure and also the level of description of it.

We now explain the gaps observed for the results of the embodied emissions in imports. As for 'avoided' emissions results, we show a same type of aggregation bias. However, for this indicator, the gap with the hybrid IOT continually increases with the level of aggregation. With the two sector description (*AGG_EnComp*), we get 292 $MtCO_2$ of embodied emissions in imports (+45%) and with four sectors (*AGG_4Sec*), we get 268 $MtCO_2$ (+33%). Not as for 'avoided' emissions, the result is less sensitive to the only aggregation of coal and oil products (+6%).
By assessing emission intensity factors for the French partners, we rely on the GTAP database that does not give the same level of description on energy products that we have in the hybrid IOT. In particular, the database describes the coal sector and petroleum products sector without distinguishing the different products into these two sectors. We therefore estimate average emission intensities for coal and petroleum products (weighted by the French partners). Consequently, we allocate to each euro of imports of the various coal products (coking coal, bituminous coal, etc.) or petroleum products (gasoline, jetfuel, fuel oil, etc.) of the hybrid case, the same estimated average intensity. Therefore, aggregating these products does not change in a significant way the outcome for the first level of aggregation (*AGG_IndEner*). This is less the case by aggregating more and more the economy to few sectors. We then attribute to imports average intensities very different of what are initially estimated.

2010 France, $MtCO_2$	**'Avoided' emissions**	**Embodied emissions in net imports**
Hybrid IOT	135.2	201.7
AGG_IndEner	312	214.3
AGG_4Sec	190.9	268
AGG_EnComp	134.9	292.3

Table 6.7 – Allocated emissions to imports by level of aggregation

A^{dom} matrix raised to n power	A^{dom}	A^{dom^2}	A^{dom^3}	A^{dom^4}	A^{dom^5}
Hybrid IOT	0.503	0.256	0.107	0.043	0.017
AGG_IndEner	0.483	0.194	0.076	0.030	0.012
AGG_4Sec	0.343	0.131	0.056	0.022	0.009
AGG_EnComp	0.392	0.155	0.061	0.024	0.010

Table 6.8 – Highest coefficient of domestic A^{dom} matrix raised to n power by aggregation level

We observe that some results are very sensitive to the initial sectoral description of the study. However it is not the only level of description that could biased the analysis. Thus, it would be interesting to analyse if the level of French import partners embedded in the assessment of the rest of-world emission intensity ($COEF_{RoW}$) changes much these results. This could be the subject of future studies for probation of the developed method described in section 6.2

Finally, in a qualitative way, we observe the bahaviour of the Leontief matrix because results may also be affected by the speed at which the technical coefficients matrix raised to the n^{th} power tends to zero as n approaches infinity. Indeed, results are intimately linked to the Leontief matrix which can be analytically developed as : $I + A^{dom} + A^{dom^2} + A^{dom^3} + ...A^{dom^{+\infty}}$
So, we sum up in Table 6.8 these qualitative differences by stressing the highest elements of the technical coefficient matrix, for different level of aggregation, and for different power given to the matrix.

According to the level of aggregation, we see that the bahaviour of the technical coefficient matrix raised to the n^{th} power is not the same, and therefore, it must introduce a bias in the results. When the matrix is squared, the highest resulting coefficient is 50% lower than the one in the matrix A^{dom} for the disaggregated case of hybrid IOT. For all cases of aggregation, the highest resulting coefficient is 60% lower than the one in the matrix A^{dom}. At the power of 3, the gap is widening.
We can imagine that, the more quickly the coefficients resulting of the technical coefficient matrix raised to the n power, converge to zero, the less the emissions induced by the consumption of a goods by another goods are significant. This quantitative analysis could lead to an analytical calculation.

6.4 Conclusion

This chapter proposes a method to highlight the different attributions of CO_2 emissions for a given country, and their distributions between sectors. We show that the responsibility -in terms of emissions- at national or sectoral scale, differ depending the accounting system used for inventories. The allocation is often implicitly a territorial or production-based inventory. However, we show that the diagnosis changes if we consider a consumption-based accounting system. This is a significant fact because it changes the weight of a country or sector within global emissions, and this may influence negotiations for any attempt to implement environmental policies to reduce emissions.

In explaining the method used, we show that assessing dual accounting system of emissions is very data-intensive, either for France or for the rest of-world description in order to give a good picture of emission balances at base year. As we re-built our own database for France, we rely on exogenous harmonised database for the description of the French partners. While this is saving-time, once we look at how the results are sensitive to data, it becomes difficult to control information.

In this work, we only observe the impact of the sectoral level description of the results. Still, it would be interesting to analyse the hypothesis made on the description of the rest of world. We assume that setting up the description on the first fifteen French partners covering 75% of its imports would capture largely emissions embodied in imports. Moreover, we assume that the rest of-world is equivalent to a "quasi-closed" economy to France. Thus, we neglect the export flows from France which are then re-imported into the country. The robustness of these two hypotheses might be explored by observing if any revision of these assumptions affect significantly the assessment of embodied emissions in imports.

Finally, this chapter provides an overview of different emission allocation schemes without harmonising the whole world description. Beyond this "inventory" at a base year, we developed a method that we can easily articulate with the Imaclim-S France CGE model to analyse how any regional French policy can influence results related to international trade, in value, as well as, in emissions terms. In this context, the assumptions made previously regarding the description of the rest of the world are justified. The idea is not to develop a harmonised MRIO model, but really to focus our method on the initial description of France, which is the core of the Imaclim-S France model.

General conclusion

The underlying attempt of this thesis is to provide a modelling framework which would be able to: (i) to support discussions around the Nationally Determined Contributions (NDCs) implications of the Paris Agreement, (ii) and to improve the relevance of models for policy decision.
Despite a large progress for energy-environment-economic modelling in decision support of policy-makers, we believed that there were still efforts to be made for the transparency of modelling representations, their limits and their incidences on results. Hybrid "complex" models provide powerful insights for policy-making but their validations require time to understand precisely the underlying mechanisms and avoid a black box denomination.

Hence, this thesis challenges the limits of macroeconomic modelling tools for climate policy analysis while clarifying technical approaches. In addition, it steps further in the building of hybrid models by gathering many relevant information sources (energy balance, national accounts, sectoral based studies, etc.).
The work has been conducted for France in order to contribute to climate policy discussion for national carbon transition. At its beginning, the work has started with the construction of the database for a new IMACLIM-S model that provides insights on crucial industrial sectors for carbon policy implications.

In Chapter 1, we gather information on data treatment for calibrating hybrid computable general equilibrium (CGE) models in order to bridge the gap between energy balance and economic accounting system. Data hybridisation methods are not standardised, and models are often elusive on the way they reconcile energy and economic information. Thus, we begin with a literature review on existing protocols, and, we pursue by describing the IMACLIM hybridisation procedure. Compared to existing methods, the procedure includes information about energy flows, heterogeneous prices and quantities coming from energy statistics, without alteration on this data. All this information is then introduced within a consistent social accounting framework. Relying on previous work at CIRED, we systemise the procedure that is implemented with deeper details on energy system. In addition, we extent it to physical flows other than energy. Indeed, we also embark physical flows for two industrial sectors:

steel and iron sector and cement sector. This extension provides a double opportunity. First it allows isolating "sub"-sectors that are originally aggregated into National Accounts. Secondly, it represents a chance for bridging the gap with technical system on energy-intensive sectors. At the end, we have built a hybrid Input-Ouput table (IOT) for France with twenty-nine sectors. Different hybridisation techniques have different impacts on key empirical features at the initial state of the economy which are commented in the chapter.

Therefore, Chapter 2 pursues to tackle the issue of different hybridisation techniques for energy policy evaluation. We have tried to demonstrate the incidences of the methods on results using a standard Capital-Labour-Energy ("KLEM") CGE model for energy policy evaluation. The model is alternatively calibrated either using different hybrid IOTs and the unmodified original input-output data from national accounts. We show that data treatment has substantial consequences: model calibrated on hybridised data produce systematically lower welfare costs estimates, when targeting energy reduction alternatively on firm consumptions and household consumptions. We conclude that hybridisation technique descriptions and the clarification of its incidences are important and overlooked in a context of Energy-Economy-Environment (E3) CGE model and climate policy analysis.

In parallel to the description of data treatment and their consequences in a standard CGE model, we have developed a new modelling platform around the France case to benefit from the empirical material of the thesis of previous chapters, and to be able to contribute to national climate policy debate.
Chapter 3 focuses on the development of the model. It presents the challenges of the new platform development. The framework particularly requires great flexibilities on the initial description to be easily adapted to a large range of economical context and countries. Compared to the other versions, it provides an "aggregation" module that allows to run simulations at different levels of sectoral granularity relying on a same consistent database. These flexibility options are set up with the view of facilitating upcoming international collaborations. Indeed, working at the country scale is consistent with the agenda of the fight against global warming under NDCs which need to combine mitigation objectives and economic objectives.
The chapter also introduces the IMACLIM-S FRANCE model by first giving a general overview and then detailing the economic modelling features used in the thesis. Part of the economical representation choices rely on previous IMACLIM-S developments and our specific methodological works are completing the overall model. The IMACLIM-S FRANCE model is hybrid CGE model built on a hybrid accounting system that highlights the interplay between sectors, and economic agents. It also represents "second best" economic systems with possible underemployment and imperfect markets of goods. In this thesis, the version used is based on a comparative static framework which computes a single step distortion of the economy to first isolate the analysis from the dynamic issues.

The development of a flexible Imaclim-S country platform provides an opportunity to highlight the implications of the sectoral description level for carbon tax policy analysis. Chapter 4 tackles the issues of aggregation consequences using Imaclim-S France model.
First, we analyse the impact of a carbon tax at a high level of sectoral aggregation (two energy sectors and the rest of the economy) to retrieve coincident mechanisms with similar works on anterior model version. Matching with literature, we find that macroeconomic results are sensitive to carbon tax revenue uses. By returning carbon tax revenues to firms or households, the overall economy is prejudiced by the environmental reform. By using revenues to reduce existing labour tax, a double dividend mechanism emerged with benefits for both the economy and the environment.
Then, we alternatively calibrate the model on different level of sectoral description and study the incidences on results of the CGE model disaggregation. We observe that macroeconomic results are slightly sensitive to the sectoral description. However, we observe that aggregated model hides important disparities among sectors. We conclude that to conciliate environmental challenges and economic issues, energy-intensive and trade-exposed sectors must be embarked into modelling framework to tackle competitiveness issues and thus better preserving the domestic economy. Finally, the chapter qualitatively confirms the interplay between wage formation and trade elasticities. But, it concludes on the necessity to better control the uncertainties range for the underlying parameters. Chapter 5 focuses on this issue.

Chapter 5 tackles the empirical challenges of the international trade settings for a disaggregated model. It also highlights the interplay between trade elasticities and wage curve for representing exposed and protected sectors to the any changes in the terms of trade following a fiscal reform.
We note that the importance of sectoral values given to trade elasticities is overlooked, and recent literatures with details on industrial sectors for France are not available. This is a similar problem to the articulation of top-down and bottom-up analyses in the sense that there is a gap between the trade elasticity to prices for a specific country, and what we could perform at the sectoral level. In this chapter, a major effort has been made to conduct discussions on the interpretation of trade elasticities from the literature because of the difference between elasticity assessment for volume transaction and for monetary transaction. We thus develop a protocol to help securing the consistency between econometric information and sectoral requirements of the hybrid Imaclim model in real volume.
Then, we propose a method to link wage formation to the degree of exposure, with sectoral specific assumptions. To do so, we define three categories with different settings for wage curve indexation according to the sector exposure. Heterogeneous sectoral wage curve allows taking into account concrete specificities for some sectors and their reactions to energy price increase. We end by observing that heterogeneous wage curve preserve the increase of energy cost share for industrial sectors compared to wage curve based on international prices for all industries.

In parallel to the empirical work around Imaclim-S France we have developed an input-output analysis for embodied emissions in trade and consumptions for France.
Chapter 6 presents this work. Competitiveness issues potentially involve carbon leakage, and attention is now given for embodied emissions in French imports. Indeed, the French carbon transition law states that these emissions should be stabilised while domestic emissions decrease. We propose a method which is based on the hybrid IOT to evaluate at the initial state different inventories of CO2. We show that consumption-based emissions are higher than production-based emissions and we study the drivers of emissions embodied in household consumptions with sectoral distribution. Under our own method, we asses emissions embodied in imports by relying on exogenous information on French international partners. The original idea was to link this Input-Ouput analysis (IOA) with Imaclim-S France model to implement border tax adjustment for carbon emissions. This linkage has been developed but the analyses on such a reform have been let for a next step of the work.

Obviously, by finishing this thesis, we are aware that our empirical work on France for climate policy analysis still needs further developments to provide a model with useful insights for stakeholders. The main goals has been to provide a transparent protocol from the data treatment to the model development, and to explicit the mechanisms at play with a sectoral disaggregated representation for climate policy reform in order to get a global picture with articulations between competitiveness issues and macroeconomic challenges. Some limits deserve to be pointed out. In fact, they represent next research steps for a robust model to understand possibilities and incidences of a low carbon transition in France.
First, our empirical studies have been focused on static comparative analysis without implementing dynamics through a growth engine. Implicitly, results give an economic picture of France at the year of calibration as if there had been a climate reform twenty years earlier with smooth transition toward the resulting outcomes. Prospective analyses with objectives at 2050 horizon using Imaclim-S France have started but first results are not reported in this thesis. Anyway, without recursive dynamic it is not possible to capture or force specific effects at different time within pathway toward the medium term horizon.
Secondly, the hybridisation work aims to bridge the gap between technical system and economic model. We do embark physical quantities, but so far we have not link Imaclim-S France with any bottom-up models. Coupling Imaclim-S France with engineering model is on the agenda for better consistency on technical constraints and elasticities of substitution.
Then, while developing the new version of Imaclim-S France , we implement a disaggregation option of households into ten income classes. This is a key point to study the equity issues under climate policy. Looking further the articulation sectoral wages and competitiveness with households' inequalities, would provide relevant analyses.
Finally, we have implemented within the Imaclim-S France modelling framework an IOA with the initial willing to test environmental reforms such as border tax adjustment for carbon. Even though we have not so far analysed such policy consequences, it represents an avenue

to explore new research areas. Nevertheless, because France is part of the Schengen area, it involves further development on the "rest of the World" representation. To be consistent, international trade of European partners with France should be separated from trade with the non-European "rest of the World".

Ultimately, we hope that this thesis will give important progresses, beyond the established results. We expect that the overall method developed can be useful for better understanding synergies for low carbon transition in France. It can provide insights on how the transition, using it as a possible lever for more inward-oriented economic developments, could change the French terms of the degree of the autonomy, the public finance, or the funding of the social protection. Obviously, we would be even more capable to discuss carbon transition if the modelling tool would be used to support sectoral studies in order to enriching the description of the economic growth engine in France.

At the end of this thesis, we conclude by reminding that the success of climate policy is an international matter by nature. Climate commitments are done at the regional scale but the objective of keeping a global warming below +2° is worldwide. If country scale modelling tools are required to analyse pathways and solutions to achieve energy transition and low-carbon society objectives, there is still a need to have a look on the incidence for a larger scale. We have developed a country modelling platform with the expectation of further deployments to quickly become a multi-country platform. In a large-range perspective, this could solve the scale integration problems in the analysis, between results provided by the worldwide models and results provided by country analysis.

Appendix A

Details on hybridisation procedure

A.1 Data sources

Economic information
INSEE - National accounts database
INSEE – EACEI Survey 2010 (Enquête sur les consommations d'énergie dans l'industrie)
INSEE – ESANE Survey 2010

Price information
SOeS - Pégase Database (Pétrole, Électricité, Gaz et Autres Statistiques de l'Énergie)
ENERDATA - Global Energy & CO2 Data
IAE - Prices and Taxes Database
ADEME – AMORCE Survey 2010 (Enquête sur les conditions d'accueil des professionnels dans les déchèteries publiques)

Physical information
Union Française des industries pétrolières (UFIP) – Database 2010
Comité professionnel du pétrole 2010
ODYSSEE Energy Efficiency Database
Bulletin statistique - Transport aérien commercial – Direction générale de l'aviation civile
IPCC - Guidelines for National Greenhouse Gas Inventories, Volume 2 : Energy - Chapter 2 (2006)
ADEME – Emission Factor Documentation – Carbon Database (2014)

Syndicat Français de l'Industrie Cimentière (SFIC)
World Steel Association

A.2 Input-Output tables for France

The database has been published on Mendeley Data (Le Treut and Ghersi, 2018). All tables are freely available under the following reference:
Le Treut, Gaëlle; Ghersi, Frédéric (2018), "Hybrid Input-Output tables for France at year 2010", Mendeley Data, v1, http://dx.doi.org/10.17632/gyv6hxcwt3.1

Table A.1 gives the correspondences with the INSEE nomenclature (NAF rev2).

Sectors of hybrid IOT	**NAF Rev2 INSEE**
Crude oil	A88.06
Natural gas	A38.DZ
Coking coal	A88.05
Bituminous coal	A88.05
Coke oven coke	A38CD
Other coal products	A88.24
Gasoline / biogasoline	A38CD
LPG	A38CD
Jet Fuel	A38CD
Diesel and biofuel	A38CD
Heating fuel	A38CD
Heavy fuel oil	A38CD
Other petroleum products	A38CD
Electricity	A38.DZ
Heat, Geothermal, Solar Th	A38.DZ
Iron and steel	A88.24.1/A88.24.2/A88.24.3
Non ferrous metals	A88.24.4/A88.24.5
Cement and clinker	A88.23.51
Other non-metallic minerals	A88.23
Construction	A88.41
Chemical and petrochemical	A.38.CE.CF
Paper, pulp and print	A88.17
Mining and quarrying	A88.07.08
Transport equipement	A88.29.30
Transport - Sectors	A.88.49.50.51
Agricuture and forestry	A88.01.02
Fishing	A88.03
Agri-food industry	A88.10
Composite	The rest

Table A.1 – Correspondence between hybrid Input-Ouput table (IOT) and NAF rev2 nomenclature from INSEE

France 2010, energy (physical and 'quasi' quantities (Mtoe, Mtons)		Crude oil	Natural gas	Coking coal	Bituminous coal	Coke oven coke	Other coal products	Gasoline + biogasoline	LPG	Jet Fuel	Diesel and biofuel	Heating fuel	Heavy fuel oil	Other petroleum products	Electricity	Heat, Geothermal, Solar Th
Energy sectors	Crude oil	-	-	-	-	-	-	17	2	5	25	10	5	4	-	-
	Natural gas	0	-	-	-	0	0	0	0	0	0	0	0	0	4	3
	Coking coal	-	-	-	-	3	1	-	-	-	-	-	-	-	-	-
	Bituminous coal	-	-	-	-	-	-	-	-	-	-	-	-	-	5	0
	Coke oven coke	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Other coal products	-	-	-	-	0	0	-	-	-	-	-	-	-	0	-
	Gasoline / biogasoline	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	LPG	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Jet Fuel	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Diesel and biofuel	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Heating fuel	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0
	Heavy fuel oil	-	-	-	-	-	-	-	-	-	-	-	-	-	1	0
	Other petroleum products	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0
	Electricity	0	0	-	0	0	0	0	0	0	0	0	0	0	-	0
	Heat, Geothermal, Solar Th	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Hybrid Industries	Iron and steel	-	0	-	-	0	0	0	0	0	0	0	0	0	0	0
	Cement and clinker	-	0	-	-	0	0	0	0	0	0	0	0	0	0	0

France 2010, energy (physical and 'quasi' quantities (Mtoe, Mtons)		Iron and steel	Non ferrous metals	Cement and clinker	Other non-metallic minerals	Construction	Chemical and petrochemical	Paper, pulp and print	Mining and quarrying	Transport equipement	Transport - Sectors	Agricuture and forestry	Fishing	Agri-food industry	Composite	Public consumption	Households consumption	Investment	Export	TOTAL USES	Output	Imports	BALANCE
Energy sectors	Crude oil	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	67	2	65	-
	Natural gas	1	0	0	1	0	1	1	0	0	0	0	0	2	11	14	-	-	3	43	1	42	-
	Coking coal	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	3	-	3	-
	Bituminous coal	2	0	0	0	-	0	0	-	-	-	-	-	0	0	0	-	-	0	8	0	8	-
	Coke oven coke	3	-	-	0	-	0	-	-	0	-	-	-	0	0	-	-	-	0	3	2	1	-
	Other coal products	0	-	-	-	-	-	-	-	-	-	-	-	-	0	0	-	-	0	1	1	0	-
	Gasoline / biogasoline	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	-	-	7	15	14	1	-
	LPG	0	0	0	0	-	1	0	0	0	0	0	-	0	1	1	-	-	1	4	2	2	-
	Jet Fuel	-	-	-	-	-	-	-	-	-	3	-	-	-	0	-	-	-	5	8	4	4	-
	Diesel and biofuel	0	0	0	0	0	1	0	0	0	8	2	0	0	7	16	-	-	3	38	22	16	-
	Heating fuel	0	0	0	0	0	1	0	0	0	2	0	0	0	4	6	-	-	-	13	8	5	-
	Heavy fuel oil	-	0	0	0	-	0	0	0	0	1	0	-	0	0	0	-	-	8	11	4	7	-
	Other petroleum products	0	0	1	0	-	2	-	-	-	-	-	-	0	0	0	-	-	3	6	4	2	-0
	Electricity	1	1	0	0	0	2	1	0	1	1	0	0	1	15	14	-	-	4	42	40	2	-
	Heat, Geothermal, Solar Th	-	-	-	-	-	-	-	-	-	-	0	-	0	2	0	-	-	-	2	2	-	-
Hybrid Industries	Iron and steel	10	1	0	0	0	0	0	0	2	0	0	-	0	12	0	-	0	20	46	30	16	-
	Cement and clinker	0	0	15	2	1	0	0	0	1	0	0	0	0	12	2	-	-	1	36	33	3	-

