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(How) does sectoral detail affect the robustness of policy insights from energy system models? The refining sector's example

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Abstract

In this research, we rekindle an old debate by questioning the impact on mitigating policy evaluation of detailing a subsector in a global energy-transportation model. We chose the refining sector because it is a relevant case of a sector for which representation widely differs across models and because it offers a unique set of complex joint production in the energy sector. To investigate whether the level of detail in the description of the refinery impacts optimal mitigation options, we take the example of a long-term, national, linear programming based, energy-transport system model (TIMES based). We found that the refinery description used in the energy system model matters when trying to evaluate energy or climate policy applied to the transportation sector. It impacts the policy costs but also the technology trajectories chosen at the optimum. Essentially, the balance between energy efficiency and carbon intensity of transport may be affected by the accuracy of the description of the pivotal refining sector. Consequently, increasing this sector accuracy level should not only be motivated by the wish to gain wider quantitative insights on potential evolution of the energy system but also by the wish to improve the robustness of the model outcomes.

JEL classification:

Keywords: Energy modeling, Refinery modeling, Parsimony, Level of details

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1 Introduction

The use of energy-economy-environment system models to analyze global issues raised by climate change is now widespread and in constant evolution. Historically developed since the 1970s, such models have been used by the public and private spheres to address two main broad questions: energy security and sustainability/climate change. They provide, broadly speaking, insights concerning the costs and benefits of policy objectives and designs and also (potentially unexpected) system effects. Policy makers and stakeholders can thus enhance their mental models of the world and take better-informed decisions. As the interdependencies between subsystems and the complexity of the long-term issues grow, so do the models and the underlying databases. The intricacy of economic concepts, model designs and large data amounts add up to the intrinsic, radical uncertainty of socio-economic phenomena, to produce long-term scenarios that suffer themselves from these drawbacks. This makes uncertainty analysis a cornerstone of long-term modeling. Practitioners have set up a whole set of tools to elaborate scenarios that traduce uncertainty about the future (eventually endogenously - e.g. through stochastic programming) or investigate the impact of uncertain data (still through scenarios, eventually with Monte-Carlo simulation). More recent operation research techniques are also used to investigate either dimension of the uncertainty set. However, two other facets of this issue are much more rarely assessed. They deal with (i) the nature of the economic assumptions and (ii) the extent to which sectors or sub-sectors are modeled with detail in a given exercise. Specifically, we question the following point: how does modeling bias (to be understood as the accuracy with which sectors are depicted) affect model outcomes and thus policy insights?

In this paper, we focus on the latter and on bottom-up models, which are often used to formulate and evaluate policies intending to limit GHG emissions. These policies can be global (CO_2 market or CO_2 tax) or sectoral (regulations on technology standards or investment incentives for green technologies as in Waide & Brunner (2011)). The description of energy models remains usually quite general; it mostly focuses on economic assumptions (partial, general equilibrium) and solution properties (optimization, simulation) whereas the information provided on the technological detail by sector is generally scarce (see Bhattacharyya & Timilsina (2010)). In bottom-up models, various sectors of the energy system coexist: industry, transportation, refining, agriculture, heat and power. Each sector is represented by a process or a group of processes depending on the complexity or level of detail of its description. What we call here level of detail is also sometimes called level of complexity; it can be described as "greatness of process description" (Paudel & Jawitz, 2012) or as "an assessment of the extent to which the observable system elements and the assumed system relationships are included in the model" (Brooks & Tobias, 1996). The technological description is rarely available; however, depending on the specific question, the relevance of the model outputs may crucially depend on such details. In turn, insights gained from conducting such evaluations may vary because of this.

Motivations for analyzing the oil refining case

For the sake of the analysis, we need to select a relevant case of a sector for which representation may widely differ across models. Oil refining clearly falls into this category. The level of detail of each sector description within a specific model is often linked to the available public technical data or with the competencies of the modelers' team, but it is also clearly linked to the "real" complexity of these sectors (we refer here to the Collins English dictionary's definition of complex: "Made up of various interconnected parts; composite"). For example, the power sector plants are rather simple since there are few co-products and only one or two processes: fuel enters the turbine and the outputs are mainly power and sometimes heat and power. On the contrary, some sectors are much more complex to depict: there are lots of possible refinery's inputs (different kinds of crude oil, natural gas, hydrogen, naphtha, ethanol, FAME...) and even more outputs with varying yields and qualities (LPG, naphtha, several gasoline and diesel, jet fuel, kerosene, heating oil, marine bunker fuel, fuel oil with several sulfur contents, coke...). Furthermore, a refining plant contains from 10 up to 40 process units and refining schemes can vary a lot. Within the overall energy system, it shows a unique chain of complex, interdependent and largely integrated process units. It is very costly in terms of time and resources to implement each refining process in energy system models; that is why the refining sector is generally modeled as a single process. Moreover, the refining scheme competency is rather scarce. Only a few global energy models incorporate detailed refining descriptions (NEMS for example Morris *et al.* (2002)). If there have been a few

attempts to incorporate condensed descriptions of the refining sector in larger models (Babusiaux & Champlon, 1982), the discrepancies between these representations and the "real" sector complexity clearly leads to misspecifications.
From the economic viewpoint, oil refining also represents a textbook case for several reasons. First, climate change and security of supply somehow aim at reducing the use of oil, which is used in the form of refined products. So, the relevance of substitution options will depend on their relative prices compared to fossil fuels, which in turn depend on the extent of the description of this sector. Second, refining offers a unique set of complex joint production (Baumol, 1972) in the energy sector: its products are then sold in the global energy system, and specifications of final products related to the qualities of crude oil imply that intermediate products are numerous, and only partially substitutable.

The question
To investigate whether the level of detail in the description of the refinery impacts optimal mitigation options, we take the example of a long-term, national, linear programming based, energy-transport system model. The specific case of transport makes sense because diesel, gasoline and jetfuel are (in quantity) the main outputs of refineries. In the transportation sector, emissions can globally be computed as:

$$CO_2 = \underbrace{CarbonIntensity}_{\frac{g_{CO_2}}{MJ_{energy}}} \times \underbrace{EnergyEfficiency}_{\frac{MJ_{energy}}{km_{travelled}}} \times \underbrace{DistanceTravelled}_{km_{travelled}} \tag{1}$$

(2)

Mitigation policies in the transport sector thus include three main categories: reducing the carbon intensity of transport energy, increasing the energy efficiency of mobility devices, and managing demand. The relative weight of these three options to reach a given abatement target clearly depends on their relative costs, which are affected by the baseline of oil products valuation.
In the case of oil refining, most of the rigidities are linked to the final product specifications and most of the flexibilities come from crude oil mix changes, investment options at the process level and changes in the functioning of existing units. So, our main assumption is the following: flexibility and valuation of oil products change with the description of the sector (the marginal cost of the products or services outgoing the poorly represented sectors are often not very representative); this will in turn affect optimal technological abatement options, e.g. the incorporation of biofuels, the mix of demand-side technologies or even aggregate energy efficiency of the sector.
Numerical experiments are undertaken to test this assumption and measure the magnitude of these effects. In section 2, we present a very small stylized model to understand how the technology description impacts marginal values. In section 3, we describe the TIMES-model used for the study and the refinery models we added to the original one and in section 4 we described the scenarios employed and the main results obtained.

2 Pricing - from theory to practical application in energy systems models

2.1 Principles

As a model based on the TIMES paradigm, MIRET is a partial equilibrium of the french energy-transportation system. In short, it computes at the optimum both equilibrium energy flows and associated prices. Then, the production-consumption balance of each and every intermediate product within the model must be positive: producers (sellers) are mandated to produce at least the amount that consumers (buyers) are willing to buy. Shadow prices are computed as the dual values of these balance constraints - or, the decisions variable of the dual linear program. It is said that shadow prices equal marginal values of the traded commodities.

