Preparação de Modelagem para Estimar os Impactos Socioeconômicos da Adoção de um Instrumento de Precificação de Carbono como parte do Pacote de Implementação da NDC Brasileira - Componente 2a (Modelagem)

PRODUTO 1 – REVISÃO DE LITERATURA

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1. Introduction

Component 2a of Brazil PMR project aims at estimating the expected socioeconomic impacts of the adoption of carbon pricing instruments as part of Brazil´s NDC implementation package with a robust modelling approach. One key prerequisite to perform such analysis and select the appropriate modelling approach and strategy is to identify and build on the state-of-the-art practices in modelling the different aspects about the socioeconomic impacts of climate policy. To do so, the present report aims at reviewing recent international literature about these issues to identify the best practices and the main remaining constraints with current assessment modelling. The conclusions will help to draw the blueprint for a relevant modelling strategy for the project.

The question of the economic impacts of climate policies dates back to the early 90s. At this time the long-term problem with GHG emissions and climate change is made clear and grows on the international political agenda. The question about concrete mitigation actions and plans becomes the priority: the key issue is then to define the concrete mitigation measures to implement, their temporal distribution and to assess their potential economic cost. Economic modelling tools such as CGE models, started then to be developed to perform ex ante assessments of climate policy. Following waves of climate policy making in the 90s, 2000s and 2010s, a growing literature developed and forms today a very larger corpus of publications.

Assessing the socio-economic impacts of climate policies means in practice to estimate the impacts on a range of social and economic indicators linked to implementing a policy mix (including carbon pricing instruments) and the resulting transformations of technical and economic systems in the short, medium and long run needed to reach climate targets. Socio-economic impacts are first about macroeconomic implications in terms of GDP and its components: investment, household consumption, trade balance, employment, etc. Socio-economic impacts are then about impacts at sector level and for the different institutional sectors: households, public administrations and private companies. For each important economic sector climate policy can impact the level of production, employment, related investments, and competitiveness. Climate policy will further impact on household’s income, purchasing power and expenses, public budget and debt and profitability of the private sector. Finally, socio-economic impacts are about the distributive implications among sectors and economic agents in terms of structural changes and income distribution.

In standard environmental economics, pricing CO2 or GHG emissions is considered the key cost-effective instrument to reach a given climate objective, whether it is implemented by means of carbon markets or carbon taxes. However, carbon-pricing alone may not be the silver bullet to manage the transition towards low carbon development. At least the existence of market failures, constraints in implementing compensations and the necessary alignment with non-climate policy goals, impose to add complementary policies in the policy packages such as specific sectoral “command and control” policies or investment plans in long-lived infrastructures. On the whole, introducing a carbon pricing instrument as a key policy tool to foster low carbon development has at least two major interests: (i) establishing a long-term signal to guide efficient economic choices towards low carbon activities and (ii) generating carbon revenues that can be used to reconcile abatement objectives with others socio-economic goals along a low carbon transition.

Considering the significance of the socio-economic impacts of climate policy instruments such as carbon pricing, the relevant models to address these issues should include a top-down component based on a macroeconomic framework to represent economy-wide mechanisms, but with enough sectoral and technical details to represent sectoral policies and measures, as well as the sector specific consequences of the implementation of policy packages. SAM (Social Accounting Matrix) -based models, such as Computable General Equilibrium Models – CGE models- and multisectoral macroeconometric models have been models of choice fitted for this purpose. However these models have been criticized for several reasons including a lack of technological explicitness (Grubb et al., 2002) with production and consumption trade-offs represented by means of aggregated functions embedding stylized substitution possibilities with limited technical information; a lack of flexibility beyond current production and consumption patterns whether it be through econometric functions (macroeconometrics) or calibrated production functions (neo-classical CGE model); consequently the difficulty to represent unprecedented technical routes, induced technological change and deep decarbonization pathways. To overcome these limitations, hybrid and integrated modelling architectures have been developed to combine the strengths of both partial equilibrium (PE) bottom-up (BU) engineering and top-down (TD) approaches (Hourcade et al., 2006). Historically the first hybrid approach has been to couple a compact growth model with an energy system model to create a full economy model with technological detail about the energy system (Manne and Wene, 1992). In such modelling frameworks the macroeconomy is represented by means of a single good/sector production function combining macroeconomic capital and labor with energy services possibly broken down in different aggregates. Such models can be labeled **BU based hybrids**. Numerous IAMs such as MESSAGE, WITCH or else REMIND models are based on this approach. However, such models do not represent the inter-industry relationships or the economic interactions between representative economic agents. They thus remain limited to assess socio-economic impacts beyond aggregated GDP and final consumption. On the other hand, multi-sector SAM-based models (mainly CGE models) have been developed towards including technological information and explicitness for key energy sectors to become **TD based hybrid models** (Böhringer, 1998; Crassous et al., 2006; Paltsev et al., 2005; Proen\cca and Aubyn, 2013; Sue Wing, 2008). Finally, a third research avenue has consisted in **soft-linking** pre-existing standalone models in order to combine the full strength of different model types. The model linkage usually consists in linking a CGE model to one or several PE BU models detailing the dynamics of energy or land-use systems. Model coupling consists in exchanging data between the linked models (the output of one model is the input of the other) until convergence.

Numerous example exist in the literature (Drouet et al., 2005; Fortes et al., 2014; Hasegawa et al., 2016; Martinsen, 2011).

Therefore, to limit the review to modelling studies relevant for Component 2a activities, we will only retain studies based on the types of modelling approaches described above, all especially able to perform economy-wide analysis. PE equilibrium BU energy or land-use models used standalone are not considered in this review, but only if part of a linking approach to another economy-wide model. The modelling studies reviewed can be based on global or regional models in scope but should include minimum regional disaggregation.

This report reviews the state-of-the-art modelling approaches used to assess the key aspects of the socio-economic impacts of climate policies and carbon pricing instruments along different sub topics. For each topic we will frame the issues at stake, review the different existing modelling approaches to address them, characterize the strengths and limits of the different approaches and discuss the best practices and the possible remaining constraints.

2. Literature Review – Modelling Socioeconomic Impacts of Climate Policies: Key aspects

2.1. Land use change

Land use change is a crucial topic considering the GHG composition in Brazil: more than 60% of GHG emissions in Brazil came from AFOLU (Agriculture, Forestry and land-use) sectors in 2015. Reducing AFOLU emissions is else the key component to reach 2025 and 2030 NDC targets in Brazil. Mitigation levers in these sectors include avoided deforestation and reforestation, changes of agriculture practices (zero-tillage cultivation, increase livestock GHG efficiency, livestock land productivity, etc.) and indirectly the development of bioenergy crops (sugar cane and soybeans). AFOLU sectors and the related mitigation measures are linked through the competition for land which is a limited resource. For instance in Brazil increasing the productivity of livestock is considered a key lever to free huge volumes of land for other mitigation measures including reducing deforestation, and upscaling reforestation and to a lesser extent developing crops for bioenergy[1] (de Gouvello, 2010). This land-use competition issue has been made famous one decade ago with the example of indirect land-use change triggered by the development of crops for bioenergy. In this view, the development of bioenergy by converting existing croplands may contribute to the expansion of arable lands and generate additional emissions (Searchinger et al., 2008). Overall, mitigation measures in AFOLU sectors are intrinsically linked by land-use dynamics. Practical mitigation policies in these sectors currently include command and control instruments to reduce deforestation and subsidized credit for agricultural activities with low carbon emissions. No economic instrument to create a price signal for GHG emissions is currently proposed but might be in the future. Therefore, a relevant modelling approach to assess climate policy in Brazil should include a detailed representation of AFOLU sectors and land-use dynamics. In addition, it should include the key channels for the broad socio-economic impacts of mitigation measures and climate policy instruments not only in the AFOLU sectors but in connection with the rest of the economy and energy sectors. For example, a carbon tax applied on oil-based fuels may trigger a substitution towards biofuels which will impact on land-use dynamics with possible macroeconomic feedbacks linked to changes in agriculture jobs, food and commodity prices, changes of income from land factor, etc. In the following we review how existing models address land-use issues in connection to the broader socio-economic system.

Models have been recently developed to include the key aspects of land-use dynamics. First of all BU based hybrid models have been developed towards the integration of a land-use module next to the energy system module. For instance in the REMIND-MAgPIE modelling framework (Klein et al., 2014), the MAgPIE module minimizes the total cost of production of

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[1] To be effective in practice such mechanism requires a strong regulatory framework to avoid further land conversion incentivized by the higher profitability of land resulting from the land productivity gain of livestock production

a given regional food and bioenergy demand taking into account production costs, yield-increasing technological change costs and land-conversion costs. The module takes into account spatially explicit data on potential crop yields, land, and water constraints and derives specific land-use patterns, yields and total costs of agriculture production. Such approach provides a fairly detailed representation of land-use dynamics and competition for land among detailed crops and productions at regional scale and can be useful to assess mitigation measures in AFOLU sectors. However, this approach remains limited to assess the broad socio-economic impacts of AFOLU sectors mitigation or of the combined AFOLU / energy sector mitigation measures because of a too simplistic macroeconomic approach and too aggregated connections between AFOLU sectors, energy sectors and the macroeconomy. For example, the model will be able to evaluate how land-use constraints will lead to an increase of bioenergy prices and further impact on aggregated economic growth but will say nothing about the impact of the increase of food prices on households' budgets, about the implications in terms of employment in bioenergy sectors, level of exports of agricultural commodities, etc.

Conversely, TD based hybrid and multi-sector CGE models representing several agriculture sectors connect agricultural markets and land-use choices to the rest of the economy to assess the detailed economy-wide implications of land-use dynamics. For instance, these models capture the implications for labour and capital markets with quantifying the variations of employment in the different agricultural sectors, the impacts of investments in land-use sectors on the global capital markets. Such models further represent the feedbacks of land, food and bioenergy prices on the rest of the economy. Food and bioenergy prices impact household's purchasing power, industry production costs and the trade competitiveness of commodities. The land rent also impacts the income of households. However, CGE models usually include a rough representation of land allocation with land as a homogenous and perfectly mobile production factor between a small number of agricultural sectors. Beyond the low level of details about agriculture productions and technical processes of production, such approach neither takes into account the spatial heterogeneity of land with specific yields nor any constraints linked to land conversion.

To overcome these limitations, CGE models have been improved towards higher crop, commodity and technology details and better land supply representations. (Kretschmer and Peterson, 2010) perform an extensive review of such improvements concerning the integration of bioenergy into CGE models. Some models first include bioenergy technologies as latent technologies. These are production technologies made available at the model at a certain price, which are not active in the base year of the model because of their initially high cost and that become profitable in the future. These biofuel technologies – similar as a carbon-free backstop technologies – are included in the production functions with their input and cost structures and appropriate mark-ups as the difference between biofuel production costs and prevalent energy (fossil fuel) prices. For instance (Reilly and Paltsev, 2009) includes second-generation biofuel technologies in the EPPA model. Higher crop and agriculture production details can be obtained through disaggregating the SAM used to calibrate the model (Birur et al., 2008; Taheripour et al., 2007). An effort to disaggregate bioenergy sectors in GTAP database has been carried out to produce a GTAP-BIO database further used by different CGE models such as in (Birur et al., 2008) which distinguishes three biofuel sectors (two ethanol sectors and one biodiesel sector). In addition, better land supply representation can be based on advanced land supply functions combined with the distinction of agro-ecological zones (AEZ). A popular way of introducing some more details to the representation of the input factor land is via a constant elasticity of transformation (CET) framework. The idea is that land can be transformed to different uses, the ease of this transformation being represented by the elasticity of transformation. For instance (Banse et al., 2008) incorporate a three-level CET nesting structure with differing land use transformability across types of land use. A first nest distinguishes horticulture, Other crops and Field Crops/Pasture. The latter is split up further into Pasture, Sugar and Cereals/Oilseeds/Proteins, which again consist of a nest of wheat, coarse grains and oilseeds. Along this structure, the ease of transformability increases. In (Fujimori et al., 2014) the CET formulation is compared to a logit formulation. The CET has the advantage that it is easily handled by modeling tools, but it does not maintain area balance, whereas logit does. In order to represent longer-term and hence possibly radical land use changes (Gurgel et al., 2007) do not choose the CET framework and instead introduce conversion costs that accrue when one type of land is changed into another type. Finally, beyond a refined global land supply representation, CGE models have been improved towards distinguishing different agro-ecological zones (AEZ). An agro-ecological zone is characterized by similar climatic and soil conditions. In (Lee et al., 2009) a total of 18 AEZs are distinguished at global scale. Within each AEZ, a two-level nested CET function determines the allocation of land among different uses. The upper nest determines the allocation into crop, pasture and forest land cover before the second nest splits up the crop cover into its different uses, i.e. various types of crops. To sum up, CGE models have been significantly improved towards higher crop, agriculture sectors and technology resolution (including bioenergy technologies) and better representation of the constraints linked to land-use change. However, they generally do not capture the same resolution of spatially explicit mechanisms and crop details as in partial equilibrium land-use models, which can be a constraint for the detailed analysis of land-use issues at regional scale.

In order to combine the strengths of partial equilibrium land-use models and CGE models, a second research avenue consists in soft-linking the two models within and hybrid modelling architecture. Soft-linking the two models makes it possible to maintain the highest resolution about both spatially explicit detailed land-use dynamics and economy-wide processes beyond agricultural markets. Soft-linking is based on exchanging data between the two models until a convergence criterion is met. A first important example illustrating the general approach with soft-linking a CGE and a land-use model is (Ronneberger et al., 2009). In this work the GTAP-EF CGE model is coupled to the KLUM land-use model. The GTAP-EF includes a fair representation of agricultural sectors connected to the rest of the economy and a macro representation of the technical possibilities to increase aggregated land productivity for each sector through factor and input substitution (labour, capital, fertilizers, energy). However, the model cannot inform the real constraints linked to land allocation at sub-regional scale taking into account local economic and biophysical specifics. On the other hand, the KLUM model can compute at the detailed agro-economic zones level the dynamics of land allocation between crop types taking into account biophysical constraints and specific economic behaviours (risk management for instance). However, it takes crop demand as exogenous and does not capture the macro drivers of land productivity evolution. Soft-coupling the two models makes it possible to combine their strengths. Therefore, in the coupling procedure, the GTAP-EF model first computes the crop prices and demand and the macro evolution of land productivity deriving from general equilibrium drivers and pass it to the KLUM model. On this basis the KLUM model computes the related land allocation choices at sub-regional level and provides the aggregated information for the next GTAP-EF run. More recently, a similar coupling procedure was carried out in (Verstegen et al., 2015) to assess indirect land-use change in Brazil linked to biofuel production. (Hasegawa et al., 2016) is another recent example of soft-liking between the AIM/CGE model and the AFOLU model. In a similar approach as in (Ronneberger et al., 2009), the AIM model provides crop demand and yields and prices (crop, capital, energy, carbon) to the AFOLU model which derives the land allocation choices and transmit it back to the CGE model. More specifically in this study, the AFOLU model represents detailed mitigation measures and GHG emissions sources in AFOLU sectors and computes mitigation costs on a BU basis and inform it to the CGE model. The difference of macroeconomic cost assessment between the CGE as a standalone tool and the coupled architecture illustrates the importance of capturing the BU based mechanisms of land allocation and AFOLU mitigation to assess the economy-wide implications of mitigation measures in AFOLU sectors. Finally, the soft-linking approach seems the best compromise if the goal is to keep the full strengths and details of the linked models, about the issues with land-use dynamics in particular.