Table A.2 – Hybrid input-output table in quantities for France

France 2010, CO2 Emissions from energy consumption		Crude oil	Natural gas	Coking coal	Bituminous coal	Coke oven coke	Other coal products	Gasoline + biogasoline	LPG	Jet Fuel	Diesel and biofuel	Heating fuel	Heavy fuel oil	Other petroleum products	Electricity	Heat, Geothermal, Solar Th
Energy sectors	Crude oil	-	-	-	-	-	-	4.8	0.2	1.9	8.7	3.3	1.0	0.2	-	-
	Natural gas	0.0	-	-	-	0.0	0.0	0.5	0.1	0.2	0.7	0.3	0.1	0.1	9.8	5.9
	Coking coal	-	-	-	-	10.0	2.7	-	-	-	-	-	-	-	-	-
	Bituminous coal	-	-	-	-	-	-	-	-	-	-	-	-	-	19.3	0.0
	Coke oven coke	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Other coal products	-	-	-	-	1.9	0.5	-	-	-	-	-	-	-	3.5	-
	Gasoline + biogasoline	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	LPG	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Jet Fuel	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Diesel and biofuel	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Heating fuel	-	-	-	-	-	-	-	-	-	-	-	-	-	0.4	0.0
	Heavy fuel oil	-	-	-	-	-	-	-	-	-	-	-	-	-	2.7	0.0
	Other petroleum products	-	-	-	-	-	-	-	-	-	-	-	-	-	0.3	0.5
	Electricity	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Heat, Geothermal, Solar Th	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
TOTAL Direct Emissions		0.0	-	-	-	12.0	3.2	5.3	0.2	2.0	9.4	3.6	1.1	0.3	36.0	6.5

France 2010, CO2 Emissions from energy consumption		Iron and steel	Non ferrous metals	Cement and clinker	Other non-metallic minerals	Construction	Chemical and petrochemical	Paper, pulp and print	Mining and quarrying	Transport equipement	Transport - Sectors	Agricuture and forestry	Fishing	Agri-food industry	Composite	Households consumption	TOTAL USES
Energy sectors	Crude oil	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	20.2
	Natural gas	1.9	0.5	0.7	2.9	0.1	1.9	2.0	0.1	1.1	0.2	0.5	0.0	5.6	24.8	33.8	93.9
	Coking coal	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	12.7
	Bituminous coal	6.3	0.0	1.2	0.4	-	1.2	0.1	-	-	-	-	-	1.0	0.5	1.6	31.8
	Coke oven coke	12.1	-	-	0.3	-	0.1	-	-	0.0	-	-	-	0.1	0.1	-	12.7
	Other coal products	2.6	-	-	-	-	-	-	-	-	-	-	-	-	0.1	0.3	9.0
	Gasoline + biogasoline	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.6	0.1	0.0	0.0	0.7	20.7	22.2
	LPG	0.0	0.0	0.0	0.0	-	2.1	0.0	0.0	0.0	0.0	0.7	-	0.2	1.7	3.5	8.5
	Jet Fuel	-	-	-	-	-	-	-	-	-	9.5	-	-	-	0.0	-	9.5
	Diesel and biofuel	0.1	0.1	0.1	0.2	0.2	4.2	0.1	0.1	0.3	23.1	7.1	0.8	0.7	20.9	47.1	105.0
	Heating fuel	0.0	0.0	0.1	0.1	0.1	2.2	0.0	0.3	0.0	4.8	1.0	0.1	0.1	10.9	18.5	38.6
	Heavy fuel oil	-	0.0	0.1	1.0	-	1.0	0.1	0.0	0.0	2.3	0.1	-	0.8	0.4	0.6	9.2
	Other petroleum products	0.0	0.4	1.6	0.0	-	7.7	-	-	-	-	-	-	0.0	0.7	0.9	12.2
	Electricity	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Heat, Geothermal, Solar Th	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
TOTAL Direct Emissions		23.1	1.1	3.9	5.0	0.3	20.4	2.5	0.6	1.5	40.6	9.5	0.9	8.6	60.8	127.0	

Table A.3 – Hybrid input-output table of CO_2 emissions for France

France, 2010 - Prices (€/toe, €/tons)		Crude oil	Natural gas	Coking coal	Bituminous coal	Coke oven coke	Other coal products	Gasoline + biogasoline	LPG	Jet Fuel	Diesel and biofuel	Heating fuel	Heavy fuel oil	Other petroleum products	Electricity	Heat, Geothermal, Solar Th	Iron and steel	Non ferrous metals	Cement and clinker	Other non-metallic minerals
Energy sectors	Crude oil	436	436	436	436	436	436	436	436	436	436	436	436	436	436	436	436	436	436	436
	Natural gas	329	439	439	439	329	329	329	329	329	329	329	329	329	329	329	329	329	329	329
	Coking coal	238	238	238	238	238	238	238	238	238	238	238	238	238	238	238	238	238	238	238
	Bituminous coal	146	146	146	146	146	146	146	146	146	146	146	146	146	132	172	172	172	172	172
	Coke oven coke	386	386	386	386	386	386	386	386	386	386	386	386	386	386	386	386	386	386	386
	Other coal products	349	349	349	349	329	329	349	349	349	349	349	349	349	329	349	329	349	349	349
	Gasoline / biogasoline	1 099	1 099	1 099	1 099	1 099	1 099	1 099	1 099	1 099	1 099	1 099	1 099	1 099	1 099	1 099	1 430	1 430	1 430	1 430
	LPG	879	879	879	879	879	879	879	879	879	879	879	879	879	879	879	1 076	1 076	1 076	1 076
	Jet Fuel	532	532	532	532	532	532	532	532	532	532	532	532	532	532	532	532	532	532	532
	Diesel and biofuel	1 016	1 016	1 016	1 016	1 016	1 016	1 016	1 016	1 016	1 016	1 016	1 016	1 016	1 016	1 016	1 135	1 135	1 135	1 135
	Heating fuel	642	642	642	642	642	642	642	642	642	642	642	642	642	596	596	596	596	596	596
	Heavy fuel oil	440	440	440	440	440	440	440	440	440	440	440	440	440	409	409	440	409	409	409
	Other petroleum products	522	522	522	522	522	522	522	522	522	522	522	522	522	526	526	526	600	600	600
	Electricity	580	580	788	580	580	580	580	580	580	580	580	580	580	788	580	504	504	504	504
	Heat, Geothermal, Solar Th	682	682	682	682	682	682	682	682	682	682	682	682	682	682	682	682	682	682	682
Hybrid Industries	Iron and steel	610	912	610	610	912	912	912	912	912	912	912	912	912	912	912	90	912	912	912
	Cement and clinker	138	195	138	138	195	195	195	195	195	195	195	195	195	195	195	195	195	58	195

France, 2010 - Prices (€/toe, €/tons)		Construction	Chemical and petrochemical	Paper, pulp and print	Mining and quarrying	Transport equipement	Transport - Sectors	Agricuture and forestry	Fishing	Agri-food industry	Composite	Public consumption	Households consumption	Investment	Export
Energy sectors	Crude oil	436	436	436	436	436	436	436	436	436	436	436	436	436	458
	Natural gas	476	329	329	408	408	408	476	476	408	408	725	530	530	201
	Coking coal	238	238	238	238	238	238	238	238	238	238	238	238	238	238
	Bituminous coal	146	172	172	146	146	146	146	146	172	172	172	187	187	132
	Coke oven coke	386	386	386	386	386	386	386	386	386	386	386	386	386	386
	Other coal products	349	349	349	349	349	349	349	349	349	112	779	383	383	387
	Gasoline / biogasoline	1 430	1 430	1 430	1 430	1 430	1 430	1 430	663	1 430	1 430	1 711	1 796	1 796	663
	LPG	879	1 076	1 076	1 076	1 076	917	1 076	879	1 076	1 076	1 425	1 463	1 463	469
	Jet Fuel	532	532	532	532	532	532	532	532	532	532	532	532	532	532
	Diesel and biofuel	1 135	1 135	1 135	1 135	1 135	1 099	698	627	1 135	1 135	1 357	1 385	1 385	512
	Heating fuel	596	596	596	596	596	596	604	596	596	596	835	776	776	590
	Heavy fuel oil	440	409	409	409	409	409	419	440	409	409	428	1 232	1 232	450
	Other petroleum products	522	512	522	522	522	522	522	522	600	600	532	781	781	512
	Electricity	865	504	504	727	580	580	865	865	580	865	1 451	1 205	1 205	518
	Heat, Geothermal, Solar Th	682	682	682	682	682	682	684	682	684	684	769	827	827	675
Hybrid Industries	Iron and steel	912	912	912	912	912	912	912	610	912	912	912	740	912	616
	Cement and clinker	195	195	195	195	195	195	195	195	195	195	195	153	153	212

Table A.4 – Hybrid input-output table in prices for France

	France, 2010, million of euro	Crude oil	Natural gas	Coking coal	Bituminous coal	Coke oven coke	Other coal products	Gasoline + biogasoline	LPG	Jet Fuel	Diesel and biofuel	Heating fuel	Heavy fuel oil	Other petroleum products	Electricity	Heat, Geothermal, Solar Th	Iron and steel	Non ferrous metals	Cement and clinker	Other non-metallic minerals	Construction	Chemical and petrochemical	Paper, pulp and print	Mining and quarrying	Transport equipement	Transport - Sectors	Agriculture and forestry	Fishing	Agri-food industry	Composite	Public consumption	Households consumption	Investment	Export	TOTAL USES
	Crude oil	0	0	0	0	0	0	7 408	773	2 360	10 897	4 149	2 025	1 609	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24	29 246
	Natural gas	3	0	0	0	0	0	70	7	22	103	39	19	15	1 379	826	262	71	101	403	19	264	287	24	188	36	100	0	967	4 313	10 436	0	0	513	20 470
	Coking coal	0	0	0	0	602	163	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20	784
	Bituminous coal	0	0	0	0	0	0	0	0	0	0	0	0	0	642	2	273	0	52	18	0	54	5	0	0	0	0	0	45	24	70	0	0	2	1 187
	Coke oven coke	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1 042	0	0	27	0	6	0	0	2	0	0	0	8	12	0	0	0	32	1 129
	Other coal products	0	0	0	0	81	22	0	0	0	0	0	0	0	148	0	113	0	0	0	0	0	0	0	0	0	0	0	0	2	58	0	0	1	426
	Gasoline / biogasoline	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	2	4	3	73	2	2	5	337	33	2	12	364	13 380	0	0	4 419	18 642
Energy sectors	LPG	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	10	10	18	0	873	16	15	17	7	308	0	98	712	1 945	0	0	513	4 551
	Jet Fuel	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1 716	0	0	0	1	0	0	0	2 704	4 421
	Diesel and biofuel	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	28	28	46	93	62	1 581	46	50	104	8 445	1 644	161	260	7 861	21 211	0	0	1 408	43 026
	Heating fuel	0	0	0	0	0	0	0	0	0	0	0	0	0	77	1	8	8	26	13	17	434	4	51	2	947	197	25	22	2 156	5 141	0	0	0	9 126
	Heavy fuel oil	0	0	0	0	0	0	0	0	0	0	0	0	0	350	0	0	6	14	131	0	127	20	5	0	308	19	0	104	48	84	0	0	3 456	4 674
	Other petroleum products	0	0	0	0	0	0	0	0	0	0	0	0	0	54	90	6	85	320	9	0	1 211	0	0	0	0	0	0	2	131	151	0	0	1 327	3 385
	Electricity	16	10	0	3	0	0	40	4	13	59	22	11	9	0	105	431	315	155	232	17	1 166	388	35	367	609	246	9	839	12 762	19 737	0	0	2 237	39 836
	Heat, Geothermal, Solar Th	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	181	1 400	74	0	0	0	1 659
	Iron and steel	0	4	0	0	0	17	2	4	0	18	4	2	3	15	0	870	639	14	206	147	208	14	8	1 993	12	11	0	9	11 294	167	0	60	12 509	28 232
	Non ferrous metals	0	6	0	0	1	26	3	6	0	28	6	3	4	22	0	5 748	959	10	320	221	311	21	13	2 989	18	16	0	14	16 938	250	0	90	7 786	35 809
	Cement and clinker	0	6	0	0	0	0	0	0	0	1	0	0	0	20	0	32	8	853	469	213	79	15	34	118	16	32	3	32	2 384	425	0	0	278	5 019
	Other non-metallic minerals	0	47	0	0	0	2	1	2	0	8	2	1	1	165	4	268	65	434	2 673	1 803	670	127	287	1 000	132	269	24	273	20 137	3 562	0	0	4 483	36 438
	Construction	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1 482	0	0	0	0	0	0	0	0	3	0	0	44 214	0	45 699
	Chemical and petrochemical	0	703	0	0	5	4	32	57	3	256	55	27	40	2 459	52	117	623	46	440	227	24 204	1 052	132	1 703	130	6 690	371	1 424	30 404	33 980	25 869	0	74 547	205 653
	Paper, pulp and print	0	6	0	0	0	0	1	2	0	10	2	1	2	22	0	4	19	25	240	61	1 393	3 404	27	191	75	158	6	1 708	14 569	4 899	0	0	6 413	33 239
Other industrial sectors	Mining and quarrying	0	1	0	0	0	14	0	1	0	2	0	0	0	2	0	431	2 295	120	1 144	180	1 173	121	138	79	8	117	43	705	2 513	76	0	0	627	9 790
	Transport equipement	0	5	0	0	0	0	1	2	0	7	1	1	1	16	0	6	33	4	37	7	49	13	8	33 749	1 853	172	2	64	17 328	64 747	142	26 006	81 526	225 782
	Transport - Sectors	0	9	0	0	0	0	3	6	0	25	5	3	4	33	1	6	30	6	60	33	199	28	13	80	10 974	48	4	167	20 939	25 161	2 836	0	16 453	77 128
	Agriculture and forestry	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	48	129	0	0	0	13 757	0	32 874	5 199	28 793	0	1 348	12 867	95 014
	Fishing	0	4	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0	7	6	0	0	0	0	7	42	1 903	362	3 568	0	0	519	6 430
	Agri-food industry	0	9	0	0	0	0	2	4	0	16	3	2	2	32	1	15	79	5	50	52	2 269	306	104	139	280	6 098	75	27 956	36 229	120 103	210	0	24 876	218 917
	Composite	206	2 393	0	4	41	82	274	486	29	2 174	462	225	336	8 377	178	2 496	12 742	712	6 803	23 652	26 656	7 200	1 860	60 751	35 031	9 842	565	28 611	1 053 198	733 310	492 586	305 003	200 613	3 016 897
	Labour_income	21	1 267	0	1	3	14	20	35	2	156	33	16	24	4 435	94	1 348	1 295	194	2 967	5 182	7 616	2 021	570	9 349	24 533	11 018	330	13 249	654 675					
	Labour_Tax	9	557	0	1	1	6	9	15	1	69	15	7	11	1 948	41	592	569	94	1 294	2 277	3 346	888	250	4 107	10 778	4 840	145	5 820	287 605					
Value-added	Capital_income	116	1 343	0	2	2	7	16	28	2	124	26	13	19	4 700	100	630	740	238	611	1 154	2 968	939	1 303	5 069	11 563	10 743	343	4 180	222 606					
	Production_Tax	-6	287	0	0	2	2	11	19	1	87	18	9	13	1 006	21	192	357	179	229	435	1 102	278	99	1 063	1 351	-6 418	-1	1 488	55 482					
	Profit_margin	69	1 237	0	-2	6	4	42	74	4	332	71	34	51	4 329	92	398	225	76	905	3 259	4 969	326	-270	-1 535	-555	5 931	-54	452	328 294					
	M_value	28 751	9 799	784	1 039	311	35	627	1 163	1 932	8 117	1 912	1 729	615	1 025	0	10 972	12 401	310	6 373	0	62 069	9 223	2 571	66 458	2 995	8 183	1 368	26 736	245 164					
	Trade_margins	25	0	0	107	56	16	368	654	39	2 927	623	303	452	0	0	1 436	1 659	777	8 360	0	50 314	4 062	1 184	24 640	0	19 025	2 668	55 665	-175 359	-				
	Transp_margins	21	266	0	6	11	5	69	123	7	552	117	57	85	932	20	440	508	150	1 611	0	4 416	1 222	1 207	1 181	-30 229	1 648	124	6 133	9 316	-				
	SpeMarg_Crude_oil	0	-1	0	0	0	0	0	0	0	0	0	0	0	-6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0					
	SpeMarg_Natural_gas	0	0	0	0	0	0	0	0	0	0	0	0	0	-4	0	1	0	2	0	0	0	0	0	0	0	0	0	0	0					
	SpeMarg_Coking_coal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0					
	SpeMarg_Bituminous_coal	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0					
	SpeMarg_Coke	0	0	0	0	0	-5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0					
	SpeMarg_Other_coal	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0					
	SpeMarg_Gasoline	0	-23	0	0	0	0	0	0	0	0	0	0	0	-14	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0					
	SpeMarg_LPG	0	-2	0	0	0	0	0	0	0	0	0	0	0	-1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0					
	SpeMarg_Jetfuel	0	-7	0	0	0	0	0	0	0	0	0	0	0	-5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0					
	SpeMarg_Fuel	0	-34	0	0	0	0	0	0	0	0	0	0	0	-21	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0					
	SpeMarg_Fuel_oil	0	-13	0	0	0	0	0	0	0	0	0	0	0	-8	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0					
	SpeMarg_Heavy_fuel_oil	0	-6	0	0	0	0	0	0	0	0	0	0	0	-4	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0					
	SpeMarg_Other_fuel_prod	0	-5	0	0	0	0	0	0	0	0	0	0	0	-3	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0					
	SpeMarg_Electricity	0	-460	0	-68	0	-9	0	0	0	0	-6	-27	0	0	0	5	0	6	0	0	0	0	0	0	0	0	0	0	0					
	SpeMarg_HeatGeoSol_Th	0	-276	0	0	0	0	0	0	0	0	0	0	1	-38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0					
	SpeMarg_Steel_Iron	0	-87	0	42	0	-7	0	1	0	3	-1	0	0	-243	0	-5 023	0	9	0	0	0	0	0	0	0	0	0	0	0					
Margins	SpeMarg_NonFerrousMetals	0	-24	0	0	0	0	0	2	0	3	-1	0	11	-178	0	212	0	2	0	0	0	0	0	0	0	0	0	0	0					
	SpeMarg_Cement	0	-34	0	8	0	0	0	2	0	5	-2	-1	41	-88	0	5	0	-1 182	0	0	0	0	0	0	0	0	0	0	0					
	SpeMarg_OthMin	0	-135	0	3	0	0	1	3	0	10	-1	-10	1	-131	0	68	0	136	0	0	0	0	0	0	0	0	0	0	0					
	SpeMarg_Buildings_constr	0	1	0	0	0	0	1	0	0	6	-1	0	0	1	0	49	0	62	0	0	0	0	0	0	0	0	0	0	0					
	SpeMarg_ChemicalPharma	0	-88	0	8	0	0	17	159	0	165	-33	-10	-24	-658	0	69	0	23	0	0	0	0	0	0	0	0	0	0	0					
	SpeMarg_Paper	0	-96	0	1	0	0	0	3	0	5	0	-2	0	-219	0	5	0	4	0	0	0	0	0	0	0	0	0	0	0					
	SpeMarg_Mining	0	-2	0	0	0	0	1	3	0	5	-4	0	0	-3	0	3	0	10	0	0	0	0	0	0	0	0	0	0	0					
	SpeMarg_TranspEquipment	0	-14	0	0	0	0	1	3	0	11	0	0	0	-132	0	660	0	34	0	0	0	0	0	0	0	0	0	0	0					
	SpeMarg_Transport_serv	0	-3	0	0	0	0	78	0	-2	640	-72	-24	0	-219	0	4	0	5	0	0	0	0	0	0	0	0	0	0	0					
	SpeMarg_Agri_Forestry	0	8	0	0	0	0	8	56	0	-749	-32	-1	0	22	0	4	0	9	0	0	0	0	0	0	0	0	0	0	0					
	SpeMarg_Fishing	0	0	0	0	0	0	-1	0	0	-100	-2	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0					
	SpeMarg_Food_industry	0	-73	0	7	0	0	3	18	0	27	-2	-8	0	-301	1	3	0	9	0	0	0	0	0	0	0	0	0	0	0					
	SpeMarg_Composite	0	-326	0	4	0	-5	84	130	0	823	-164	-4	17	1 132	4	3 740	0	690	0	0	0	0	0	0	0	0	0	0	0					
	SpeMarg_C	0	2 268	0	-5	0	27	-635	-33	0	-367	301	-133	-47	2 192	-5	26	0	83	0	0	0	0	0	0	0	0	0	0	0					
	SpeMarg_G	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0					
	SpeMarg_I	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0					
	SpeMarg_X	1	-566	0	0	0	0	441	-348	2	-488	0	220	-1	-1 072	0	145	0	97	0	0	0	0	0	0	0	0	0	0	0					
	VA_Tax	0	2 006	0	16	0	5	657	695	0	3 584	871	14	50	6 823	13	40	24	40	656	5 006	5 075	1 062	28	12 907	1 353	1 612	172	6 557	86 315					
	Energy_Tax_IC	0	275	0	0	0	0	294	149	0	6 133	320	29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0					
Taxes	Energy_Tax_FC	0	0	0	0	0	0	8 660	188	0	7 096	315	119	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0					
	ClimPolCompensbySect	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0					
	OtherIndirTax	16	232	0	12	5	0	31	55	3	246	52	25	38	813	17	19	14	6	40	185	723	20	42	-935	-5 593	-1 335	3	360	41 518					
	Total SUPPLY	29 246	20 470	784	1 187	1 129	426	18 642	4 551	4 421	43 026	9 126	4 674	3 385	39 836	1 659	28 232	35 809	5 019	36 438	45 699	205 653	33 239	9 790	225 782	77 128	95 014	6 430	218 917	3 016 897					

Table A.5 – Hybrid input-output table for France - Values

Appendix B

IMACLIM-S FRANCE notation

Calibration consists in providing a set of values to all variables and then determining the values that should be given to the parameters so that the set of equations defining the model holds. The exercise is therefore to determine what values the parameters must take in order for the values drawn from national accounts to be linked by the set of equations. However, all parameters do not receive their values from the calibration: the carbon tax, for instance, is a purely exogenous parameter; other parameters have their values set according to some econometric estimation on data superseding the national accounts as described by the input-output table and the economic account table. As a result of these distinctions, the notations below are presented in three categories, (i) the variables of the model properly speaking, (ii) the parameters of the model that are calibrated on statistical data, and (iii) the exogenous parameters. Within each of these categories the notation are listed in alphabetical order (the Greek letters are classified according to their English name rather than according to their equivalent in the Latin alphabet).