Supply-demand equilibria in linear programming take the well-known graphical form of stepwise constant supply and demand curves, which are implicitly built by the model (Figure 1). There, each step in the supply and demand curves represent the offer and demand of the good by a given technology. Marginal values are used as internal cession prices between the various sectors. Their interpretation (differing from that of marginal costs) is the following: the marginal value may reflect

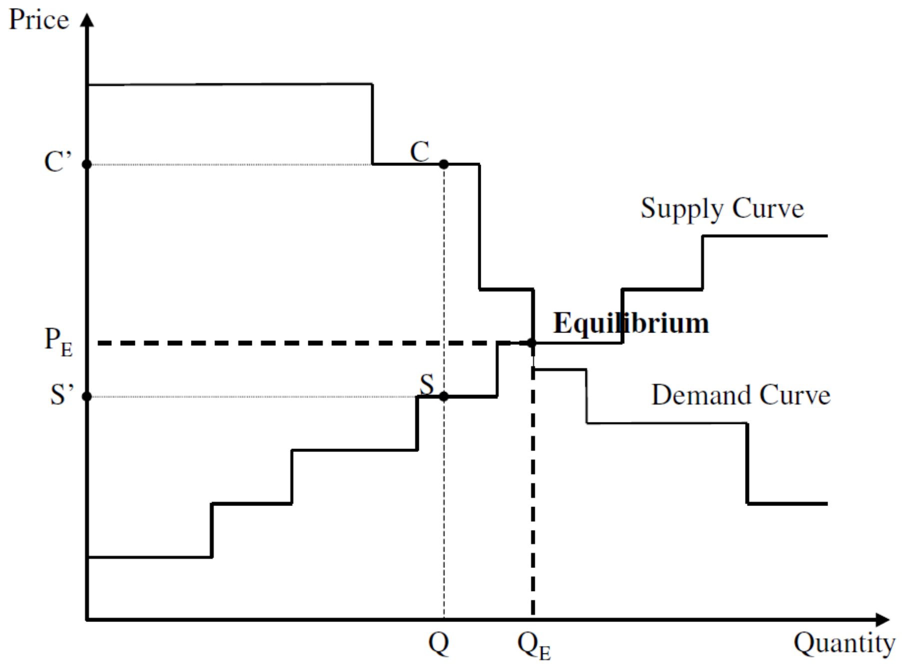


Figure 1: Supply and demand equilibrium of an endogenously traded good within MIRET

adaptation on the supply or the demand side of the market for the considered good. In the case of joint production processes (such as oil refining), marginal values of the joint goods are dependent from each other. At least three phenomena are likely to modify the structure of the supply and demand curves for a given good, in the presence of joint production:

- the formal description of joint production technologies;
- the techno-economic description of the various technologies;
- the presence of other constraints, such as e.g. a global carbon cap.

The interplay of these three forces is likely to cause that different technology descriptions, even within the same modeling framework, could bias the structure of marginal values, and thus the competitiveness of e.g. abatement options in a carbon-constrained world. We now illustrate this phenomenon with the following stylized model.

2.2 A stylized model

To understand the impact of technology description, we build a small stylized energy-transportation model.
In this model, primary energy is transformed in order to meet two exogenous demands: one of mobility and one of gasoline (see figure 2). To comply with the mobility constraint, the users have the choice of using a regular diesel car (DSLCar) or a low energy diesel car (LEDCAR) with a better efficiency but whose cost per kilometer is higher ($c_{ml} > c_{mc}$). The vehicles are fueled with diesel and biofuel, and there is a norm on biofuel incorporation (it can not represent more than N of the global fuel). The biofuel (x_b) is produced by the processing of biomass (in quantity x_2), c_2 is the cost of production of one unit of biofuel (it includes the costs of biomass and its processing). Diesel (x_d) comes from the processing of crude oil in the refinery (in quantity x_1), gasoline (x_g) is jointly produced with diesel (c_1 is the sum of the purchase and the refining of one unit of crude oil).

We build two models, one with a fixed yields refinery, the other with a completely flexible refinery. Our problem is to minimize the cost of the global system given the exogenous levels of demand of mobility and gasoline (eq 4 and 5), the production constraints (eq 6 to 11), the biofuel specification (eq 12) and the CO2 emissions ceiling (eq 13).
It can be written using the following form:

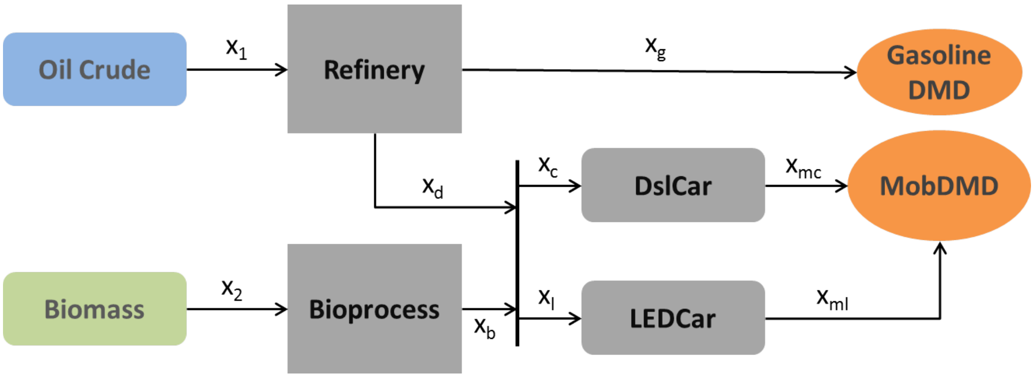


Figure 2: Small Model

For the Fixed yields Refinery:

$$\begin{cases} \min c_1x_1 + c_2x_2 + c_{ml}x_{ml} + c_{mc}x_{mc} & & (3) \\ s.t. & & \\ x_{mc} + x_{ml} \geq MobDMD & (y) & (4) \\ x_g \geq GDMD & (y_g) & (5) \\ x_d + x_b \leq x_c + x_l & (y_i) & (6) \\ x_g - \Gamma_g x_1 = 0 & (\theta_g) & (7) \\ x_d - \Gamma_d x_1 = 0 & (\theta_d) & (8) \\ x_b - \Gamma_b x_2 = 0 & (\theta_b) & (9) \\ x_{mc} - \gamma_c x_c = 0 & (\theta_{mc}) & (10) \\ x_{ml} - \gamma_l x_l = 0 & (\theta_{ml}) & (11) \\ -(1-N)x_d + Nx_b \leq 0 & (\beta) & (12) \\ \varepsilon_g x_g + \varepsilon_d x_d \leq \bar{E} & (\sigma) & (13) \end{cases}$$

Where x_g and x_d are the quantity of gasoline and diesel produced by the refinery. x_{mc} and x_{ml} are respectively the number of kilometers traveled with diesel cars and low emissions diesel cars. ε_g, ε_d the emission factor of gasoline and diesel. $\bar{E}$ is the ceiling on CO_2 emissions. Γ_g, Γ_d, Γ_b, Γ_{mc} and Γ_{ml} are respectively the yields of the refinery in gasoline and diesel, of the bioprocess in biofuel, and of the regular and the high efficiency diesel cars.
In the case of the flexible refinery, the equations are the same except the (7) and (8) which have to be replaced by:

$$x_d + x_g = x_1 \qquad (\lambda) \qquad (14)$$

The variables in parentheses are the Lagrangian multipliers associated to each variable. First order conditions give for the fixed yields refinery:

$$\begin{cases} 0 \leq c_1 - \theta_g\Gamma_g - \theta_d\Gamma_d & \perp x_1 \geq 0 & (15) \\ 0 \leq c_2 - \theta_b\Gamma_b & \perp x_2 \geq 0 & (16) \\ 0 \leq -y_g + \theta_g + \sigma\varepsilon_g & \perp x_g \geq 0 & (17) \\ 0 \leq \theta_d - y_i - N\beta + \sigma\varepsilon_d & \perp x_d \geq 0 & (18) \\ 0 \leq \theta_b - y_i + (1-N)\beta & \perp x_b \geq 0 & (19) \\ 0 \leq c_{mc} - y + \theta_{mc} & \perp x_{mc} \geq 0 & (20) \\ 0 \leq c_{ml} - y + \theta_{ml} & \perp x_{ml} \geq 0 & (21) \\ 0 \leq -\theta_{ml}\Gamma_{ml} + y_i & \perp x_l \geq 0 & (22) \\ 0 \leq -\theta_{mc}\Gamma_{mc} + y_i & \perp x_c \geq 0 & (23) \end{cases}$$

And for the flexible one:

$$\begin{cases} 0 \leq c_1 - \lambda & \perp x_1 \geq 0 \quad (24) \\ 0 \leq c_2 - \theta_b \Gamma_b & \perp x_2 \geq 0 \quad (25) \\ 0 \leq - y_g + \sigma\varepsilon_g + \lambda & \perp x_g \geq 0 \quad (26) \\ 0 \leq - y_i - N\beta + \sigma\varepsilon_d + \lambda & \perp x_d \geq 0 \quad (27) \\ 0 \leq \theta_b - y_i + (1-N)\beta & \perp x_b \geq 0 \quad (28) \\ 0 \leq c_{mc} - y + \theta_{mc} & \perp x_{mc} \geq 0 \quad (29) \\ 0 \leq c_{ml} - y + \theta_{ml} & \perp x_{ml} \geq 0 \quad (30) \\ 0 \leq - \theta_{ml}\Gamma_{ml} + y_i & \perp x_l \geq 0 \quad (31) \\ 0 \leq - \theta_{mc}\Gamma_{mc} + y_i & \perp x_c \geq 0 \quad (32) \end{cases}$$

We now make two scenarios to solve this minimization problem and to compare the CO_2 marginal values obtained for the two different refineries (see appendix A.1 for the resolution and the other Lagrange multiplier values).