La Rovere *et al* (2016) and Wills (2016) could be mentioned as successful soft-links between CGE and Land-Use models in Brazil. IMACLIM-R BR, a hybrid, recursive CGE model (based in Wills, 2013), and BLUM (Brazilian Land Use Model), a partial equilibrium land use model, were integrated through a soft-link. Data on GDP growth, demand for biofuels, agriculture and livestock goods are exchanged, as well as information on investments needed by each sector to change its way of production. Those interactive runs were conducted until reaching convergence between the two models for each scenario simulated. A data template was prepared on a spreadsheet and used to exchange the key datasets between models in a practical way. This template was filled in with the outputs of each of the models: the outputs of one model functioned as inputs for the other model, for each interactive run.

2.2. Design of pricing instruments - GHG emissions taxes, emissions trading systems and hybrid systems

Environmental economic theory tells that carbon pricing is the cost-efficient way to reach a given emissions target. In practice carbon pricing can actually take two forms: a carbon or GHG emissions tax – as a Pigouvian tax – or indirectly through an emissions cap with trading of emissions allowances. In economic theory these are two sides of the same coin. Under standard neoclassical economic assumptions, implementing either a price or a quantity-based carbon constraint lead to the same marginal abatement costs conditions and same total emissions level: with the price-based instrument each economic agent reduces its emissions until its marginal abatement cost equals the carbon tax. Conversely with a quantity-based constraint, whatever the initial allocation of a given emissions cap, economic agents trade emissions allowances until all marginal abatement costs equal the price of the carbon allowance on the market. In both cases the same total mitigation cost is reached. The only difference lies in the distribution of this cost between economic agents, which depends on the particular design of the instrument and not on the nature of the instrument itself. With full carbon taxes, economic agents pay for the remaining emissions beyond mitigation costs. In an Emissions Trading Scheme (ETS) the breakdown of costs depends on the initial allocation of allowances. It is especially important to notice that a 100% auction ETS leads to the same distribution as the tax. Overall, economic theory supposes an equivalence between the two types of instruments (tax and ETS).

In the last 20 to 30 years numerous models of this type have been used to assess the economy-wide impacts of price or quantity-based carbon pricing instruments on different economies. First of all in BU based models based on a single sector optimal growth framework, carbon price is only modeled as the economy-wide marginal abatement cost (corresponding to the shadow price of the emissions constraint) with no explicit payment transfers. In addition, these models generally do not consider any other pricing scheme than an unique implicit carbon price in the economy. They thus neither can differentiate between a carbon tax and an ETS nor can explore different emission allocation schemes between sectors and alternative recycling options of a carbon tax. Such model would thus be too limited for the present study.

Conversely, multi-sector CGE models are pretty flexible to explore alternative carbon pricing schemes. In these models, carbon pricing impacts production costs and consumption expenses at the scale of each distinguished economic sector or each representative economic agent (like a given households group). These costs induce substitutions in production inputs and consumption baskets as embedded in production and demand functions. Such functions implicitly reflect the own (Marginal Abatement Cost Curve) MACCs of sectors and economic agents. Several differences arise compared to the partial equilibrium (PE) case with fixed sectoral MACCs and where the design of the carbon pricing instrument / the distributive conditions have no impact on the marginal conditions at equilibrium and on total mitigation costs. On the contrary in general equilibrium (GE), the MAC curves embedded in production functions depend on input prices beyond the carbon price which are modified by general equilibrium (GE) feedbacks. MACCs thus endogenously depend on GE feedbacks. In addition, the design of the carbon pricing instrument (wether tax or ETS) induces different cost break-down at sector level which further impact on GE feedbacks and the sectoral MACCs. Therefore the full design of the pricing instrument beyond the strength of the incentive or the constraint has an impact on the final equilibrium contrary to the PE case. In the meantime, carbon costs induce real payment transfers in these models and generate income that can be further recycled in the economy (see section 2.6). Overall CGE models are well fitted to study the impacts of alternative carbon pricing schemes.

CGE models have been widely used to assess the impacts of economy-wide carbon pricing instruments whether it be a carbon tax or an ETS. National analysis of this kind is today very standard and has been performed for a sizable share of countries often with national specific CGE models. (Timilsina, 2018) carries out a recent review of the deep literature on the carbon tax from the past 30 years including an extensive review of the recent CGE analysis at regional and national levels. The review especially shows how state-of-the art CGE models can address different issues about carbon taxes including the economic impacts and costs, the distributional impacts across household income groups, the tax revenue recycling scheme or else the competitiveness issues.

Beyond the single economy-wide carbon price case, multi-sector CGE models can first assess the impacts of carbon price differentiation among sectors. For instance numerous studies have assessed the implications of exempting specific economic sectors from carbon pricing - like energy-intensive industries (Babiker et al., 2003). The possible alternative sectoral perimeters of carbon pricing or the possible carbon price differentiation among sectors that can be tested typically depends on the sectoral disaggregation of the model: a given model could in practice test the impacts of as many carbon price levels in the economy as the number of distinguished sectors and representative agents. Models can also test the differentiation of carbon prices between emission types linked to different fuels or sources. For instance (Landis et al., 2018) analyze the impact of differentiating the carbon price between fuel types on the economic costs of decarbonization. As for sectors, the level of fuel aggregation in the model determines the pricing differentiation possibilities. In practice the emissions linked to the combustion of fossil fuels are computed based on the related energy flows in physical units combined with fuel specific emission factors.

As a general rule the level of sectoral disaggregation in the model corresponds to the level of disaggregation of (micro-founded) economic behaviors. Thus, the model cannot capture specific mechanisms playing at a sub-sector level. For example, if a CGE model distinguishes the cement sector it will be able to represent the aggregated response of the sector to a carbon price instrument but not the underlying mechanisms linked to emissions trading between different cement companies for instance.

In addition, CGE frameworks can model carbon taxes or ETS alternatively with different scope, thresholds and differentiation, but also a combination of the two types of instruments including with some overlap on certain sectors (a carbon tax on top of an ETS or the other way around). For instance (Böhringer et al., 2016) analyze the combination of the ETS with carbon taxes applied on non-ETS sectors in the EU. Conversely, (Lee et al., 2008) and (Li and Jia, 2017) explore the implications of combining a carbon tax and an ETS either on the whole economy or for specific industry sectors. Models are also flexible to test hybrid instruments between a carbon tax and an ETS, ie an ETS or cap and trade system with a price ceiling and/or price floor. For instance (Weng et al., 2018) performs a general equilibrium analysis of floor prices for China’s national carbon emissions trading system.

Finally CGE models can evaluate other specific carbon pricing instruments such as carbon boarder tax adjustments to target emissions embodied in imports (Böhringer et al., 2018; Tang et al., 2015) and can analyze the articulation between carbon prices and other specific energy taxes (Lele et al., 2015).

In a nutshell CGE models are very versatile tools to model many different characteristics of carbon pricing instruments whether a carbon tax, an ETS or any combination of the two including carbon price differentiation for sectors and/or emission sources. The main constraints for the alternatives of analysis are the levels of disaggregation of the models.

2.3.Design aspects of emissions trading systems

After introducing how models can generally handle carbon pricing instruments in the precedent section, this section analyzes more closely how state-of-the-art models deal with different designs of emissions trading systems.

As previously described, under an ETS, the price of carbon is implemented indirectly: the regulatory authority sets the allowable total quantity of emissions; this then yields a price of carbon emissions through the market for allowances. The provision for allowance trading is a critical element of cap and trade, as it promotes the emergence of a single market price for emissions faced by all market participants at any given time.

Modeling ETS in applied CGE models has become standard and follow the same approach developed earlier (Böhringer et al., 1998; Edwards and Hutton, 2001; Jensen and Rasmussen, 2000). Instead of implementing an exogenous carbon tax paid by production sectors and households in proportion of their emissions and computing total endogenous emission level as the sum of sectors and households derived emissions, the model works the other way around and sets a total emissions level exogenously and computes the single dual variable – the carbon price paid for each ton of emission – needed across sectors and households to respect the emission cap. Said differently, by turning total emissions into a parameter and the carbon price into a variable, the model represents an additional market of emissions allowances characterized by a fixed supply (the total cap of emissions) which must balance the sum of the demand of each economic agent which depends on the price of the allowance through their production or demand function. In addition, such an approach surmises a single perfect market of allowances with perfect information by all agents based on auctions where ex post equilibrium matches ex ante expectations. As such this modeling approach is used to represent an ETS with full auction of emission allowances that is where each emission allowance is paid for by economic agents at the single market price. Furthermore, free allowances are generally modeled through windfall transfers to the different economic agents. If a given economic sector or agent initially receives A free allowances it will receive a windfall transfer payment of A x TC with TC the carbon price on the market. In practice for a productive sector in a CGE model benefitting A free allowances, its production price will be reduced by A x TC /Y with TC the endogenous carbon price and Y the endogenous production level. Everything happens as if the sector had to pay full auctioned allowances first and then receive in a second step a windfall subsidy of A x TC. Subsequently, it is possible to model any permit allocation type with this approach with part of the permits being auctioned and the rest given for free and allocated with different allocation rules (grandfathering, etc.). In the simple case of free permit allocation, it is else possible to calculate ex-post the number of permits traded by each sector or agent by subtracting the number of permits initially allocated to the actual number of allowances used which is endogenously computed by the model as emission level of its sector. A positive number means that the sector has bought a net positive number of permits in the market whereas negative numbers means that the sector is a net seller of permits.

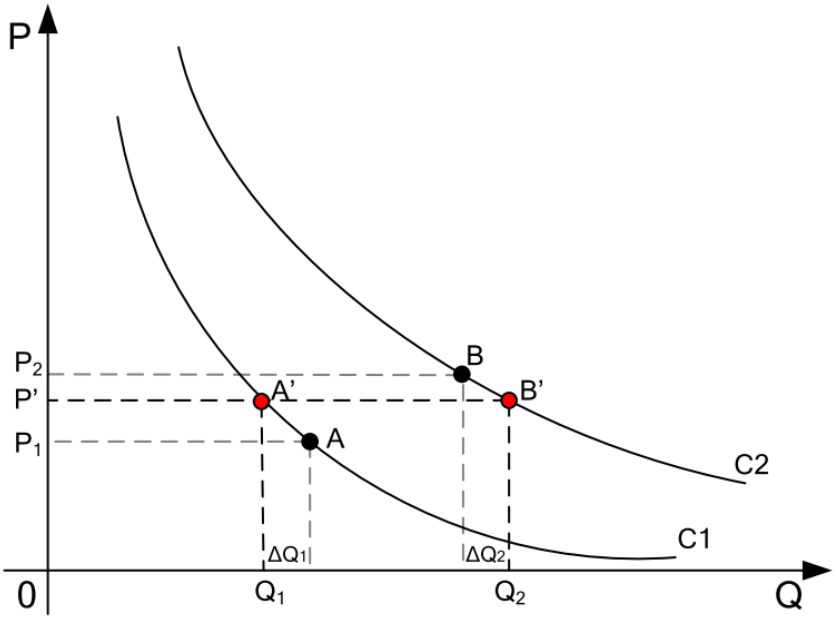

Fig. 1. Mechanism of carbon emission trade between sectors.

(Wang et al., 2015a)

Finally, in the case of partly auctioned permits, the difference between the total emissions cap and the sum of all free allowances corresponds to the total of permits auctioned. It is possible to calculate for each sector the number of permits auctioned and bought or sold on the carbon market.

This general framework has been widely used in the CGE literature to assess multiple different designs of ETS in different countries and regions. Since the early 2000s, empirical analysis based on CGE modelling has followed the real-life development of ETS instruments in different regions of the world. The European Union ETS was the first regional ETS starting in 2005 and the applied CGE literature has focused on the EU ETS in the 2000s (Böhringer et al., 2009; Klepper and Peterson, 2006). Then in the 2010s, the literature developed quickly on analyzing the newly scheduled or established ETSs in new regions of the world, whether at country scale (e.g New Zealand (Lennox and Van Nieuwkoop, 2010) and South Korea (Choi et al., 2017)) or at subnational scale for specific states in the US or Canada (California (Caron et al., 2015)). Finally an important literature emerged to accompany the development of ETS in China at both the Province (Wang et al., 2015a; Wu et al., 2016c) and national levels (Cui et al., 2014; Li and Jia, 2016; Tang et al., 2016).

Concretely an ETS is defined for a certain period of time and is characterized by three main aspects: 1) the sectoral scope, 2) the total emissions cap and 3) the permit allocation rule.

CGE models are fundamentally based on computing static general equilibrium for a year time period as calibrated on a given year SAM. Recursive dynamic CGE models compute a succession of static GE with different possible time steps (every year or every five years for most models). The time step of a recursive dynamic CGE model determines the shortest ETS period that can be analyzed and, in any case, most CGE models cannot perform infra-year analysis. Therefore, a CGE model with a yearly time step can study the dynamic impact of the succession of yearly ETS characterized by a different emission caps each year. However as detailed after, with a few exceptions, CGE models are not equipped to model possible connections between two ETS periods through borrowing or banking of permits because they are based on myopic behaviors with no intertemporal (inter-period) dimension. As the goal of carbon pricing and ETS is to decrease emissions across time to reach a medium-run target like NDCs, in recursive dynamic CGE studies the ETS analyzed is often based on a decreasing emission cap for each time steps. The cap can be an absolute emission target or a relative target depending on the country climate proposals. For instance to study the case of China which has committed an intensive target (China intends to lower CO2 emissions per unit of GDP by 60-65 % from the 2005 level in 2030) the cap can be expressed as a similar intensive target (Li and Jia, 2016).

The second key characteristic of an ETS is the permit allocation rule. Two main rules are generally considered: either permits are allocated for free with different possible distribution criteria amongst sectors, or permits are auctioned. In the first case sectors pays for emissions only beyond the level of their initial free allowances whereas in the auctioning case sectors have to buy an allowance for each of their emitted ton. Historically in the early ETS introduced like the EU ETS, permits were allocated for free in early phases and auctioning is introduced step by step. This is partly for political reasons to favor acceptance of the system amongst stakeholders. Indeed, without considering any further redistributive measure, free allocation provides an economic advantage for sectors compared to auctions equivalent to a resulting windfall subsidy proportional to the amount of free emissions allocated. In addition, any hybrid allocation rules can be contemplated with part of the total emission cap being freely allocated, the rest being auctioned. In practice CGE models have broadly analyzed either allocation rules or hybrid combinations of the two. For instance (Li and Jia, 2016) analyzes the macroeconomic and environmental impacts of different ratio of free quotas in the ETS in China.

Beyond the distinction between free allocation and auctioning, many different free allocation schemes can be designed. Allocation can first depend on past historical, current or projected criteria. Permits allocation based on historical criteria is called *grandfathering*.. For instance (Yu et al., 2018) explores the implications of different free allocation schemes between based on future emission volumes in a BAU scenario compared to a grandfathered allocation based on historical data. In addition, the allocation criteria can be sector emissions (emission-based allocation) or sector output (output-based allocation or intensity caps)In the first case the amount of allowances is indexed on historical or future BAU sectoral emissions whereas in the second the amount of free allowances a firm or sector gets is proportional to its current or past output level. For instance, (Böhringer and Lange, 2005) provides an early comparison between emission-based and output-based free allocation in a theoretic framework then applied on the EU case. (Lennox and Van Nieuwkoop, 2010) and (Takeda et al., 2014) both explore in depth with a CGE model the issue of output-based allocation for industry sectors for New Zealand and Japan respectively.As mentioned earlier most CGE models represent any free allocation scheme with similar modeling features as equivalent of a two steps process: first the sector fully pays its emissions allowances as in the auctioning process and this payment induces changes in production choices as embedded in the production function; and then receives a windfall transfer corresponding to the amount of free allowances valorized at the permit market price. However, this two steps occur simultaneously in the general equilibrium computation. Various free allocation schemes whether emission or output-based are thus modeled by means of different windfall transfers to the economic agents linked to the level of free allowances which depends on the criteria chosen (emission or output). .