B.1 Variables of IMACLIM-S FRANCE

Variable Name	**Description**
α_{ij}	Technical coefficient, quantity of good i entering the production of one good j
OT	Other transfers
OT_H	Other transfers to the households
OT_F	Other transfers to firms

continued on next page

OT_G	Other transfers to the public administrations
AFC_H	Self-financing capacity of class h
AFC_F	Self-financing capacity of firms
AFC_G	Self-financing capacity of the public administrations
AFC_{ROW}	Self-financing capacity of the rest of the world
C_{i_h}	Final consumption of good i by household class h
D_h	Net debt of class h - Calibrated on the net financial assets of 'Comptes de patrimoine' from Institut national de la statistique et des études économiques (INSEE)
D_F	Net debt of firms - Calibrated on the net financial assets of 'Comptes de patrimoine' from INSEE
D_G	Net public debt - Calibrated on the net financial assets of 'Comptes de patrimoine' from INSEE
D_{ROW}	Net debt of the rest of the world - Calibrated on the net financial assets of 'Comptes de patrimoine' from INSEE
d_i	Reform-induced interest rate differential
GOS_H	Gross operating surplus accruing to households
GOS_F	Gross operating surplus accruing to firms
GOS_G	Gross operating surplus accruing to public administrations
$GFCF_h$	Gross fixed capital formation of household class h
$GFCF_F$	Gross fixed capital formation of firms
$GFCF_G$	Gross fixed capital formation of public administrations
$\gamma_{IC_{ij}}$	CO2 emissions per unit of good i consumed in the production of good j
γ_{FC_i}	CO2 emissions per unit of good i consumed by households
G_i	Final public consumption of good i
i_H	Effective interest rate on the net debt of households
i_F	Effective interest rate on the net debt of firms
i_G	Effective interest rate on the net debt of public administrations
I_i	Final consumption of good i for the investment
CPI	Consumer price index (Fisher)
k_i	Capital intensity of good i
l_i	Labour intensity of good i
LS_H	Lump-sum transfers from carbon tax revenues to households
LS_F	Lump-sum transfers from carbon tax revenues to firms

continued on next page

ω_{L_h}	Share of labour income accruing to household class h
M_i	Imports of good i
SM	Sum across goods and uses of the specific sale margins
N_{L_h}	Employed population of household class h (full time equivalent)
p_{M_i}	Import price of good i
p_i	Average price of the resource in good i (domestically produced and imported)
$p_{IC_{ij}}$	Price of good i for the production of good j
p_{C_i}	Consumption price of good i
p_{G_i}	Public price of good i
p_{I_i}	Investment price of good i
Φ_i	Endogenous technical progress coefficient applying to the production of good i
p_K	Cost of capital input (weighted sum of investment prices)
p_{L_i}	Cost of labour input in the production of good i
p_{X_i}	Export price of good i
p_{Y_i}	Production price of good i
RBT_F	Before-tax gross disposable income of firms
RBT_h	Before-tax gross disposable income of household class h
RBT_H	Before-tax gross disposable income of all households classes (H)
R_F	Gross disposable income of firms
R_G	Gross disposable income of public administrations
R_h	Gross disposable income of household class h
R_{CONS_h}	Consumed income of household class h
R_O	Social transfers to households not elsewhere included
R_U	Sum of unemployment benefits
R_P	Sum of retirement pensions
ρ_{O_h}	Average per capita not-elsewhere-included transfers of household class h
ρ_{P_h}	Average per capita pensions of household class h
ρ_{U_h}	Average per capita unemployment benefits of household class h
σ_{Θ_i}	Elasticity of the decreasing returns coefficient of production i to its output.
T	Total taxes and social contributions
T_L	Sum of social contributions of the employer and the employee

continued on next page

T_{En}	Fiscal revenues from excise tax on energy products (so called Taxe intérieure de consommation sur les produits énergétiques (TICPE))
T_{OP}	Fiscal revenues of excise taxes other than the energy product tax
T_{VA}	Value-added tax revenues
T_F	Firms tax revenues
T_{I_h}	Revenue from household class h income tax payments
T_{D_h}	Revenue from other direct taxes paid by household class h
T_{carb}	Carbon tax revenues
Θ_i	Decreasing returns coefficient for the production of good i
τ_{T_L}	Social contribution rate applicable to net wages
$\tau_{CM_{COM}}$	Trade mark-up on the commercial good or on the aggregate encompassing it
$\tau_{CM_{TRANS}}$	Transport mark-up on the transport good or on the aggregate encompassing it
u	Unemployment rate
u_h	Household class h unemployment rate
ω_i	Average net wage in the production of good i
Ω	Average net wage across productions
X_i	Good i exports
Y_i	Good i production

Table B.1 – Variables for solving IMACLIM-S FRANCE

B.2 Parameters calibrated on statistical data

Variable Name	**Description**
$\overline{L}$	Total active population in full-time equivalents
$\overline{L_h}$	Active population of household class h in full-time equivalents
λ_{ij}, λ_{L_i}, λ_{K_i}	Coefficients of the Constant Elasticity of Substitution (CES) production function governing the variables shares of conditional factor demands. Calibrated on the first order conditions of cost minimisation applied to the no-policy equilibrium (functions of prices $p_{IC_{ji_0}}$, $p_{L_{i_0}}$ and $p_{K_{i_0}}$, of quantities α_{ji_0}, l_{i_0} and k_{i_0}, and of basic need shares β_{ji}, β_{K_i} and β_{L_i}).

continued on next page

$\overline{N_h}$	Total population of household class h.
$\overline{N_{P_h}}$	Number of retirees of household class h.
$\overline{\omega_{OT_h}}$	Share of the other transfers accruing to households devoted to household class h.
$\overline{\omega_{OT_H}}$	Share of other transfers accruing to households (all classes together). Calibrated on the economic account table.
$\overline{\omega_{OT_F}}$	Share of other transfers accruing to firms. Calibrated on the economic account table (aggregate of financial and non financial firms, and of non-profit organisations).
$\overline{\omega_{OT_G}}$	Share of other transfers accruing to public administrations. Calibrated on the economic account table.
$\overline{\omega_{K_h}}$	Share of the capital income of households accruing to household class h. Calibrated as the share accruing to household class h of revenues other than those of labour, in the m-class aggregation .
$\overline{\omega_{K_H}}$	Share of capital income accruing to households (all classes). Calibrated on the economic account table.
$\overline{\omega_{K_F}}$	Share of capital income accruing to firms. Calibrated on the economic account table (aggregate of financial and non financial firms, and of non-profit organisations).
$\overline{\omega_{K_G}}$	Share of capital income accruing to public administrations. Calibrated on the economic account table
$\overline{\pi_i}$	Mark-up rate of profit margins(rate of net operating surplus) in the production of good i. Calibrated as the ratio of net operating surplus to distributed output (input-output table and more broadly INSEE data).
$\overline{t_{OPT_i}}$	Excise taxes other than the energy product tax per unit of consumption of good i. Calibrated as the ratio of the corresponding fiscal revenue of each good i (input-output table data after subtraction of the energy product tax) to total domestic consumption in the no-policy equilibrium $Yi0 + Mi0 - Xi0$ (exports are assumed to be exempted).

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$\overline{t_{EnT_{FC_i}}}$	energy product tax per *toe* of energy product consumptions by households. The energy product tax is isolated from other excise taxes. The split between energy product tax on intermediate vs. final sales is calibrated on data from the *Comité professionnel Du Pétrole (CPDP)*.
$\overline{t_{EnT_{IC_i}}}$	energy product tax per *toe* of energy product in intermediate consumptions. The energy product tax is isolated from other excise taxes. The split between energy product tax on intermediate vs. final sales is calibrated on data from the Comité Professionnel Du Pétrole (CPDP).
$\overline{\tau_{TI_h}}$	Effective income tax rate of household class h. Calibrated as the ratio of income tax payments to the before-tax gross disposable income. Both aggregates are distributed among household classes based on the shares observed in the m-class aggregation .
$\overline{\tau_{T_F}}$	Effective firms tax rate. Calibrated as the ratio of the firms tax fiscal revenue, to the share of the gross operating surplus (GOS) accruing to firms.
$\overline{\tau_{SM_{IC_{ij}}}}$	Specific mark-up rate on intermediate consumptions (if i is not a hybrid good then the rate is nil). Defined during the hybridisation procedure.
$\overline{\tau_{SM_{C_i}}}$	Specific mark-up rate on household consumptions (if i is not a hybrid good then the rate is nil). Defined during the hybridisation procedure.
$\overline{\tau_{SM_{G_i}}}$	Specific mark-up rate on public consumptions (if i is not a hybrid good then the rate is nil). Defined during the hybridisation procedure. Under the convention that public energy consumptions are nil.
$\overline{\tau_{SM_{I_i}}}$	Specific mark-up rate on investment (if i is not a hybrid good then the rate is nil). Defined during the hybridisation procedure.
$\overline{\tau_{SM_{X_i}}}$	Specific mark-up rate on exports (if i is not a hybrid good then the rate is nil). Defined during the hybridisation procedure.
$\overline{\tau_{S_h}}$	Savings rate of household class h. Calibrated as the ratio of the savings of class h to its gross disposable income (R_h), with the data being derived from all the main data sources.

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$\overline{\tau_{VAT_i}}$	Value-added tax rate applying to the final consumption of good i. Calibrated on input-output table data by treating the VAT as a simple sales tax levied indifferently on C, G and i.

Table B.2 – Calibrated parameters for IMACLIM-S FRANCE

B.3 Exogenous parameters

Variable Name	**Description**
$\beta_{\omega_{CPI_i}}$	Indexation coefficient of wage from good i on consumer price in the wage curve. The value "0" stands for no-indexation of wages on consumer price - wage curve is on nominal wage. The value "1" stands for a complete indexation of the wage curve on consumer price.
β_{i_h}	Share of the good i consumption of household class h that corresponds to a basic need. Set for each good i at a level that defines a basic need equal to 80% of the real consumption of the class for which it is the lowest.
$\beta_{IC_{ji}}$	Technical asymptote of the technical coefficient α_{ij} .
β_{K_i}	Technical asymptote of the capital intensity of good i.
β_{L_i}	Technical asymptote of the labour intensity of good i.
ϕL_i	Labour productivity improvements of good i.
σ	Substitution elasticity of the variable shares of production factors.
σ_{CR_i}	Income-elasticity of household consumption of good i. An econometric estimate over aggregate 1985-2006 data.
σ_{CP_i}	Price-elasticity of household consumption of good i. An econometric estimate over aggregate 1985-2006 data.
$\sigma_{M_{p_i}}$	Elasticity of the ratio of imports to domestic production of good i, to the corresponding terms of trade.
σ_{Θ_i}	Elasticity of the technical progress coefficient of production i to its fixed capital consumption (whose variations are taken as a proxy of those of cumulated investment).
$\sigma_{X_{p_i}}$	Elasticity of good i exports to the corresponding terms of trade.
σ_{w_u}	Elasticity of the average net wage (nominal or real, see supra) to the unemployment rate.

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$t_{carb_{IC}}$	Carbon tax on the carbon emissions of intermediate consumptions.
$t_{carb_{FC}}$	Carbon tax on the carbon emissions of household consumptions.
t_{ref}	Time of development of the reform (years).

Table B.3 – Exogenous parameters for IMACLIM-S FRANCE

Appendix C

"KLEM" model formulary of Chapter 2

Abbreviation	
C	Consumption
G	Government
I	Investment
X	Exports
K	Capital
M	Imports
SMC	Composite margins
SME	Energy margins
SPC	Finale consumption margins
SMG	Government margins
SMI	Investment margins
SMX	Export margins
VAT	Value added taxes
Excise E IC	Excise on energy interm. consumption
Excise E FC	Excise on energy final consumption
Excise Oth.	Other excise

Table C.1 – KLEM model notations

Appendix D

Further information on Chapter 4

D.1 Aggregated IMACLIM-S FRANCE model

Sectoral correspondance with disaggregated hybrid IOT	
Crude oil	PrimEn
Natural gas	PrimEn
Coking coal	PrimEn
Bituminous coal	PrimEn
Coke oven coke	PrimEn
Other coal products	PrimEn
Gasoline / biogasoline	FinEn
LPG	FinEn
Jet Fuel	FinEn
Diesel and biofuel	FinEn
Heating fuel	FinEn
Heavy fuel oil	FinEn
Other petroleum products	FinEn
Electricity	FinEn
Heat, Geothermal, Solar Th	FinEn
Iron and steel	AllComp
Non ferrous metals	AllComp
Cement and clinker	AllComp
Other non-metallic minerals	AllComp
Construction	AllComp
Chemical and petrochemical	AllComp
Paper, pulp and print	AllComp
Mining and quarrying	AllComp
Transport equipement	AllComp
Transport - Sectors	AllComp
Agricuture and forestry	AllComp
Fishing	AllComp
Agri-food industry	AllComp
Composite	AllComp

Table D.1 – Sectoral correspondence for three-sector IMACLIM-S FRANCE model

Wage curve indexed	Reference	Carbon tax rate at 500€/tCO_2 Half on international price Half on consumer price	On consumer price
Variation in percentage (%)	REF	W_HALF	W_CPI
Real GDP (Laspeyres)	4.61	3.06	-0.21
Imports/Domestic production ratio	1.37	1.42	1.54
Imports of Non Energy goods in volume	4.11	4.25	4.56
Exports of Non Energy goods in volume	0.14	-1.29	-4.30
Total Employment	6.26	4.54	0.93
Unemployment rate (% points)	-0.06	-0.04	-0.01
Net-of-tax wages	9.98	11.15	13.70
Labour Intensity (Laspeyres)	2.05	1.90	1.60
Labour tax rate (% points)	-0.25	-0.24	-0.21
Energy Input Price (Laspeyres)	164.10	164.23	164.70
Energy Intensity (Laspeyres)	-4.99	-6.05	-8.31
Energy cost share for composite sector	142.33	138.86	131.74
Production Price (Laspeyres)	1.21	2.83	6.40
Production Price Non Energy goods (Laspeyres)	-0.11	1.53	5.16
Real Households consumption (Laspeyres)	3.54	2.52	0.37
Energy in Households consumption	-0.63	-0.64	-0.67
Non Energy goods in Households consumption	4.18	3.16	1.03
Public Deficits	9.39	9.65	10.22
Total Emissions	-12.56	-13.29	-14.82

Table D.2 – Carbon tax impact with different options for wage curve indexation

Decarbonisation potential for households	Carbon tax rate at 500€/tCO_2 Low	Reference	High
Variation in percentage (%)	DCH_L	REF	DCH_H
Real GDP (Laspeyres)	4.98	4.61	3.93
Imports/Domestic production ratio	1.35	1.37	1.40
Imports of Non Energy goods in volume	3.81	4.11	4.66
Exports of Non Energy goods in volume	0.51	0.14	-0.55
Total Employment	6.44	6.26	5.91
Unemployment rate (% points)	-0.06	-0.06	-0.05
Net-of-tax wages	10.51	9.98	9.03
Labour Intensity (Laspeyres)	2.08	2.05	1.99
Labour tax rate (% points)	-0.26	-0.25	-0.23
Energy Input Price (Laspeyres)	163.99	164.10	164.30
Energy Intensity (Laspeyres)	-3.24	-4.99	-8.14
Energy cost share for composite sector	143.14	142.33	140.82
Production Price (Laspeyres)	0.81	1.21	1.98
Production Price Non Energy goods (Laspeyres)	-0.52	-0.11	0.66
Real Households consumption (Laspeyres)	3.65	3.54	3.34
Energy in Households consumption	0.00	-0.63	-1.79
Non Energy goods in Households consumption	3.65	4.18	5.13
Public Deficits	9.71	9.39	8.80
Total Emissions	-9.24	-12.56	-18.74

Table D.3 – Carbon tax impact with different decarbonisation potential for households

Sensility of external trade to prices	**Carbon tax rate at 500€/tCO_2**		
	Low	**Reference**	**High**
Variation in percentage (%)	TRD_L	REF	TRD_H
Real GDP (Laspeyres)	4.47	4.61	4.65
Imports/Domestic production ratio	1.36	1.37	1.37
Imports of Non Energy goods in volume	3.89	4.11	4.20
Exports of Non Energy goods in volume	0.18	0.14	0.16
Total Employment	6.13	6.26	6.30
Unemployment rate (% points)	-0.06	-0.06	-0.06
Net-of-tax wages	9.63	9.98	10.09
Labour Intensity (Laspeyres)	2.07	2.05	2.04
Labour tax rate (% points)	-0.25	-0.25	-0.25
Energy Input Price (Laspeyres)	164.04	164.10	164.12
Energy Intensity (Laspeyres)	-5.10	-4.99	-4.95
Energy cost share for composite sector	142.80	142.33	142.20
Production Price (Laspeyres)	0.98	1.21	1.28
Production Price Non Energy goods (Laspeyres)	-0.35	-0.11	-0.04
Real Households consumption (Laspeyres)	3.32	3.54	3.60
Energy in Households consumption	-0.64	-0.63	-0.63
Non Energy goods in Households consumption	3.96	4.18	4.24
Public Deficits	8.98	9.39	9.51
Total Emissions	-12.68	-12.56	-12.53

Table D.4 – Carbon tax impact with different trade elasticities

Wage curve Sensibility of external trade to prices Variation in percentage (%)	Carbon tax rate at 500€/tCO_2 Composite sector indexed on consumer price Low TDR_L+CPI	 Reference W_CPI
Real GDP (Laspeyres)	6.19	-0.21
Imports/Domestic production ratio	0.34	1.54
Imports of Non Energy goods in volume	18.77	4.56
Exports of Non Energy goods in volume	-9.47	-4.30
Total Employment	6.32	0.93
Unemployment rate (% points)	-0.06	-0.01
Net-of-tax wages	42.14	13.70
Labour Intensity (Laspeyres)	0.26	1.60
Labour tax rate (% points)	-0.19	-0.21
Energy Input Price (Laspeyres)	171.61	164.70
Energy Intensity (Laspeyres)	0.54	-8.31
Energy cost share for composite sector	103.59	131.74
Production Price (Laspeyres)	26.30	6.40
Production Price Non Energy goods (Laspeyres)	25.29	5.16
Real Households consumption (Laspeyres)	12.60	0.37
Energy in Households consumption	-0.32	-0.67
Non Energy goods in Households consumption	12.92	1.03
Public Deficits	40.65	10.22
Total Emissions	-7.73	-14.82

Table D.5 – Carbon tax impact with low trade elasticities and wage curve indexed on consumer price

D.2 The granularity effect of calibration

Sectoral correspondance with disaggregated hybrid IOT			
Original disaggregated IOT	**AGG_3Sec**	**AGG_MetMinEn**	**AGG_IndEner**
Crude oil	Primary Energy	Crude oil	Crude oil
Natural gas	Primary Energy	Natural gas	Natural gas
Coking coal	Primary Energy	Coal	Coal
Bituminous coal	Primary Energy	Coal	Coal
Coke oven coke	Primary Energy	Coal	Coal
Other coal products	Primary Energy	Coal	Coal
Gasoline / biogasoline	Final Energy	Fuel Products	Fuel Products
LPG	Final Energy	Fuel Products	Fuel Products
Jet Fuel	Final Energy	Fuel Products	Fuel Products
Diesel and biofuel	Final Energy	Fuel Products	Fuel Products
Heating fuel	Final Energy	Fuel Products	Fuel Products
Heavy fuel oil	Final Energy	Fuel Products	Fuel Products
Other petroleum products	Final Energy	Fuel Products	Fuel Products
Electricity	Final Energy	Electricty	Electricty
Heat, Geothermal, Solar Th	Final Energy	HeatGeoSol Th	HeatGeoSol Th
Iron and steel	All Composite	Metals	Steel Iron
Non ferrous metals	All Composite	Metals	Non Ferrous Metals
Cement and clinker	All Composite	Non-metallic minerals	Cement
Other non-metallic minerals	All Composite	Non-metallic minerals	Other Minerals
Construction	All Composite	Other Industries	Other Industries
Chemical and petrochemical	All Composite	Other Industries	Other Industries
Paper, pulp and print	All Composite	Other Industries	Other Industries
Mining and quarrying	All Composite	Other Industries	Other Industries
Transport equipement	All Composite	Other Industries	Other Industries
Transport - Sectors	All Composite	Other Industries	Other Industries
Agricuture and forestry	All Composite	Agriculture	Agriculture
Fishing	All Composite	Agriculture	Agriculture
Agri-food industry	All Composite	OthIndus	OthIndus
Composite	All Composite	Composite	Composite

Table D.6 – Sectoral correspondences with original hybrid Input-Ouput table (IOT) of different

D.2.1 Complementary tables for *AGG_3Sec* profile

France, 2010	**Reference value in thousand of people**
Population	64613
Retired	16170
Unemployed	2618
Labour_force	28345
Nb_Households	27107

Table D.7 – Socio demograhic table of IMACLIM-S FRANCE model

		PrimEn	***FinEn***	***AllComp***
w	*kilo €/FTE*	54 637.1	55 321.6	29 244.1
pL	*kilo €/FTE*	78 639.7	79 624.9	42 091.3
pK	*€/toe, €/ton*	1 076.0	1 076.0	1 076.0
pY	*€/toe, €/ton*	1 468.3	668.9	1 000.0
pM	*€/toe, €/ton*	343.4	442.2	1 000.0
p	*€/toe, €/ton*	401.2	606.1	1 000.0