Scenario Bio:
We suppose that :

- the Ledcar technology is not used because too expensive: $cml \to \infty, x_{ml} = x_l = 0$
- The biofuel constraint is not saturated: $\beta = 0$

Flexible Refinery

$$\sigma_{flex}^{bio} = (\frac{c_2}{\Gamma_b} - c_1)\frac{1}{\varepsilon_d}$$

Fixed yields Refinery

We consider that gasoline is in excess: $y_g = 0$

$$\sigma_{fix}^{bio} = (c_2\frac{\Gamma_d}{\Gamma_b} - c_1)\frac{1}{\varepsilon_d\Gamma_d + \varepsilon_g\Gamma_g}$$

Notation : σ_{fix}^{bio} is the marginal value associated with the carbon constraint in the scenario Bio for the fixed yields refinery.

Scenario Ledcar:
We suppose that biofuels are not used because too expensive: $c_2 \to \infty, x_2 = x_b = 0, \beta = 0$

Flexible Refinery

$$\sigma_{flex}^{ledcars} = (\frac{c_{ml} - c_{mc}}{\Gamma_{ml} - \Gamma_{mc}}\Gamma_{mc}\Gamma_{ml} - c_1)\frac{1}{\varepsilon_d}$$

Fixed yields Refinery

We consider that gasoline is in excess: $y_g = 0$

$$\sigma_{fix}^{ledcars} = \frac{1}{\varepsilon_d\Gamma_d + \varepsilon_g\Gamma_g}(-c_1 + \Gamma_d\frac{c_{ml} - c_{mc}}{\Gamma_{ml} - \Gamma_{mc}}\Gamma_{mc}\Gamma_{ml})$$

The first thing we can notice is that the marginal value associated to the CO_2 constraint (σ) differs between refinery descriptions for a given scenario. It means that for the same level of the carbon ceiling, the technological options chosen to mitigate emissions could differ.
We plot the evolution of the objective function value with the carbon cap for the two refineries with a given set of parameters (figure 3 and see appendix A.3 for the parameters values). The carbon ceiling is not binding at the same level for the two refineries. In the fix refinery case, gasoline is in excess (the mobility constraint is saturated but the gasoline one is not) hence the total emissions of this model are higher than the one of the flexible refinery model. Because of the parameters values we have in this case: $\sigma_{fix}^{bio} < \sigma_{fix}^{ledcar}$ and $\sigma_{flex}^{bio} < \sigma_{flex}^{ledcar}$. It explains why the first option chosen to mitigate emissions is biofuel. An other interesting point is the fact that biofuel use allows to mitigate more emissions in the fix refinery case than in the flex one (3 units vs 2.5 units). Indeed, using more biofuels reduces the need of diesel so the refinery treats less crude oil and reduces its gasoline production. Gasoline excess is then less important so incorporating biofuel in the vehicle fuel helps also to reduce emissions due to gasoline. This is not the case for the flexible refinery since in this model there is no gasoline excess.

We then use parameter values that would allow a different result, we raise c_2 in order to have $\sigma_{flex}^{bio} > \sigma_{flex}^{ledcar}$ (see figure 4). And moreover, we modify the fix refinery yields, lowering the diesel yield and raising the gasoline one.

In this case since the diesel yield is so low, it is optimal for the fix refinery model to use ledcars even with no carbon constraint. The comparison of the two models' runs with a carbon ceiling is distorted since the flexible refinery does not have this problem. The marginal values of the carbon

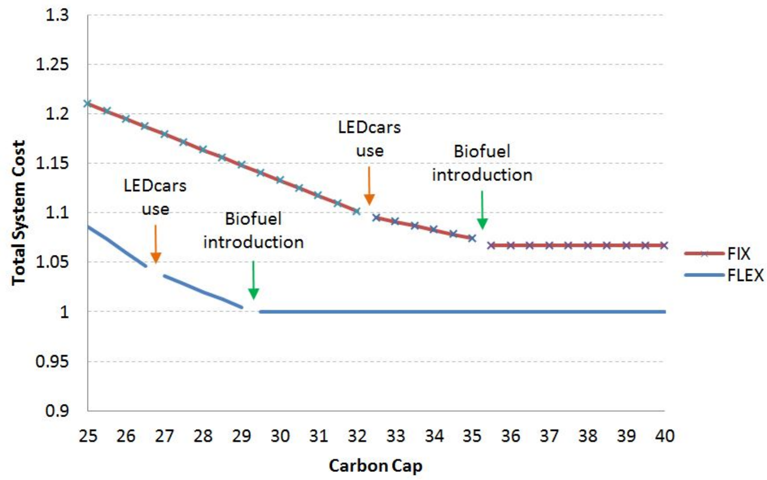


Figure 3: Objective function evolution with the carbon ceiling

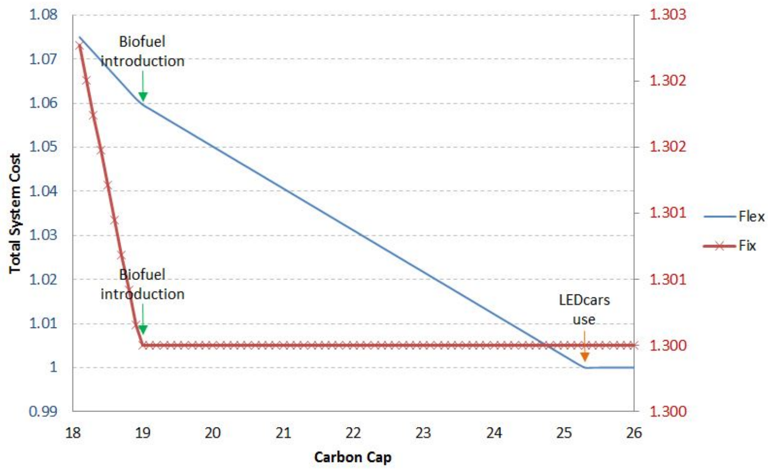


Figure 4: Objective function evolution, low diesel yield

constraint are really different (see the slope of the two curves) hence if the choice of mitigation technologies were larger we can not be assured that the same technologies would be chosen to abate emissions.

Moreover, with this set of parameters these two models have different abatement capacities: the fix one can abate up to 1.5 units of carbon when the flex one can abate 7.8 units of carbon.

To understand how a complex refinery would behave, we added two processes to the fix refinery (HC1 and HC2): these processes convert gasoline into diesel with different costs and yields. It is not mandatory to use the new processes. The new refining scheme and parameter values can be found in appendix A.2. We did the same exercise than earlier and for the initial values of the parameters, we obtain the following results (see figure 5):

The cheapest process HC1 is used even when there is no carbon constraint as it allows to reduce the gasoline waste. After that, the cost ratios of the other options lead biofuels to be introduced first, then HC2 and finally the low-energy vehicle technology. The little flexibility introduced with the two new processes is not sufficient for the objective function trajectory to change drastically. Yet, we can observe that the "complex" refinery trajectory is nested between the two others and that the flexibility delays the adoption of new technologies.

This simple stylized example illustrates that refinery models characterized by different levels of flexibility exhibit different shadow price structures. Submitted to a series of carbon caps, we show that the responses of the three models differ: abatement options are utilized differently in quantity and timing. This bias is an issue, at least theoretically; whether this is the case in a more complex,

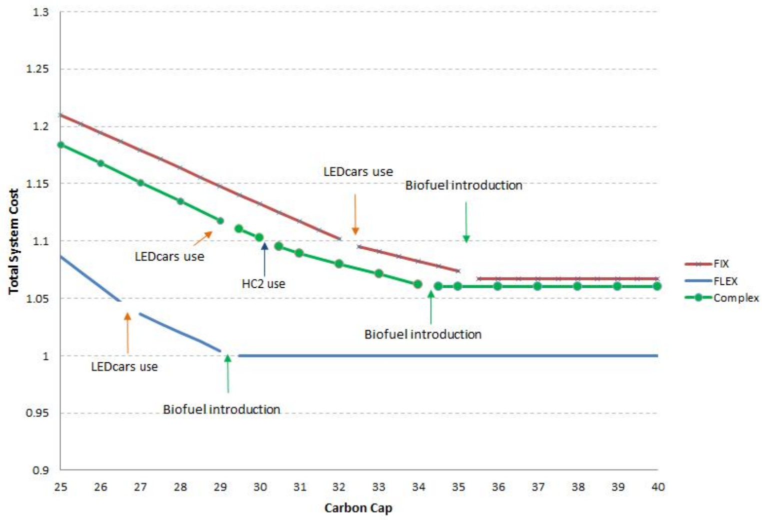


Figure 5: Objective function evolution, with 3 refineries

real-size model is the question addressed in the next section.