Finally free allocation of permits can also be about allocating permits between different regions of a given country which calls for different types of criteria compared to criteria suited for sectors of firms. (Wu et al., 2016a) for instance analyzes the impacts in China of different allocation rules among Chinese provinces for the national ETS based on different equity-based criteria. Emissions allowances are distributed in proportion of GDP, population and historical emissions alternatively.

Finally, CGE models can analyze various possible designs of an ETS with different exemption schemes. As previously mentioned the possible designs depend on the level of sectoral disaggregation in the model. As a single sector is the minimum decision center, the model cannot assess any mechanisms at a lower level. For instance, most CGE models are not capable of capturing the implications of alternative allocation rules between different firms of a given economic sector.

One other aspect of an ETS is the possible intertemporal mechanisms between periods. For instance, during the first EU ETS phase (2005 – 2007) banking and borrowing of permits was allowed between years. Consequently, a permit allocated in 2006 could be used in 2007 (banking) or in 2005 (borrowing). In order to model such mechanisms and the related behaviors of economic agents, recursive dynamic CGE models must be extending towards including intertemporal behaviors. Very few CGE models have explored this track so far. (Brink et al., 2016) can be seen a reference in such an attempt with the WORLDSCAN model. Authors adapted their typical recursive dynamic CGE model that initially included agents only behaving myopically reacting to current prices only. To do so they introduced forward looking behavior of firms based on intertemporal optimization under expectations of future permits prices. Concretely they model the stock of allowances as a non-renewable resource. Only banking is allowed and profit maximization with perfect foresight and market competition lead to a permit price that grows with the rate of return on alternative assets. This situation is analogous to the Hotelling rule of a carbon price growing at the discount rate to meet a given carbon budget under intertemporal optimization. Overall modeling temporary flexibility mechanisms such as banking or borrowing of permits is not mainstreamed in CGE modeling and only has been explored on specific cases within an idealized economic environment over a long period. There is somehow a trade-off between performing a stylized analysis of permit banking in intertemporal optimization and keeping the recursive dynamics core of most multi-sector CGE models used for climate policy analysis without analyzing this aspect.

CGE models cannot capture intra-period price volatility and thus cannot model price stabilization schemes aiming at reduced intra-period volatility. However, they can model stabilization schemes across periods through price floors and/or price ceilings. Price floors in the permit market or auction price reserve are modeled in the same way in a CGE model. Finally models can test additional instruments to force economic agents to comply to an actual level of emissions by adding a fine mechanism on top of the ETS proportional to the possible additional emissions not covered by an allowance bought on the market (Li and Jia, 2016).

In conclusion state-of-the-art CGE models are fitted to model many different possible ETS instruments with different designs pertaining to the scope of sectors, the yearly evolution of the cap and the permit allocation scheme. The main constraints of the models are linked to the level of disaggregation of sectors and the difficulty to handle with temporary flexibility mechanisms.

2.4. Differentiating outcomes of different carbon pricing instruments under the same initial conditions

The goal of component 2a is to provide model-based evidence to design possible attractive carbon pricing packages to reach NDCs in Brazil. To do so the suite of models used should thus be able to simulate different policy packages and rely on differentiated computed outcomes under the same initial conditions to discuss the relative attractiveness of the different policy package based on contrasted socio-economic impacts. One aspect in this debate is the question of the most attractive carbon pricing instrument and the relative attraction of an ETS versus a carbon tax to reach a given climate goal. In order to design an appropriate applied modeling tool fitted to address this question we should first analyze what economic theory says about the relative attractions of a "pure" ETS, a carbon tax and hybrid options and about the dimensions along which the approaches can actually have different impacts. (Goulder and Schein, 2013) provides a recent synthesis about these issues.

One first key conclusion is that the various options are equivalent along more dimensions than often are recognized. First of all, both types of instruments provide equivalent incentives to reduce emissions. Even when permits are received for free in an ETS, eachadditional unit of emissions carries an opportunity cost equal to the price of allowances on the market or else to the exogenous carbon tax rate. Finally, a carbon tax and an ETS provides equivalent mitigation incentives whatever the permit allocation rule of the ETS (free or auction). Second, both instruments have the flexibility in compensating for uneven direct and indirect distributional impacts. For instance, a carbon tax system can be designed to mimic the direct distributional impacts of an ETS with free permit allocation by granting a tradable tax exemption for a certain amount of emissions – that is, the tax applies only to emissions in excess of a certain quantity. For a given emitting firm, this carbon tax policy has an impact identical to an ETS in which the firm is freely granted emissions allowances of that same quantity. In addition, revenues from auctioned allowances or from the carbon tax can be used to address indirect distributive issues in the same way through appropriate tax cuts or lump-sum transfers to firms or households. Eventually, comparably designed systems imply the same distribution of policy costs (or policy-generated windfalls) across households or firms; the relevant design features are the extent to which firms are allowed inframarginal emissions without charge and the way that revenues from auctioned emissions allowances or a carbon tax are spent. Third, each of the policy tools may include or exclude offsets. And fourth the different policy tools have similar capabilities for mitigating potential adverse impacts on the international competitiveness of carbon-intensive domestic firms. This depends on whether the policies are introduced upstream or downstream, and the extent to which provisions for border adjustments or output-based subsidies are included; the three policies have equal potential along these lines. Thus, the incentives for emissions abatement, the distributional impacts, the connection with offsets, and the ability to safeguard international competitiveness depend primarily on the specifics of design, not on the general instrument type.

Furthermore (Goulder and Schein, 2013) identify dimensions where the instruments can have different impacts. First of all, a carbon tax minimizes administrative costs compared to an ETS. Second, a pure ETS has the drawback to leave the emission price uncontrolled (contrary to the tax) and the market can experience detrimental price volatility. Price floor and/or ceiling are solutions to help control price volatility and the possibility for firms to bank or borrow permits across period can help smooth decisions and price variations. Third, carbon taxes or ETS carry uncertainties on different aspects. The carbon tax makes it possible to control the marginal cost of emission reductions and somehow the related economic implications but leave the environmental outcome uncertain. On the contrary with an ETS the total emission level is imposed but the implied marginal cost is uncertain from policymakers who imperfectly know the private mitigation costs of the different economic agents. One important aspect is the interaction with other policy instruments. For instance, in the presence of an ETS, an additional performance standard may not yield additional emission reductions because overall emissions are determined by the cap of allowances in circulation. If the norm yields additional emission reductions for some firms compared to the ETS alone, the related allowances will be sold in the market and yield a decrease of the allowance price and final same total emissions that without the performance standard. Conversely with a carbon tax introducing the additional norm would not change the price of emissions and would not lead to emissions leakage. With a carbon tax, supplementary policies can generate larger reductions in emissions. A similar advantage of an exogenous carbon price is that it enables to control the possible strategic behavior of oil exporting countries that could try to capture part of the domestic carbon rent by playing with the oil price. Finally (Goulder and Schein, 2013) identifies a set of practical differences between the two instruments especially linked to institutional constraints, perception an political feasibility.

To summarize (Goulder and Schein, 2013) show that under most economic considerations a carbon tax, an ETS or a hybrid instrument with similar design are equivalent instruments with no inherent difference in mitigation incentive and distributional impacts. Therefore, we cannot expect economic based models to lead differentiated outcomes with similar designs of these instruments, unless state-of-the-art models capture part of the differentiating features summarized above in a second step. As previously mentioned models generally cannot capture the price volatility effects linked to imperfect foresight and market temporary disequilibria. In addition, the banking or borrowing mechanisms are addressed by very few models in intertemporal optimal settings so that they cannot discriminate the outcomes between a tax and an ETS in the end (with both approaches the carbon price increases like the discount rate). The uncertainty issue from the administrator point of view about certain/uncertain mitigation cost versus certain/uncertain environmental outcome usually cannot be addressed by models which are deterministic on these aspects (the modelers know the private mitigation costs of every economic agent). In addition, the strategic response of foreign oil producers to the type of carbon pricing instruments put in place in Brazil may be a minor issue at least for a country that is not mostly dependent upon imports of crude oil and petroleum products (like Brazil). Finally, the only economic issue worth differentiating in the previous list is the interaction between the carbon pricing instruments with other policies. Of course, economic models generally do not address the institutional and political constraints specific to the different instruments and these issues should be discussed outside the modelling part.

In conclusion, except for the issue of instrument interactions (see section 2.5), it is difficult to expect the modelling tool used for this project to differentiate outcomes for similar design (scope, level of incentive, distributional framework) of either a carbon tax or an ETS. One solution can be to discriminate upstream different possible designs between the two instruments based on non-economic considerations. In collaboration with component 1 and 2b a discussion should be organized to identify the institutional or political reasons that could justify building and modelling different designs for the two instruments. For instance, there may be practical constraints to implement similar redistribution schemes between the two instruments as pointed out by Metcalf (2007) in the US case, etc.

2.5. Interactions between carbon pricing instruments and other sectoral policies

Carbon pricing instruments are policy tools intrinsically designed to incentivize emission reductions in the different sectors of the economy. However other existing policies can lead to direct or indirect emission reductions. For instance, policy supports to renewable energy REN) sources and technologies will lead to the higher penetration of renewable energy in the energy matrix and can lead to emission reductions through the substitution of fossil fuels by renewable energy sources. Policy support to REN can take various forms in practice ranging from direct subsidies (eg subsidy of biofuels in Brazil) to indirect measures (feed-in tariffs for REN power technologies, blending mandates for biofuels in Brazil). Policies targeting energy efficiency will lead to decreased final energy consumption and thus energy related emissions. Energy efficiency policies can take various forms depending on the sector where they are implemented: energy efficiency standards or lower interest rates for energy efficiency renovation in buildings, energy or CO2 mandates for light duty vehicles, etc. Outside energy, industrial processes can be controlled through production standards, land-use change and deforestation can be controlled by command and control measures (eg in Brazil). Such policies can be motivated by other purposes than decarbonization in the first place (eg support of biofuels for energy security/independence and socio-economic development) and most of the time part of these policies is already in place prior to the design of a possible carbon pricing instrument. Furthermore key questions to design an attractive climate policy package include to understand the possible interactions between a future carbon pricing instrument and other already existing (or practicable) sectoral policies, identify to what extent interaction may be synergistic or else antagonistic and counterproductive for overall emissions reduction, socio-economic impacts and other policy objectives (energy security, etc.) and finally identify how sectoral policies and carbon pricing should be adjusted to yield the best outcomes.

Such issues have been addressed by the modelling literature. A prerequisite is to represent in models the above mentioned existing or practicable policy instruments besides carbon pricing at sector scale and the endogenous sectoral response of the cumulated policies. In practice economy-wide models include complementary policies under two main forms: price based (tax or subsidy) or non-price based (norms, production standards or command and control policies) instruments. Tax as a price-based instrument is a standard feature of CGE models and a given tax or subsidy can be applied to specific fuel or technology according to the level of disaggregation of the model (biofuels, REN power technologies, etc.). The model further computes the endogenous sectoral responses to given tax changes. In addition, models generally represent non-pricing policies through their resulting effects with adjusting specific exogenous parameters. For instance, a command and control policy aiming at reducing deforestation will be implemented through exogenous variations of forest area. To give another example, CO2 emission mandates for new LDVs will be implemented through exogenous CO2 efficiency coefficients (Paltsev et al., 2015). Beyond, other policy types (eg investment programs in infrastructure , etc.) can be implemented through their resulting effect by means of exogenous "pushes" in macroeconomic models (Duscha et al., 2016). More complex sectoral policy instruments such as lower interest rates (eg. for financing energy efficiency renovation, subsidized credit for agricultural activities with low carbon emissions) or specific incentives for R&D investments can be analyzed with specific partial equilibrium models including forward-looking behaviors. However, such instruments and the endogenous economic response are usually not included in economy-wide analysis (or only included through their resulting effects).

The sectoral implementation of policy mixes in general equilibrium models makes it possible to study the economy-wide impacts of the interaction between carbon pricing instruments and other policies. (Corradini et al., 2018) synthesizes the main related issues identified in the literature. First of all, CGE studies analyze the cost and mitigation effectiveness of overlapping instruments often based on single interaction mechanisms. In accordance with the theory, when no other market failure than the climate externality is assumed, overlapping instruments lead to additional economic costs. For instance (Böhringer et al., 2016) study the implication of cumulating the ETS in the EU with meeting the REN target through an additional subsidy or the energy efficiency target with a tax on primary energy. In both cases cumulating the policy instruments leads to additional GDP losses. The supplementary targets actually trigger additional mitigation with higher marginal costs than the "pure" ETS price in both cases and thus incur additional macroeconomic costs. Similarly (Paltsev et al., 2015) analyze the interaction between the ETS and LDVs emission standards in the EU and reach similar conclusions with LDVs standards on top of the ETS leading to net added costs. In addition, in both studies cumulating policies does not yield net additional emission reductions but only a displacement of emissions between sectors because total emissions are capped by the ETS. This is a general rule with an ETS. For instance in (Böhringer et al., 2016) the push for additional penetration of REN beyond the economic optimum (through a subsidy but can be another instrument) causes a decrease in the demand for emission allowances on the market, a decrease of the ETS price and finally the displacement of the additional reduced emissions from REN towards other sectors under the ETS. (Dai et al., 2017) show similar effects in more details in the case of China where REN policies are combined with a set of different ETS designs. Such emission leakage effects are confirmed by partial equilibrium analyses (Delarue and Van den Bergh, 2016). This aspect can provide some preference for a carbon tax compared to an ETS because a carbon tax, through the exogenous carbon price, makes it possible to implement cumulative incentives with other policies. However, the cumulative incentives could be an issue in practice if the sectoral policies turn out to be more restrictive than expected.

However global cost-effectiveness may not be the only policy objective and a mix of instruments can be justified to reach simultaneously other policy goals than the climate. For example developing REN sources can lead to a decrease of imports of fossil fuel in Europe and thus increase energy independence and security. A policy mix is even more desirable when other non-climate externalities and market failures of real economies are taken into account. For instance (Duscha et al., 2016) suggest that even if REN are not the most cost-effective option, they can help achieve a triple dividend (emissions reduction, energy security and jobs creation), when labor market imperfections (with possible unemployment) and macroeconomic Keynesian mechanisms are taken into account. Macroeconomic impacts of climate policies else strongly depend on the second-best economic mechanisms modeled and the macroeconomic approach used (see section 2.6 and 2.15). Finally, the socio-economic impacts of alternative policy packages should in general better be analyzed with a multi-objective approach taking into account the specific second best features of the economy under study (see section 2.6 and 2.15).