Table D.8 – Complementary prices for three-sector calibration

D.2.2 Complementary tables for *AGG_MetMinEn* profile

France, 2010 in billions of euro		Intermediate consumption											Final consumption				Uses
		Crude oil	*Gas*	*Coal*	*Fuel Products*	*Electricty*	*Heat Geo Sol Th*	*Metals*	*Non-metallic minerals*	*Other Industries*	*Agriculture*	*Composite*	*C*	*G*	*I*	*X*	
Intermediate consumption	*Crude oil*	0.0	0.0	0.0	29.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	29.2
	Gas	0.0	0.0	0.0	0.3	1.4	0.8	0.3	0.5	1.8	0.1	4.3	10.4	0.0	0.0	0.5	20.5
	Coal	0.0	0.0	0.9	0.0	0.8	0.0	1.4	0.1	0.1	0.0	0.0	0.1	0.0	0.0	0.1	3.5
	Fuel Products	0.0	0.0	0.0	0.0	0.5	0.1	0.2	0.7	17.0	2.4	11.3	41.9	0.0	0.0	13.8	87.8
	Electricty	0.0	0.0	0.0	0.2	0.0	0.1	0.7	0.4	3.4	0.3	12.8	19.7	0.0	0.0	2.2	39.8
	Heat Geo Sol Th	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	1.4	0.1	0.0	0.0	0.0	1.7
	Metals	0.0	0.0	0.0	0.1	0.0	0.0	8.2	0.6	6.0	0.0	28.2	0.4	0.0	0.2	20.3	64.0
	Non-metallic minerals	0.0	0.1	0.0	0.0	0.2	0.0	0.4	4.4	4.8	0.3	22.5	4.0	0.0	0.0	4.8	41.5
	Other Industries	0.0	0.7	0.0	0.6	2.6	0.1	3.7	2.2	118.0	13.8	122.0	249.0	29.1	70.2	204.4	816.2
	Agriculture	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	35.0	13.8	5.6	32.4	0.0	1.3	13.4	101.4
	Composite	0.2	2.4	0.1	4.0	8.4	0.2	15.2	7.5	183.8	10.4	1053.2	733.3	492.6	305.0	200.6	3016.9
Value-added	*Labour income*	0.0	1.3	0.0	0.3	4.4	0.1	2.6	3.2	62.5	11.3	654.7					
	Labour Tax	0.0	0.6	0.0	0.1	1.9	0.0	1.2	1.4	27.5	5.0	287.6					
	Capital income	0.1	1.3	0.0	0.2	4.7	0.1	1.4	0.8	27.2	11.1	222.6					
	Production Tax	0.0	0.3	0.0	0.2	1.0	0.0	0.5	0.4	5.8	-6.4	55.5					
	Profit margin	0.1	1.2	0.0	0.6	4.3	0.1	0.6	1.0	6.6	5.9	328.3					
Imports	*M value*	28.8	9.8	2.2	16.1	1.0	0.0	23.4	6.7	170.1	9.6	245.2					
Margins	*Trade margins*	0.0	0.0	0.2	5.4	0.0	0.0	3.1	9.1	135.9	21.7	-175.4					
	Transp margins	0.0	0.3	0.0	1.0	0.9	0.0	0.9	1.8	-16.1	1.8	9.3					
	SpeMarg Crude oil	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0					
	SpeMarg Natural gas	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0					
	SpeMarg Coal	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0					
	SpeMarg FuelProd	0.0	-0.1	0.0	0.0	-0.1	0.0	0.0	0.0	0.0	0.0	0.0					
	SpeMarg Electricty	0.0	-0.5	-0.4	-0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0					
	SpeMarg HeatGeoSol Th	0.0	-0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0					
	SpeMarg Metals	0.0	-0.1	0.4	0.0	-0.4	0.0	0.0	0.0	0.0	0.0	0.0					
	SpeMarg Non-metal. minerals	0.0	-0.2	0.0	-0.2	-0.2	0.0	0.0	0.0	0.0	0.0	0.0					
	SpeMarg Oth. Indus	0.0	-0.3	0.0	0.8	-1.5	0.0	0.0	0.0	0.0	0.0	0.0					
	SpeMarg Agriculture	0.0	0.0	0.0	-0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0					
	SpeMarg Composite	0.0	-0.3	0.0	1.8	1.1	0.0	0.0	0.0	0.0	0.0	0.0					
	SpeMarg C	0.0	2.3	0.0	0.3	2.2	0.0	0.0	0.0	0.0	0.0	0.0					
	SpeMarg G	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0					
	SpeMarg I	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0					
	SpeMarg X	0.0	-0.6	0.0	-2.0	-1.1	0.0	0.0	0.0	0.0	0.0	0.0					
Taxes	*VA Tax*	0.0	2.0	0.0	5.9	6.8	0.0	0.1	0.7	32.0	1.8	86.3					
	Energy Tax IC	0.0	0.3	0.0	6.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0					
	Energy Tax FC	0.0	0.0	0.0	16.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0					
	ClimPolCompensbySect	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0					
	OtherIndirTax	0.0	0.2	0.0	0.5	0.8	0.0	0.0	0.0	-5.2	-1.3	41.5					
	Carbon Tax	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0					
Supply		29.2	20.5	3.5	87.8	39.8	1.7	64.0	41.5	816.2	101.4	3016.9					

Table D.9 – '*AGG_MetMinEn*' Input-Output table (IOT)

France, 2010 ktoe	Intermediate consumption											Final consumption				Production	Imports
	Crude oil	*Gas*	*Coal*	*Fuel Products*	*Electricty*	*Heat Geo Sol Th*	*Metals*	*Non-metallic minerals*	*Other Industries*	*Agriculture*	*Composite*	*C*	*G*	*I*	*X*	*Y*	*M*
Crude oil	0.0	0.0	0.0	66 967.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.8	2 406.3	64 614.3
Natural gas	9.8	0.0	1.8	841.2	4 190.7	2 510.9	1 011.4	1 532.1	4 693.3	210.5	10 570.0	14 396.4	0.0	0.0	2 556.5	636.2	41 888.4
Coal	0.0	0.0	3 528.4	0.0	5 324.3	10.9	4 636.4	475.5	650.8	0.0	190.2	484.6	0.0	0.0	178.1	3 389.3	12 089.9
Fuel Products	0.0	0.0	0.0	0.0	1 087.8	173.0	259.2	1 119.1	20 246.2	3 336.8	11 799.3	31 451.9	0.0	0.0	25 861.7	58 184.8	37 150.3
Electricty	27.0	17.1	5.0	272.2	0.0	181.0	1 480.6	768.1	6 280.5	294.8	14 753.5	13 602.1	0.0	0.0	4 316.2	40 430.5	1 567.5
HeatGeoSol Th	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	264.0	6.4	2 047.4	96.8	0.0	0.0	0.0	2 414.7	0.0
Labour - Full time equivalent	0.3	23.2	0.5	4.2	81.1	1.7	78.4	104.2	1214.3	249.4	23464.7						

Table D.10 – Physical quantities and labour for *AGG_MetMinEn* calibration

France, 2010 MtCO2	Crude oil	Gas	Coal	Fuel Products	Electricty	Heat Geo Sol Th	Metals	Non-metallic minerals	Other Industries	Agriculture	Composite	C	Total
Crude oil	0	0	0	20.2	0	0	0	0	0	0	0	0	
Natural gas	0	0	0	2	9.8	5.9	2.4	3.6	11	0.5	24.8	33.8	
Coal	0	0	15.2	0	22.9	0	21	1.9	2.6	0	0.8	1.9	
Fuel Products	0	0	0	0	3.3	0.5	0.8	3.4	60.8	9.9	35.2	91.2	
Electricty	0	0	0	0	0	0	0	0	0	0	0	0	
HeatGeoSol Th	0	0	0	0	0	0	0	0	0	0	0	0	
Total	0	0	15.2	22.2	36	6.4	24.2	8.9	74.4	10.4	60.8	126.9	385.4

Table D.11 – CO_2 emissions for *AGG_MetMinEn* ccalibration

France, 2010 €/toe, €/ton	Intermediate consumption											Final consumption			
	Crude oil	*Gas*	*Coal*	*Fuel Products*	*Electricty*	*Heat Geo Sol Th*	*Metals*	*Non-metallic minerals*	*Other Industries*	*Agriculture*	*Composite*	*C*	*G*	*I*	*X*
Crude oil	436.4	436.4	436.4	436.4	436.4	436.4	436.4	436.4	436.4	436.4	436.4	436.4	436.4	436.4	458.2
Gas	329.0	438.8	329.0	329.0	329.0	329.0	329.0	329.0	380.4	476.0	408.0	724.9	529.9	529.9	200.8
Coal	226.4	226.4	245.9	226.4	148.3	171.9	308.2	203.6	185.3	226.4	199.9	265.8	269.9	269.9	299.7
Fuel Products	799.1	799.1	799.1	799.1	442.0	526.1	723.1	612.2	838.6	715.6	955.4	1 332.6	1 323.0	1 323.0	534.7
Electricty	580.0	580.0	580.0	580.0	788.3	580.0	504.0	504.0	544.7	865.0	865.0	1 451.0	1 204.7	1 204.7	518.2
Heat Geo Sol Th	681.7	681.7	681.7	681.7	681.7	681.7	681.7	681.7	683.7	683.7	683.7	768.6	827.3	827.3	674.6
Metals	1 068.3	1 068.3	1 068.3	1 068.3	1 068.3	1 068.3	1 068.3	1 068.3	1 068.3	1 068.3	1 068.3	1 203.2	1 203.2	1 203.2	1 067.5
Non-metallic minerals	1 367.2	1 367.2	1 367.2	1 367.2	1 367.2	1 367.2	1 367.2	1 367.2	1 367.2	1 367.2	1 367.2	1 656.6	1 656.6	1 656.6	1 365.5
Other Industries	1 168.4	1 168.4	1 168.4	1 168.4	1 168.4	1 168.4	1 168.4	1 168.4	1 168.4	1 168.4	1 168.4	1 286.6	1 286.6	1 286.6	1 178.9
Agriculture	1 282.9	1 282.9	1 282.9	1 282.9	1 282.9	1 282.9	1 282.9	1 282.9	1 282.9	1 282.9	1 282.9	1 354.6	1 354.6	1 354.6	1 302.7
Composite	960.3	960.3	960.3	960.3	960.3	960.3	960.3	960.3	960.3	960.3	960.3	1 017.6	1 017.6	1 017.6	945.7

Table D.12 – Intermediate and final prices for *AGG_MetMinEn* calibration

		Crude oil	*Gas*	*Coal*	*Fuel Products*	*Electricty*	*Heat Geo Sol Th*	*Metals*	*Non-metallic minerals*	*Other Industries*	*Agriculture*	*Composite*
w	*kilo €/FTE*	78 689.7	54 676.0	39 053.7	68 014.5	54 676.0	54 676.0	33 723.6	30 349.4	51 485.6	45 504.5	27 900.4
pL	*kilo €/FTE*	113 258.8	78 695.6	56 210.4	97 893.9	78 695.6	78 695.6	48 538.6	43 682.1	74 103.7	65 495.0	40 157.3
pK	*€/toe, €/ton*	1 059.9	1 059.9	1 059.9	1 059.9	1 059.9	1 059.9	1 059.9	1 059.9	1 059.9	1 059.9	1 059.9
pY	*€/toe, €/ton*	180.0	12 404.8	330.1	614.0	748.0	666.4	1 000.0	1 000.0	1 000.0	1 000.0	1 000.0
pM	*€/toe, €/ton*	445.0	233.9	179.5	433.3	654.1	666.4	1 000.0	1 000.0	1 000.0	1 000.0	1 000.0
p	*€/toe, €/ton*	435.4	416.0	212.4	543.6	744.5	666.4	1 000.0	1 000.0	1 000.0	1 000.0	1 000.0

Table D.13 – Complementary prices for *AGG_MetMinEn* calibration

Variable			Crude oil	Gas	Coal	Fuel Products	Electricty	Heat Geo Sol Th	Metals	Non-metallic minerals	Other Industries	Agriculture	Composite
			Eleven sector model (AGG_MetMinEn)										
$t_{CARB_{IC}}$	e/tCO_2	Crude oil	100	100	100	100	100	100	100	100	100	100	100
		Gas	100	100	100	100	100	100	100	100	100	100	100
		Coal	100	100	100	100	100	100	100	100	100	100	100
		Fuel Products	100	100	100	100	100	100	100	100	100	100	100
		Electricty	100	100	100	100	100	100	100	100	100	100	100
		Heat Geo Sol Th	100	100	100	100	100	100	100	100	100	100	100
		Metals	100	100	100	100	100	100	100	100	100	100	100
		Non-metallic minerals	100	100	100	100	100	100	100	100	100	100	100
		Other Industries	100	100	100	100	100	100	100	100	100	100	100
		Agriculture	100	100	100	100	100	100	100	100	100	100	100
		Composite	100	100	100	100	100	100	100	100	100	100	100
t_{CARB_C}	e/tCO_2		100	100	100	100	100	100	100	100	100	100	100
$\beta_{IC_{ji}}$		Crude oil	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Gas	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Coal	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Fuel Products	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Electricty	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Heat Geo Sol Th	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Metals	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Non-metallic minerals	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Other Industries	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Agriculture	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Composite	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
β_{K_i}			0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
β_{L_i}			0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
β_{i_h}			0.5	0.5	0.5	0.5	0.5	0.5	Nan	Nan	Nan	Nan	Nan
σ			1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
$\sigma_{M_{p_i}}$			0	0	0	0.5	0.5	0.5	1	1	1	1	1
$\sigma_{X_{p_i}}$			0	0	0	0	0	0	1	1	1	1	1
σ_{CP_i}			-0.03	-0	-0	-0.39	-0.03	-0.03	Nan	Nan	Nan	Nan	Nan
σ_{CR_i}			0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
σ_{w_u}			-0.1	-0	-0	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
$\beta_{w_{CPI}}$			1	1	1	1	1	1	1	1	1	1	1

Table D.14 – Simulation parameters for *AGG_MetMinEn* calibration at sub-section 4.2.3

D.2.3 Complementary tables for *AGG_IndEner* profile

		Crude oil	*Natural gas*	*Coal*	*Fuel Products*	*Electricty*	*HeatGeoSol Th*	*Steel Iron*	*Non Ferrous Metals*	*Cement*	*Other Minerals*	*Other Industries*	*Agriculture*	*Composite*
w	*kilo €/FTE*	78 689.7	54 676.0	39 053.7	68 014.5	54 676.0	54 676.0	35 000.0	32 490.3	39 179.1	29 908.6	51 485.6	45 504.5	27 900.4
pL	*kilo €/FTE*	113 258.8	78 695.6	56 210.4	97 893.9	78 695.6	78 695.6	50 375.8	46 763.6	58 251.9	42 954.9	74 103.7	65 495.0	40 157.3
pK	*€/toe, €/ton*	1 059.9	1 059.9	1 059.9	1 059.9	1 059.9	1 059.9	1 059.9	1 059.9	1 059.9	1 059.9	1 059.9	1 059.9	1 059.9
pY	*€/toe, €/ton*	180.0	12 404.8	330.1	614.0	748.0	666.4	504.7	1 000.0	113.6	1 000.0	1 000.0	1 000.0	1 000.0
pM	*€/toe, euro/ton*	445.0	233.9	179.5	433.3	654.1	666.4	690.6	1 000.0	100.9	1 000.0	1 000.0	1 000.0	1 000.0
p	*€/toe, €/ton*	435.4	416.0	212.4	543.6	744.5	666.4	568.6	1 000.0	112.5	1 000.0	1 000.0	1 000.0	1 000.0

Table D.15 – Complementary prices for *AGG_IndEner* calibration

D.2.4 Complete results tables

Variation in percentage (%)	Carbon tax rate at 100 euro/tCO2 No recycling of tax revenues AGG_3Sec	AGG_MetMinEn	AGG_IndEner
Real GDP (Laspeyres)	-3.28	-3.35	-3.27
Households consumption in GDP	-2.10	-2.12	-2.02
Public consumption in GDP	-0.47	-0.45	-0.42
Investment in GDP	-0.65	-0.66	-0.65
Exports in GDP	-0.48	-0.57	-0.61
Imports in GDP	0.43	0.44	0.42
Imports/Domestic production ratio	0.42	0.18	0.34
Imports of Non Energy goods in volume	-0.98	-1.04	-0.88
Exports of Non Energy goods in volume	-2.11	-2.41	-2.81
Total Employment	-3.09	-3.05	-2.98
Unemployment rate (% points)	0.03	0.03	0.03
Net-of-tax wages	1.13	0.97	1.13
Labour Intensity (Laspeyres)	0.30	0.26	0.25
Labour tax rate (% points)	0.00	0.00	0.00
Energy Input Price (Laspeyres)	33.95	34.71	34.74
Energy Intensity (Laspeyres)	-5.25	-5.89	-6.17
Energy cost share for non-energetic sector	26.52	26.82	26.16
Production Price (Laspeyres)	2.71	2.65	2.78
Production Price Energy goods (Laspeyres)	14.10	13.30	13.37
Production Price Non Energy goods (Laspeyres)	2.46	2.41	2.54
Real Households consumption (Laspeyres)	-3.73	-3.76	-3.59
Energy in Households consumption	-0.30	-0.25	-0.25
Non Energy goods in Households consumption	-3.43	-3.51	-3.34
Public Deficits	-7.82	-7.67	-7.34
Total Emissions	-8.36	-10.44	-10.85

Table D.16 – Macroeconomic impacts by implementing a carbon tax without recycling revenues for different sectoral aggregation levels at calibration - Section 4.2.3.1

Variation in percentage (%)	**Carbon tax rate at 100 euro/tCO2 Labour tax reduction** AGG_3Sec	AGG_MetMinEn	AGG_IndEner
Real GDP (Laspeyres)	0.16	-0.06	-0.02
Households consumption in GDP	0.19	0.10	0.18
Public consumption in GDP	0.40	0.41	0.43
Investment in GDP	0.00	-0.03	-0.02
Exports in GDP	-0.25	-0.40	-0.45
Imports in GDP	-0.17	-0.14	-0.16
Imports/Domestic production ratio	0.37	0.17	0.32
Imports of Non Energy goods in volume	1.35	1.25	1.38
Exports of Non Energy goods in volume	-1.10	-1.68	-2.12
Total Employment	0.43	0.37	0.38
Unemployment rate (% points)	0.00	0.00	0.00
Net-of-tax wages	3.28	3.19	3.36
Labour Intensity (Laspeyres)	0.38	0.32	0.31
Labour tax rate (% points)	-0.05	-0.05	-0.05
Energy Input Price (Laspeyres)	33.63	34.46	34.51
Energy Intensity (Laspeyres)	-2.57	-3.52	-3.87
Energy cost share for non-energetic sector	27.45	27.35	26.61
Production Price (Laspeyres)	1.54	1.68	1.85
Production Price Energy goods (Laspeyres)	13.41	12.76	12.86
Production Price Non Energy goods (Laspeyres)	1.27	1.43	1.61
Real Households consumption (Laspeyres)	0.33	0.18	0.31
Energy in Households consumption	-0.20	-0.16	-0.15
Non Energy goods in Households consumption	0.54	0.34	0.47
Public Deficits	2.61	2.49	2.74
Total Emissions	-6.11	-8.39	-8.86

Table D.17 – Macroeconomic impacts by implementing a carbon tax recycled into labour tax reduction for different sectoral aggregation levels at calibration - Section 4.2.3.1

Trade elasticities	Carbon tax rate at 100 euro/tCO2 Labour tax reduction LOW		REF	
Variation in percentage (%)	AGG_3Sec	AGG_IndEner	AGG_3Sec	AGG_IndEner
Real GDP (Laspeyres)	1.49	2.11	0.16	-0.02
Households consumption in GDP	*1.28*	*1.99*	*0.19*	*0.18*
Public consumption in GDP	*0.86*	*1.14*	*0.40*	*0.43*
Investment in GDP	*0.27*	*0.42*	*0.00*	*-0.02*
Exports in GDP	*-0.32*	*-0.54*	*-0.25*	*-0.45*
Imports in GDP	*0.61*	*0.90*	*0.17*	*0.16*
Imports/Domestic production ratio	0.40	0.21	0.37	0.32
Imports of Non Energy goods in volume	3.08	4.24	1.35	1.38
Exports of Non Energy goods in volume	-1.41	-2.44	-1.10	-2.12
Total Employment	1.65	2.35	0.43	0.38
Unemployment rate (% points)	-0.02	-0.02	0.00	0.00
Net-of-tax wages	6.36	8.82	3.28	3.36
Labour Intensity (Laspeyres)	0.25	0.11	0.38	0.31
Labour tax rate (% points)	-0.06	-0.06	-0.05	-0.05
Energy Input Price (Laspeyres)	34.16	35.43	33.63	34.51
Energy Intensity (Laspeyres)	-1.46	-1.70	-2.57	-3.87
Energy cost share for non-energetic sector	25.89	24.44	27.45	26.61
Production Price (Laspeyres)	3.53	5.47	1.54	1.85
Production Price Energy goods (Laspeyres)	14.59	14.90	13.41	12.86
Production Price Non Energy goods (Laspeyres)	3.28	5.26	1.27	1.61
Real Households consumption (Laspeyres)	2.28	3.53	0.33	0.31
Energy in Households consumption	-0.14	-0.05	-0.20	-0.15
Non Energy goods in Households consumption	2.42	3.58	0.54	0.47
Public Deficits	6.16	8.95	2.61	2.74
Total Emissions	-4.91	-6.45	-6.11	-8.86

Table D.18 – The influence of the trade elasticities on carbon tax impact according to different level of sectoral description - Section 4.2.3.2

Appendix E

Further information on Chapter 5

E.1 Heterogeneous trade elasticities

Trade elasticities	$\sigma_{M_{p_i}}$	$\sigma_{X_{p_i}}$	Source
Crude oil	0.00	0.00	Author's hypothesis
Natural gas	0.00	0.00	Author's hypothesis
Coking coal	0.00	0.00	Author's hypothesis
Bituminous coal	0.00	0.00	Author's hypothesis
Coke oven coke	0.00	0.00	Author's hypothesis
Other coal products	0.00	0.00	Author's hypothesis
Gasoline + biogasoline	2.00	2.00	Author's hypothesis
LPG	2.00	2.00	Author's hypothesis
Jet Fuel	2.00	2.00	Author's hypothesis
Diesel and biofuel	2.00	2.00	Author's hypothesis
Heating fuel	2.00	2.00	Author's hypothesis
Heavy fuel oil	2.00	2.00	Author's hypothesis
Other petroleum products	2.00	2.00	Author's hypothesis
Electricity	0.10	0.10	Author's hypothesis
Heat, Geothermal, Solar Th	0.00	0.00	Author's hypothesis
Basic metals	*0.55*	*0.35*	*Fouquin et al. (2001)*
Iron and steel	0.10	0.10	Author's hypothesis
Non ferrous metals	0.95	0.75	Author's calculation
Non Metallic minerals	*0.85*	*0.77*	*Fouquin et al. (2001)*
Cement and clinker	0.10	0.10	Author's hypothesis
Other non-metallic minerals	0.89	0.81	Author's calculation
Construction	0.10	0.10	Author's hypothesis
Chemical and petrochemical	0.79	0.55	Fouquin et al. (2001)
Paper, pulp and print	1.05	0.40	Fouquin et al. (2001)
Mining and quarrying	0.55	0.35	Fouquin et al. (2001)
Transport equipement	0.68	2.45	Fouquin et al. (2001)
Transport - Sectors	0.00	0.00	Author's hypothesis
Agricuture and forestry	1.01	0.24	Fouquin et al. (2001)
Fishing	1.01	0.24	Fouquin et al. (2001)
Agri-food industry	1.01	0.24	Fouquin et al. (2001)
Composite	0.77	0.16	Author's calculation
Global level	0.74	0.58	Ducoudré and Heyer (2014)

Table E.1 – Sectoral details on trade elasticities for the most disaggregated version of France Input-Ouput table (IOT)