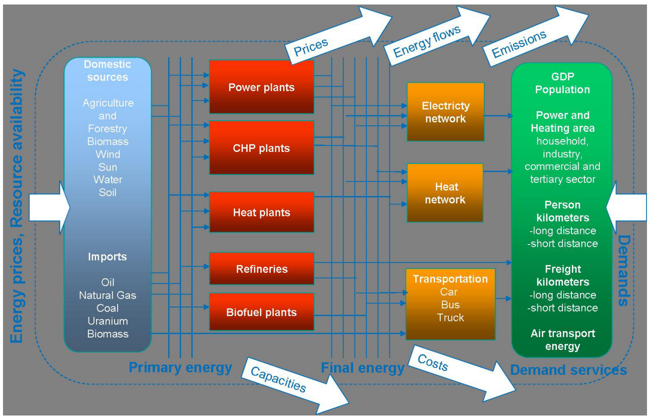
3 An energy-transport system model

We now turn to the presentation of the scaled up framework. In this section, we present the IFPEN-developed MIRET model: a long-term, multi-period, techno-economic planning model that covers the energy-transport system in detail. Its scope is continental France, and the time horizon is 2050, with 2007 as base-year.
The TIMES model generator is used as a modeling framework. Under this well established paradigm Labriet *et al.* (2010), Lorne & Tchung-Ming (2012), a Reference Energy System is built to cover the stock of equipment and flows for the reference year, the characteristics of future technologies, the potential and costs for primary energy. This being given, the model aims at providing final energy services / energy (mobility for passengers and freight, electricity, etc.) at minimum cost. To do this, investment and operation decisions are made for the technologies embraced in the model; subsequent primary energy uses are obtained.

3.1 General presentation

The model schematics is presented in Figure 1. It presents a block diagram that links elements described in the model according to four main dimensions: energy supply, technologies, demand and policies (Loulou et al, 2005).

Figure 6: Model schematics



The reference energy system is thus composed (from left to right) of:

- *a primary energy* supply block: includes imported fossil energy (crude oil, coal, natural gas), biomass (starch crops – wheat, corn; sugar crops – sugar beet; oil crops – rapeseed, sunflower; lignocellulosic biomass – forest wood, crop residues, dedicated energy crops);
- an energy technology block, whose technologies transform primary energy into energy vectors and energy services: it includes oil refining (see next section), biofuel units (first generation – ethanol, FAME , HVO ; second generation – ethanol and synthetic FT-Diesel), electricity generation (power plants – all technologies; combined heat and power), preparation of fuels for transport at blending (diesel, biodiesel B30, gasoline grades E5 and E10 and E85, jet fuel – including fossil and bio bases), and end-use technologies for road mobility (personal vehicles and Light – thermal, hybrid, plug-in hybrid / gasoline, diesel, natural gas, flexfuel, electric cars; buses and trucks – thermal, hybrid / gasoline, diesel, biodiesel);
- a final energy / energy services demands block: Electricity demand by time period (four days representing each season, the power load being hourly described for each of these days), mobility demands (short and long distance for passenger vehicles and buses, traffic for LUV, demand for freight mobility), demands for exported products (oil products, electricity);
- a policies block: includes measures and constraints of several types affecting all sectors. Some are of microscopic nature, such as quality norms for refinery products, number of functioning hours of fuel turbines power plants, etc. Some are macroscopic in nature, e.g. sectoral carbon tax.

3.2 Basic formalism

The objective function of the underlying linear program takes the form:

$$OBJ = \sum_{t \in periods} DISC(t)\Big[INVCOST(t) + INVTAXSUB(t) + INVDECOM(t) + FIXCOST(t) + FIXTAXSUB(t) + VARCOST(t)\Big] - SALVAGE$$

It is simply the discounted sum of investment costs (including taxes and subsidies), decommissioning costs, fix costs (including taxes and subsidies), variable costs, and economic value of investments whose life extends beyond the time horizon. The linear program P_{ref} refers to the "reference" case:

$$(P_{ref}) = \begin{cases} \min \ c^T x \\ s.c. \\ Ax \geq b & (y) \\ Tx = 0 & (\tau) \\ Kx \leq k & (\lambda) \\ Qx \leq q & (\omega) \\ Sx \leq s & (\sigma) \\ x \geq 0 \end{cases}$$

c is the column vector of all discounted unit costs. The constraints $Ax \geq b$ correspond to the final demands of energy and energy services to be satisfied. The equation set $Tx = 0$ describes the fundamental input-output relationships of each technology, namely the mass or energy balance of each technology. The set $Kx \leq k$ includes all capacity constraints, either technology or resource based. For example, (i) the electricity produced by a given technology is limited by the combination of the stock installed and seasonal or hourly availability factors, (ii) the use of scarce resources, e.g. woody biomass, are limited for use for power, heat, combined heat and power and biofuels production. $Qx \leq q$ accounts for the quality equations of some of the products. This is especially the case of refinery products, whose quality must respect certain specifications to be marketed . Finally, the set $Sx \leq s$ includes all sorts of institutional constraints (e.g., the French legislation limits the number of functioning hours of certain power plants – notably fuel turbines), calibration constraints and share constraints.

3.3 The refinery sector – from aggregated to detailed

In this section we detail the four refinery models used in the study.

Three concise models of the French refining sector

In the first MIRET model, the refinery is modeled with a single process. The process inputs are crude oil, natural gas and oxygen and the outputs are LPG, Naphtha, gasoline (GSL), jet fuel, heating oil (HOL), diesel (DSL), fuel oil (RFO) and coke (see Figure 7).

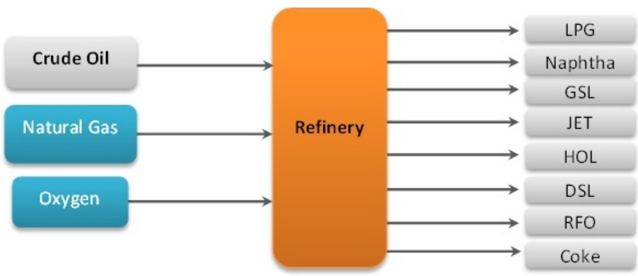


Figure 7: MIRET's semi-flexible Refinery

The throughput yields can each vary between two values and are optimized by the model (with the obvious constraint that the yields sum equals 1). These two minimum and maximum values for each petroleum product have been determined with regard to the 2007 french refining tool and they evolve with time (see Figure 8) in order to take into account a possible adaptation of the refining industry to the local market changes. There is no cost associated with this yields' evolution.

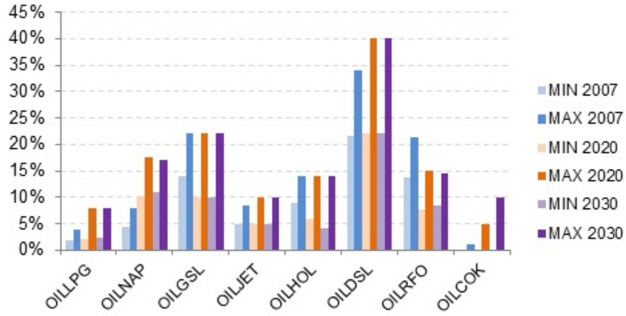


Figure 8: Product yields variations - French semi-flexible Refinery

For the purpose of our study, we declined this initial semi-flexible refinery model: we built what we call a Fix refinery where the yields vector is fix (it evolves with times only, see Figure 9) and a totally flexible one, called Flexible Refinery, for which the throughput yields can take any value between 0 and 1, allowing the model to get rid of the co-product issue. These two models are extreme: the fix one forbids any adaptation so that the amount of fatal products of the refinery cannot be reduced but by lowering the refinery's utilization rate. On the contrary, with the flexible refinery, the fatal products are not a problem since they are not produced at all.