A second example of policy interaction concerns the mutual influence between EE and the carbon pricing mechanism. From one side EE contributes to the emissions reduction goal and also reduces the vulnerability of consumers to high and volatile energy prices, thus enhancing the security of the energy system. From the other side, if substantial energy savings are achieved, energy becomes cheaper. Accordingly, the reduction in energy prices could further lead to an increase in energy demand due to a rebound effect mechanism (Barker et al., 2007; Bentzen, 2004; Gillingham et al., 2013)

An optimal climate policies portfolio should include both carbon pricing and support for clean energy technologies because while the latter can address knowledge-related market failures, only the former can stimulate demand for low-emission technologies and their diffusion and adoption, thus providing enough incentives for radical innovation and backstop technologies in the long-term (Gerlagh et al., 2014; Popp, 2016)

2.6. Impacts on the tax burden, revenue recycling and double dividend issues

Carbon tax payments and/or auctions from an ETS yield revenue transfers towards public administrations and become income components of the public budget. The economic literature generally considers three polar types of usage of these new economic resources within the public budget: 1) reduction of public deficit and debt, 2) lump sum transfers to economic agents and 3) reduction of other existing taxes. In practice any combination of these types can be contemplated. A first key issue is thus to assess the implications of different carbon revenue recycling schemes for the public budget and the net tax burden on the economy, ie understand how carbon pricing instruments can be part of a broader tax reform. However, part of carbon revenues can be allocated to more specific usages such as supporting the development of REN technologies through dedicated subsidy or helping specific “loosers” of the energy transition. Overall, the fundamental general policy question is about how to design the usage of carbon revenues to address different policy goals simultaneously (beyond the climate goal) including optimizing the macroeconomic efficiency of the carbon fiscal reform, reducing public debt, reducing inequalities and poverty and any other more specific objective: insure minimum industry competitiveness, reduce energy poverty, develop REN technologies, etc.

First of all, economic theory provides a rationale to analyze the macroeconomic efficiency of a carbon tax reform. It especially postulates that under specific conditions, recycling carbon revenues in reducing the marginal tax rate of other existing distortive taxes makes it possible to partially offset the primary technical abatement costs and even more than offset these primary costs to yield an economic benefit. These are the weak and strong double dividend hypotheses (climate and economic dividends). The strong double dividend hypothesis especially carries much political attraction as net economic benefit could be reached without taking into account the climate benefit. Economists have intensively worked on the topic for more than two decades without reaching general conclusions. (Goulder, 2013) provides a recent synthesis on the issue. He argues that a necessary condition for double dividend is that the initial tax system must be inefficient along some non-environmental dimension, and the revenue-neutral tax reform reduces this non-environmental inefficiency. Practical cases include inefficient relative taxation of labor and capital, inefficiently light taxation of resource rents, an informal labor market and associated inefficiently low taxation of informal labor income. However double dividend is most of the time not likely partly because of a mechanism generally overlooked, the tax-interaction effect which tend to increase the economic burden of carbon pricing beyond the primary abatement costs. When carbon pricing is implemented in an economic system with pre-existing taxes (income, labour or sales taxes), the tax burden finally falls on the income that enabled the additional tax payment. Therefore, additional carbon pricing increases the initial economic distortion linked to pre-existing taxation. Consequently, carbon recycling via reduction of pre-existing marginal tax rates has to more than offset the cumulated primary abatement costs and tax-interaction costs which can only happen in specific situation of very inefficient pre-existing tax system. His analysis else underlies the importance of the overall design of climate policy to optimize economic efficiency. For instance, in the case where carbon revenues are recycled lump-sum or the ETS is based on freely allocated allowances, the tax-interaction effect is not offset and adds to primary abatement costs. Therefore, exploiting the revenue-recycling effect to offset part of fiscal interaction is important for the cost-effectiveness of carbon pricing. More, once fiscal interactions are taken into account in general equilibrium, choosing emissions pricing over more conventional approaches like command and control does not guarantee cost-savings and higher cost-effectiveness without appropriate recycling. The same author shows in (Goulder et al., 2016) that under some conditions a renewable portfolio standard for instance can be more effective than a comparably scaled carbon tax. Thus, while the choice of type of instrument is important, fiscal interactions imply that the particular design of the chosen instrument is critical as well.

Overall in the absence of general statements, double dividend is an empirical issue that should be analyzed taking into account the specific context under study. Many CGE model based studies have been carried out to study these issues for different country contexts. (Freire-González, 2018) provides a meta-analysis of these studies. 40 studies in different regions of the world have been analyzed and on the 69 simulations reviewed, 55% achieve some double dividend, which confirm the context specific aspect of the issue. From another angle, (Timilsina, 2018) reviews the existing CGE analysis about alternative carbon revenue recycling schemes. Most cases show the same hierarchy of the cost effectiveness of the different recycling schemes: reducing government deficit leads to the highest economic costs; a lump-sum transfer to households reduces the costs but less than cutting existing taxes (labor, capital, income taxes, VAT, etc.). Therefore cutting existing taxes increases chances to yield a double dividend. The review also shows that using carbon revenues to finance environmental policies - such as clean energy subsidy - leads to better environmental outcome but at higher economic cost.

As earlier mentioned, double dividend and macroeconomic efficiency of climate policy is only one aspect of the policy analysis within a broader multi-objective approach. In this view some studies have analyzed to what extent economic efficiency could be aligned with reduced inequality. Most studies point to the existence of an efficiency/equity trade-off. (Combet et al., 2010a) shows how decreasing payroll taxes in France provides a macroeconomic dividend with increased inequality whereas lump-sum transfers to households provides less economic efficiency but makes it possible to reduce income inequality significantly. (Alton et al., 2014) shows similar results for South Africa with two alternative recycling options; reducing capital tax or financing a social program. Distributive implications linked to revenue recycling are the subject of many studies (Beck et al., 2015), (Rausch et al., 2011). The multi-objective approach can be developed in many directions. For example, (Van Heerden et al., 2006) show how a triple dividend (environmental, economic and poverty) can be reached in South Africa through reducing food prices.

To be able to model the different possible usages of carbon revenues seeking different policy objectives, the precise composition of the public budget, the possible transfers between economic agents and the possible tax interaction effects, CGE models need to include a sufficiently detailed representation of the specific pre-existing tax system of the country under study. Models generally distinguish at least labor (payroll) taxes, capital taxes, production taxes and sales taxes. The most advanced models consider a secondary income distribution structure and distinguish between direct and indirect taxes. For instance the IMACLIM-BR model (Lefèvre, 2016) distinguishes a set of direct taxes paid by production sectors (payroll and production taxes) and consumers (sales tax) and a set of indirect taxes paid by institutional sectors (corporation tax paid by firms and tax on income paid by households). A detailed representation of the tax system and tax breakdown makes it possible not only to compute how different carbon revenues recycling schemes impact the public budget and the global fiscal burden under different forms of recycling neutrality, but also the magnitude and structure of the fiscal burden at the scale of sectors or representative economic agents. It can also inform about the changes of different tax types income and transfers linked both to adjustments of tax rates and variation of economic activity. (Rausch and Reilly, 2012) and (McKibbin et al., 2015) use such detailed tax breakdown in a CGE model to study how a fiscal reform including a carbon tax could align macroeconomic efficiency and reduced public deficit.

2.7.Modeling distributive issues between households

Climate policy and carbon pricing instruments have heterogeneous consequences on different types of households depending on their income level, expenditure pattern, and other socioeconomic characteristics. As demonstrated by (Rausch et al., 2011) a carbon tax can have very different implications for households welfare depending on their income and expenditure pattern. The consequences are generally all the more contrasted as household's heterogeneity is initially high whether it be about income level or consumption patterns, a key feature of Brazilian society. So, climate policy analysis is not only about the net global implications of carbon pricing instruments but also the different possible distributive impacts and costs-benefits distribution among households. Climate policy analysis should aim at identifying the possible winners and losers of policy instruments and design compensation for losers to make policies acceptable and align climate goals with other development objectives. Standard CGE models are based on the single representative household's hypothesis and usually do not distinguish households by income or other attributes. Such an approach makes it not possible to capture heterogeneous implications of climate policy on households, although a key aspect of the project. Hopefully many CGE models have been developed to address the issue of the household's distributive analysis by including a form of household heterogeneity. Initially household's income distribution in CGE models has been developed to address economic development issues (Savard, 2003) and was only more recently applied to climate policy analysis.

In the standard CGE approach, the representative household is endowed with total primary factors (labor, capital, land, resources, etc.) which generate aggregated income that is further expensed or saved according to an aggregated preference scheme. Heterogeneity between Households can be introduced at two main levels in CGE modeling (Bertola et al., 2014): 1) for the income structure, introducing heterogeneity about income sources (related to heterogeneous factor endowment and wages rates) and 2) for the preferences structure about consumption and savings. As developed by (Van Ruijven et al., 2015), three modeling approaches stand out in the literature to capture households heterogeneity and distribution: 1) the explicit modeling of multiple household types within the CGE framework, 2) micro-simulation modeling, and 3) direct modeling of income distribution.

In the first approach, the representative household in the CGE framework is divided into several household types representing different households' sub-groups. Except for increasing the number of representative households, the CGE structure remains the same. In this approach each household type is characterized by a specific factor endowment, type of labor supply or income structure and specific consumption and savings patterns linked to a specific utility function (with possibly differentiated price and income elasticities). The representation of the behavior of each household's type is directly part of the CGE framework and GE effects are fully endogenous. The number of household's types can vary from minimum two to thousands as in a national household's survey.

The most common household disaggregation criteria in climate policy analysis is the income and most CGE models considers different households groups based on defined income ranges or percentiles in the income distribution. (Rausch et al., 2011) uses the USREP static CGE for the USA which distinguishes more than 15000 household groups to analyze the impacts of a carbon tax on the US economy including different tax revenues recycling schemes. The key finding of this work is that "variation in impacts within broad socioeconomic groups may swamp the average variation across groups" which highlights the relevance of the distribution analysis. (Rausch and Mowers, 2014) uses the more compact version of the USREP model with 9 households types to study the distributional impacts of renewable energy standards for electricity. (Combet et al., 2010b) uses the IMACLIM-S CGE model distinguishing 20 household's income groups to study the impact of alternative carbon tax policy in France. The results show that trade-offs exist between aggregated macroeconomic impacts and inequality performances. Finally a few models in climate policy analysis have considered other definitions of household types than pure income criteria such as based on the urban – rural divide. (Yusuf and Resosudarmo, 2015) analyzes the distributional impacts of a carbon tax in a developing economy, Indonesia, and show that the carbon tax policy may not be regressive when taking into account the specific endowment of rural and lower income households. (Liang and Wei, 2012) perform the same type of analysis for China.

Including different household types within the CGE framework proved to be an efficient and practical way to provide robust assessment of distributive implications of climate policy and carbon pricing instruments. A main remaining limitation is about controlling the dynamic link between the definition of household types and income distribution when types are not based on the income criterion.

The two alternative approaches to represent household's heterogeneity with CGE models are to use micro-simulation modeling or direct modeling of income distribution.

As explained by (Van Ruijven et al., 2015) micro-simulation models simulate outcomes for a large number of household types up to and including treating each household in a nationally representative sample survey as its own type, and make it consistent with the aggregated outputs of a macro-CGE model. These models differ from multiple household CGE models, in that the multiple household CGE models replace a single household with multiple households within the macro model itself, whereas a micro-simulation model uses the results of the household type(s) in the macro model to simulate outcomes with a higher degree of heterogeneity. Micro-simulation models can be used as sequential calculation after the CGE run (top-down) or in iteration between micro-simulation and CGE model (top-down/bottom up). In addition, micro-simulation models can vary widely in sophistication, from nonbehavioral/arithmetic/accounting approaches, to approaches that include behavioral responses (i.e., changes in occupation or savings behavior) of households (or household members) to changes in labor markets and prices of goods.

In practice very few micro-simulation / CGE approaches have been used to address climate policy issues. (Ghersi and Ricci, 2014) uses arithmetic sequential micro-simulation to assess the fuel poverty implication of the French energy transition. The basic limitation with the sequential arithmetic approach is that it informs about the distributional impacts of policy instruments a through a one-way downscaling of the aggregated information of the CGE model with benchmark household survey datawithout feedback at the macro level. Behavioral sequential micro-simulation has mainly been used to assess macroeconomic crises or shocks. (Mauricio et al., 2006) uses this method to study the consequences of trade liberalization in Brazil for the transition from agriculture to non-agriculture workers. One key drawback with behavioral microsimulation is that it is very data intensive since it needs background data that characterize household members to define the behavioral choice modeling. Finally (Savard, 2010) develops an iterative macro-micro approach for the case of the Philippines. The method includes iterating the CGE and micro-simulation model several times, exchanging information on prices and employment, until the models converge to a similar result analyzing a specific macroeconomic shock or investment. A key constraint with iterative simulation is that results are very dependent on the way feedbacks from the micro-simulation to the CGE are modeled which else poses the question of data consistency between the two models.

As a last existing approach, direct modeling of income distribution more simply assumes a relative income distribution within a single representative household based on different functions possibly fitted on household survey data. The mean income in the function matches the mean income of the representative household. However, the distribution analysis is only ex-post based on CGE results and the distribution has no feedback on the general equilibrium mechanisms. Although this simple method can be appealing for a quick distributional analysis it cannot inform about the key endogenous mechanisms linked to heterogeneous income generation and consumption choices in presence of carbon pricing instruments.

Overall the multiple household types within CGE approach seems to be the most relevant for the current project. It makes it possible to capture heterogeneity over the key endogenous mechanisms and feedbacks linked to carbon pricing at a fair level of detail. Micro-simulation is an interesting complementary approach to downscale the impact assessment on households but generally lack the key feedback mechanisms.

Eventually, a key constraint to overcome in order to build a robust CGE model including different household types is to build a single and consistent database to calibrate the model. National accounts generally do not provide information for different household types. This information has to be looked for in household survey data. However, key data about consumption levels, incomes and assets can deviate significantly for the total aggregates between national accounts and household surveys. Consequently, an important prerequisite is to reconcile the data from the household survey with the data from the Social Accounting Matrices (SAM). Careful data treatment has to be carried out by adjusting data survey, the SAM or both.

2.7.1. Regional disaggregation

For big countries composed of very different sub-regions in terms of social economic and geographical conditions, analyzing the distributive impacts of climate policy between these sub-regions may be an important aspect of the analysis. Downscaling analysis at sub-regional level is required when key climate policy instruments are settled at sub-regional scale. This is for instance a key aspect in China where the national ETS is based on the aggregation of ETS initially designed at the state level. Furthermore, studying the distributive implications between the sub-regions of a country obviously requires a form of disaggregation of the representation of the national economy in different composing sub-regions. The most common one way to perform this is to work under a multi-region CGE framework. The multi-region CGE framework is mainstreamed for global models but less developed at national scale. One of the reasons is that national multi-region CGE models show a higher degree of complexity because they represent both infra-national (between sub-regions) and inter-national (between the country and the rest of the world) trade. In any case as for global models, national multi-region CGE models are based on a set of sub-region specific SAM connected through infra-national trade and other economic flows with the additional feature that the sum of these SAM are else connected to the rest of the world through international trade. Sectoral and household disaggregation is usually similar in all the regions but sectoral and household's behaviors are region specific.

In practice, most national multi-region models used to assess climate policy have been developed for the US and China cases (and the EU). For instance the USREP model (Rausch et al., 2010) distinguishes 12 sub-regions in the US. The regional structure distinguishes larger states, allows representation of separate electricity interconnects, and captures some of the diversity among states in use and production of energy. Capital is mobile across regions, but labor is not. Regions are connected through infra-regional trade with different features for the different sectors. Bilateral flows are accounted for non-energy goods through Armington specification whereas energy goods are supposed to be homogenous goods among different region groups and for each region groups infra-national trade is based on a pool that demands domestic exports and supplies domestic imports. The model makes it possible to assess the differentiated emission reductions and welfare impacts per region of different climate policy packages. Many applied CGE models have been recently developed for China and some of them based on a multi-region structure. Some of them only include 2 sub-regions (one specific region and the rest of China) to focus on one given sub-region. (Wu et al., 2016c) and (Yu et al., 2018) are two recent examples of a 2 sub-region model in China used to assess climate policy in Shanghai. Fully disaggregated multi-region models have also been developed. The TermCO2 (Liu et al., 2017) and CE3MS (Wu et al., 2016b) models both include the distinction of 30 regions, each represented through a specific SAM, allowing for trade, investment and labor movements across regions. Multi-region modelling has also been developed for Brazil but not in the context of climate policy analysis to the best of our knowledge. For instance the B-MARIA-27 model (Haddad, 2003) proposes a state level disaggregation to study inter-state trade.