E.1.1 Complementary tables of sub-section 5.1.1

Parameters			Crude oil	Natural gas	Coal	Fuel Products	Electricty	HeatGeoSol Th	Steel Iron	Non Ferrous Metals	Cement	Other Minerals	Other Industries	Agriculture	Composite
			Thirteen sector model (AGG_IndEner)												
$t_{CARB_{IC}}$	€/tCO_2	Crude oil	500	500	500	500	500	500	500	500	500	500	500	500	500
		Natural gas	500	500	500	500	500	500	500	500	500	500	500	500	500
		Coal	500	500	500	500	500	500	500	500	500	500	500	500	500
		Fuel Products	500	500	500	500	500	500	500	500	500	500	500	500	500
		Electricty	500	500	500	500	500	500	500	500	500	500	500	500	500
		HeatGeoSol Th	500	500	500	500	500	500	500	500	500	500	500	500	500
		Steel Iron	500	500	500	500	500	500	500	500	500	500	500	500	500
		Non Ferrous Metals	500	500	500	500	500	500	500	500	500	500	500	500	500
		Cement	500	500	500	500	500	500	500	500	500	500	500	500	500
		Other Minerals	500	500	500	500	500	500	500	500	500	500	500	500	500
		Other Industries	500	500	500	500	500	500	500	500	500	500	500	500	500
		Agriculture	500	500	500	500	500	500	500	500	500	500	500	500	500
		Composite	500	500	500	500	500	500	500	500	500	500	500	500	500
t_{CARB_C}	€/tCO_2		500	500	500	500	500	500	500	500	500	500	500	500	500
$\beta_{IC_{ji}}$		Crude oil	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Natural gas	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Coal	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Fuel Products	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Electricty	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		HeatGeoSol Th	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Steel Iron	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Non Ferrous Metals	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Cement	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Other Minerals	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Other Industries	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Agriculture	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Composite	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
β_{K_i}			0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
β_{L_i}			0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
β_{i_h}			0.5	0.5	0.5	0.5	0.5	0.5	Nan	Nan	Nan	Nan	Nan	Nan	Nan
σ			1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
$\sigma_{M_{P_i}}$			0	0	0	2	0.1	0	0.1	0.95	0.1	0.89	0.75	1.01	0.77
$\sigma_{X_{P_i}}$			0	0	0	2	0.1	0	0.1	0.75	0.1	0.81	0.35	0.24	0.16
σ_{CP_i}			-0.03	-0.03	-0.03	-0.39	-0.03	-0.03	Nan	Nan	Nan	Nan	Nan	Nan	Nan
σ_{CR_i}			0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
σ_{w_u}			-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
$\beta_{w_{CPI}}$			0	0	0	0	0	0	0	0	0	0	0	0	0

Table E.2 – Simulation parameters for calibration at sub-section 5.1.1

Wage curve indexed	**International price**	**Carbon tax rate at 500€/tCO$_2$ Half on international price Half on consumer price**	**Consumer price**
Variation in percentage (%)	1.CGC_INT	1.CGC_HALF	1.CGC_CPI
Real GDP (Laspeyres)	6.81	6.60	6.16
Households consumption in GDP	4.67	5.55	7.62
Public consumption in GDP	3.80	3.89	4.16
Investment in GDP	1.23	1.23	1.23
Exports in GDP	-0.68	-0.90	-1.38
Imports in GDP	2.20	3.18	5.47
Imports/Domestic production ratio	0.80	0.91	1.16
Imports of Non Energy goods in volume	10.98	15.03	24.54
Exports of Non Energy goods in volume	-2.17	-3.10	-5.09
Total Employment	8.53	7.90	6.60
Unemployment rate (% points)	-0.08	-0.11	-0.06
Net-of-tax wages	19.59	26.63	43.73
Labour Intensity (Laspeyres)	1.19	0.81	0.01
Labour tax rate (% points)	-0.24	-0.22	-0.18
Energy Input Price (Laspeyres)	168.60	169.42	171.49
Energy Intensity (Laspeyres)	-12.66	-12.77	-13.00
Energy cost share for non-energetic sector	124.49	114.64	94.88
Production Price (Laspeyres)	8.65	14.48	28.44
Production Price Energy goods (Laspeyres)	61.05	63.04	68.07
Production Price Non Energy goods (Laspeyres)	7.48	13.39	27.55
Real Households consumption (Laspeyres)	8.28	9.86	13.53
Energy in Households consumption	-0.32	-0.26	-0.11
Non Energy goods in Households consumption	8.60	10.12	13.64
Public Deficits	20.07	26.69	42.70
Total Emissions	-13.97	-13.49	-12.37

Table E.3 – Macro-impact of a 500€/tCO_2 carbon tax for different wage curve indexations with constant government consumption - sub-section 5.1.1

1.CGC_INT simulation	Sectoral details for a 500€/tCO$_2$ carbon tax recycling into labour tax reduction Wage curve indexed on international price												
Variation (%)	Crude oil	Natural gas	Coal	Fuel Products	Electricty	HeatGeoSol Th	Steel Iron	Non Ferrous Metals	Cement	Other Minerals	Other Industries	Agriculture	Composite
Production Price	10.13	4.68	843.86	32.53	73.32	209.79	99.74	10.37	79.71	21.59	13.90	13.76	5.47
Real Households consumption	Nan	1.56	-0.63	-9.86	2.46	1.53	-26.04	9.35	-32.84	0.65	5.58	3.75	10.76
Exports in volume	0.00	0.00	0.00	-21.27	-5.21	-100.00	-4.43	-4.49	-5.34	-11.03	-3.29	-2.66	-0.78
Imports in volume	-33.84	-8.49	-23.59	16.94	2.95	-54.06	-0.49	8.73	-4.60	15.08	10.22	13.07	12.38
Trade balance	-33.87	-9.08	-31.42	188.93	111.69	Nan	412.75	20.87	-598.90	44.25	-12.44	-1.51	49.16
Energy Cost share	75.64	46.65	19.05	2.80	310.66	24.64	243.69	99.00	97.46	176.50	117.58	130.01	103.43
Energy/Labour cost	89.29	51.49	308.97	26.33	571.45	173.30	529.79	114.65	213.21	224.67	141.09	154.56	111.66
Labour	-32.59	-7.55	109.33	-28.41	2.99	29.41	0.92	1.00	0.99	-0.12	2.45	1.73	9.01
Unitary Labour Cost	2.18	1.33	174.76	7.85	6.01	41.28	9.00	2.32	13.30	3.55	2.79	2.79	1.37
Net nominal wages	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95
Net real wages (Consumer Price Index)	5.20	5.20	5.20	5.20	5.20	5.20	5.20	5.20	5.20	5.20	5.20	5.20	5.20
Purchasing power of wages	19.77	-60.37	-90.62	-48.62	-29.08	-60.98	-23.69	12.82	-30.71	3.84	8.93	7.05	14.28

Table E.4 – Sectoral impact of a 500€/tCO_2 carbon tax for wage curve indexed on international price with constant government consumption - sub-section 5.1.1

1.CGC_HALF simulation	Sectoral details for a 500€/tCO$_2$ carbon tax recycling into labour tax reduction Wage curve indexed half on international price/half on consumer price												
Variation (%)	Crude oil	Natural gas	Coal	Fuel Products	Electricty	HeatGeoSol Th	Steel Iron	Non Ferrous Metals	Cement	Other Minerals	Other Industries	Agriculture	Composite
Production Price	14.84	7.78	846.70	33.36	76.30	212.00	103.81	15.51	83.86	26.82	19.02	18.95	11.56
Real Households consumption	Nan	2.23	0.02	-8.73	3.13	2.20	-22.50	13.10	-30.13	3.82	8.67	6.11	11.84
Exports in volume	0.00	0.00	0.00	-21.58	-5.37	-100.00	-4.56	-6.44	-5.55	-13.19	-4.37	-3.55	-1.61
Imports in volume	-33.87	-8.18	-23.33	18.17	3.53	-53.97	-0.15	11.52	-3.81	18.47	13.75	18.31	17.11
Trade balance	-33.90	-8.82	-31.18	198.70	115.72	Nan	426.33	27.17	-619.18	54.30	-16.57	-3.35	54.09
Energy Cost share	71.02	45.03	18.95	2.39	304.49	24.33	237.76	92.36	93.97	166.76	109.57	121.18	94.55
Energy/Labour cost	92.53	55.20	306.86	27.88	575.93	174.99	494.33	103.34	196.87	205.98	127.26	139.67	99.97
Labour	-31.53	-6.13	115.38	-27.99	4.76	31.82	-0.07	-1.42	0.29	-1.60	1.65	1.12	8.40
Unitary Labour Cost	2.01	0.72	176.77	6.77	5.50	41.06	15.83	9.27	20.13	10.57	9.76	9.77	8.54
Net nominal wages	16.16	16.16	16.16	16.16	16.16	16.16	27.09	27.09	27.09	27.09	27.09	27.09	27.09
Net real wages (Consumer Price Index)	-2.22	-2.22	-2.22	-2.22	-2.22	-2.22	6.97	6.97	6.97	6.97	6.97	6.97	6.97
Purchasing power of wages	15.91	-61.79	-90.92	-50.26	-32.44	-62.48	-20.31	16.30	-28.16	6.75	11.74	9.11	15.00

Table E.5 – Sectoral impact of a 500€/tCO_2 carbon tax for wage curve indexed half on international price and half on consumer price with constant government consumption - sub-section 5.1.1

1.CGC_CPI simulation	Sectoral details for a 500€/tCO$_2$ carbon tax recycling into labour tax reduction												
	Wage curve indexed on consumer price												
Variation (%)	**Crude oil**	**Natural gas**	**Coal**	**Fuel Products**	**Electricty**	**HeatGeoSol Th**	**Steel Iron**	**Non Ferrous Metals**	**Cement**	**Other Minerals**	**Other Industries**	**Agriculture**	**Composite**
Production Price	26.22	15.80	853.30	35.33	83.98	217.65	113.34	27.68	93.64	39.25	31.16	31.24	26.19
Real Households consumption	Nan	3.77	1.51	-6.10	4.65	3.73	-14.17	22.03	-23.88	11.21	15.88	11.58	14.36
Exports in volume	0.00	0.00	0.00	-22.28	-5.76	-100.00	-4.88	-10.49	-6.01	-17.73	-6.69	-5.46	-3.39
Imports in volume	-33.94	-7.42	-22.73	21.11	4.89	-53.71	0.65	17.88	-1.99	26.38	22.01	30.76	28.21
Trade balance	-33.97	-8.22	-30.62	221.99	126.17	Nan	457.91	41.71	-667.31	77.84	-27.29	-8.69	65.84
Energy Cost share	61.53	41.19	18.70	1.41	289.46	23.54	224.86	78.99	86.37	146.69	93.14	103.08	76.91
Energy/Labour cost	96.72	61.30	300.68	29.31	573.40	175.53	423.55	81.17	164.00	169.23	99.99	110.33	77.20
Labour	-29.36	-3.17	125.17	-27.58	8.34	36.05	-2.04	-6.49	-1.00	-4.73	0.01	-0.14	7.10
Unitary Labour Cost	3.64	1.36	182.41	6.13	6.40	42.43	32.37	26.14	36.70	27.59	26.67	26.72	25.98
Net nominal wages	11.01	11.01	11.01	11.01	11.01	11.01	44.42	44.42	44.42	44.42	44.42	44.42	44.42
Net real wages (Consumer Price Index)	-14.67	-14.67	-14.67	-14.67	-14.67	-14.67	11.01	11.01	11.01	11.01	11.01	11.01	11.01
Purchasing power of wages	10.58	-63.91	-91.34	-52.52	-38.04	-64.78	-12.37	24.59	-22.28	13.54	18.31	13.93	16.76

Table E.6 – Sectoral impact of a 500€/tCO_2 carbon tax for wage curve indexed on consumer price with constant government consumption - sub-section 5.1.1

Wage curve indexed	International price	Carbon tax rate at 500€/tCO_2 Half on international price Half on consumer price	Consumer price
Variation in percentage (%)	1.CTB_INT	1.CTB_HALF	1.CTB_CPI
Real GDP (Laspeyres)	5.57	5.44	5.28
Households consumption in GDP	5.95	6.22	6.56
Public consumption in GDP	-1.25	-1.56	-1.94
Investment in GDP	0.88	0.85	0.83
Exports in GDP	-0.15	-0.16	-0.19
Imports in GDP	-0.15	-0.09	-0.02
Imports/Domestic production ratio	0.55	0.56	0.57
Imports of Non Energy goods in volume	1.17	1.40	1.68
Exports of Non Energy goods in volume	0.04	-0.04	-0.13
Total Employment	7.72	7.52	7.27
Unemployment rate (% points)	-0.07	-0.07	-0.07
Net-of-tax wages	15.12	16.30	17.79
Labour Intensity (Laspeyres)	2.06	2.02	1.97
Labour tax rate (% points)	-0.38	-0.38	-0.39
Energy Input Price (Laspeyres)	165.49	165.49	165.49
Energy Intensity (Laspeyres)	-12.63	-12.65	-12.69
Energy cost share for non-energetic sector	150.12	149.27	148.21
Production Price (Laspeyres)	-3.77	-3.36	-2.86
Production Price Energy goods (Laspeyres)	53.78	53.78	53.80
Production Price Non Energy goods (Laspeyres)	-5.06	-4.64	-4.13
Real Households consumption (Laspeyres)	10.56	11.04	11.64
Energy in Households consumption	-0.33	-0.32	-0.31
Non Energy goods in Households consumption	10.89	11.36	11.94
Public Deficits	4.39	4.73	5.15
Total Emissions	-14.62	-14.57	-14.50

Table E.7 – Macro-impact of a 500€/tCO_2 carbon tax for different wage curve indexations with constant trade balance - sub-section 5.1.1

1.CTB_INT simulation Variation (%)	Sectoral details for a 500€/tCO$_2$ carbon tax recycling into labour tax reduction Wage curve indexed on international price Crude oil	Natural gas	Coal	Fuel Products	Electricty	HeatGeoSol Th	Steel Iron	Non Ferrous Metals	Cement	Other Minerals	Other Industries	Agriculture	Composite
Production Price	-1.87	-7.64	835.63	30.39	61.49	200.85	90.59	-0.81	70.39	10.29	2.88	2.68	-7.41
Real Households consumption	Nan	2.20	-0.03	-10.77	3.20	2.19	-29.96	7.04	-35.30	-1.00	4.27	4.02	14.62
Exports in volume	0.00	0.00	0.00	-20.44	-4.55	-100.00	-4.11	0.39	-4.86	-5.74	-0.73	-0.55	1.20
Imports in volume	-33.29	-8.99	-24.24	14.63	1.66	-55.01	-1.96	1.28	-7.27	6.65	3.13	3.92	-0.13
Trade balance	-33.32	-9.30	-32.02	169.69	94.77	Nan	387.08	3.65	-561.52	19.13	-7.37	-3.57	26.66
Energy Cost share	86.56	54.04	19.34	3.84	337.54	25.91	257.26	113.27	105.31	199.10	136.76	151.40	123.70
Energy/Labour cost	108.76	63.96	328.22	41.20	675.03	198.68	617.79	140.37	252.03	270.28	175.35	191.88	139.03
Labour	-31.22	-7.15	132.27	-23.99	3.87	34.17	2.52	5.61	1.57	2.47	5.00	5.21	7.96
Unitary Labour Cost	-12.31	-13.22	160.75	-4.12	-8.83	26.83	-5.14	-11.99	-0.63	-10.91	-11.54	-11.56	-13.35
Net nominal wages	15.29	15.29	15.29	15.29	15.29	15.29	15.29	15.29	15.29	15.29	15.29	15.29	15.29
Net real wages (Consumer Price Index)	11.57	11.57	11.57	11.57	11.57	11.57	11.57	11.57	11.57	11.57	11.57	11.57	11.57
Purchasing power of wages	15.32	-61.21	-90.96	-50.54	-27.03	-61.39	-24.17	15.88	-29.95	7.18	12.88	12.61	24.08

Table E.8 – Sectoral impact of a 500€/tCO_2 carbon tax for wage curve indexed on international price with constant trade balance - sub-section 5.1.1

1.CTB_HALF simulation Variation (%)	Sectoral details for a 500€/tCO$_2$ carbon tax recycling into labour tax reduction Wage curve indexed half on international price/half on consumer price Crude oil	Natural gas	Coal	Fuel Products	Electricty	HeatGeoSol Th	Steel Iron	Non Ferrous Metals	Cement	Other Minerals	Other Industries	Agriculture	Composite
Production Price	-1.63	-7.68	835.76	30.43	61.45	200.82	90.87	-0.46	70.67	10.66	3.24	3.05	-6.99
Real Households consumption	Nan	2.39	0.15	-10.59	3.39	2.38	-29.46	7.68	-34.87	-0.43	4.85	4.54	15.09
Exports in volume	0.00	0.00	0.00	-20.45	-4.55	-100.00	-4.12	0.22	-4.88	-5.93	-0.82	-0.63	1.14
Imports in volume	-33.26	-8.96	-24.22	14.75	1.70	-55.05	-1.98	1.41	-7.27	6.84	3.43	4.43	0.06
Trade balance	-33.29	-9.26	-32.01	170.55	94.67	Nan	388.36	3.91	-563.42	19.64	-7.82	-4.00	26.22
Energy Cost share	86.12	54.06	19.34	3.81	337.65	25.92	256.77	112.56	105.01	198.17	136.00	150.58	122.76
Energy/Labour cost	110.48	65.39	328.63	42.30	681.66	200.29	614.25	139.11	250.36	268.32	173.92	190.35	137.73
Labour	-30.93	-6.85	134.90	-23.63	4.27	34.92	2.37	5.32	1.41	2.28	4.96	5.28	7.74
Unitary Labour Cost	-13.01	-14.01	160.53	-4.84	-9.60	26.14	-4.66	-11.51	-0.13	-10.42	-11.05	-11.07	-12.85
Net nominal wages	14.39	14.39	14.39	14.39	14.39	14.39	16.48	16.48	16.48	16.48	16.48	16.48	16.48
Net real wages (Consumer Price Index)	10.36	10.36	10.36	10.36	10.36	10.36	12.37	12.37	12.37	12.37	12.37	12.37	12.37
Purchasing power of wages	14.41	-61.51	-91.03	-50.93	-27.58	-61.69	-23.47	16.81	-29.34	8.02	13.75	13.41	24.85

Table E.9 – Sectoral impact of a 500€/tCO_2 carbon tax for wage curve indexed half on international price and half on consumer price with constant trade balance - sub-section 5.1.1

1.CTB_CPI simulation Variation (%)	Sectoral details for a 500€/tCO$_2$ carbon tax recycling into labour tax reduction Wage curve indexed on consumer price Crude oil	Natural gas	Coal	Fuel Products	Electricty	HeatGeoSol Th	Steel Iron	Non Ferrous Metals	Cement	Other Minerals	Other Industries	Agriculture	Composite
Production Price	-1.32	-7.71	835.93	30.49	61.42	200.79	91.23	-0.01	71.03	11.11	3.69	3.51	-6.46
Real Households consumption	Nan	2.62	0.37	-10.36	3.62	2.61	-28.83	8.48	-34.33	0.29	5.58	5.20	15.67
Exports in volume	0.00	0.00	0.00	-20.48	-4.55	-100.00	-4.13	0.00	-4.90	-6.16	-0.93	-0.72	1.05
Imports in volume	-33.23	-8.92	-24.21	14.89	1.75	-55.11	-2.00	1.57	-7.27	7.07	3.80	5.07	0.30
Trade balance	-33.26	-9.22	-31.99	171.64	94.59	Nan	389.97	4.23	-565.79	20.29	-8.38	-4.54	25.67
Energy Cost share	85.58	54.07	19.33	3.78	337.72	25.92	256.15	111.70	104.64	197.03	135.07	149.56	121.60
Energy/Labour cost	112.50	67.11	329.06	43.59	689.45	202.18	609.87	137.57	248.29	265.91	172.16	188.47	136.14
Labour	-30.57	-6.48	138.06	-23.21	4.76	35.80	2.18	4.96	1.22	2.05	4.91	5.37	7.48
Unitary Labour Cost	-13.82	-14.91	160.31	-5.68	-10.50	25.34	-4.06	-10.90	0.49	-9.80	-10.44	-10.45	-12.22
Net nominal wages	13.37	13.37	13.37	13.37	13.37	13.37	17.97	17.97	17.97	17.97	17.97	17.97	17.97
Net real wages (Consumer Price Index)	8.94	8.94	8.94	8.94	8.94	8.94	13.37	13.37	13.37	13.37	13.37	13.37	13.37
Purchasing power of wages	13.39	-61.85	-91.11	-51.37	-28.22	-62.02	-22.59	17.98	-28.58	9.07	14.83	14.41	25.80

Table E.10 – Sectoral impact of a 500€/tCO_2 carbon tax for wage curve indexed on consumer price with constant trade balance - sub-section 5.1.1

E.1.2 Complementary tables of sub-section 5.1.2

			Thirteen sector model (AGG_IndEner)												
Parameters			**Crude oil**	**Natural gas**	**Coal**	**Fuel Products**	**Electricty**	**HeatGeoSol Th**	**Steel Iron**	**Non Ferrous Metals**	**Cement**	**Other Minerals**	**Other Industries**	**Agriculture**	**Composite**
$t_{CARB_{IC}}$	€/tCO_2	Crude oil	500	500	500	500	500	500	500	500	500	500	500	500	500
		Natural gas	500	500	500	500	500	500	500	500	500	500	500	500	500
		Coal	500	500	500	500	500	500	500	500	500	500	500	500	500
		Fuel Products	500	500	500	500	500	500	500	500	500	500	500	500	500
		Electricty	500	500	500	500	500	500	500	500	500	500	500	500	500
		HeatGeoSol Th	500	500	500	500	500	500	500	500	500	500	500	500	500
		Steel Iron	500	500	500	500	500	500	500	500	500	500	500	500	500
		Non Ferrous Metals	500	500	500	500	500	500	500	500	500	500	500	500	500
		Cement	500	500	500	500	500	500	500	500	500	500	500	500	500
		Other Minerals	500	500	500	500	500	500	500	500	500	500	500	500	500
		Other Industries	500	500	500	500	500	500	500	500	500	500	500	500	500
		Agriculture	500	500	500	500	500	500	500	500	500	500	500	500	500
		Composite	500	500	500	500	500	500	500	500	500	500	500	500	500
t_{CARB_C}	€/tCO_2		500	500	500	500	500	500	500	500	500	500	500	500	500
$\beta_{IC_{ji}}$		Crude oil	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Natural gas	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Coal	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Fuel Products	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Electricty	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		HeatGeoSol Th	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Steel Iron	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Non Ferrous Metals	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Cement	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Other Minerals	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Other Industries	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Agriculture	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Composite	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
β_{K_i}			0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
β_{L_i}			0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
β_{i_h}			0.5	0.5	0.5	0.5	0.5	0.5	Nan	Nan	Nan	Nan	Nan	Nan	Nan
σ			1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
$\sigma_{M_{P_i}}$			0.00	0.00	0.00	0.50	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58
$\sigma_{X_{P_i}}$			0.00	0.00	0.00	0.00	1.09	0.99	1.09	1.73	1.09	1.79	1.33	1.23	1.15
σ_{CP_i}			-0.03	-0.03	-0.03	-0.39	-0.03	-0.03	Nan	Nan	Nan	Nan	Nan	Nan	Nan
σ_{CR_i}			0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
σ_{w_u}			-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
$\beta_{w_{CPI}}$			0	0	0	0	0	0	0	0	0	0	0	0	0