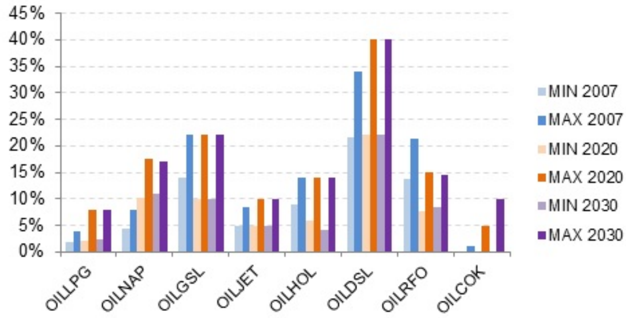


Figure 9: Yields vectors - Fix Refinery

The mathematical representation of the 3 kinds of refinery models is the following:

Semi-flexible Refinery

$$\begin{cases} \forall i \in [1,8] \\ \lambda_i CR \leq y_i \leq \upsilon_i CR \\ 0 \leq \lambda_i \leq \upsilon_i \leq 1-\delta \\ s.t. \\ \sum_i y_i = CR(1-\delta) \end{cases}$$

Flexible Refinery

$$\begin{cases} \forall i \in [1,8] \\ 0 \leq y_i \leq CR(1-\delta) \\ s.t. \\ \sum_i y_i = CR(1-\delta) \end{cases}$$

Fix Refinery

$$\begin{cases} \forall i \in [1,8] \\ y_i = \alpha_i CR \\ With \\ \sum_i y_i = CR(1-\delta) \end{cases}$$

With y_i the quantity of the eight refinery outputs, CR the crude oil quantity entering the refinery and δ the autoconsumption and losses of the refinery. These models differ only by the yields' vector. The cost per unit of input, the refinery CO_2 emissions, the nature of the outputs... are the same for the three models.

A detailed model of the French refining sector

The initial Miret's refinery model and its two variants have several issues that we tried to tackle by building a more complex French refining model. The first issue is that the yields' flexibility allowed by the simple refinery model is free which is far from being realistic. To change the throughputs of his refinery, the refiner can first switch to a crude oil more appropriate to meet his production targets. But, this solution does not enable him to deeply change the plant production profile. To

do so he has to adapt the process units' utilization rate which can be costly or he has to invest in new units. For example, to produce more diesel and less fuel oil, the conversion units have to run more and since they have high operational expenditures, the refining cost is going to increase.
The second issue of the simple refinery model regards the fuel specifications. Usually, simple models do not take into account the oil and product quality and the difficulty (and cost) to meet the fuel specifications. Although this aspect is really important and constraining particularly for the blending of biofuel in the transportation fuels (ethanol in gasoline).
The third problem of the simple model is the representation of the petroleum product marginal values and more particularly of their ratio which are distorted, among other things by the cost-less flexibility of the yield vector.
And finally, a more complex model of the refining sector allows to improve its CO_2 emissions representation. Indeed, in the three simple refinery models the CO_2 emissions are linearly correlated with the amount of crude oil treated whereas in the complex refinery model, the CO_2 emissions are related to the amount and type of fuel used in the refinery plant fuel (natural gas, internal fuel gas, fuel oil, FCC coke, hydrogen...).
For the reasons presented above, we built a Complex refinery model. The retained refining structure

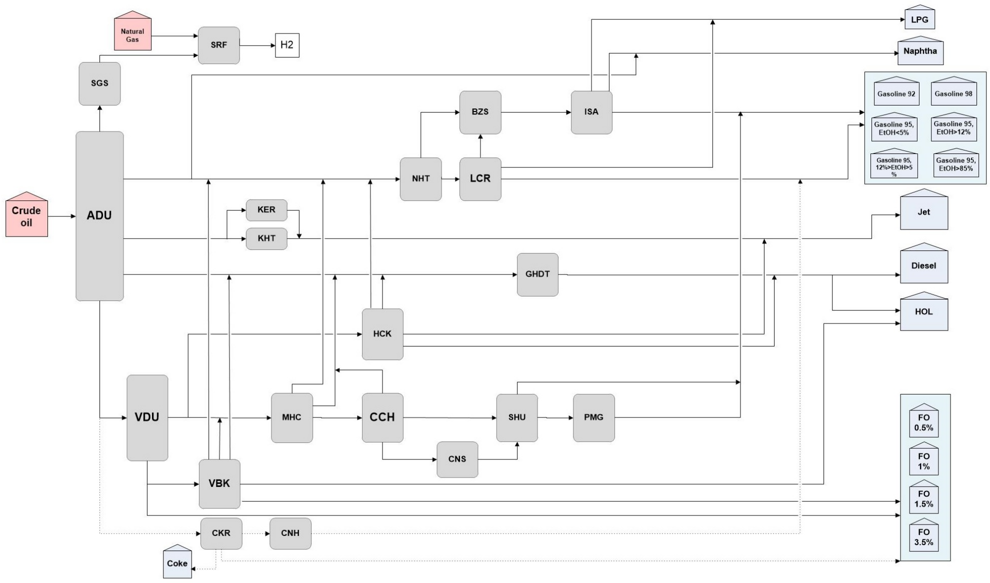


Figure 10: French refining scheme

consisted in the most common processing units, among which an atmospheric distillation unit, a vacuum distillation unit, a catalytic reforming unit, a gasoil hydrodesulphurization unit, an ETBE unit, a catalytic cracker, an hydrocracker, combined with alkylation and isomerization units to improve the quality of the gasoline pool, and a visbreaking unit to process residues from these units (the refining scheme is presented in Figure 10). This conversion refinery is very close to the current structure of the French refining industry but it may change to be adapted in line with future developments or in some scenarios considered over the next thirty years. To face the possible evolutions of demand and measures that could be adopted about the tightening of petroleum product specifications such as reduction in the sulphur content in diesel oil and heavy fuel oil, a coking unit has been added in the modeled refining structure in order to permit a lesser production of fuel oil. More expensive deep conversion units as partial oxydation unit and a deep hydrodesulphurization unit are not in the model since the French refining has been in a bad shape for a decade and large investments in this industry seem pretty unrealistic. Regarding the main input of the refinery, there is at the moment only one crude oil entering the refinery whose characteristics are representative of the mix of crude oil used in France in 2007.

To summarize, the three simple refinery models are very close except for the yields' vector. For the same crude oil treatment, the refining cost and emissions will be similar but we will obtain different amounts of petroleum products (see table 1). And more importantly, the marginal value ratios of the petroleum products will vary a lot between the three models: with the flexible one, all ratios are equal to 1 since at the optimum, all the produced products have the same marginal values, for the fix refinery the ratios risk to take extreme values whereas the simple model should give moderate but not necessarily accurate ratios.

	Complex	Semi-flexible	Flexible	Fix
Yields	Flexible, with costs	Flexible within allowed ranges. The flexibility is free.	Totally flexible. The flexibility is free.	Totally fixed
Product specifications	Yes	No		
CO_2 emissions	Depend on the processes used	Proportional to the quantity of crude oil treated		
Costs	Depend on the processes used	Proportional to the quantity of crude oil treated		

Table 1: Refineries, Summary

4 Model detail, global mitigation strategies and sectoral policies

4.1 Scenarios

Economic assumptions
GDP (2007€) scenario is built based on existing projections for France. At the 2030 horizon, DGTPE scenarios is selected; 2050 extension is based on OECD long-term growth projections. This scenario traduces a slow-down of growth in the next decades.

	2010-2020	2020-2030	2030-2050
GDP growth	1.4%	2%	1.4%

Table 2: French GDP growth

Population scenario is based on the central scenario of INSEE regional projections for 2040. 2050 extension is based on 2030-2040 average annual growth rate (see figure 11).

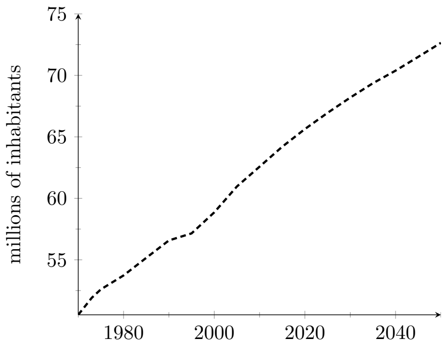


Figure 11: French population evolution

The table below (fig 12) provides the main sources for numerical assumptions and parameters and in particular for technological costs:

Scenario components	Sector	Data sources
Primary energy	Fossil energy	IEA (2011)
	Agricultural biomass	INRA
	Woody biomass	FCBA
Energy technologies	Refining	Internal IFPEN
	Biofuels	Internal IFPEN
	Road mobility (Passengers and Freight)	Internal IFPEN
	Power plants	EDF, IEA (2010), MINEFI (2008)
Demand scenarios	Other oil products	IFPEN/LEPII
	Pass. And Freight mobility	CAS (2009)
	Electricity	RTE (2011)
Policies	Carbon price	IEA (2011)
	Biofuels	EC (2009), EC (2010)

Figure 12: Main sources for numerical assumptions

Sets
4 refineries described in 2.3

Carbon constraints
Two types of carbon constraints have been tested. In the first case, a cap is applied on the cumulative global CO_2 emissions. In the second case, the cap is applied on cumulative fossil CO_2 emissions from transportation only.
Even though an annual cap is more likely to be instituted, we chose to use a cap on cumulative emissions and this mainly for a modeling reason: with this constraint we obtain a unique CO_2 price for each refinery model. With an annual ceiling, there is one CO_2 marginal value per year and since the refinery models do not necessarily adapt at the same time, the interpretation of the CO_2 marginal value variations between the models is not easy. The other reason is that it gives more flexibility to the model: an annual decreasing ceiling largely drives (and constrains) the model when a global one allows the model to adapt at any time.
For both constraints (global and sectoral), the cap is fixed thanks to a reference level. This reference level is the CO_2 emission value obtained in the base case, i.e. a case with no constraint on CO_2 emissions (see Figure 13). We can notice on this figure that the various refinery models have very