One key constraint to develop a multi-region model is the data availability at the scale required. For instance, in the US the IMPLAN dataset provides SAMs at the state level and in China the National Bureau of Statistics provides Provincial Input–Output Tables on a regular basis.

2.7.2. Sectoral disaggregation

The sectoral disaggregation discussion is more common in CGE modeling. CGE models used to assess climate policies usually distinguish a set of energy and non-energy sectors (or end-use energy sectors). The energy sectors represent the processes of primary energy extraction (oil, gas, coal, etc.), energy conversion and final energy supply (oil, coal and gas refining, electricity generation, etc.) and are usually divided in 5 to 10 sectors in CGE models. Electric generation technologies (coal, gas, nuclear, wind, etc.) can sometimes be considered as individual sectors

(Paltsev et al., 2005). Furthermore, a first level of disaggregation distinguishes the main end-use or non-energy sectors: agriculture, energy intensive industries, other industries, transport and services. These sectors else correspond to the main energy end-use types in energy modeling: agriculture, industry, transport and buildings. Part of buildings (residential) and transportation (private vehicles) activities are allocated to household's final consumption in national accounts and thus in CGE models. Such a level of aggregation (a dozen economic sectors with half energy and half non-energy sectors (Paltsev et al., 2005; Waisman et al., 2012)) makes it possible to capture the key relationships at macro level between the energy matrix (including the main aspects of the energy balance: primary energy supply, energy conversion and final energy consumption broken down in key end-use sectors) and the macroeconomic dynamics. It makes it else possible to perform model linking with BU models for specific aspects (power generation, transportation, buildings, etc.). Additional disaggregation can be needed for specific purposes taking into account the specifics of the context under study. For instance, as earlier mentioned, further disaggregation is needed for agriculture sectors as a prerequisite to improve the representation of land-use dynamics. Agriculture is then disaggregated in different products including several crops, livestock, forestry and bioenergy. Another type of standard further disaggregation target the industry sectors in order to assess the contrasted policy impacts among industry branches related to competitiveness and leakage issues especially. Further disaggregation generally distinguishes between energy intensive (cement, steel, paper, non-ferrous metals, mining, ceramics, chemicals, etc.) and less energy intensive industries (food, textiles, other manufacturing, etc.). Many CGE studies aim at assessing the distributional impacts of carbon pricing instruments on different industry branches. Beyond, any further disaggregation is possible but most CGE models used to assess climate policies consider less than a total of 50 sectors for computational reasons.

Overall existing CGE models are well equipped to assess distributive issues between households/ sectors/ regions at national scale especially due to relevant disaggregation possibilities. However, few models attempt to combine the highest disaggregation level for all the dimensions previously discussed. Beyond the trade-offs due to computational issues[2], disaggregation choices in models depend on the specific research questions under study. For instance, the USREP model distinguishes 12 regions, 9 household's types and only 5 non-energy sectors to focus on the heterogeneity of income distribution amongst the key regions in the US. Differently, the CE3MS model distinguishes 30 regions, 12 non energy sectors with a single representative household to focus on the trade effects between Chinese regions linked to different economic sectors. To take just one final example the CGE model used in (Chen et al., 2013) includes only one region, one representative household and distinguishes 19 non-energy sectors to assess the sectoral implications of climate policy in Brazil.

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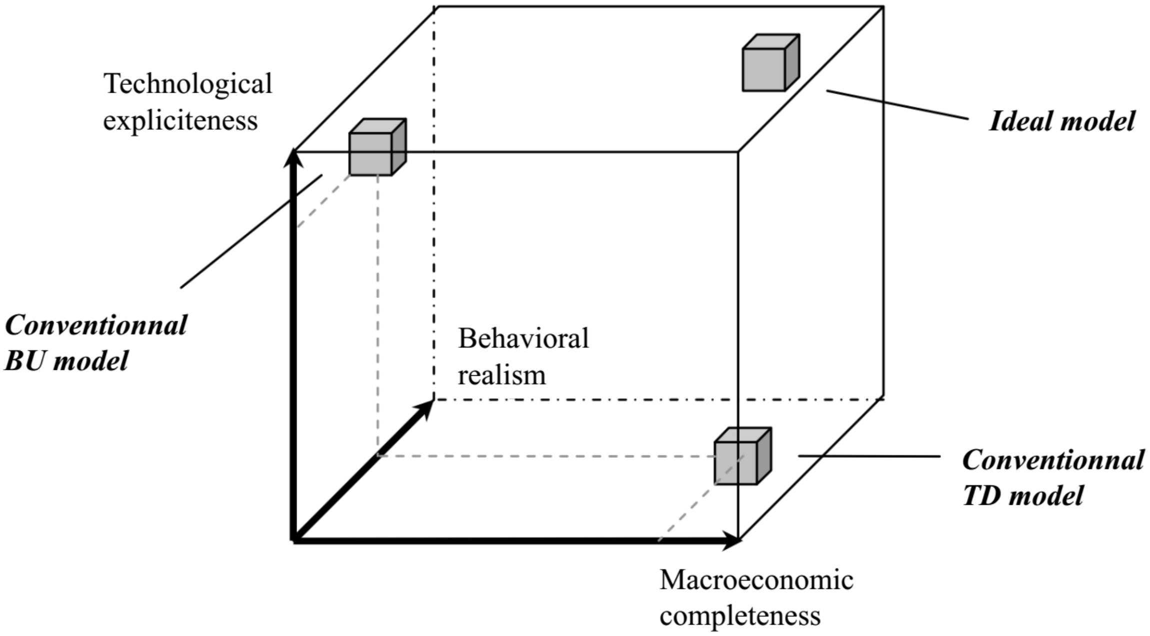
[2] The computational burden of the disaggregation of sectors is higher than with households and regions because the required computing power increases exponentially with sector disaggregation (because of the I-O) whereas it is usually linear with households groups and regions.

2.8.Integration, linkages between models

According to (Hourcade et al., 2006), ideally energy-economy-environment models used to perform economy-wide integrated assessment of climate policy and mitigation pathways should perform well along the three following dimensions summarized in Figure 2: it should (i) take into account economy-wide feedbacks with high macroeconomic completeness, (ii) represent the competition of explicit technologies in energy supply and demand sectors, and (ii) represent realistic economic behaviors. As further illustrated on Figure 2, conventional bottom-up models perform well in technology explicitness but generally includes low behavioral realism and no macroeconomic feedback (as partial equilibrium models). Behavioral realism is higher in BU simulation models than in energy system optimizing models based on computing least system costs (MARKAL type models). Conversely, conventional top-down models include full macroeconomic feedbacks but are not technology-explicit and include limited behavioral realism. Macroeconomic completeness is higher in SAM based multi-sector models than in compact growth models. In addition, conventional TD models include micro founded behaviors based on representative agents' surplus maximization. One challenge in E3 modelling was thus to improve models towards the right end corner of the figure by hybridizing the strengths of conventional models to build hybrid models.



Beyond energy-economy hybridization, another key modelling challenge was to connect within modelling architectures the socio-economic system with other earth sub-systems such as land and atmosphere/ocean systems to perform so-called integrated assessments. To address both challenges modelling tools were especially developed towards the integration of pre-existing modelling approaches and strategies and the integration of the representation of different sub-systems. Integration is further performed by model linking in the broader sense. (Wene, 1995) classifies model linking as (informal) soft-linking versus (formal) hard-linking. (Böhringer and Rutherford, 2008) do not use the term “hard-linking”, but define three categories: 1) Coupling of existing large-scale models, 2) having one main model complemented with a reduced form representation of the other, and 3) directly combining the models as mixed complementarity problems. The first approach is usually referred to as soft-linking and consists in coupling pre-existing standalone models by exchanging inputs and outputs until convergence. We describe this approach further after. The second approach, a main model complemented by a reduced form, is a very broad category and include most state-of-the-art so-called integrated assessment models (IAMs). The main model can first be a BU model further complemented by some TD features to become a TD-based hybrid model. IAMs based on the combination of an energy system optimizing model and a compact optimal growth model fall in this category (REMIND, MESSAGE, etc.). On the other hand the main modelling approach can be TD enriched with specific BU features to become a TD based hybrid model. Multi-sector CGE models which have been developed towards representing distinct power generation technologies or distinct generation of LDVs fall in this category (GEM-E3, EPPA, etc.). The direct combination of BU and TD models as mixed complementarity problems is less frequent and further described after.

A prerequisite for this project is to work under a multi-sector economy-wide framework as mentioned in introduction. The following thus reviews in more depth the model linking issues in the context of a core multi-sector CGE model (BU based hybrid approaches are thus excluded in the following). In this context the key objective is to improve the behavioral and technological aspects at sectoral scale to overcome the limitations of the conventional TD production function. Attempts at integrating engineering-based representations of technical systems at sectoral scale in CGE models actually show that the nature of the representation strongly impacts climate and energy policy assessment. For instance (Böhringer, 1998) and more recently (Lanz and Rausch, 2011) compare the impact of alternative formulations of the power generation sector within a larger CGE model: two standard constant elasticities of substitution (CES) production functions with KLEM[3] inputs and one engineering based formulation with discrete technologies. In both cases two conclusions arise. First, the differences between engineering based and aggregated production function representations are structural and have a large effect on policy assessment. Second, the engineering based representation shows a non-monotonic behavior that would be very difficult to capture through the use of conventional production functions. (Hourcade and Ghersi, 2006) confirms that integrating bottom-up information in a general equilibrium framework can significantly alter the economic and technical diagnosis, even at a macro scale. This means that different

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[3] Capital, Labour, Energy and Materials.

degrees and forms of bottom-up integration may thus impact energy and climate policy assessment differently. Integrating engineering based representations of technology in CGE based analysis of climate policy is also necessary to improve the dialogue between engineers and economists and enhance the quality control and credibility of CGE model assessment of climate and energy policies (Böhringer, 1998).

In order to characterize the existing options to integrate engineering-based mechanisms in CGE models, it is useful to summarize the features of the standard toolkit used in a conventional CGE model: the top-down production function. CGE modelers traditionally use an aggregated production function to represent the technical possibilities for each economic sector. This function embodies the space of possible efficient combinations of aggregated factors and inputs (capital, labor, energy and others inputs) at time t - to produce one unit of output: Y = Ft(K; L; E; M). Such ”KLEM” production functions originate from aggregated growth models (Solow, 1957) and have been applied to the sector level in multisector CGE models. The CES (Constant Elasticity of Substitution) form is the most common among CGE models and can be nested to different levels of complexity. However, capital, labor, energy and other inputs are not disaggregated at the technology level (in the engineering sense) in conventional CGE models. Production functions are customary calibrated on a given year SAM. Elasticities of substitution are exogenously prescribed and sometimes come from specific econometric studies. Zero-profit assumption and cost minimization are used to calibrate the coefficients. These coefficients exactly correspond to the cost-shares in the initial input-output matrix. These cost-shares form a cost structure, which defines production inputs in terms of intermediate consumption – including energy, capital rent, labor wages and taxes. The weakness of the technical content of the calibrated top-down production function is thus rather intuitive. The calibration process starts from rough assumptions about substitutions possibilities between factors (most of the time of the nested-CES form) and the prescription of elasticities values. Then the heroic assumption of instantaneous optimum for base year historical data and for any future time steps, makes it possible to infer from a single year cost shares the future substitution constraints of one given production sector. Serious doubts about the technical content of production functions have further been formulated. Solow himself has warned that the macroeconomic cost-shares “‘wrinkle’ is acceptable only at an aggregate level (for specific purposes) and implies to be cautious about the interpretation of the macroeconomic production functions as referring to a specific technical content ”(Solow, 1988). Furthermore, Frondel and Schmidt (2002) raise concerns on this methodology, since the estimates for capital-energy elasticities are already driven by the cost shares and may not represent technological substitution: “inferences obtained from previous empirical analyses appear to be largely an artefact of cost shares and have little to do with statistical inference about technology relationship”.

The three linking approaches introduced above have been developed to overcome the limits of conventional production function in CGE models.

As earlier mentioned the first approach is about building TD-based hybrid models and has been developed in CGE models by expanding the production function to introduce some technological explicitness. This category includes the approaches based on an expansion of the usual sector production function by sub-scaling inputs and factors cost structure to the single technology level (in the engineering sense). Furthermore, individual technologies are singled out by means of their own cost structure - calibrated on engineering costs - and compete to supply sector output within the production function. Within this category, approaches mainly differ about the type of aggregation of technologies, either a CES or logit aggregation (Schumacher and Sands, 2007) . In the first case technologies are directly singled-out in an usual CES nesting structure (Wing, 2006). However, these approaches only correspond to a “surrogate” representation of activity analysis because they do not challenge the basics of the neo-classical production function. It implies first an aggregated vision of technology substitution by means of constant elasticity of substitution or logit market shares. Second, capital remains a neo-classical object which mixes up investment decisions and activity remuneration and does not distinguish between production level and capacity, a key feature of activity analysis in bottom-up models. In a nutshell the advantages of this approach are the consistency of the standalone global model with the inclusion of technology information without challenging the production function approach. However, the technology disaggregation remains limited in practice for data and computational reasons and the processes of technological competition are still based on TD substitution elasticities with the risk to miss key technical mechanisms and constraints.

The second approach consists in soft-linking a CGE model with a BU model to inform about the technical trade-offs at sector scale. In practice it amounts to replacing the production and consumption trade-offs of the CGE model by the equivalent trade-offs resulting from a bottom-up model through variables exchange and iterative simulation until convergence. This coupling approach has gained success owing to the convenient “soft” combination of two pre-existing models. Numerous attempts exist in the literature with the coupling between a CGE model and a bottom-up model for a single sector alone, like the residential sector (Drouet et al., 2005), the power sector (Martinsen, 2011) or the entire energy system (Fortes et al., 2014). The main advantages of this approach are thus the ease of implementation with relying on pre-existing models and to combine the full strengths of the linked models. However, the approach raises important consistency issues generally not entirely discussed in practice about the linking variables and the possible overlaps and convergence issues between the models. The subsequent risk is to lack the needed quality control of the overall energy-economy picture generated.

Finally, the last approach consists in fully integrating BU/TD representations. Beyond considering discrete technologies, it means embarking activity analysis in a CGE framework and capturing investment dynamics of technology-specific producing capacities with specific utilization rates and rent generation. In addition, all coupling inconsistencies are removed through built-in joint evolution and full integration. This approach is based on solving a mixed complementarity problem (MCP). The strengths of this approach are evident. It offers both full consistency between technology substitutions and the macroeconomy and technology dynamics based on BU activity analysis. However, for computational reasons such an approach is difficult to expand on a full multi-sector dynamic CGE model with many technologies and few applied CGE models on this type actually exists in practice.