Table E.11 – Simulation parameters for calibration at sub-section 5.1.2

Wage curve indexed	International price	Carbon tax rate at 500€/tCO$_2$ Half on international price Half on consumer price	Consumer price
Variation in percentage (%)	2.CGC_INT	2.CGC_HALF	2.CGC_CPI
Real GDP (Laspeyres)	2.97	0.93	-2.20
Households consumption in GDP	1.08	0.16	-1.25
Public consumption in GDP	2.48	1.95	1.13
Investment in GDP	0.39	0.01	-0.59
Exports in GDP	-0.71	-0.97	-1.37
Imports in GDP	0.27	0.21	0.11
Imports/Domestic production ratio	2.33	2.39	2.48
Imports of Non Energy goods in volume	3.27	3.08	2.78
Exports of Non Energy goods in volume	-3.05	-4.19	-5.93
Total Employment	5.40	3.16	-0.25
Unemployment rate (% points)	-0.05	-0.03	0.00
Net-of-tax wages	7.41	7.83	8.47
Labour Intensity (Laspeyres)	1.75	1.65	1.49
Labour tax rate (% points)	-0.23	-0.22	-0.19
Energy Input Price (Laspeyres)	167.90	167.96	168.17
Energy Intensity (Laspeyres)	-10.95	-12.28	-14.31
Energy cost share for non-energetic sector	127.59	125.16	121.55
Production Price (Laspeyres)	0.79	2.03	3.99
Production Price Energy goods (Laspeyres)	56.49	56.63	57.14
Production Price Non Energy goods (Laspeyres)	-0.45	0.80	2.80
Real Households consumption (Laspeyres)	1.92	0.28	-2.22
Energy in Households consumption	-0.50	-0.53	-0.58
Non Energy goods in Households consumption	2.42	0.81	-1.64
Public Deficits	6.93	6.22	5.14
Total Emissions	-19.94	-20.91	-22.40

Table E.12 – Macro-impact of a 500€/tCO_2 carbon tax for different wage curve indexations with constant government consumption after reinterpreting trade elasticities - sub-section 5.1.2

2.CGC_INT simulation Variation (%)	Crude oil	Natural gas	Coal	Fuel Products	Electricty	HeatGeoSol Th	Steel Iron	Non Ferrous Metals	Cement	Other Minerals	Other Industries	Agriculture	Composite
	Sectoral details for a 500€/tCO$_2$ carbon tax recycling into labour tax reduction Wage curve indexed on international price												
Production Price	2.55	-3.07	838.24	31.18	65.94	204.20	93.12	3.03	71.89	14.10	7.07	6.95	-2.70
Real Households consumption	Nan	-0.94	-3.03	-12.82	0.00	-0.96	-27.83	0.29	-35.49	-7.14	-2.80	-3.71	4.78
Exports in volume	0.00	0.00	0.00	0.00	-40.27	-100.00	-31.56	-3.16	-39.44	-15.74	-6.37	-6.93	2.99
Imports in volume	-16.67	-12.68	-43.30	-3.67	91.68	156.24	25.69	-5.83	68.57	11.57	4.93	4.05	0.05
Trade balance	-16.69	-13.31	-51.59	-143.46	-85.29	Nan	-208.49	-13.40	698.38	56.29	-34.02	-14.75	-1.46
Energy Cost share	80.38	48.68	19.26	3.45	327.29	25.44	253.35	107.86	105.37	191.54	131.61	145.67	116.36
Energy/Labour cost	99.07	56.60	321.52	35.48	634.52	189.05	584.02	129.98	240.53	252.95	164.86	180.61	128.95
Labour	-14.45	-11.22	66.28	-6.92	-8.16	28.89	-51.03	-7.58	-18.46	-5.64	-2.56	-3.20	6.14
Unitary Labour Cost	-7.08	-7.97	165.45	0.17	-3.47	32.01	-0.24	-6.88	3.66	-5.75	-6.37	-6.37	-8.06
Net nominal wages	7.86	7.86	7.86	7.86	7.86	7.86	7.86	7.86	7.86	7.86	7.86	7.86	7.86
Net real wages (Consumer Price Index)	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21
Purchasing power of wages	7.82	-63.95	-91.55	-54.48	-32.20	-64.27	-23.81	5.88	-31.90	-1.96	2.61	1.66	10.62

Table E.13 – Sectoral impact of a 500€/tCO_2 carbon tax for wage curve indexed on international price with constant government consumption after reinterpreting trade elasticities - sub-section 5.1.2

2.CGC_HALF simulation Variation (%)	Crude oil	Natural gas	Coal	Fuel Products	Electricty	HeatGeoSol Th	Steel Iron	Non Ferrous Metals	Cement	Other Minerals	Other Industries	Agriculture	Composite
	Sectoral details for a 500€/tCO$_2$ carbon tax recycling into labour tax reduction Wage curve indexed half on international price/half on consumer price												
Production Price	3.38	-2.96	838.69	31.33	66.05	204.27	93.96	4.11	72.69	15.20	8.16	8.06	-1.41
Real Households consumption	Nan	-1.54	-3.60	-13.14	-0.61	-1.55	-28.38	-0.96	-36.11	-8.31	-4.10	-5.15	2.90
Exports in volume	0.00	0.00	0.00	0.00	-40.31	-100.00	-31.68	-4.23	-39.68	-16.73	-7.27	-7.93	1.55
Imports in volume	-17.34	-13.74	-44.06	-4.42	89.45	151.54	24.68	-6.44	66.55	10.78	4.59	3.79	0.08
Trade balance	-17.35	-14.43	-52.37	-149.29	-83.41	Nan	-201.39	-14.26	679.13	54.79	-33.74	-14.80	-0.46
Energy Cost share	79.16	48.59	19.24	3.37	327.04	25.43	251.96	105.98	104.57	189.01	129.54	143.40	113.85
Energy/Labour cost	102.58	59.61	322.26	37.74	647.47	192.36	574.50	126.70	236.21	247.74	161.03	176.52	125.56
Labour	-14.37	-11.72	68.00	-6.87	-8.62	28.24	-51.90	-9.84	-20.30	-7.87	-4.58	-5.16	3.87
Unitary Labour Cost	-8.57	-9.66	165.07	-1.44	-5.13	30.54	1.21	-5.41	5.07	-4.26	-4.88	-4.88	-6.53
Net nominal wages	3.79	3.79	3.79	3.79	3.79	3.79	8.31	8.31	8.31	8.31	8.31	8.31	8.31
Net real wages (Consumer Price Index)	-4.51	-4.51	-4.51	-4.51	-4.51	-4.51	-0.36	-0.36	-0.36	-0.36	-0.36	-0.36	-0.36
Purchasing power of wages	3.74	-65.32	-91.87	-56.21	-34.79	-65.63	-23.61	5.63	-31.86	-2.21	2.28	1.17	9.74

Table E.14 – Sectoral impact of a 500€/tCO_2 carbon tax for wage curve indexed half on international price and half on consumer price with constant government consumption after reinterpreting trade elasticities - sub-section 5.1.2

2.CGC_CPI simulation **Variation (%)**	**Sectoral details for a 500€/tCO$_2$ carbon tax recycling into labour tax reduction** **Wage curve indexed on consumer price** **Crude oil**	**Natural gas**	**Coal**	**Fuel Products**	**Electricty**	**HeatGeoSol Th**	**Steel Iron**	**Non Ferrous Metals**	**Cement**	**Other Minerals**	**Other Industries**	**Agriculture**	**Composite**
Production Price	4.87	-2.22	839.57	31.59	66.76	204.80	95.32	5.83	73.98	16.94	9.90	9.81	0.65
Real Households consumption	Nan	-2.46	-4.48	-13.64	-1.55	-2.47	-29.23	-2.86	-37.08	-10.12	-6.08	-7.35	0.02
Exports in volume	0.00	0.00	0.00	0.00	-40.56	-100.00	-31.86	-5.87	-40.06	-18.26	-8.65	-9.49	-0.66
Imports in volume	-18.36	-15.37	-45.23	-5.55	86.82	144.86	23.14	-7.39	63.47	9.57	4.07	3.39	0.13
Trade balance	-18.37	-16.16	-53.58	-158.29	-81.24	Nan	-190.56	-15.61	649.82	52.48	-33.29	-14.88	1.09
Energy Cost share	77.32	48.08	19.21	3.24	325.43	25.35	249.82	103.29	103.35	185.21	126.40	139.95	110.18
Energy/Labour cost	105.31	62.20	322.07	39.41	656.02	194.60	559.97	121.91	229.65	239.92	155.23	170.29	120.58
Labour	-14.64	-12.80	67.75	-7.40	-9.80	26.01	-53.23	-13.26	-23.10	-11.26	-7.66	-8.15	0.42
Unitary Labour Cost	-9.42	-10.73	165.37	-2.55	-6.16	29.69	3.53	-3.05	7.32	-1.88	-2.52	-2.51	-4.09
Net nominal wages	-0.24	-0.24	-0.24	-0.24	-0.24	-0.24	8.98	8.98	8.98	8.98	8.98	8.98	8.98
Net real wages (Consumer Price Index)	-9.63	-9.63	-9.63	-9.63	-9.63	-9.63	-1.27	-1.27	-1.27	-1.27	-1.27	-1.27	-1.27
Purchasing power of wages	-0.31	-66.70	-92.19	-57.93	-37.57	-67.02	-23.33	5.24	-31.83	-2.62	1.75	0.38	8.36

Table E.15 – Sectoral impact of a 500€/tCO_2 carbon tax for wage curve indexed on consumer price with constant government consumption after reinterpreting trade elasticities - sub-section 5.1.2

Wage curve indexed	**International price**	**Carbon tax rate at 500€/tCO$_2$** **Half on international price** **Half on consumer price**	**Consumer price**
Variation in percentage (%)	2.CTB_INT	2.CTB_HALF	2.CTB_CPI
Real GDP (Laspeyres)	6.50	6.23	5.89
Households consumption in GDP	8.58	8.52	8.45
Public consumption in GDP	-3.04	-3.18	-3.36
Investment in GDP	1.05	0.99	0.93
Exports in GDP	0.07	0.04	0.01
Imports in GDP	0.16	0.15	0.13
Imports/Domestic production ratio	2.15	2.16	2.17
Imports of Non Energy goods in volume	2.46	2.42	2.37
Exports of Non Energy goods in volume	0.42	0.29	0.12
Total Employment	8.75	8.45	8.07
Unemployment rate (% points)	-0.08	-0.08	-0.07
Net-of-tax wages	21.43	21.68	22.00
Labour Intensity (Laspeyres)	1.94	1.93	1.91
Labour tax rate (% points)	-0.42	-0.42	-0.42
Energy Input Price (Laspeyres)	167.03	166.95	166.86
Energy Intensity (Laspeyres)	-7.38	-7.54	-7.74
Energy cost share for non-energetic sector	136.94	136.59	136.18
Production Price (Laspeyres)	-2.66	-2.53	-2.37
Production Price Energy goods (Laspeyres)	54.44	54.24	54.04
Production Price Non Energy goods (Laspeyres)	-3.94	-3.80	-3.63
Real Households consumption (Laspeyres)	15.23	15.12	15.00
Energy in Households consumption	-0.24	-0.24	-0.24
Non Energy goods in Households consumption	15.47	15.36	15.24
Public Deficits	6.56	6.44	6.30
Total Emissions	-16.51	-16.62	-16.75

Table E.16 – Macro-impact of a 500€/tCO_2 carbon tax for different wage curve indexations with constant trade balance after reinterpreting trade elasticities - sub-section 5.1.2

2.CTB_INT simulation Variation (%)	Crude oil	Natural gas	Coal	Fuel Products	Electricty	HeatGeoSol Th	Steel Iron	Non Ferrous Metals	Cement	Other Minerals	Other Industries	Agriculture	Composite
	Sectoral details for a 500€/tCO_2 carbon tax recycling into labour tax reduction Wage curve indexed on international price												
Production Price	-0.90	-6.52	835.88	30.56	62.62	201.70	90.59	-0.15	69.47	10.97	3.99	3.88	-6.28
Real Households consumption	Nan	3.93	1.63	-9.58	4.98	3.92	-20.28	12.44	-28.29	4.12	9.12	8.62	19.54
Exports in volume	0.00	0.00	0.00	0.00	-39.08	-100.00	-31.21	0.17	-38.71	-12.73	-3.76	-4.00	7.53
Imports in volume	-14.12	-9.24	-41.02	-0.83	93.62	160.59	27.04	-5.77	71.94	12.41	6.87	8.00	-3.12
Trade balance	-14.13	-9.59	-49.23	-121.02	-86.63	Nan	-217.82	-15.62	730.18	55.69	-39.58	-22.58	-21.44
Energy Cost share	83.90	51.03	19.34	3.75	335.10	25.80	257.24	112.29	107.47	198.20	137.29	151.90	122.45
Energy/Labour cost	104.69	60.17	326.94	39.63	664.37	196.19	609.22	137.39	250.36	266.14	174.73	191.35	136.83
Labour	-11.61	-7.51	78.37	-2.66	-3.90	34.87	-49.11	-2.50	-14.43	-0.28	4.31	5.59	9.23
Unitary Labour Cost	-10.97	-11.85	161.60	-2.99	-7.43	28.14	-4.00	-10.71	0.36	-9.62	-10.18	-10.19	-11.97
Net nominal wages	21.74	21.74	21.74	21.74	21.74	21.74	21.74	21.74	21.74	21.74	21.74	21.74	21.74
Net real wages (Consumer Price Index)	16.75	16.75	16.75	16.75	16.75	16.75	16.75	16.75	16.75	16.75	16.75	16.75	16.75
Purchasing power of wages	21.75	-59.11	-90.46	-48.58	-22.09	-59.34	-13.60	21.85	-22.29	12.83	18.25	17.70	29.55

Table E.17 – Sectoral impact of a 500€/tCO_2 carbon tax for wage curve indexed on international price with constant trade balance after reinterpreting trade elasticities - sub-section 5.1.2

2.CTB_HALF simulation Variation (%)	Crude oil	Natural gas	Coal	Fuel Products	Electricty	HeatGeoSol Th	Steel Iron	Non Ferrous Metals	Cement	Other Minerals	Other Industries	Agriculture	Composite
	Sectoral details for a 500€/tCO_2 carbon tax recycling into labour tax reduction Wage curve indexed half on international price/half on consumer price												
Production Price	-0.94	-6.93	835.80	30.55	62.23	201.40	90.67	-0.04	69.54	11.08	4.11	4.00	-6.14
Real Households consumption	Nan	3.90	1.59	-9.59	4.95	3.89	-20.27	12.40	-28.29	4.07	9.06	8.53	19.41
Exports in volume	0.00	0.00	0.00	0.00	-38.93	-100.00	-31.22	0.04	-38.73	-12.85	-3.87	-4.12	7.36
Imports in volume	-14.19	-9.36	-41.09	-0.91	92.73	159.56	26.90	-5.86	71.65	12.30	6.84	8.01	-3.15
Trade balance	-14.21	-9.70	-49.30	-121.61	-85.85	Nan	-216.82	-15.78	727.42	55.44	-39.61	-22.69	-21.53
Energy Cost share	83.73	51.31	19.34	3.75	336.05	25.85	257.06	111.91	107.36	197.80	136.99	151.60	121.99
Energy/Labour cost	107.38	62.30	328.02	41.42	675.71	198.95	607.95	136.78	249.75	265.35	174.18	190.79	136.24
Labour	-11.23	-7.28	81.20	-2.09	-3.53	35.85	-49.22	-2.79	-14.67	-0.56	4.08	5.39	8.92
Unitary Labour Cost	-12.24	-13.23	160.92	-4.23	-8.80	26.88	-3.83	-10.54	0.52	-9.45	-10.02	-10.02	-11.80
Net nominal wages	19.38	19.38	19.38	19.38	19.38	19.38	22.00	22.00	22.00	22.00	22.00	22.00	22.00
Net real wages (Consumer Price Index)	14.38	14.38	14.38	14.38	14.38	14.38	16.88	16.88	16.88	16.88	16.88	16.88	16.88
Purchasing power of wages	19.40	-59.87	-90.64	-49.58	-23.43	-60.09	-13.43	22.03	-22.14	12.99	18.40	17.83	29.65

Table E.18 – Sectoral impact of a 500€/tCO_2 carbon tax for wage curve indexed half on international price and half on consumer price with constant trade balance after reinterpreting trade elasticities - sub-section 5.1.2

2.CTB_CPI simulation Variation (%)	Crude oil	Natural gas	Coal	Fuel Products	Electricty	HeatGeoSol Th	Steel Iron	Non Ferrous Metals	Cement	Other Minerals	Other Industries	Agriculture	Composite
	Sectoral details for a 500€/tCO_2 carbon tax recycling into labour tax reduction Wage curve indexed on consumer price												
Production Price	-0.96	-7.31	835.73	30.55	61.86	201.11	90.77	0.10	69.62	11.22	4.25	4.15	-5.96
Real Households consumption	Nan	3.85	1.55	-9.60	4.91	3.85	-20.25	12.34	-28.29	4.01	8.98	8.43	19.26
Exports in volume	0.00	0.00	0.00	0.00	-38.79	-100.00	-31.23	-0.11	-38.76	-12.99	-4.00	-4.27	7.15
Imports in volume	-14.28	-9.51	-41.18	-1.02	91.81	158.39	26.73	-5.97	71.31	12.16	6.81	8.03	-3.20
Trade balance	-14.30	-9.85	-49.39	-122.34	-85.03	Nan	-215.59	-15.97	724.08	55.14	-39.65	-22.84	-21.66
Energy Cost share	83.53	51.58	19.34	3.75	336.96	25.89	256.85	111.47	107.23	197.35	136.64	151.24	121.47
Energy/Labour cost	110.14	64.51	329.06	43.25	687.34	201.74	606.42	136.09	249.01	264.42	173.53	190.12	135.55
Labour	-10.84	-7.06	84.09	-1.50	-3.18	36.81	-49.35	-3.15	-14.96	-0.91	3.78	5.13	8.53
Unitary Labour Cost	-13.50	-14.60	160.28	-5.45	-10.17	25.62	-3.63	-10.33	0.72	-9.25	-9.81	-9.81	-11.58
Net nominal wages	17.04	17.04	17.04	17.04	17.04	17.04	22.33	22.33	22.33	22.33	22.33	22.33	22.33
Net real wages (Consumer Price Index)	11.99	11.99	11.99	11.99	11.99	11.99	17.04	17.04	17.04	17.04	17.04	17.04	17.04
Purchasing power of wages	17.06	-60.64	-90.82	-50.57	-24.78	-60.83	-13.22	22.25	-21.97	13.19	18.60	18.00	29.78

Table E.19 – Sectoral impact of a 500€/tCO_2 carbon tax for wage curve indexed on consumer price with constant trade balance after reinterpreting trade elasticities - sub-section 5.1.2

E.2 Indexation of the wage curve

Million of euros, 2010 **Naf Rev.2 code**	**Denomination**	**Import**	**Export**	**Value-added**	**Production**
A88.09	Mining support service activities	0	0	70	194
A88.11	Manufacture of beverages	4 353	11 224	7 376	28 538
A88.12	Manufacture of tobacco products	1 875	453	528	1 375
A88.13	Manufacture of textiles	5 392	4 077	2 098	7 168
A88.14	Manufacture of wearing apparel	15 988	7 494	1 957	6 776
A88.15	Manufacture of leather and related products	6 907	5 269	1 334	2 792
A88.16	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	3 810	1 756	3 266	10 139
A88.18	Printing and reproduction of recorded media	51	71	4 238	10 919
A88.22	Manufacture of rubber and plastic products	14 731	11 780	10 458	29 601
A88.25	Manufacture of fabricated metal products, except machinery and equipment	12 738	10 317	20 677	55 990
A38.CI	Manufacture of computer, electronic and optical products	43 228	27 200	5 971	22 309
A38.CJ	Manufacture of electrical equipment	19 875	17 866	6 499	26 578
A38.CK	Manufacture of machinery and equipment n.e.c.	33 800	31 552	11 534	37 472
A88.31	Manufacture of furniture	5 783	1 750	2 862	7 235
A88.32	Other manufacturing	13 333	10 040	4 347	9 706
A88.33	Repair and installation of machinery and equipment	1 643	2 126	17 666	41 130
A88.36	Water collection, treatment and supply	0	0	3 760	10 197
A88.37	Sewerage	0	0	5 876	8 772
A88.38	Waste collection, treatment and disposal activities; materials recovery	2 389	4 780	8 235	24 623
A88.39	Remediation activities and other waste management services	0	0	248	628
A88.42	Civil engineering	0	0	11 707	37 613
A88.43	Specialised construction activities	0	0	82 788	179 188
A88.45	Wholesale and retail trade and repair of motor vehicles and motorcycles	0	0	23 040	36 815
A88.46	Wholesale trade, except of motor vehicles and motorcycles	3 485	9 242	93 858	191 357
A88.47	Retail trade, except of motor vehicles and motorcycles	0	0	75 307	125 279
A88.52	Warehousing and support activities for transportation	6 675	3 672	27 850	52 275
A88.53	Postal and courier activities	721	676	8 859	12 645
A88.55	Accommodation	0	0	10 388	21 134
A88.56	Food and beverage service activities	0	0	34 302	65 578
A88.58	Publishing activities	2 876	2 085	11 114	26 115
A88.59	Motion picture, video and television programme production, sound recording and music publishing activities	2 165	1 156	6 730	16 059
A88.60	Programming and broadcasting activities	0	0	2 793	9 643
A38.JB	Telecommunications	2 191	2 706	28 016	64 426
A88.62	Computer programming, consultancy and related activities	1 462	1 226	34 631	55 516
A88.63	Information service activities	0	0	4 478	10 095
A88.64	Financial service activities, except insurance and pension funding	3 512	6 281	56 409	110 751
A88.65	Insurance, reinsurance and pension funding, except compulsory social security	1 940	762	12 474	45 145
A88.66	Activities auxiliary to financial services and insurance activities	0	0	15 225	32 669
A88.69	Legal and accounting activities	1 368	901	27 577	37 875
A88.70	Activities of head offices; management consultancy activities	2 243	2 541	31 733	82 918
A88.71	Architectural and engineering activities; technical testing and analysis	6 226	5 312	25 602	56 329
A88.72	Scientific research and development	3 631	3 009	15 329	36 986
A88.73	Advertising and market research	1 845	711	8 702	18 809
A88.74	Other professional, scientific and technical activities	14	19	4 280	8 549
A88.75	Veterinary activities	0	0	1 332	2 283
A88.77	Rental and leasing activities	5 538	8 124	33 307	62 327
A88.78	Employment activities	0	0	27 182	31 509
A88.79	Travel agency, tour operator and other reservation service and related activities	0	0	2 450	7 729
A88.80	Security and investigation activities	0	0	5 686	7 867
A88.81	Services to buildings and landscape activities	0	0	14 161	20 248
A88.82	Office administrative, office support and other business support activities	5 017	3 026	18 901	50 923
A38.OZ	Public administration and defence; compulsory social security	0	0	120 727	175 239
A38.PZ	Education	0	0	98 663	120 821
A38.QA	Activités pour la santé humaine	267	876	100 531	137 031
A88.87	Residential care activities	0	0	28 997	36 187
A88.88	Social work activities without accommodation	0	0	25 867	29 824
A88.90	Creative, arts and entertainment activities	372	585	9 786	16 252
A88.91	Libraries, archives, museums and other cultural activities	109	220	2 333	3 302
A88.92	Gambling and betting activities	0	0	1 646	4 855
A88.93	Sports activities and amusement and recreation activities	0	0	10 826	20 028
A88.94	Activities of membership organisations	0	0	9 165	15 524
A88.95	Repair of computers and personal and household goods	0	0	5 396	9 221
A88.96	Other personal service activities	1 305	795	12 006	16 160
A88.97	Activities of households as employers of domestic personnel	0	0	7 081	7 081
A88.98	Undifferentiated goods- and services-producing activities of private households for own use	0	0	0	0
A88.99	Activities of extraterritorial organisations and bodies	0	0	0	0
	TOTAL	**238 859**	**201 680**	**1 308 234**	**2 450 323**