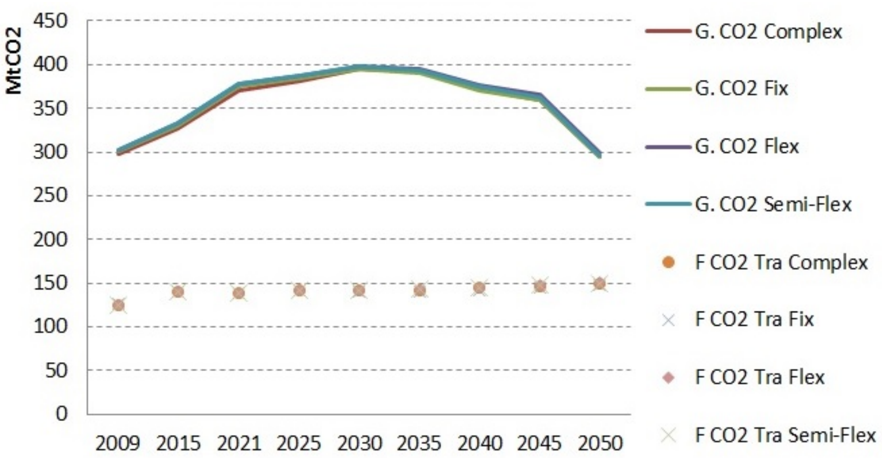


Figure 13: Global & Fossil Transportation CO_2 emissions for the base case (No emission ceiling)

few impacts on the global or sectoral emissions when no constraint is applied on CO_2.
Six levels of carbon constraints have been applied on the cumulative emissions of CO_2 between 2011 and 2050. The ceiling on emissions varies between 40% and 90% of the total emissions obtained in the base case.

4.2 Results

4.2.1 Global carbon constraint

For the first set of carbon constraint, the global CO_2 cap, the differences between the runs with the complex refinery model and those with the three other types of refinery are not very important. Indeed, GHG emission reduction is very expensive in the transportation sector so when a global cap is applied on CO_2 emissions, the reduction effort is first supported by the other industrial sectors (see Figure 14 for an illustration). In the semi-flex refinery case, the emission reduction first

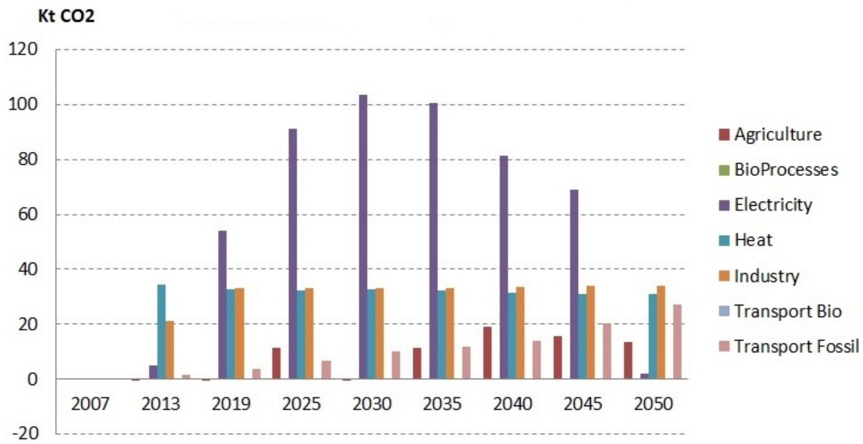


Figure 14: CO_2 emission abatement by sector for the semi-flex refinery model with a 60% ceiling

comes from the heating sector because it is relatively cheap to switch from gas produced heat to bio produced heat. Then the power sector contributes to the emission reduction with an increased use of renewables and a decreased use of coal and gas processes. The transportation sector's emission reductions are very low until 2030, at this date the sector stands for 65% of global CO_2 emissions (versus 45% in 2007).

The paths followed by the objective function or the CO_2 marginal values are slightly similar for the four different models (see Figure 15) when the constraint is not too stringent. When the CO_2 ceiling reaches very low values, the four models began to behave diversely.

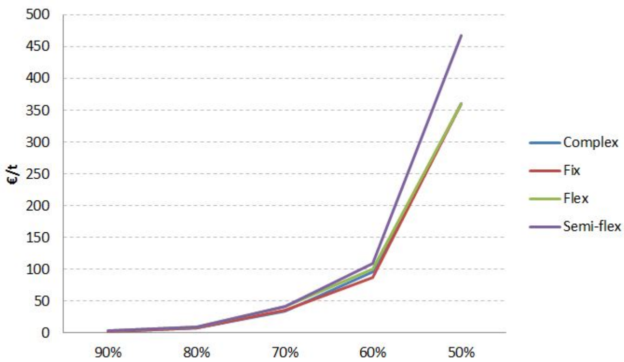


Figure 15: CO_2 marginal value for different levels of the ceiling

Finally, we can observe that when trying to evaluate the impact of a global CO_2 ceiling on the energy-transport system, adding details to the refinery model is not compulsory. It begins to be important when the ceiling evaluated is very ambitious (for example, the 50% ceiling leads to a CO_2 marginal value of 360€/t which is a very high value regarding the actual European CO_2 market). When the ceiling values are more classic, the refinery model does not impact the optimal solution.

4.2.2 Sectoral carbon constraint

The following results present scenarios with a sectoral cap: end-pipe fossil CO_2 emissions are capped.
The first notable thing is the diversity in the adaptation adopted by the different models. The possible arbitrage is the following: the model can wait to adapt but will have to abate much more future emissions or it can reduce its emissions immediately which will allow him to emit more in the future. By looking at the CO_2 emission trajectories of the models, we can notice that the complex refinery model usually reacts first, and lowers its emissions in two steps when the other refineries adapt in a more abrupt way (see figure 16). The flexible refinery does not react very early but its reaction is radical when it happens. An other way to notice the differences induced

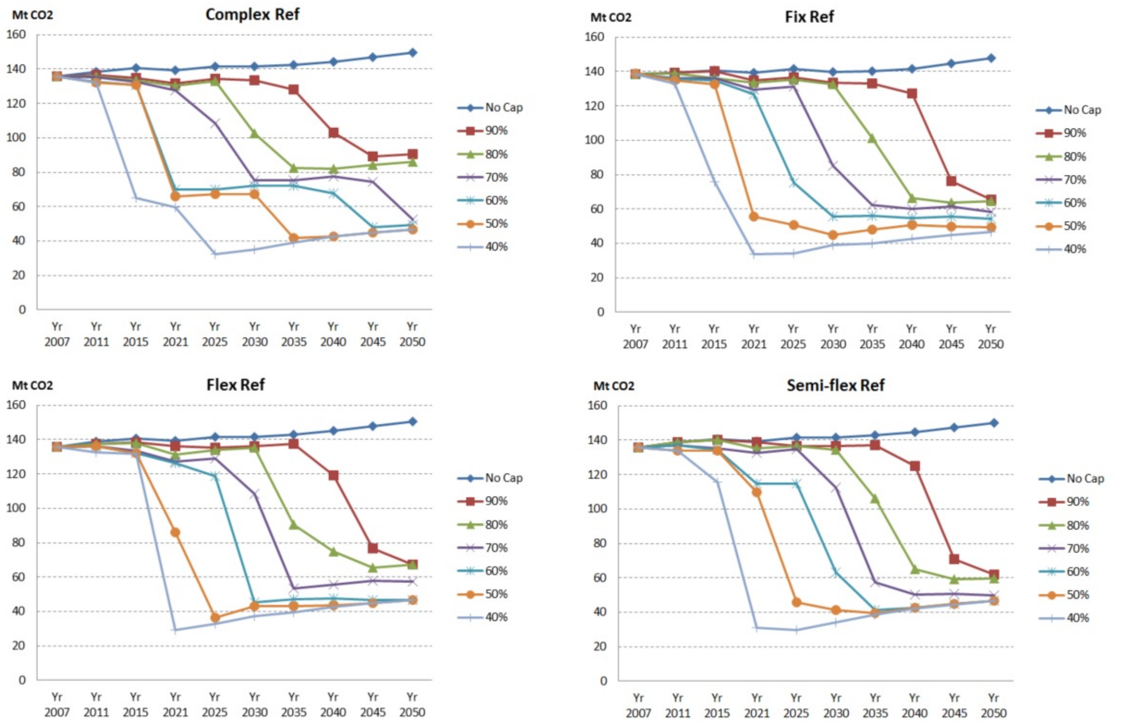


Figure 16: Fossil CO_2 emissions of transport for the various models

by the various refinery models in the energy system models is to look at the four objective values trajectories which are slightly different (see appendix B).
These CO_2 trajectories are the result of the different ways of adapting adopted by the four models. To comply with the emission ceilings, the model has 3 possibilities:

- decarbonize the fuels burnt in the vehicles by using biofuels for example
- use vehicles with a better energy efficiency
- switch to new energy sources for transportation, as electric vehicles for example

Decreasing the mobility demand is not an option, in this case we consider an inelastic demand (the demand is an exogenous input of the model.
These 3 ways of reducing transportation sector emissions are all used when the constraint is high enough but not necessarily in the same proportions.