Eventually, one key element for the appropriate integration of engineering-based bottom-up representations into CGE models relies on the good control of the variables exchanged or linking variables. The consistency between physical volumes, money flows and the price system of the resulting hybrid model is at stake. Standard CGE models rely on accounting all values, including physical volumes, in economic terms. The modelers thus have to rely on manipulations to transfer information but not variables. For instance in (Drouet et al., 2005), the ”objects” of the dialog between bottom-up and top-down representations are ”volumes” of energy, transport services, etc and/or related prices. Nevertheless, “the models [...] are formulated in different units” so that there is in truth two variables with two different units (physical units vs dollar-weighted index) for the same object in the resulting hybrid model and “a connection must be made” between the variables. The usual “scaling procedure” consists in imposing a proportional link between the two variables. One solution to overcome such limits and improve the quality of the BU/TD integration is to account for volumes directly in physical units in the CGE model while ensuring the consistency with money flows through the price system. (Schumacher and Sands, 2007) and (Hourcade and Ghersi, 2006) adopt this strategy. A key prerequisite is to rely on a consistent database to calibrate the CGE model, which articulates physical flows with money flows and the price system. In practice, such a database basically results from the integration of national accounts (the SAM), material balances (energy balance) and sector and technology specific data. For example (Le Treut et al., 2014) and (Sands and Fawcett, 2005) discuss the issue of national accounts and energy balance integration. In any case, building such databases remains a challenge that needs substantial data adjustments due to different accounting methods and substantial problems in gaining consistency to be solved.

Eventually, the best indicated approach for the project is undoubtedly to rely on a soft-linking approach between a core multi-sector CGE model and specific BU models. Consistency issues in model linking will have to be addressed carefully.

2.9.Treatment of multiple emission sources

CGE models used to assess climate policy have been first developed to study issues related to CO2 emissions linked to fossil fuel combustion. They have then been extended to treat a wider range of GHG emissions. For instance, the EPPA projects emissions of carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), and sulfur hexafluoride (SF6), gases that have direct radiative forcing effects in the atmosphere. It also projects sulfur dioxide (SO2) emissions—a major source of aerosols that are thought to have a cooling effect, and CO, NOx, non-methane volatile organic compounds (NMVOCs), ammonia (NH3), black carbon (BC), and organic carbon (OC). The approach for developing a reference case level of emissions of these substances is based on specific emissions inventories as documented in Sarofim et al. (2005). Energy related CO2 emissions are generally estimated based on the linked energy flows accounted in physical units (toe). Then emission factors are used to compute CO2 emissions related to the different energy flows. Furthermore, the model computes the fuel switching and other trade-off linked to energy consumption resulting from the implementation of climate policy and projects the variations of related CO2 emissions. Such an approach requires careful initial calibration based on crossing energy balance and CO2 emissions data. The fuel disaggregation of the model is else a crucial component for robust CO2 emissions projections. A minimum of three fossil fuel aggregates are generally considered in models (coal, gas and petroleum products) and further disaggregation increases the robustness of the model emissions computation. Heterogeneous emissions factors between different consuming sectors for a given fuel aggregate can also be used to reflect the heterogeneity of fuels (eg gasoline versus oil fuel both included in petroleum products).

Following the examples of AIM (Fujino et al., 2006) and EPPA (Hyman et al., 2003), other emissions types and gases are directly introduced in the nest structure of each production sectors. In most cases, the greenhouse gases are introduced into a top nest. Process emissions of CO2 from coal gasification and from shale oil production are introduced as a Leontief input in such a top nest for these sectors, indicating that emissions of CO2 from these processes are fixed in relation to total production of coal gas or shale oil. Most other substances enter as a CES inputs, and the elasticities of substitution are fit to match bottom-up estimates of abatement possibilities (MACCs).

If state-of-the-art CGE models can project a wide range of GHG gases they still struggle to project GHG emissions linked to complex biophysical processes such as land-use changes for instance. In any case linking a CGE model with specific sectoral models makes it possible to decentralize accounting of GHG emissions. For instance, a CGE model coupled with both energy and land-use models can decentralize accounting of sector specific emissions to these models. The land-use modules will provide robust calculations of complex GHG emissions involved in AFOLU sectors. However maximum consistency should be sought between the emissions computed in sectoral models and the related emissions computed in the CGE model. Overall, linking a CGE model to sectoral models provide the double attraction to reflect BU based technical mechanisms and give the opportunity to decentralize a robust accounting of a wide range of GHG emissions. The consistency of physical flows (energy and emissions) between the CGE and sectoral models is a crucial issue to assure the alignment of the models and a good level of realism to the simulation.

2.10. Treatment of structural changes

Climate policy is designed to drive a transition towards medium run targets like NDCs, which imply a time horizon beyond a decade generally. To address socio-economic impacts over such time horizon requires taking into account structural changes that may happen in the economy under study. To put it short structural changes are about the changes of the structure and content of future economic growth compared to present situation. In scenario modelling structural changes are generally understood as the structural changes happening in baselines and refer to different aspects including changes in production processes, preferences, markets functioning and more concretely to the resulting changes in the composition of GDP. Structural changes are generally controlled in modeled baselines to reflect specific storylines. CGE models control the computed structural changes through different mechanisms and exogenous parameters, similar across models (Chen et al., 2015) (Chateau et al., 2014). Supply and demand drivers of structural changes can be distinguished.

On the supply side the main drivers are linked to the pattern of changes of factor productivity (mostly exogenous). At the macroeconomic level, different assumptions regarding the technical progress can be considered between neutral technical progress and biased technical progress towards labor or capital factors. In the former case natural economic growth is driven by the sole increase of labor productivity. Productivity and intensity changes can also target energy (through AEEI) and other intermediary inputs. For instance, a trend increase of service intensity of production can reflect a trend towards digitalization of economies. Trends of factor and input productivity can be differentiated among sectors to drive specific changes of sectoral composition of GDP.

On the demand side the main drivers of structural changes are household’s consumption patterns and international trade patterns. The sectoral composition of GDP is first impacted by the household’s income elasticities of demand for different goods and services which reflect consumer’s preference and drive the structure of GDP as consumers are getting richer. The preferences themselves can be updated across time. Finally, the structure of GDP is impacted by international markets, the world demand of different goods and services through time and the world prices of key commodities such as fossil fuels.

In a nutshell CGE modelers can “play” with the above described different drivers to generate expected baseline structural changes consistent with a given storyline. Part of driver’s adjustments can be based on external existing projections or partial equilibrium analyses but it will remain at some point a matter of modeler’s judgement. This inevitably rises the issue of the empirical validation.

2.11. The explicit representation of other world regions and competitiveness issues

Climate change is a global issue and has to be mitigated at this scale with the contributions of all regions of the world in terms of emissions reduction. Although in the aftermath of Paris Agreement climate policy is very shaped by NDCs, national contributions based on national strategies – including carbon pricing - can lead to an appropriate global mitigation response only if implemented simultaneously. Practical policy instruments like carbon pricing can also be organized at an international and interregional level. Therefore, national climate policy analysis needs to take into account climate action implemented in other parts of the world because it will interact with domestic strategy through different channels including 1) the repercussions on international trade and 2) the perspective to link possible domestic carbon pricing instruments such as an ETS with other national and regional similar instruments. For instance, depending on the level of action in the rest of the world, competitiveness and leakage issues can happen with the implementation of a domestic carbon price. In case the stringency of domestic carbon pricing is significantly higher than in the rest of the world, the increase of domestic energy costs may hinder sectoral competitiveness through the rise of domestic prices for energy intensive exposed industries. This may further lead to the degradation of the sectoral trade balance and a displacement of part of industrial activity to the rest of the world with the linked leakage of emissions. Inversely more stringent global climate action will lead to lower demands and prices of fossil fuels which may cause positive domestic competitiveness and purchasing power effects. In addition, linking a domestic carbon pricing instrument like an ETS to another regional ETS will open the possibility to exchange permits with another world region, which will lead to international displacement of emissions and international money transfers according to the allocation rule of allowances between the different countries. Such transfers between the domestic economy and foreign regions will impact the domestic economy through changes on the foreign account and exchange rate.

These international interactions of climate policies have been extensively addressed in the modelling literature. Multi-regional models encompassing full endogenous trade effects between a set of regions have been the first tools of choice to perform such analysis. Multi-regional models – global models especially – capture endogenous trade effects between regions through two main specifications. They can first capture all bilateral imports and exports flows and related economic transfers between the regions modeled (Paltsev et al., 2005; Weitzel et al., 2015). To do so they usually rely on a two-level Armington structure for imports (substitution between domestic goods and aggregated imports further broken down in different imported goods from the different trade partners) to reflect that imported and domestic goods are not homogenous and depend on their origin (Armington, 1969). An existing alternative to avoid capturing possibly complex bilateral flows is to model a single global pool for each good that “buys” goods from exporting regions and “sells” them to importing regions at an average world price (Waisman et al., 2012). A single nested Armington structure is further used in each region to reflect the trade-off between domestic and imported goods. Both modelling approaches make it possible to capture endogenous international trade mechanisms with simultaneous endogenous adjustments of imports, exports, domestic and world prices faced by each region.

Multi-regional models have been first used to study competitiveness and leakage effects in given regions. For example (Kuik and Hofkes, 2010) use a global multi-regional model to study the unilateral implementation of the ETS in the EU and how boarder adjustments enable to limit competitiveness losses and emission leakage. They show that boarder adjustments increasing import prices make it possible to reverse the higher imports trend and linked carbon leakage resulting from the ETS compared to BAU for specific energy-intensive industries. In addition, such multi-regional models have been used to study the integration of carbon pricing instruments across regions. (Zhang et al., 2017) analyze the effects of integrating the Chinese ETS with other ETS across the world (EU, US, Australia-NZ, Japan, South Korea) on international emission trading, REN development in China, sectoral competitiveness and industrial leakage. They show that integrating Chinese ETS leads to significant higher domestic emission reductions, REN development and exports of allowances. However it implies losses of competitiveness, reductions of industrial outputs and increase of imports. (Liu and Wei, 2016) produce similar analysis about EU and China ETS integration. Finally national multi-regional models can be used to study sectoral competitiveness effects linked to carbon pricing between two sub-regions of a given country like China (Tian et al., 2017) (Li et al., 2018).

Single country models can also be used to study part of these issues. Contrary to multi-regional global models, world/ import prices are exogenous in these models and trade flows variations have no feedback effect on these prices. Therefore, they cannot inform about the impacts of climate action in the rest of the world on international trade and world/import prices especially. However, they can be used to study the competitiveness effects of hypothetic unilateral climate action of a given country and the possible solutions to address them. For instance (Liang et al., 2016) use a single country model for China to study how border tax adjustments (BTAs) can be used to address the competitiveness implications of a unilateral domestic carbon tax. However, implementing BTAs with a national model requires estimating the carbon content of imports, which cannot be endogenously calculated contrary to with a multi-regional model. In practice the usual assumption is to use the carbon embodiment rates of corresponding domestic goods. Certain single country models have been improved with an additional trade module disaggregating the foreign account in different trade partners with a two-level nested Armington and CET (constant elasticity of transformation) framework. However these features do not change the exogenous character of imports and world prices. (Tang et al., 2015) use this approach to study the impacts of BTAs implemented by its trade partners on Chinese sectoral exports.

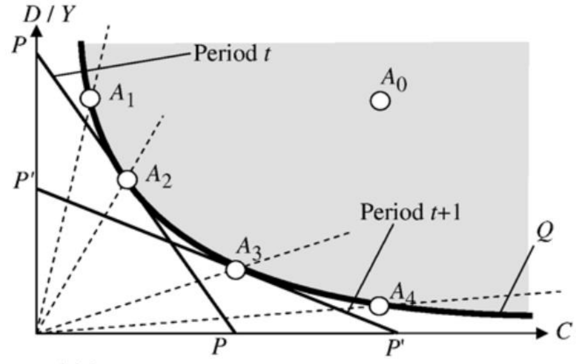
In summary, on the one hand single country models cannot capture the key international trade effects linked to climate policies in the rest of the world. On the other hand multi-regional global models are designed to capture full endogenous trade effects but usually lack precision and specificities in representing a given national economy (households heterogeneity, specific tax system, etc.) which is needed to perform appropriate and robust analysis of climate policy from a national point of view. One attractive solution to keep the strength of both approaches is to soft-link a single country model with a global multi-regional model. (Weitzel et al., 2015) develops such a solution and identifies the additional insights obtained from a national model when taking into account that the rest of the world is also engaging in climate change and causing changes on international markets. To do so, baselines are first harmonized between the two models, for the country under study (India). Then a global climate policy scenario is simulated with the global model based on the climate policy package for India and for the rest of the world. This scenario embodies the endogenous trade effects linked to the simultaneous implementation of carbon pricing instruments in India and in the rest of the world. Then the linkage with the single country model is based on the one-way transfer of information about international and import price changes in the policy scenario that are not considered in the single country approach and that reflect changes in terms of trade. Price changes include the significant drop of fossil fuel prices due to lower demand and slight variations of the import prices of non-energy goods. The single country model can further compute the domestic climate policy scenario with and without the updated import prices changes to size the importance of taking into account the implications of foreign climate action on international trade. The paper further analyzes the distributive impacts of such price changes on households, which the single country model can assess due to further household disaggregation. The global model can also compute the money transfers involved in a possible integration of a domestic ETS with other regional ETS and these transfers can be exogenously informed in the national model.

Finally due to the objective to perform detailed national analysis, the soft-linking approach is the best option for the project and we suggest to link the core national model with a global multi-regional model following the approach developed in (Weitzel et al., 2015). We may consider to develop further the one-way model-linking into an iterative linking.

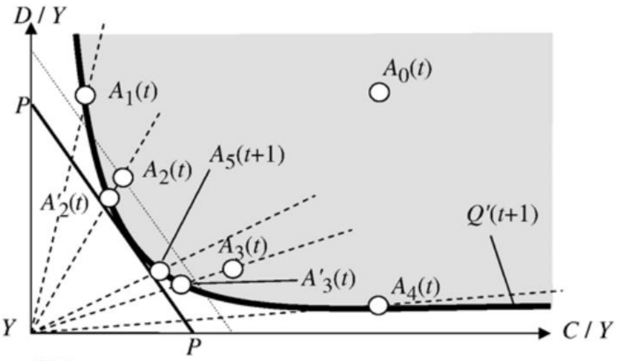
2.12. Representation of technical progress

It is widely recognized that technological progress is not only an autonomous process but can be induced by specific policies including carbon pricing. Failure to consider this aspect generally leads to overestimating the economic costs of mitigation. (Grubb et al., 1995) earlier recognized this reality which advocates that models should endogenize part of the technical or technological progress. Subsequently models have been improved to include technological progress dependent upon socioeconomic variables such as prices, R&D investments or cumulative production. Following studies have confirmed that taking into account mechanisms of induced technological progress in models significantly reduce mitigation costs (Grubb et al., 2002) (Löschel, 2002).

How do state-of-the art models deal with technological progress and induced technological progress especially? First of all confusion sometimes remain between the concepts of technological *progress*, technological *change* (ITC) and technological *substitution*. (Sue Wing, 2006) summarizes the general economic conception of these aspects and helps to clarify the issue. In the quadrant A) the production frontier at time t embodies the continuous basket of efficient technologies (all A points) actually available at time t. Furthermore, a price change between P and P' within the period will induce a substitution between technology A2 and A3. No technological progress is involved, only substitution. Technological progress is actually about the inward shift of the production frontier between t and t+1 either with the apparition of a radically new technology (point A5(t+1) in quadrant B)) or the incremental improvement of existing technologies (from A2 and A3 to A2' and A3'). These better technologies enable more output to be produced using the same quantities of inputs, or, symmetrically, allow the same level of output to be produced from smaller quantities of inputs. Finally, technological change is the combination of technological progress and technological substitution: it can be decomposed as the inward shift of the production frontier and the shift along the production frontier.