Table E.20 – Decomposition and economic details on 'Composite aggregate'

Million of euros, 2010					
Naf Rev.2 code	**Denomination**	**Import**	**Export**	**Value-added**	**Production**
A88.41	Construction	0	0	12 306	40 508
A.38.CE.CF	Chemical and petrochemical	62 069	74 547	20 002	85 110
A88.17	Paper, pulp and print	9 223	6 413	4 451	17 673
A88.07.08	Mining and quarrying	2 571	627	1 952	4 742
A88.29.30	Transport equipement	66 458	81 526	18 053	121 547
A.88.49.50.51	Transport - Sectors	2 995	16 453	47 670	108 641
	Total	143 316	179 566	104 434	378 221

Table E.21 – Decomposition and economic details on 'Other Industries' aggregate

			Thirteen sector model (AGG_IndEner)												
Parameters			**Crude oil**	**Natural gas**	**Coal**	**Fuel Products**	**Electricty**	**HeatGeoSol Th**	**Steel Iron**	**Non Ferrous Metals**	**Cement**	**Other Minerals**	**Other Industries**	**Agriculture**	**Composite**
		Crude oil	500	500	500	500	500	500	500	500	500	500	500	500	500
		Natural gas	500	500	500	500	500	500	500	500	500	500	500	500	500
		Coal	500	500	500	500	500	500	500	500	500	500	500	500	500
		Fuel Products	500	500	500	500	500	500	500	500	500	500	500	500	500
		Electricty	500	500	500	500	500	500	500	500	500	500	500	500	500
		HeatGeoSol Th	500	500	500	500	500	500	500	500	500	500	500	500	500
$t_{CARB_{IC}}$	€$/tCO_2$	Steel Iron	500	500	500	500	500	500	500	500	500	500	500	500	500
		Non Ferrous Metals	500	500	500	500	500	500	500	500	500	500	500	500	500
		Cement	500	500	500	500	500	500	500	500	500	500	500	500	500
		Other Minerals	500	500	500	500	500	500	500	500	500	500	500	500	500
		Other Industries	500	500	500	500	500	500	500	500	500	500	500	500	500
		Agriculture	500	500	500	500	500	500	500	500	500	500	500	500	500
		Composite	500	500	500	500	500	500	500	500	500	500	500	500	500
t_{CARB_C}	€$/tCO_2$		500	500	500	500	500	500	500	500	500	500	500	500	500
		Crude oil	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Natural gas	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Coal	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Fuel Products	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Electricty	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		HeatGeoSol Th	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
$\beta_{IC_{ji}}$		Steel Iron	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Non Ferrous Metals	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Cement	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Other Minerals	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Other Industries	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Agriculture	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Composite	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
β_{K_i}			0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
β_{L_i}			0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
β_{i_h}			0.5	0.5	0.5	0.5	0.5	0.5	Nan	Nan	Nan	Nan	Nan	Nan	Nan
σ			1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
$\sigma_{M_{p_i}}$			0.00	0.00	0.00	0.50	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58
$\sigma_{X_{p_i}}$			0.00	0.00	0.00	0.00	1.09	0.99	1.09	1.73	1.09	1.79	1.33	1.23	1.15
σ_{CP_i}			-0.03	-0.03	-0.03	-0.39	-0.03	-0.03	Nan	Nan	Nan	Nan	Nan	Nan	Nan
σ_{CR_i}			0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
σ_{w_u}			-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
$\beta_{w_{CPI}}$			0	0	0	0	0	0	0.4	0	0.8	0.4	0	0	0.8

Table E.22 – Reference simulation parameters for calibration at sub-section 5.2.2

E.2.1 Macroeconomic results

Level of indexed of wage curve on domestic price	**Carbon tax rate at 500€/tCO_2**										
					Low*					**Reference**	**High***
Variation in percentage (%)	WG_0.1	WG_0.2	WG_0.3	WG_0.4	WG_0.5	WG_0.6	WG_0.7	WG_0.8	WG_0.9	WG_REF	WG_1.1
Real GDP (Laspeyres)	2.76	2.53	2.28	2.02	1.72	1.40	1.04	0.64	0.20	-0.31	-0.90
Households consumption in GDP	0.99	0.89	0.78	0.67	0.54	0.40	0.24	0.07	-0.13	-0.36	-0.62
Public consumption in GDP	2.42	2.36	2.28	2.21	2.12	2.03	1.93	1.82	1.70	1.55	1.39
Investment in GDP	0.35	0.31	0.26	0.21	0.16	0.09	0.03	-0.05	-0.14	-0.23	-0.35
Exports in GDP	-0.74	-0.76	-0.79	-0.81	-0.85	-0.88	-0.92	-0.96	-1.01	-1.07	-1.14
Imports in GDP	0.27	0.27	0.26	0.26	0.25	0.24	0.24	0.23	0.22	0.20	0.19
Imports/Domestic production ratio	2.33	2.34	2.34	2.34	2.35	2.36	2.36	2.37	2.38	2.39	2.41
Imports of Non Energy goods in volume	3.25	3.24	3.23	3.21	3.20	3.18	3.15	3.13	3.10	3.06	3.02
Exports of Non Energy goods in volume	-3.16	-3.27	-3.39	-3.52	-3.67	-3.84	-4.02	-4.22	-4.45	-4.71	-5.02
Total Employment	5.16	4.89	4.60	4.29	3.95	3.58	3.17	2.72	2.21	1.63	0.97
Unemployment rate (% points)	-0.05	-0.04	-0.04	-0.04	-0.04	-0.03	-0.03	-0.02	-0.02	-0.01	-0.01
Net-of-tax wages	7.48	7.55	7.62	7.70	7.78	7.87	7.97	8.08	8.20	8.34	8.49
Labour Intensity (Laspeyres)	1.74	1.72	1.71	1.70	1.68	1.67	1.65	1.63	1.61	1.58	1.55
Labour tax rate (% points)	-0.23	-0.23	-0.23	-0.22	-0.22	-0.22	-0.22	-0.21	-0.21	-0.20	-0.20
Energy Input Price (Laspeyres)	167.91	167.91	167.92	167.93	167.94	167.95	167.97	168.00	168.03	168.07	168.11
Energy Intensity (Laspeyres)	-11.06	-11.18	-11.31	-11.46	-11.62	-11.80	-12.00	-12.23	-12.48	-12.78	-13.12
Energy cost share for non-energetic sector	127.38	127.15	126.90	126.63	126.33	126.00	125.64	125.23	124.77	124.25	123.64
Production Price (Laspeyres)	0.94	1.09	1.26	1.44	1.63	1.85	2.09	2.36	2.66	3.01	3.40
Production Price Energy goods (Laspeyres)	56.50	56.51	56.53	56.55	56.58	56.62	56.67	56.72	56.80	56.88	56.99
Production Price Non Energy goods (Laspeyres)	-0.31	-0.15	0.02	0.20	0.40	0.62	0.87	1.14	1.45	1.80	2.20
Real Households consumption (Laspeyres)	1.76	1.58	1.39	1.18	0.96	0.71	0.43	0.12	-0.23	-0.63	-1.09
Energy in Households consumption	-0.50	-0.51	-0.51	-0.51	-0.52	-0.52	-0.53	-0.53	-0.54	-0.55	-0.55
Non Energy goods in Households consumption	2.26	2.09	1.90	1.70	1.47	1.23	0.95	0.65	0.31	-0.09	-0.54
Public Deficits	6.87	6.81	6.75	6.67	6.59	6.50	6.40	6.29	6.15	6.00	5.82
Total Emissions	-20.02	-20.11	-20.20	-20.31	-20.43	-20.56	-20.70	-20.86	-21.05	-21.26	-21.51

Table E.23 – Macroeconomic results for a large range of wage curve indexation at sub-section 5.2.2

E.2.2 Sectoral results and distributional impacts

WC_1.1 Variation (%)	Crude oil	Natural gas	Coal	Fuel Products	Electricty	HeatGeoSol Th	Steel Iron	Non Ferrous Metals	Cement	Other Minerals	Other Industries	Agriculture	Composite
	Sectoral details for a 500€/tCO_2 carbon tax recycling into labour tax reduction Wage curve indexation compared to reference values												
Production Price	4.63	-2.46	839.32	31.54	66.54	204.63	94.31	4.70	73.59	15.59	7.78	7.04	0.39
Real Households consumption	Nan	-2.04	-4.08	-13.39	-1.12	-2.05	-28.65	-1.61	-36.57	-8.82	-4.15	-4.67	0.88
Exports in volume	0.00	0.00	0.00	0.00	-40.48	-100.00	-31.72	-4.80	-39.95	-17.09	-6.95	-7.02	-0.40
Imports in volume	-17.68	-14.58	-44.60	-4.78	88.29	147.53	23.72	-7.15	65.08	9.72	3.73	2.62	0.76
Trade balance	-17.69	-15.33	-52.93	-152.57	-82.47	Nan	-194.62	-15.76	665.21	51.60	-28.98	-11.23	4.43
Energy Cost share	77.56	48.24	19.22	3.27	325.94	25.37	251.47	105.15	103.72	188.23	130.38	145.58	110.60
Energy/Labour cost	104.53	61.50	322.15	38.98	653.86	194.03	580.51	136.20	230.02	251.20	172.26	188.79	120.73
Labour	-14.11	-12.15	68.79	-6.79	-9.09	27.08	-52.13	-9.81	-22.14	-8.80	-3.47	-3.64	1.44
Unitary Labour Cost	-9.17	-10.46	165.26	-2.26	-5.90	29.89	0.36	-9.07	7.16	-5.13	-8.80	-8.97	-4.22
Net nominal wages	1.00	1.00	1.00	1.00	1.00	1.00	5.36	1.00	9.71	5.36	1.00	1.00	9.71
Net real wages (Consumer Price Index)	-8.01	-8.01	-8.01	-8.01	-8.01	-8.01	-4.05	-8.01	-0.08	-4.05	-8.01	-8.01	-0.08
Purchasing power of wages	0.93	-66.28	-92.09	-57.40	-36.71	-66.59	-25.74	-1.83	-31.26	-5.10	-4.37	-4.88	9.33

Table E.24 – Sectoral results for the *WC_1.1* simulation of wage curve indexation at sub-section 5.2.2

WC_REF Variation (%)	Crude oil	Natural gas	Coal	Fuel Products	Electricty	HeatGeoSol Th	Steel Iron	Non Ferrous Metals	Cement	Other Minerals	Other Industries	Agriculture	Composite
	Sectoral details for a 500€/tCO_2 carbon tax recycling into labour tax reduction Reference wage curve indexation												
Production Price	4.30	-2.62	839.14	31.48	66.38	204.52	94.11	4.42	73.33	15.34	7.62	6.95	-0.07
Real Households consumption	Nan	-1.87	-3.92	-13.30	-0.95	-1.88	-28.52	-1.30	-36.40	-8.54	-3.90	-4.45	1.46
Exports in volume	0.00	0.00	0.00	0.00	-40.43	-100.00	-31.70	-4.54	-39.87	-16.86	-6.82	-6.93	0.09
Imports in volume	-17.51	-14.29	-44.40	-4.60	88.73	148.79	24.02	-6.96	65.62	9.99	3.90	2.80	0.68
Trade balance	-17.53	-15.02	-52.72	-151.10	-82.82	Nan	-196.70	-15.43	670.36	52.24	-29.58	-11.63	3.68
Energy Cost share	77.97	48.35	19.22	3.29	326.29	25.39	251.78	105.57	103.96	188.78	130.66	145.75	111.41
Energy/Labour cost	104.04	61.02	322.22	38.68	652.36	193.63	581.60	135.67	231.52	251.76	171.65	188.10	121.87
Labour	-14.10	-11.96	68.80	-6.72	-8.88	27.51	-51.94	-9.39	-21.59	-8.28	-3.22	-3.45	2.14
Unitary Labour Cost	-9.03	-10.28	165.19	-2.07	-5.73	30.04	0.18	-8.92	6.64	-5.31	-8.62	-8.77	-4.79
Net nominal wages	1.76	1.76	1.76	1.76	1.76	1.76	5.61	1.76	9.47	5.61	1.76	1.76	9.47
Net real wages (Consumer Price Index)	-7.04	-7.04	-7.04	-7.04	-7.04	-7.04	-3.52	-7.04	0.00	-3.52	-7.04	-7.04	0.00
Purchasing power of wages	1.70	-66.02	-92.03	-57.08	-36.18	-66.33	-25.53	-0.93	-31.33	-4.73	-3.55	-4.10	9.55

Table E.25 – Sectoral results for the reference wage curve indexation (*WC_REF*) at sub-section 5.2.2

WC_0.9 Variation (%)	Crude oil	Natural gas	Coal	Fuel Products	Electricty	HeatGeoSol Th	Steel Iron	Non Ferrous Metals	Cement	Other Minerals	Other Industries	Agriculture	Composite
						Sectoral details for a 500€/tCO_2 carbon tax recycling into labour tax reduction Wage curve indexation compared to reference values							
Production Price	4.02	-2.74	838.98	31.43	66.26	204.43	93.94	4.19	73.10	15.12	7.49	6.89	-0.47
Real Households consumption	Nan	-1.72	-3.78	-13.22	-0.80	-1.74	-28.40	-1.04	-36.25	-8.30	-3.70	-4.28	1.97
Exports in volume	0.00	0.00	0.00	0.00	-40.39	-100.00	-31.67	-4.31	-39.80	-16.66	-6.71	-6.87	0.52
Imports in volume	-17.37	-14.04	-44.22	-4.45	89.12	149.89	24.28	-6.79	66.09	10.22	4.04	2.97	0.60
Trade balance	-17.39	-14.75	-52.54	-149.84	-83.15	Nan	-198.52	-15.13	674.80	52.81	-30.14	-12.01	3.00
Energy Cost share	78.32	48.44	19.23	3.32	326.57	25.40	252.05	105.93	104.18	189.24	130.88	145.86	112.12
Energy/Labour cost	103.54	60.55	322.24	38.37	650.75	193.22	582.43	135.12	232.83	252.18	171.01	187.39	122.88
Labour	-14.10	-11.81	68.72	-6.68	-8.71	27.85	-51.78	-9.05	-21.11	-7.84	-3.03	-3.31	2.74
Unitary Labour Cost	-8.87	-10.08	165.14	-1.86	-5.53	30.20	0.05	-8.75	6.19	-5.45	-8.42	-8.56	-5.28
Net nominal wages	2.47	2.47	2.47	2.47	2.47	2.47	5.86	2.47	9.25	5.86	2.47	2.47	9.25
Net real wages (Consumer Price Index)	-6.14	-6.14	-6.14	-6.14	-6.14	-6.14	-3.04	-6.14	0.06	-3.04	-6.14	-6.14	0.06
Purchasing power of wages	2.41	-65.77	-91.97	-56.77	-35.69	-66.08	-25.34	-0.10	-31.40	-4.38	-2.78	-3.37	9.73

Table E.26 – Sectoral results for the $WC\_0.9$ simulation of wage curve indexation at sub-section 5.2.2

WC_0.8 Variation (%)	Crude oil	Natural gas	Coal	Fuel Products	Electricty	HeatGeoSol Th	Steel Iron	Non Ferrous Metals	Cement	Other Minerals	Other Industries	Agriculture	Composite
						Sectoral details for a 500€/tCO_2 carbon tax recycling into labour tax reduction Wage curve indexation compared to reference values							
Production Price	3.77	-2.84	838.85	31.39	66.17	204.36	93.79	3.99	72.90	14.94	7.39	6.85	-0.83
Real Households consumption	Nan	-1.59	-3.66	-13.16	-0.67	-1.61	-28.30	-0.81	-36.13	-8.10	-3.52	-4.14	2.41
Exports in volume	0.00	0.00	0.00	0.00	-40.35	-100.00	-31.65	-4.11	-39.74	-16.50	-6.63	-6.84	0.90
Imports in volume	-17.25	-13.81	-44.07	-4.31	89.48	150.87	24.50	-6.64	66.50	10.43	4.17	3.12	0.53
Trade balance	-17.27	-14.51	-52.38	-148.75	-83.44	Nan	-200.11	-14.87	678.68	53.32	-30.66	-12.37	2.38
Energy Cost share	78.64	48.51	19.23	3.34	326.78	25.41	252.28	106.24	104.37	189.65	131.06	145.93	112.76
Energy/Labour cost	103.04	60.08	322.24	38.05	649.07	192.78	583.06	134.56	234.01	252.50	170.35	186.66	123.79
Labour	-14.11	-11.68	68.58	-6.66	-8.58	28.12	-51.65	-8.76	-20.69	-7.45	-2.88	-3.21	3.28
Unitary Labour Cost	-8.70	-9.86	165.12	-1.65	-5.33	30.37	-0.05	-8.57	5.79	-5.56	-8.22	-8.33	-5.71
Net nominal wages	3.15	3.15	3.15	3.15	3.15	3.15	6.10	3.15	9.05	6.10	3.15	3.15	9.05
Net real wages (Consumer Price Index)	-5.30	-5.30	-5.30	-5.30	-5.30	-5.30	-2.60	-5.30	0.11	-2.60	-5.30	-5.30	0.11
Purchasing power of wages	3.10	-65.54	-91.92	-56.48	-35.24	-65.85	-25.15	0.68	-31.46	-4.05	-2.07	-2.70	9.89

Table E.27 – Sectoral results for the $WC\_0.8$ simulation of wage curve indexation at sub-section 5.2.2

WC_0.7 Variation (%)	Crude oil	Natural gas	Coal	Fuel Products	Electricty	HeatGeoSol Th	Steel Iron	Non Ferrous Metals	Cement	Other Minerals	Other Industries	Agriculture	Composite
					Sectoral details for a 500€/tCO_2 carbon tax recycling into labour tax reduction Wage curve indexation compared to reference values								
Production Price	3.56	-2.91	838.74	31.35	66.10	204.31	93.67	3.81	72.73	14.78	7.31	6.83	-1.14
Real Households consumption	Nan	-1.48	-3.55	-13.10	-0.55	-1.49	-28.22	-0.61	-36.01	-7.92	-3.38	-4.03	2.81
Exports in volume	0.00	0.00	0.00	0.00	-40.33	-100.00	-31.64	-3.94	-39.69	-16.36	-6.56	-6.81	1.25
Imports in volume	-17.15	-13.62	-43.93	-4.20	89.81	151.76	24.71	-6.50	66.86	10.62	4.29	3.26	0.46
Trade balance	-17.16	-14.30	-52.24	-147.80	-83.72	Nan	-201.54	-14.63	682.11	53.79	-31.14	-12.70	1.80
Energy Cost share	78.92	48.56	19.24	3.36	326.95	25.42	252.48	106.52	104.53	189.99	131.21	145.97	113.34
Energy/Labour cost	102.54	59.63	322.20	37.73	647.34	192.34	583.52	133.99	235.07	252.74	169.68	185.92	124.62
Labour	-14.14	-11.58	68.40	-6.66	-8.47	28.34	-51.53	-8.52	-20.32	-7.12	-2.77	-3.15	3.76
Unitary Labour Cost	-8.52	-9.64	165.12	-1.43	-5.11	30.56	-0.13	-8.37	5.44	-5.64	-8.00	-8.10	-6.10
Net nominal wages	3.80	3.80	3.80	3.80	3.80	3.80	6.34	3.80	8.87	6.34	3.80	3.80	8.87
Net real wages (Consumer Price Index)	-4.51	-4.51	-4.51	-4.51	-4.51	-4.51	-2.18	-4.51	0.15	-2.18	-4.51	-4.51	0.15
Purchasing power of wages	3.75	-65.32	-91.87	-56.20	-34.80	-65.63	-24.96	1.42	-31.52	-3.75	-1.40	-2.07	10.03

Table E.28 – Sectoral results for the *WC*_0.7 simulation of wage curve indexation at sub-section 5.2.2