When the constraint is really stringent, the four models adapt almost in the same way and with similar carbon marginal values. Indeed, with a very low carbon ceiling the choices to mitigate emissions are not numerous. It explains why the four models end up using the same technologies and biofuels. For this reason it is not very interesting to look at the low ceiling results and we are going to study the models behavior for the intermediary ceiling values.

The figure 17 shows the evolution of transportation energy intensity and carbon intensity under 2 levels of ceiling: 60% and 80%.

The trajectories of energy intensity are pretty similar for the four models even though the vehicle fleets are different. It is relatively cheap and fast to modify the car fleet composition since the cars

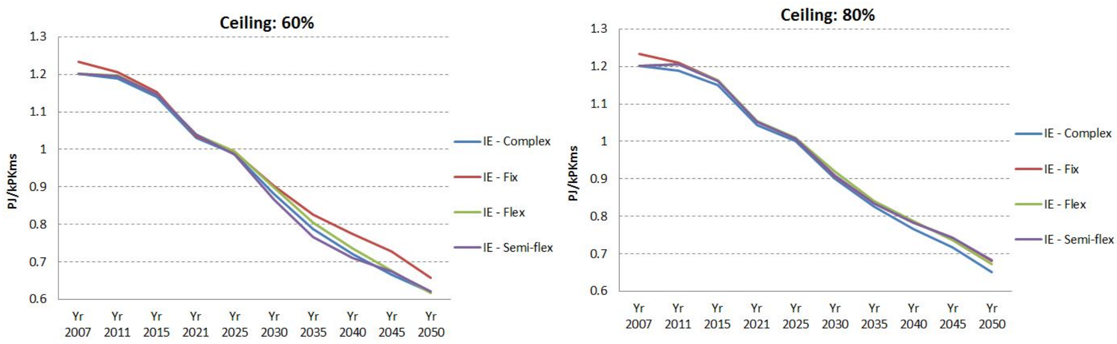


Figure 17: Transportation energy intensity with 2 ceilings: 60% and 80%

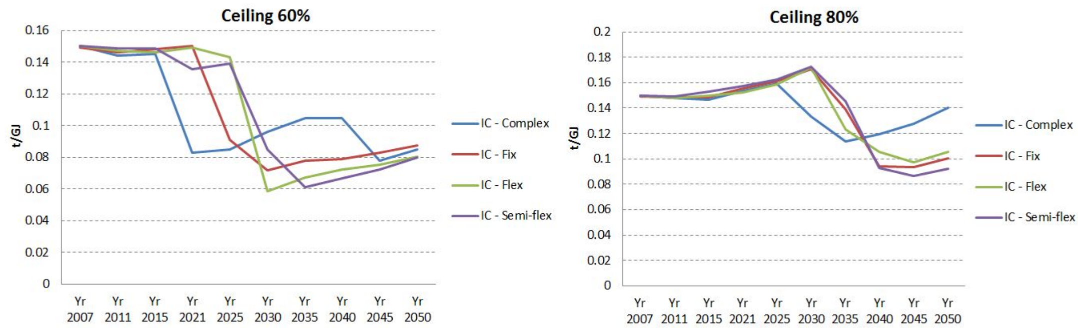


Figure 18: Transportation carbon intensity with 2 ceilings: 60% and 80%

lifetime is rather short (15 years). Besides, the efficiency of the various new car technologies does not vary a lot so the impact on the global energy intensity is minor. It is different for the carbon intensity: the decarbonization of vehicle fuel seems to happen at different periods for the four models.

Taking a look at the car fleet composition helps to understand some of the differences in the energy and carbon intensities evolution. The car fleet trajectories (figure 19) diverge notably for the small and the large cars. It is less the case for the medium size cars: in this category, the new diesel motorization is always and largely preponderant (see appendix B).

For the small size cars, the type of refinery used has a huge impact on the investment trajectory. With the 80% ceiling, the fix and the semi-flex refineries favor the natural gas cars when the flexible and the complex one use it only as a transition technology.

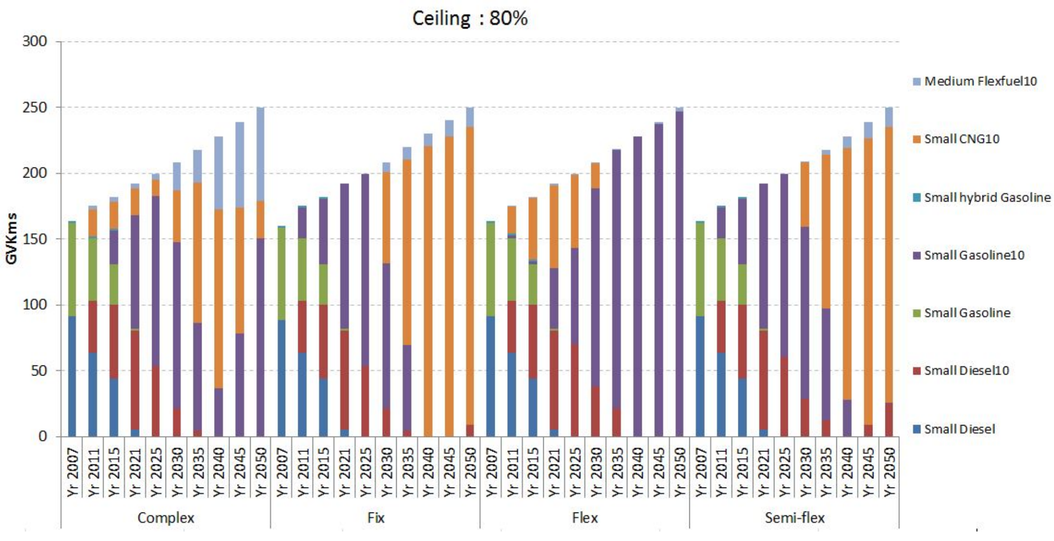


Figure 19: Small Cars activity: 80% Ceiling

An obvious other way to decarbonize the transportation sector is to use biofuels (see appendix B for figures). The complex refinery generally makes earlier use of biofuels and ends up using less of it than the other ones. When the CO_2 constraint is really stringent (the 40% cap), all models use the same amount and proportion of biofuels. Yet, when the constraint is lower the amounts are still more or less the same but the complex model uses a largest variety of biofuels: with the 80% ceiling, the complex model consumes seven times more ethanol than the other ones.

The large differences between models regarding the car fleet and the biofuel consumption can partly be explained by the refinery utilization. The cheapest way to reduce emissions in the fixed and semi-flexible refinery cases seems to be to stop using the refinery at the end of the period (figure 20). The more stringent the constraint, the earlier the refinery utilization rate collapses[1]. This leads the model to invest in car technologies independent of oil products and explains why these two models largely invest in CNG cars when the other two stick with small gasoline cars.