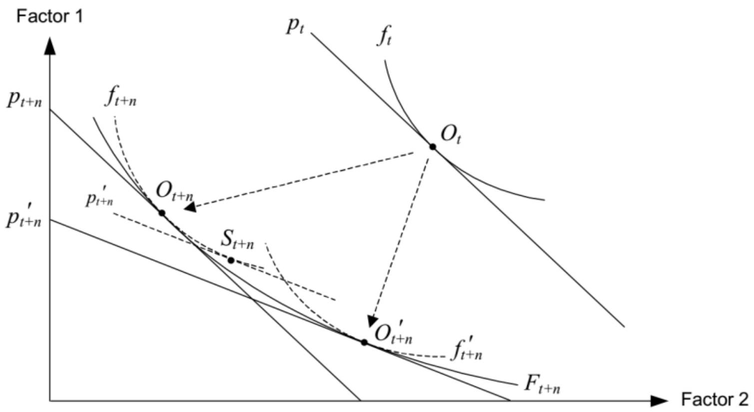


(A) Substitution with no technical change



(B) A new activity expands the production set, shifting the production point

Both inward shift of the production frontier and shift along the frontier can be partly triggered by relative prices as in the Ahmad-Binswanger-Ruttan model of ITC (Binswanger et al., 1978).



Climate policy targets the specific technological progress and innovation towards less carbon and energy intensive technologies. At the technology level it means new available technologies with increased carbon or energy efficiency or similar technologies with reduced costs. At a more macro or sectoral level, it means higher energy or carbon input productivity.

Technological progress can thus be autonomous or induced. The state-of-the-art models considered in this review all include forms of autonomous technological progress, ie not induced by policies or other economic variables in the model and thus implemented as exogenous phenomena. Models first include mechanisms of autonomous energy efficiency improvement (Manne Alan and Richels, 1992), generally modeled as factor augmenting exogenous energy technical change within production or demand functions through AEEI coefficients. Historically this approach has been used at the macroeconomic level in TD models to mimic the observed decrease of energy intensity of GDP across time that could not be explained by changes of energy and other factors relative prices. Therefore, the decrease of energy intensity of production could not be captured by production functions and elasticities of substitution so that modelers have implemented factor augmenting coefficients specific to the energy factor. Furthermore, different types of AEEI implementation exist in state-of-the art models according to the level of sector aggregation. In BU based hybrid models AEEI applies to energy services or final energy as aggregated factors in the macroeconomic production function (Manne and Richels, 2005) whereas multi-sector CGE models can implement sector specific AEEI trends (Chen et al., 2015). Therefore, AEEI can have a certain technical interpretation in multi-sector models (industry specific efficiency gains or efficiency gains of the average vehicle fleet for the transport sector, etc.). However, it embodies a global decoupling between energy and GDP in aggregated models encompassing both technical energy efficiency and structural changes towards less energy intensive goods (increase of the share of services and manufacturing in GDP for instance). In a nutshell AEEI reflects an aggregated and incremental vision of energy efficiency improvement.

Another approach to include more radical and BU based autonomous technological progress in models consists is incorporating exogenously provided new or updated technologies. In this view technological progress corresponds either to the deployment of new ``backstop'' technologies not currently available but that will be at some point in time, or to the exogenous improvement of existing technologies. Both TD and BU hybrid models have developed this approach for energy supply technologies especially. As developed in section 2.8, multi-sector CGE models have been developed towards representing the competition of discrete technologies for power generation identified by their specific costs. As detailed in (McFarland et al., 2004) and (Jacoby et al., 2006), non-extant backstop technologies (CCS, bioenergy, etc.) can be included in this framework. In practice the technology is available in the power generation CES nest through its cost at a given point in time and is characterized by an initial mark-up over conventional technology costs. Then the technology can be competitive at some point in time due to carbon pricing and be finally deployed. A fixed factor can also be used to control the pace of actual penetration of the new technology. BU based models also include exogenous changes over time in the basket of available technologies either with more efficient existing technologies or new backstop technologies (Wise and Calvin, 2011). Finally backstop technologies are sometimes considered as “semi-endogenous” technological progress but in any case, the process of innovation remains exogenous. The sole effective penetration of the technologies is endogenous and depends on market conditions.

In order to overcome the weaknesses of exogenous representations of technological progress, models have been improved towards including the inducement of innovation and technological progress from policies and other economic variables. At technology level, ``learning-by-doing'' (LBD) mechanisms have first been introduced to reflect the observed cost decline as individuals, enterprises and industries gain experience with a given technology. LBD is usually implemented by means of learning curves for advanced technologies which relate to decreasing technology costs to the level of production capacities installed as a proxy for the accumulated experience with a given technology (Azar and Dowlatabadi, 1999). Most BU based hybrid models include technology specific learning curves (Luderer et al., 2015; Manne and Richels, 2005). Hybrid CGE models can also include LBD mechanisms at technology level especially as a complementary process to backstop technology introduction. Beyond making a given backstop technology available at a given initial cost at a given point time – which is obviously an exogenous mechanism – some features are added to implement an endogenous decrease of the cost of the backstop linked to its level of deployment, which surmises an LBD mechanisms. In practice the fixed factor endowment can increase with the level of operation of the technology and thus endogenously decreases its cost.

Less developed in existing model is mechanisms of ``learning-by-searching'' at technology level which relates technology efficiency or costs evolution to a level of specific R&D investment. One exception is the WITCH model which includes ``learning-by-searching'' mechanisms for power generation technologies (Bosetti et al., 2009). Furthermore, developments have been carried out to represent induced technical progress and efficiency gains for end-use energy consumption. The modeling approach is inspired by endogenous growth models, but the key difference is that productivity gains only apply to the energy factor. It assumes that investment in a given stock of knowledge makes it possible to increase energy efficiency of production. This mechanism is usually linked to a diffusion mechanism of more efficient processes between regions to capture ``spillover'' effects. However, such mechanisms are implemented at very different levels of aggregation across models, ranging from a global disembodied vision of induced technical change to technology or sector specific mechanisms. In the WITCH model for instance, the aggregate of total final energy consumption is combined with a global energy R&D capital to ``produce'' the aggregate of total energy services within the macroeconomic production function. The endogenous accumulation of energy R&D capital makes it possible to decrease the final energy - energy services ratio. Such a model feature certainly captures global inducement of energy efficiency but remains at a very abstract level. Furthermore, its calibration is a tricky issue as the mechanism cannot be related to a clear technical reality nor any identified energy end-use sector.

Finally, state-of-the-art models are in general not well equipped to model explicitly how carbon pricing can potentially induce redirecting R&D investments into less carbon-intensive technologies and further induce "clean" innovations through this channel, at the technology scale especially. Beyond the need to work with forward-looking behavior, key reasons include the difficulty to calibrate the magnitude of the cost-benefit mechanisms involved and the deep uncertainty about R&D and innovation processes with new technologies. The good alternative in most cases is to rely on expert judgment to determine the future basket of available technologies at different points in time to be introduced in the model as an exogenous phenomenon and leave the model to compute the cost-effective choices among these available technologies. In the project, as mentioned in the ToR, the MOP Project database will provide the extensive mapping of new and prospective technologies and details of necessary investments, abatement potential and the costs involved, that we will be included exogenously in our modeling architecture.

2.13. Treatment of uncertainty

In a modeling context, one can distinguish several epistemological components of uncertainty. The first one is uncertainty about a “model’s quantities” (Boulanger and Bréchet, 2005) or “parameters”(Oreskes and Belitz, 2001), which are the numerical parameters and initial conditions also described as input assumptions. Both scenarios and system parameters fall in this category. The second one is uncertainty about model “conception” (Oreskes and Belitz, 2001). Within this category, (Boulanger and Bréchet, 2005) further distinguishes “model’s pertinence” and “model’s structure”. Pertinence refers to the scales and boundaries of the model: spatial and time scale, level of aggregation (i.e., granularity), the selection of the key variables to be included[4]. Structure refers to the type of representation of the mechanisms at

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[4] For instance, the uncertainty around the relevant level of technological detail has been at the core of the bottom-up - top-down controversy of energy-economy models.

play. It concerns the relationships between variables, in particular the functional forms used, and causal chains represented.

In addition, managing uncertainty generally includes two complementary aspects often mixed up in practice (Saltelli et al., 2008)): sensitivity analysis and uncertainty analysis itself[5]. However, the difference is actually clear: uncertainty analysis aims to quantify directly the state of uncertainty about model features (inputs and conception) and thus on model results - in order to reduce the uncertainty per se, which can only be done by improving scientific knowledge (Boulanger and Bréchet, 2005), whereas sensitivity analysis only seeks to relate uncertainty about model outputs to the uncertainty about upstream model features and input assumptions. Therefore, sensitivity analysis does not help to decrease uncertainty about the future of the system modeled per se but it is very useful to control the propagation of uncertainty within models and better understand model behaviors – and thus somehow reduce the uncertainty about the model's robustness.

We can distinguish two types of inputs or parameters in models used to assess climate policy and mitigation scenarios. Scenario parameters define the key exogenous trends as drivers of the future states of the energy-economy system. Assumptions about population growth, trend economic growth or future oil prices fall in this category. They are closely related to the storyline of the scenarios. Conversely system parameters define the functioning of the system itself in association with the functional forms used. Elasticities of substitution or technological costs are part of this category.

Uncertainty analysis is addressed differently between the two types of parameters. The scenarios parameters refer to the future world conditions. These conditions can have important implications for the impact assessment of climate policy instruments. In practice the uncertainty about these future exogenous conditions is addressed by building a set of alternative and internally consistent storylines then translated into reduced sets of combined parameters. The Share Socio Economic Pathways (SSPs) are a key example for global scenarios. The uncertainty about system parameters is addressed differently through sensitivity analysis. Advanced statistical methods exist to deal with parametric uncertainty to perform a sensitivity analysis[6] . These customary methods are crucial parts of the ”menu” for a serious evaluation of single models and are widely performed (Stern, 2007; Webster et al., 2008).

Finally, uncertainty and sensitivity analysis on the model's structure and/or pertinence is rarely explored in the existing literature (Schwanitz, 2013). The uncertainties targeted, point at the choice of variables and interdependence represented in the model as well as the form to model specific mechanisms. They relate to the conceptual vision of the system embodied in the model whereas input assumptions deal with the model quantification of it. Sensitivity

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[5] as Kydes et al. (1995) puts it, in no case running a model makes it possible to decrease uncertainty: “Applying formal modeling techniques, which are heavily influenced by exogenous assumptions about costs and rates of technical progress or efficiency improvement, provides conditional projections that help illustrate the implications of assumptions without reducing the underlying uncertainty per se”.

[6] Variance-based approaches for instance, often combined with Monte Carlo sampling of the multidimensional input space (Sobol, 2001).

analysis on model structure is thus hard to perform with a single model and requires comparing different models, with contrasted models' internal structures. Meta-analysis (Fischer and Morgenstern, 2006; Barker et al., 2006) and recent cross-model studies seek to go in this direction. This aspect is out of the scope of the present project.

In practice model evaluation and uncertainty analysis should be adapted to the type of study carried out. In the perspective of a stakeholder's process for policymaking, the hierarchy of model features and assumptions should be guided by the perception of the plausibility of the "story" carried out by the model. In practice Jasanoff (2010) describes the exercise as a "three-body-problem" involving "scientists, scientific knowledge, and committees translating science into policy relevant forms". In another context, model conceptual relevance will be assessed by its ability to reproduce stylized facts about the system represented or part of it (Wilson et al., 2013). It can also be a mix of different objectives.

2.14. Issues related to the elasticity parameters

Most economy-wide models used for climate policy analysis rely at some point on calibrated CES functions to represent production and consumption trade-offs. However, the usage of CES specifications in CGE models has been extensively criticized for the restrictive features of the functional forms used and the weak empirical basis. As earlier developed the success of calibrated CES functions owes much to the convenience and versatility of the approach to build standalone CGE framework to perform policy analysis. The calibration of nested CES functions only requires defining nesting structures, selecting exogenous elasticity parameters and calibrating the share parameters with the sectoral cost shares included in the base year SAM to get a standalone tool to generate future pathways. But this convenience comes at an empirical cost. First of all (McKitrick, 1998) underlines that first order functional forms as CES imposes influential restrictions on the model structure and a preferred alternative would be to use more flexible functional forms, such as the translog or normalized quadratic, which have enough free parameters to provide a second order approximation to any underlying preference or technology aggregator function. The resulting methodology-related artifacts of CES are recently illustrated by (Kaya et al., 2017) in the context of state-of-the-art IAMs. These are: (i) the extension of the status quo technology shares for future energy supply relying on fossil fuels with carbon capture, biomass, and nuclear; (ii) monotonically increasing marginal abatement costs of carbon; and (iii) substitution of energy with non-physical inputs (e.g., knowledge and capital) without conclusive evidence that this is possible to the extent modeled. A retrospective analysis in the same paper confirms that the restrictive constant elasticity specifications fail to match historical pattern in long term energy transition. Some studies explore how implementing non-constant elasticities over time can provide some improvements (Schaefer and Jacoby, 2005). (Sue Wing, 2006) also advocate that elasticity values should depend on the time horizon with higher elasticity for long term substitution possibilities.

Beyond restrictive functional forms, calibrated CES functions generally have weak empirical foundations. As developed by (McKitrick, 1998), researchers often use elasticities estimated for commodity and/or industry classifications which are inconsistent with those maintained in the model, and/or for countries other than the ones represented by the model, and/or obsolete estimates from past literature, not to mention outright guesses when no published figures are available. In practice many CGE models actually use similar elasticities for different regions and even sectors taken from a limited number of sources such as from (Paltsev et al., 2005). (McKitrick, 1998) explains that these expediencies detract from the ability of the model to represent the technology and tastes of the economy under study. Also, users of the simulation results have virtually no way to assess the evidence supporting the choice of most parameter values. In addition, the calibration procedure causes the quality of the model to be at least partly dependent on the quality of the data for an arbitrarily chosen benchmark year. The way out for this critique in empirical analysis is to assume the weak empirical ground of calibrated CES and proceed to serious sensitivity analysis of key elasticities within plausible ranges.

In this project the linkages with BU based models make it possible to ensure a strong empirical ground for substitution possibilities in key technical systems. Serious sensitivity analysis should be carried out for the remaining CES specifications.

2.15. Incorporating market imperfection, financial and monetary issues

Rooted in standard microeconomic theory of general equilibrium, most CGE models compute competitive equilibria with market clearing and zero-profit conditions for all markets (goods and production factors – no unemployment is allowed) without market imperfections. However even if no further market imperfection is included, usual CGE models calibrated on real economies include at least a pre-existing tax system. Such CGE models are equipped as such to study part of the possible double dividend opportunities linked to a possibly inefficient pre-existing tax system as developed in section 2.6. Furthermore, CGE models have been extended to incorporate specific market imperfections. The core neo-classical approach of standard CGE models is actually readily amenable to incorporate market failures such as information asymmetries or market power based on rigorous microeconomic theory. In practice in these models, market failures are generally reduced to the implementation of specific market imperfections for goods. For instance, the GEM-E3 model includes alternative market clearing conditions departing from zero-profit assumption with implementing targeted oligopolistic markets (Saveyn et al., 2017). However, these models incorporate limited market imperfections in practice, without challenging the core paradigm based on market clearing for all goods and production factors and optimum behaviors.

Historically, some CGE models have been developed to address specific economic development issues in developing countries characterized by multiple market imperfections and distortions. To reflect the specific distortions under study, models have been adjusted to incorporate structural assumptions not deriving from standard micro-founded specifications. In such structuralist CGE models (Taylor, 1990) rigorous microeconomic foundations are traded off towards higher empirical relevance. Such structuralist approaches have been developed to assess climate policy issues in developing countries taking into account the imperfections of labour markets especially. For instance (Devarajan et al., 2011) include structural distortions of labour markets in a CGE model to study carbon taxation in South Africa. The results show that if South Africa were able to remove distortions in the labor market, the cost of carbon taxation would be negligible. They conclude that the welfare costs of taxing carbon emissions in developing countries depend more on other distortions than on the country's own carbon emissions.