WC_0.6 Variation (%)	Crude oil	Natural gas	Coal	Fuel Products	Electricty	HeatGeoSol Th	Steel Iron	Non Ferrous Metals	Cement	Other Minerals	Other Industries	Agriculture	Composite
					Sectoral details for a 500€/tCO_2 carbon tax recycling into labour tax reduction Wage curve indexation compared to reference values								
Production Price	3.36	-2.97	838.64	31.32	66.04	204.27	93.56	3.66	72.57	14.64	7.24	6.82	-1.42
Real Households consumption	Nan	-1.38	-3.45	-13.04	-0.45	-1.39	-28.14	-0.44	-35.91	-7.77	-3.25	-3.94	3.17
Exports in volume	0.00	0.00	0.00	0.00	-40.31	-100.00	-31.62	-3.79	-39.65	-16.23	-6.50	-6.81	1.56
Imports in volume	-17.06	-13.44	-43.81	-4.10	90.12	152.56	24.89	-6.38	67.18	10.79	4.40	3.40	0.39
Trade balance	-17.07	-14.11	-52.11	-146.95	-83.98	Nan	-202.82	-14.41	685.17	54.22	-31.60	-13.03	1.26
Energy Cost share	79.18	48.60	19.24	3.38	327.07	25.43	252.65	106.77	104.68	190.30	131.33	145.98	113.87
Energy/Labour cost	102.04	59.18	322.15	37.41	645.58	191.88	583.85	133.42	236.04	252.90	169.00	185.18	125.37
Labour	-14.17	-11.49	68.17	-6.67	-8.39	28.51	-51.42	-8.31	-19.98	-6.83	-2.68	-3.10	4.19
Unitary Labour Cost	-8.33	-9.42	165.13	-1.21	-4.89	30.75	-0.19	-8.18	5.12	-5.70	-7.78	-7.87	-6.46
Net nominal wages	4.43	4.43	4.43	4.43	4.43	4.43	6.56	4.43	8.70	6.56	4.43	4.43	8.70
Net real wages (Consumer Price Index)	-3.76	-3.76	-3.76	-3.76	-3.76	-3.76	-1.79	-3.76	0.17	-1.79	-3.76	-3.76	0.17
Purchasing power of wages	4.38	-65.10	-91.82	-55.94	-34.39	-65.42	-24.79	2.13	-31.58	-3.46	-0.76	-1.47	10.15

Table E.29 – Sectoral results for the *WC*_0.6 simulation of wage curve indexation at sub-section 5.2.2

WC_0.5						Sectoral details for a 500€/tCO_2 carbon tax recycling into labour tax reduction Wage curve indexation compared to reference values							
Variation (%)	**Crude oil**	**Natural gas**	**Coal**	**Fuel Products**	**Electricty**	**HeatGeoSol Th**	**Steel Iron**	**Non Ferrous Metals**	**Cement**	**Other Minerals**	**Other Industries**	**Agriculture**	**Composite**
Production Price	3.19	-3.01	838.55	31.29	66.00	204.24	93.46	3.52	72.43	14.52	7.19	6.82	-1.68
Real Households consumption	Nan	-1.29	-3.36	-13.00	-0.36	-1.30	-28.07	-0.28	-35.82	-7.63	-3.14	-3.87	3.50
Exports in volume	0.00	0.00	0.00	0.00	-40.30	-100.00	-31.61	-3.66	-39.61	-16.12	-6.46	-6.81	1.84
Imports in volume	-16.97	-13.28	-43.70	-4.01	90.42	153.29	25.05	-6.27	67.47	10.94	4.50	3.52	0.33
Trade balance	-16.99	-13.94	-52.00	-146.21	-84.22	Nan	-203.98	-14.21	687.92	54.62	-32.04	-13.34	0.75
Energy Cost share	79.42	48.63	19.24	3.39	327.17	25.43	252.81	107.00	104.82	190.57	131.42	145.96	114.36
Energy/Labour cost	101.54	58.73	322.08	37.09	643.78	191.42	584.08	132.85	236.92	253.01	168.32	184.42	126.07
Labour	-14.21	-11.42	67.91	-6.69	-8.32	28.64	-51.34	-8.14	-19.67	-6.57	-2.62	-3.08	4.58
Unitary Labour Cost	-8.13	-9.19	165.16	-0.99	-4.66	30.95	-0.23	-7.97	4.82	-5.74	-7.55	-7.63	-6.78
Net nominal wages	5.04	5.04	5.04	5.04	5.04	5.04	6.79	5.04	8.54	6.79	5.04	5.04	8.54
Net real wages (Consumer Price Index)	-3.04	-3.04	-3.04	-3.04	-3.04	-3.04	-1.42	-3.04	0.19	-1.42	-3.04	-3.04	0.19
Purchasing power of wages	4.99	-64.90	-91.77	-55.68	-33.99	-65.21	-24.62	2.80	-31.64	-3.19	-0.15	-0.90	10.25

Table E.30 – Sectoral results for the $WC\_0.5$ simulation of wage curve indexation at sub-section 5.2.2

WC_0.4						Sectoral details for a 500€/tCO_2 carbon tax recycling into labour tax reduction Wage curve indexation compared to reference values							
Variation (%)	**Crude oil**	**Natural gas**	**Coal**	**Fuel Products**	**Electricty**	**HeatGeoSol Th**	**Steel Iron**	**Non Ferrous Metals**	**Cement**	**Other Minerals**	**Other Industries**	**Agriculture**	**Composite**
Production Price	3.04	-3.04	838.47	31.26	65.97	204.22	93.37	3.40	72.30	14.41	7.15	6.83	-1.92
Real Households consumption	Nan	-1.21	-3.29	-12.95	-0.27	-1.22	-28.01	-0.14	-35.74	-7.51	-3.05	-3.81	3.80
Exports in volume	0.00	0.00	0.00	0.00	-40.28	-100.00	-31.60	-3.54	-39.57	-16.02	-6.43	-6.82	2.11
Imports in volume	-16.90	-13.14	-43.61	-3.92	90.69	153.97	25.20	-6.17	67.73	11.09	4.60	3.64	0.27
Trade balance	-16.91	-13.79	-51.90	-145.54	-84.45	Nan	-205.03	-14.03	690.41	54.99	-32.47	-13.63	0.27
Energy Cost share	79.64	48.65	19.25	3.40	327.23	25.44	252.94	107.20	104.95	190.81	131.49	145.93	114.81
Energy/Labour cost	101.05	58.30	321.99	36.77	641.96	190.95	584.21	132.28	237.75	253.07	167.63	183.67	126.72
Labour	-14.25	-11.36	67.62	-6.72	-8.26	28.74	-51.26	-7.99	-19.39	-6.34	-2.58	-3.08	4.94
Unitary Labour Cost	-7.93	-8.95	165.20	-0.76	-4.43	31.15	-0.25	-7.76	4.55	-5.76	-7.32	-7.38	-7.07
Net nominal wages	5.63	5.63	5.63	5.63	5.63	5.63	7.01	5.63	8.39	7.01	5.63	5.63	8.39
Net real wages (Consumer Price Index)	-2.34	-2.34	-2.34	-2.34	-2.34	-2.34	-1.07	-2.34	0.21	-1.07	-2.34	-2.34	0.21
Purchasing power of wages	5.58	-64.70	-91.72	-55.43	-33.61	-65.01	-24.45	3.45	-31.69	-2.93	0.44	-0.35	10.34

Table E.31 – Sectoral results for the $WC\_0.4$ simulation of wage curve indexation at sub-section 5.2.2

WC_0.3 Variation (%)	Crude oil	Natural gas	Coal	Fuel Products	Electricty	HeatGeoSol Th	Steel Iron	Non Ferrous Metals	Cement	Other Minerals	Other Industries	Agriculture	Composite
						Sectoral details for a 500€/tCO_2 carbon tax recycling into labour tax reduction Wage curve indexation compared to reference values								
Production Price	2.90	-3.06	838.40	31.24	65.95	204.20	93.30	3.29	72.18	14.32	7.12	6.85	-2.14
Real Households consumption	Nan	-1.13	-3.21	-12.91	-0.20	-1.15	-27.96	-0.02	-35.67	-7.40	-2.97	-3.77	4.07
Exports in volume	0.00	0.00	0.00	0.00	-40.28	-100.00	-31.59	-3.43	-39.53	-15.94	-6.40	-6.83	2.35
Imports in volume	-16.83	-13.01	-43.52	-3.85	90.96	154.60	25.34	-6.08	67.97	11.22	4.69	3.75	0.21
Trade balance	-16.85	-13.66	-51.81	-144.93	-84.67	Nan	-206.00	-13.86	692.67	55.34	-32.88	-13.92	-0.19
Energy Cost share	79.84	48.67	19.25	3.42	327.27	25.44	253.06	107.39	105.06	191.02	131.54	145.89	115.23
Energy/Labour cost	100.55	57.87	321.89	36.45	640.12	190.48	584.26	131.70	238.51	253.09	166.94	182.90	127.33
Labour	-14.29	-11.31	67.31	-6.76	-8.22	28.81	-51.19	-7.86	-19.13	-6.13	-2.55	-3.09	5.28
Unitary Labour Cost	-7.73	-8.71	165.25	-0.53	-4.20	31.36	-0.26	-7.55	4.31	-5.78	-7.09	-7.13	-7.34
Net nominal wages	6.20	6.20	6.20	6.20	6.20	6.20	7.23	6.20	8.25	7.23	6.20	6.20	8.25
Net real wages (Consumer Price Index)	-1.68	-1.68	-1.68	-1.68	-1.68	-1.68	-0.73	-1.68	0.21	-0.73	-1.68	-1.68	0.21
Purchasing power of wages	6.16	-64.51	-91.68	-55.19	-33.24	-64.82	-24.28	4.09	-31.74	-2.67	1.01	0.18	10.43

Table E.32 – Sectoral results for the *WC*_0.3 simulation of wage curve indexation at sub-section 5.2.2

WC_0.2 Variation (%)	Crude oil	Natural gas	Coal	Fuel Products	Electricty	HeatGeoSol Th	Steel Iron	Non Ferrous Metals	Cement	Other Minerals	Other Industries	Agriculture	Composite
						Sectoral details for a 500€/tCO_2 carbon tax recycling into labour tax reduction Wage curve indexation compared to reference values								
Production Price	2.77	-3.07	838.34	31.22	65.94	204.20	93.23	3.19	72.08	14.24	7.10	6.88	-2.34
Real Households consumption	Nan	-1.06	-3.15	-12.88	-0.13	-1.08	-27.91	0.10	-35.61	-7.30	-2.91	-3.74	4.33
Exports in volume	0.00	0.00	0.00	0.00	-40.27	-100.00	-31.58	-3.33	-39.50	-15.86	-6.38	-6.86	2.58
Imports in volume	-16.77	-12.89	-43.44	-3.79	91.21	155.18	25.46	-5.99	68.19	11.35	4.78	3.85	0.16
Trade balance	-16.79	-13.53	-51.73	-144.39	-84.89	Nan	-206.89	-13.70	694.74	55.67	-33.27	-14.21	-0.63
Energy Cost share	80.03	48.68	19.25	3.43	327.29	25.44	253.17	107.56	105.17	191.22	131.58	145.82	115.63
Energy/Labour cost	100.06	57.44	321.77	36.12	638.26	190.01	584.24	131.13	239.22	253.07	166.25	182.14	127.90
Labour	-14.34	-11.27	66.98	-6.81	-8.19	28.85	-51.13	-7.75	-18.89	-5.95	-2.54	-3.12	5.58
Unitary Labour Cost	-7.51	-8.47	165.31	-0.30	-3.96	31.58	-0.26	-7.33	4.08	-5.78	-6.85	-6.88	-7.60
Net nominal wages	6.77	6.77	6.77	6.77	6.77	6.77	7.44	6.77	8.11	7.44	6.77	6.77	8.11
Net real wages (Consumer Price Index)	-1.03	-1.03	-1.03	-1.03	-1.03	-1.03	-0.41	-1.03	0.22	-0.41	-1.03	-1.03	0.22
Purchasing power of wages	6.72	-64.32	-91.63	-54.95	-32.88	-64.63	-24.12	4.70	-31.80	-2.43	1.56	0.69	10.50

Table E.33 – Sectoral results for the *WC*_0.2 simulation of wage curve indexation at sub-section 5.2.2

WC_0.1 Variation (%)	Crude oil	Natural gas	Coal	Fuel Products	Electricty	HeatGeoSol Th	Steel Iron	Non Ferrous Metals	Cement	Other Minerals	Other Industries	Agriculture	Composite
	Sectoral details for a 500€/tCO_2 carbon tax recycling into labour tax reduction Wage curve indexation compared to reference values												
Production Price	2.66	-3.08	838.29	31.20	65.94	204.19	93.17	3.11	71.98	14.16	7.08	6.91	-2.53
Real Households consumption	Nan	-1.00	-3.09	-12.85	-0.06	-1.01	-27.87	0.20	-35.55	-7.22	-2.85	-3.72	4.56
Exports in volume	0.00	0.00	0.00	0.00	-40.27	-100.00	-31.57	-3.24	-39.47	-15.80	-6.37	-6.89	2.79
Imports in volume	-16.72	-12.78	-43.37	-3.73	91.45	155.72	25.58	-5.91	68.38	11.46	4.86	3.96	0.10
Trade balance	-16.73	-13.41	-51.66	-143.90	-85.09	Nan	-207.72	-13.55	696.63	55.99	-33.65	-14.48	-1.05
Energy Cost share	80.21	48.68	19.25	3.44	327.30	25.44	253.27	107.71	105.27	191.39	131.60	145.75	116.00
Energy/Labour cost	99.57	57.02	321.65	35.80	636.40	189.53	584.15	130.55	239.89	253.03	165.55	181.38	128.44
Labour	-14.40	-11.24	66.64	-6.87	-8.17	28.88	-51.07	-7.66	-18.67	-5.78	-2.54	-3.15	5.87
Unitary Labour Cost	-7.30	-8.22	165.37	-0.07	-3.71	31.79	-0.25	-7.11	3.86	-5.77	-6.61	-6.63	-7.83
Net nominal wages	7.32	7.32	7.32	7.32	7.32	7.32	7.65	7.32	7.99	7.65	7.32	7.32	7.99
Net real wages (Consumer Price Index)	-0.40	-0.40	-0.40	-0.40	-0.40	-0.40	-0.09	-0.40	0.22	-0.09	-0.40	-0.40	0.22
Purchasing power of wages	7.28	-64.13	-91.59	-54.71	-32.54	-64.45	-23.97	5.30	-31.85	-2.19	2.09	1.18	10.57

Table E.34 – Sectoral results for the *WC*_0.1 simulation of wage curve indexation at sub-section 5.2.2

Appendix F

Further information on Chapter 6

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Crude oil	1.1
Natural gas	-
Coking coal	3.0
Bituminous coal	64.3
Coke oven coke	1.0
Other coal products	0.2
Gasoline / biogasoline	0.5
LPG	2.0
Jet Fuel	2.1
Diesel and biofuel	1.6
Heating fuel	1.3
Heavy fuel oil	2.0
Other petroleum products	1.4
Electricity	5.2
Heat, Geothermal, Solar Th	0.0
Iron and steel	0.9
Non ferrous metals	0.9
Cement and clinker	0.4
Other non-metallic minerals	1.3
Construction	0.0
Chemical and petrochemical	1.4
Paper, pulp and print	1.2
Mining and quarrying	0.8
Transport equipement	1.2
Transport - Sectors	2.7
Agricuture and forestry	1.0
Fishing	1.8
Agri-food industry	1.6
Composite	0.9

Table F.1 – Adjustment parameter for import balance

\hat\tau	Crude oil	Natural gas	Coking coal	Bituminous coal	Coke oven coke	Other coal products	Gasoline / biogasoline	LPG	Jet Fuel	Diesel and biofuel	Heating fuel	Heavy fuel oil	Other petroleum products	Electricity
Crude oil	26%	82%	26%	26%	99%	73%	99%	99%	99%	99%	99%	99%	99%	82%
Natural gas	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Coking coal	72%	100%	72%	72%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Bituminous coal	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Coke oven coke	27%	22%	27%	27%	28%	31%	28%	28%	28%	28%	28%	28%	28%	22%
Other coal products	13%	7%	13%	13%	11%	10%	11%	11%	11%	11%	11%	11%	11%	7%
Gasoline / biogasoline	12%	10%	12%	12%	13%	14%	13%	13%	13%	13%	13%	13%	13%	10%
LPG	54%	43%	54%	54%	57%	61%	57%	57%	57%	57%	57%	57%	57%	43%
Jet Fuel	55%	44%	55%	55%	58%	62%	58%	58%	58%	58%	58%	58%	58%	44%
Diesel and biofuel	44%	35%	44%	44%	46%	49%	46%	46%	46%	46%	46%	46%	46%	35%
Heating fuel	34%	27%	34%	34%	36%	38%	36%	36%	36%	36%	36%	36%	36%	27%
Heavy fuel oil	53%	43%	53%	53%	56%	60%	56%	56%	56%	56%	56%	56%	56%	43%
Other petroleum products	37%	29%	37%	37%	39%	42%	39%	39%	39%	39%	39%	39%	39%	29%
Electricity	8%	6%	8%	8%	9%	8%	9%	9%	9%	9%	9%	9%	9%	6%
Heat, Geothermal, Solar Th	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Iron and steel	67%	37%	67%	67%	57%	54%	57%	57%	57%	57%	57%	57%	57%	37%
Non ferrous metals	65%	36%	65%	65%	55%	52%	55%	55%	55%	55%	55%	55%	55%	36%
Cement and clinker	6%	5%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	5%
Other non-metallic minerals	20%	15%	20%	20%	19%	20%	19%	19%	19%	19%	19%	19%	19%	15%
Construction	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Chemical and petrochemical	90%	75%	90%	90%	97%	93%	97%	97%	97%	97%	97%	97%	97%	75%
Paper, pulp and print	52%	46%	52%	52%	53%	53%	53%	53%	53%	53%	53%	53%	53%	46%
Mining and quarrying	21%	66%	21%	21%	79%	58%	79%	79%	79%	79%	79%	79%	79%	66%
Transport equipement	60%	58%	60%	60%	78%	45%	78%	78%	78%	78%	78%	78%	78%	58%
Transport - Sectors	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%
Agricuture and forestry	16%	7%	16%	16%	0%	0%	0%	0%	0%	0%	0%	0%	0%	7%
Fishing	0%	56%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	56%
Agri-food industry	36%	28%	36%	36%	30%	30%	30%	30%	30%	30%	30%	30%	30%	28%
Composite	21%	11%	21%	21%	13%	14%	13%	13%	13%	13%	13%	13%	13%	11%

\hat\tau	Heat, Geothermal, Solar Th	Iron and steel	Non ferrous metals	Cement and clinker	Other non-metallic minerals	Construction	Chemical and petrochemical	Paper, pulp and print	Mining and quarrying	Transport equipement	Transport - Sectors	Agricuture and forestry	Fishing	Agri-food industry	Composite	C	G	I	X
Crude oil	82%	73%	73%	24%	24%	24%	61%	27%	26%	22%	21%	20%	20%	22%	27%	1%	0%	0%	43%
Natural gas	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	8%	0%	0%	0%
Coking coal	100%	100%	100%	67%	67%	67%	100%	75%	72%	62%	59%	56%	56%	63%	76%	4%	0%	0%	100%
Bituminous coal	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	84%	0%	0%	100%
Coke oven coke	22%	31%	31%	27%	27%	27%	28%	26%	27%	27%	24%	26%	23%	25%	24%	20%	0%	0%	0%
Other coal products	7%	10%	10%	8%	8%	8%	10%	1%	13%	6%	8%	6%	0%	11%	8%	7%	0%	5%	2%
Gasoline / biogasoline	10%	14%	14%	12%	12%	12%	13%	12%	12%	12%	11%	12%	10%	12%	11%	9%	0%	0%	0%
LPG	43%	61%	61%	53%	53%	53%	56%	53%	54%	54%	47%	51%	45%	51%	47%	41%	0%	0%	0%
Jet Fuel	44%	62%	62%	54%	54%	55%	57%	54%	55%	55%	49%	52%	46%	52%	48%	41%	0%	0%	41%
Diesel and biofuel	35%	49%	49%	43%	43%	43%	45%	43%	44%	44%	38%	41%	37%	41%	38%	33%	0%	0%	0%
Heating fuel	27%	38%	38%	33%	33%	34%	35%	33%	34%	34%	30%	32%	28%	32%	30%	26%	0%	0%	0%
Heavy fuel oil	43%	60%	60%	52%	52%	53%	55%	52%	53%	53%	47%	50%	45%	50%	46%	40%	0%	0%	40%
Other petroleum products	29%	42%	42%	36%	36%	37%	38%	36%	37%	37%	33%	35%	31%	35%	32%	28%	0%	0%	0%
Electricity	6%	8%	8%	6%	6%	9%	6%	7%	8%	7%	7%	6%	7%	7%	6%	0%	0%	0%	0%
Heat, Geothermal, Solar Th	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Iron and steel	37%	54%	54%	45%	45%	43%	54%	3%	67%	31%	40%	33%	0%	60%	44%	39%	0%	26%	39%
Non ferrous metals	36%	52%	52%	44%	44%	41%	52%	3%	65%	30%	39%	32%	0%	58%	43%	38%	0%	25%	13%
Cement and clinker	5%	6%	6%	6%	6%	6%	10%	9%	6%	11%	6%	12%	11%	13%	9%	7%	0%	0%	4%
Other non-metallic minerals	15%	20%	20%	21%	21%	20%	33%	29%	20%	35%	18%	37%	35%	42%	27%	22%	0%	0%	14%
Construction	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Chemical and petrochemical	75%	93%	93%	86%	86%	84%	82%	88%	90%	82%	81%	81%	72%	81%	80%	31%	56%	0%	5%
Paper, pulp and print	46%	53%	53%	49%	49%	45%	45%	56%	52%	44%	48%	23%	23%	39%	43%	24%	0%	0%	3%
Mining and quarrying	66%	58%	58%	19%	19%	19%	49%	21%	21%	18%	17%	16%	16%	18%	22%	1%	0%	0%	34%
Transport equipement	58%	45%	45%	52%	52%	45%	49%	46%	60%	57%	49%	56%	78%	46%	38%	47%	55%	66%	5%
Transport - Sectors	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%
Agricuture and forestry	7%	0%	0%	0%	0%	5%	8%	5%	16%	0%	7%	8%	0%	9%	7%	19%	0%	42%	0%
Fishing	56%	0%	0%	0%	0%	67%	69%	0%	0%	0%	0%	50%	57%	64%	62%	29%	0%	0%	0%
Agri-food industry	28%	30%	30%	30%	30%	34%	26%	24%	36%	18%	18%	13%	33%	26%	22%	18%	19%	0%	0%
Composite	11%	14%	14%	12%	12%	18%	12%	20%	21%	26%	-8%	15%	14%	9%	10%	7%	0%	15%	7%

Table F.2 – Import ratio of hybrid Input-Output table

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