One way to introduce labour market rigidities in a CGE model is to rely on a so-called wage curve that negatively relate wages to the unemployment rate (Blanchflower and Oswald, 2005) through a specific elasticity. The wage curve is an empirical curve that embodies multiple mechanisms especially linked to the bargaining power of workers. (Guivarch et al., 2011) use this feature to study how labour market rigidities impact mitigations costs. Results show that wage rigidity is a crucial parameter for aggregated cost formation, higher rigidity implying significant higher costs. Conversely initial market distortions can lead to additional double dividend opportunities if carbon pricing policy enables to reduce part of these distortions. Taking into account market imperfections is especially important for developing countries characterized by incomplete markets and high unemployment.

Beyond some structural assumptions about specific market distortions, some macroeconomic models challenge the macroeconomic core of CGE models and are especially based on demand-driven features of Post-keynesian theory including disequilibrium features of good and factor markets. For instance (Pollitt et al., 2015) use such a model to show that a 40% reduction in GHG emissions (compared to 1990 levels) in Europe until 2030 could lead to an increase in employment of up to 0.7 million jobs, illustrating the stimulus that climate policy could trigger on the labor market.

Such models else include very different representations of the financial system and the role of money compared to CGE models. (Pollitt and Mercure, 2018) develop the key discrepancies between the two approaches to highlight the role of financial mechanisms. They show that CGE models are based on an implicit financial system where total investment is pre-determined by savings which leads to complete 'crowding out' of capital and negative economic impacts from climate policy in virtually all cases. In contrast, macro-econometric Post-keynesian models follow non-equilibrium economic theory and adopt a more empirical approach to the financial system with investment not constrained by savings ex ante and which can be partly financed by money creation. These models generally show that green investment need not crowd out investment in other parts of the economy – and may therefore offer an economic stimulus. Authors acknowledge that CGE models have other strengths and suggest that some effort should be carried out to implement better representation of the financial system in CGE models.

3. Conclusion

In this report we have carried out an extensive review of the experience in modelling the socio-economic impacts of climate policy and carbon pricing instruments especially, along multiple different sub-topics. For each topic we have sought to portray the strengths and limits of the different existing approaches, identify the best practices and some remaining constraints to ideally tackle the different topics. This preliminary analysis will help us to design the best modelling architecture fitted for addressing the goals of component 2a of the project. In this view an important consideration is the very broad scope of the expected analysis which targets multiple dimensions at the same time: assessing possible complex and detailed designs of carbon pricing (tax or ETS) and the interactions with other instruments, their broad macroeconomic sectoral and distributive (households, public budget, etc.) impacts, the interaction with international trade, all this taking into account high details about energy and land-use processes and key structural features of the Brazilian economy. The ideal modelling architecture to perform such an analysis should combine the best practices identified for the different sub-topics and even overcome some remaining constraints. However, what our review clearly shows is that no state-of-the-art model already combines the best practices for all aspects at the same time. This is finally the real remaining constraint for the project objectives that emerges from the review: being able to combine the best practices identified for the key relevant topics. One simple reason for this remaining constraint is that from a scientific point of view a model should be designed to answer a specific policy question and trade-offs are made to retain only the modelling features that are relevant for the specific question under study. Furthermore, trying to build an all-encompassing model by integrating as many mechanisms as possible is usually not an academic research motive per se. However, the project objectives require being able to combine somehow different modelling pieces related to the different sub-topics in order to perform a policy-oriented detailed integrated assessment. We conclude that the key challenge for component 2a is to overcome that main constraint and find a form of combination of the best practices identified.

To do so considering the broad range of aspects to be analyzed, a flexible modelling approach seems the best strategy. In particular a soft-linking architecture of different sub-models offers this flexibility while meeting the standards of best practice for most reviewed topics, as demonstrated in the review. This is mainly due to the fact that soft-linking models makes it possible to keep the strengths of the different sub-models with the additional freedom to free some links between models to study part of the questions. The counterpart of this flexibility is the main constraint of guaranteeing consistency between the sub-models over the whole model architecture. This is an important aspect that should be carefully addressed.

Considering the objectives of Component 2a of the project, the soft-linking strategy makes it possible to rely on a core single-region CGE model for Brazil with detailed sectoral disaggregation. This would make it possible to assess possible complex climate policy packages including carbon pricing instruments with detailed designs (including detailed sectoral and

GHG differentiation and detailed recycling schemes of carbon revenues) following the best practices identified. The model could include different household types directly in the core model to support relevant analysis of distributional issues. However, as mentioned in section 2.7, a trade-off usually happens concerning overall model disaggregation for computational reasons and practical difficulties arise to combine high sectoral and household's disaggregation with sub-regional disaggregation. The sectoral details at national scale would make it possible to portray detailed tax system and economic transfers and impacts between sectors and economic agents as well a structural economic mechanism specific to Brazil. Combining high sectoral details and household disaggregation (and less regional detail) may be a relevant approach for the project.

Practical use of economic modelling to support the implementation of carbon pricing instruments

As of April 1, 2018, 46 countries and 26 provinces or cities have adopted carbon pricing policies (including more than 20 carbon taxes as of January 1, 2018 (Timilsina, 2018)) representing around 60% of global GDP[7] and the adoption of carbon pricing is accelerating. At some point the design of these province and country specific carbon pricing instruments has implied ex-ante energy and economic analysis to evaluate the carbon prices required and assess the expected impacts deriving from the implementation of the price instruments. In this section we briefly review the usage of economic modelling to support the design of carbon pricing instruments in three illustrating cases: the EU-ETS, the carbon tax in France and the ETS in China.

The EU-ETS was launched in 2005 and was the first large scale ETS to be implemented at that time. It entered its phase 3 in 2013 with the objective to reduce EU emissions by 20% in 2020 compared to 1990 level through a linearly reducing cap each year. The EU-ETS covers emissions of energy producing and energy-intensive industries which represent around 50% of total CO2 emissions in the EU. It was initially based on free allowance of emissions permits and in the ongoing phase 3, permits are planned to become progressively auction-based in the different industries starting with the power sector. After several years of very low levels, the ETS price strongly increased recently to reach around 20 euros/t of CO2 in 2018. Since the beginning of the EU-ETS, the European Commission has been using a suite of economic modelling tools to design and monitor the evolving ETS framework in its different phases. The modelling architecture used in-house by the Commission[8] (see figure below) is based on two core models: PRIMES and GEM-E3.

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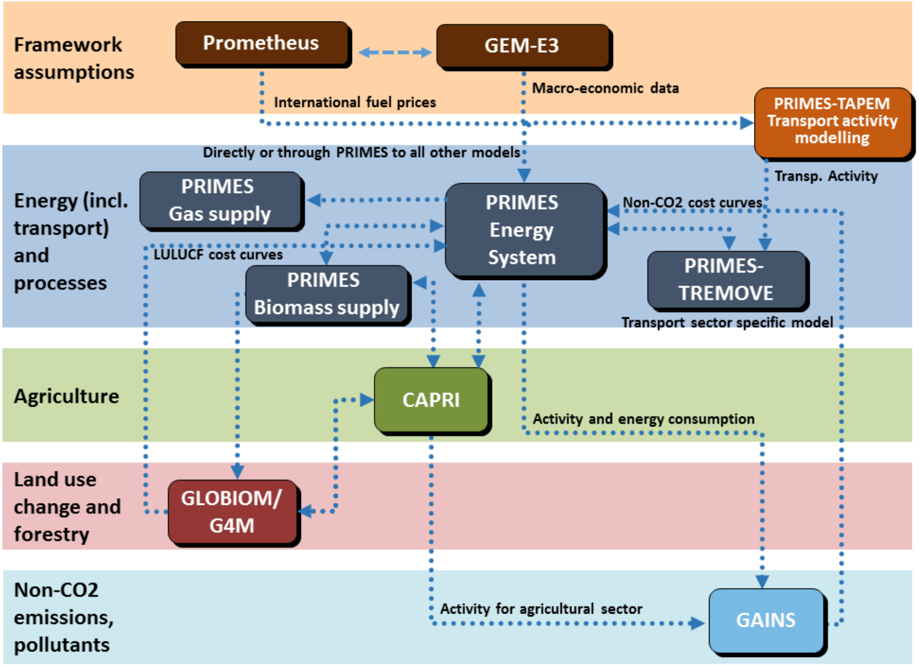
[7] https://www.i4ce.org/download/comptes-mondiaux-carbone-2018/

[8] https://ec.europa.eu/clima/policies/strategies/analysis/models_en



PRIMES is a partial equilibrium energy market model developed and maintained for all individual European countries and the internal electricity and gas markets is a sophisticated market oriented engineering-economic model with modular structure by sector, with high sectorial and technology resolution including for transport sector. It is an agent and market oriented model aiming at representing the reality of actors' behaviors and their interplay in markets, for energy commodities and for the emission allowances under the EU-ETS. The GEM-E3 general equilibrium macroeconomic model is a sophisticated multi-sector and multi-country model used for economic impact assessment and macroeconomic studies. It is a recursive dynamic CGE model solved in 5-year time steps and distinguishes 38 regions including the 28 EU countries and up to 31 economic sectors including 14 energy supply sectors. PRIMES and GEM-E3 can be fully linked to provide closed-loop energy economy-environment assessments. The PRIMES model is generally used to project energy and GHG emissions for the EU and to estimate the ETS carbon price in partial equilibrium based on cross sectoral marginal abatement costs under a global cap. GEM-E3 coupled to PRIMES computes the macroeconomic implications of the ETS including the sectoral impacts (sectoral production and competitiveness, etc.) of alternative ETS designs (auction and/or free allowances) and the transmission of sectoral costs in the economy through the price system.

A second example of the use of economic models to prepare the implementation of a carbon pricing instrument is the mobilization of available economic models to assess the impacts of the introduction of a carbon tax in France and to estimate a pathway of state-imposed shadow price of carbon (to calibrate the present and future value of the carbon tax and to guide future public investments). In 2008, the French Prime minister ordered to the Quinet's commission an evaluation of the pathway of the shadow price of carbon consistent with the EU climate objectives at that time: -20% and -60/-80% of GHG emissions in 2020 and 2050, respectively, compared to 1990[9]. To do so the commission especially called on three energy-economy models: GEMINI-E3 (EPFL, Switzerland), POLES (Grenoble University, France) and IMACLIM-R (CIRED, France). GEMINI-E3 and IMACLIM-R models are two hybrid

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[9] http://www.ladocumentationfrancaise.fr/var/storage/rapports-publics/094000195.pdf

recursive dynamic global multi-sector CGE models representing the Europe region and including some technological details in energy supply and end-use sectors. POLES is a global partial equilibrium energy model detailing the dynamics of energy markets with a focus on Europe. The three models were used to compute the carbon price pathway consistent with French and European climate objectives and the commission decided on the carbon values of 32 euros/tCO2 in 2010, 100 euros/tCO2 in 2030 and a 150-350/tCO2 range in 2050, consistent with the average pathway computed by models.

The year after, in 2009, the French government studied the possibility to introduce a carbon tax in France on emissions not covered by the EU-ETS. To help design the carbon pricing instrument, the French Ministry of Environment ordered a report to the Rocard's commission[10]. The commission especially sought to answer to two questions: 1) what would be the direct impacts in the short run of the carbon tax, 2) what would be the net macroeconomic impacts in the medium run of alternative recycling options of carbon revenues. The first question was addressed considering a 32 euros/tCO2 carbon tax aligned with Quinet's report recommendation for initial carbon value and used specific sectoral data (industry and services sectors, households) to estimate the direct sectoral cost implications of the introduction of the tax and to address related issues (industrial competitiveness, households purchasing power and inequalities, etc.). The second question was addressed by use of two macroeconomic models: MESANGE (Ministry of Finance) and IMACLIM-S France (CIRED). MESANGE is a dynamic macroeconometric model for France used to provide macroeconomic forecasts to the Ministry of Finance in France. IMACLIM-S France is a static hybrid CGE model of France in open economy else disaggregating households in 20 income groups. It is specially designed to assess the medium-run macroeconomic and distributive implications of possible carbon pricing instruments and carbon tax policies in France. The results of the two models showed that a carbon tax policy in France based on recycling carbon revenues into decreasing pre-existing distortionary taxes such as labor taxes – with constant overall fiscal pressure - could lead to a strong double environmental and economic dividend. IMACLIM-S France model else showed that a mixed recycling scheme with part of the revenues being transferred to poor households for instance would be preferable to offset the direct regressive impact of the carbon tax and to foster stronger social acceptance of the carbon pricing policy. The carbon tax was finally introduced later in 2014 starting at 7 euros/tCO2 and reached 44,50 euros/tCO2 in 2018.

A third and last example of the use of economic models to design carbon pricing instruments can be taken from the Chinese experience in designing regional and national ETS since 2011. In 2011, the National Development and Reform Commission (NDRC) approved the development of 7 regional ETS pilots. Shenzhen was the first pilot to be launched, in 2013, followed by six other regional pilots (Beijing, Tianjin, Shanghai, Chongqing, Hubei and Guangdong) and all pilots completed their first compliance period by June 2015. In order to achieve its NDC pledged in Paris to reduce its carbon intensity of GDP by 60-65% by 2030, China decided to extend the regional ETS pilots towards creating a national ETS to be launched in 2019. The market covers eight sectors for now – petrochemicals, chemicals, building materials, steel, ferrous metals, paper-making, power-generation and aviation, covering around half the emissions of the country. The market is expected to be in the range of 3-5 billion tons of carbon allowances per year in the beginning (twice as much as in the EU-ETS) to become

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[10] https://www.ecologique-solidaire.gouv.fr/sites/default/files/CEDD%20-%20Le%20rapport%20de%20la%20conf%C3%A9rence%20des%20experts%20et%20de%20la%20table%20ronde%20sur%20la%20contribution%20climat%20et%20%C3%A9nergie_0.pdf

the largest ETS in the world and the market is expected to induce proper emissions reductions from 2020. The launch price of the ETS is expected to be around five dollars per ton. The permit allowance framework follows those of the pilots with a mix of free and auctioned allowances. As in the EU case, economic modelling is being used at the different stages of the ETS implementation in China. Both energy bottom-up and top-down economic models are being used but the development of the ETS pilots and the perspective of a national market triggered the development of numerous CGE models to provide ex-ante impact assessment of ETS frameworks. The multi-sector CGE models developed in the scientific literature have different regional coverage and have provided assessment at both regional levels for the ETS pilots (Liu et al., 2017; Tian et al., 2017; Wang et al., 2015b; Wu et al., 2016c) and at China national scale for the national ETS (Tang et al., 2016; Weng et al., 2018; Wu et al., 2016a; Yu et al., 2018). Beyond scientific literature, economic models have been used for practical ETS design for both regional pilots and the national ETS. We can mention here for example two projects funded by the Asian Development Bank (ADB) that were carried out to support the development of Tianjin[11] and Shanghai ETS. The first project in 2013 especially used the IPAC suite of models developed by the Energy Research Institute (ERI) which consists of fully linked bottom-up sectoral models and a CGE models. The IPAC framework was used to define the cap of Tianjin ETS and to provide ex-ante assessment of possible impacts of alternative permit allocation methods. The second project developed a new detailed CGE model to help design the pilot Shanghai ETS.

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