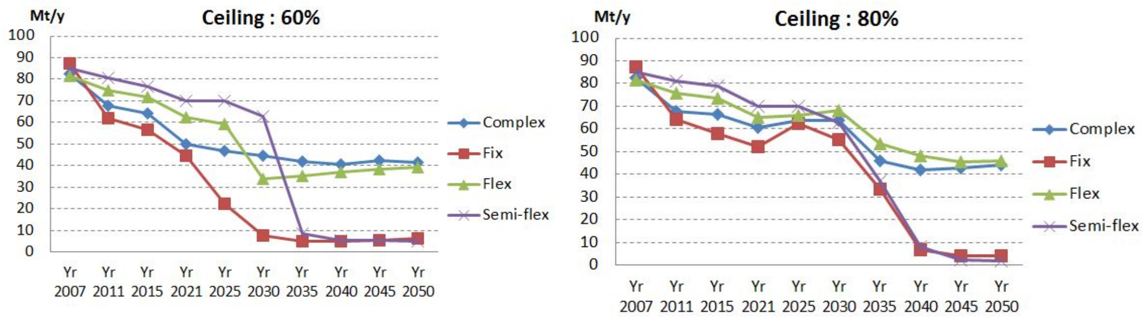


Figure 20: Refinery treatment: 60% and 80% cap

5 Conclusion

In this work, we illustrate a rarely debated issue: modeling more or less details can induce bias which can lead to different policy insights. Taking the example of the oil refining sector, a good symbol of the model developer difficulty because of its particularities: joint production, multiple flexibilities and the multiple possible origins of fuel components, we show that the refinery description used in the energy system model matters when trying to evaluate energy or climate policy applied to the transportation sector. It impacts the policy costs but also the technology trajectories chosen at the optimum. In the results presented, this is notably true for biofuels and alternative car technologies. Essentially, the balance between energy efficiency and carbon intensity of transport may be affected by the accuracy of the description of the pivotal refining sector. Consequently, increasing this sector accuracy level should be motivated by the wish to gain wider quantitative insights on potential evolution of the energy system and above all by the wish to improve the robustness of outcomes.When data is not available or when the modeling team does not possess the necessary competency to detail a sector, an extensive sensitive analysis on the sector technical parameters becomes necessary. As stated by Hedenus *et al.* (2013), “this kind of analysis is often absent from policy reports or academic literature. Yet, it allows the decision maker to gain wider insights on the energy system mechanisms and it could avoid misinterpretations due to modeling bias”.

This simple fact calls for questions for both producers and clients of long-term energy studies, which go beyond the technicalities. Past experience shows that policy makers are probably aware of such issues. Current practices seem to indicate that long-term questions are often asked to different research groups, using various models. The very fact that they get different outcomes should not necessarily be an issue - in principle, there are not necessarily specific reasons why different groups of people, using different models, explore an inherently uncertain future with the same perspective. Still, a distinction should be made between these shortcomings and bias induced by model misspecifications.

This leaves modelers with their own choices and responsibilities.The modeling team competency

[1]The scenarios leading to the refining sector shutdown are not politically acceptable (in terms of energy security and employment). But adding constraints on the refinery utilization rate would drive model outcomes too much.

and extensive knowledge of the whole model is essential when the question of the level of details arises. Detailing a sector should be done when the data are available and its mechanisms well understood. Without these two points a simpler approach should be promoted to avoid a false sense of accuracy. So, if robust analyses have to rely on accurate economical and technological descriptions, lack or excess of details are enemies of modelers. As mentioned by van Delden *et al.* (2011), "Model complexity increases with the number of variables and processes incorporated and by linking various model components. More complex models may generate unnecessary detail, while simple models may omit essential processes. It is not enough to apply Occam's razor to just one model component, as the requirements also apply to the integrating linkages between components". This theme gains in importance in other communities as well, e.g. in ecosystemic modeling: " in many cases a carefully tuned simple model can perform as well as a more complex model. On the other hand, a pragmatic review of ecosystem models by Fulton et al. (2003) concluded that the simplified webs, especially those reduced to less than 25% of the size of the original model web, are not able to represent enough of the processes and interactions in the system to faithfully reproduce system dynamics, particularly when the strength of environmental or anthropogenic pressures changes" (Hannah *et al.* , 2010). Challenges thus drive research teams in seemingly orthogonal directions: robust modeling of increasingly integrated, uncertain phenomena.

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A Stylized Model

A.1 Resolution

Scenario Bio:
We suppose that :

- the Ledcar technology is not used because too expensive
- The biofuel constraint is not saturated

$cml \to \infty, x_{ml} = x_l = 0, \beta = 0$
Flexible Refinery

$$\begin{cases} \text{With equation (24): } \lambda = c_1 \\ \text{With equations (25) \& (28): } \theta_b = y_i = \dfrac{c_2}{\Gamma_b} \\ \text{With equation (32): } \theta_{mc} = \dfrac{c_2}{\Gamma_b \Gamma_{mc}} \\ \text{With equation (27): } \sigma = (\dfrac{c_2}{\Gamma_b} - c_1)\dfrac{1}{\varepsilon_d} \\ \text{With equation (29): } y = \dfrac{c_2}{\Gamma_b \Gamma_{mc}} + c_{mc} \\ \text{With equation (26): } y_g = \dfrac{\varepsilon_g}{\varepsilon_d}(\dfrac{c_2}{\Gamma_b} - c_1) + c_1 \end{cases}$$

Fixed yields Refinery.
We consider that gasoline is in excess, $y_g = 0$

$$\begin{cases} \text{With equations (16)\& (19): } \theta_b = y_i = \dfrac{c_2}{\Gamma_b} \\ \text{With equation (23): } \theta_{mc} = \dfrac{c_2}{\Gamma_b \Gamma_{mc}} \\ \text{With equation (20): } y = \dfrac{c_2}{\Gamma_b \Gamma_{mc}} + c_{mc} \\ \text{With equations (15),(17) \& (18):} \\ \theta_g = \dfrac{\varepsilon_g}{\varepsilon_d \Gamma_d + \varepsilon_g \Gamma_g}(c_1 - c_2 \dfrac{\Gamma_d}{\Gamma_b}) \\ \theta_d = \dfrac{\varepsilon_d}{\varepsilon_d \Gamma_d + \varepsilon_g \Gamma_g}(c_1 - c_2 \dfrac{\Gamma_d}{\Gamma_b}) + \dfrac{c_2}{\Gamma_b} \\ \sigma = (c_2 \dfrac{\Gamma_d}{\Gamma_b} - c_1)\dfrac{1}{\varepsilon_d \Gamma_d + \varepsilon_g \Gamma_g} \end{cases}$$

Scenario Ledcar:
Biofuels are not used because too expensive.
$c_2 \to \infty, x_2 = x_b = 0, \beta = 0$
Flexible Refinery

$$\begin{cases} \text{With equation (24): } \lambda = c_1 \\ \text{With equations (29) to (32):} \\ \theta_{mc} = \dfrac{c_{ml} - c_{mc}}{\Gamma_{ml} - \Gamma_{mc}} \Gamma_{ml} \\ \theta_{ml} = \dfrac{c_{ml} - c_{mc}}{\Gamma_{ml} - \Gamma_{mc}} \Gamma_{mc} \\ y = \dfrac{c_{ml}\Gamma_{ml} - c_{mc}\Gamma_{mc}}{\Gamma_{ml} - \Gamma_{mc}} \\ y_i = \dfrac{c_{ml} - c_{mc}}{\Gamma_{ml} - \Gamma_{mc}} \Gamma_{mc}\Gamma_{ml} \\ \text{With equation (27): } \sigma = (\dfrac{c_{ml} - c_{mc}}{\Gamma_{ml} - \Gamma_{mc}} \Gamma_{mc}\Gamma_{ml} - c_1)\dfrac{1}{\varepsilon_d} \\ \text{With equation (16): } y_g = (\dfrac{c_{ml} - c_{mc}}{\Gamma_{ml} - \Gamma_{mc}} \Gamma_{mc}\Gamma_{ml} - c_1)\dfrac{\varepsilon_g}{\varepsilon_d} + c_1 \end{cases}$$

Fixed yields Refinery. We consider that gasoline is in excess, $y_g = 0$

$$\begin{cases} \text{With equations (20) to (23):} \\ \theta_{mc} = \dfrac{c_{ml} - c_{mc}}{\Gamma_{ml} - \Gamma_{mc}} \Gamma_{ml} \\ \theta_{ml} = \dfrac{c_{ml} - c_{mc}}{\Gamma_{ml} - \Gamma_{mc}} \Gamma_{mc} \\ y = \dfrac{c_{ml}\Gamma_{ml} - c_{mc}\Gamma_{mc}}{\Gamma_{ml} - \Gamma_{mc}} \\ y_i = \dfrac{c_{ml} - c_{mc}}{\Gamma_{ml} - \Gamma_{mc}} \Gamma_{mc}\Gamma_{ml} \\ \text{With equations (15),(17) \& (18):} \\ \theta_g = \dfrac{\varepsilon_g}{\varepsilon_d\Gamma_d + \varepsilon_g\Gamma_g} c_1 - \dfrac{\Gamma_d\varepsilon_g}{\varepsilon_d\Gamma_d + \varepsilon_g\Gamma_g} \dfrac{c_{ml} - c_{mc}}{\Gamma_{ml} - \Gamma_{mc}} \Gamma_{mc}\Gamma_{ml} \\ \theta_d = \dfrac{\varepsilon_d}{\varepsilon_d\Gamma_d + \varepsilon_g\Gamma_g} (c_1 + \Gamma_g \dfrac{\varepsilon_g}{\varepsilon_d} \dfrac{c_{ml} - c_{mc}}{\Gamma_{ml} - \Gamma_{mc}} \Gamma_{mc}\Gamma_{ml}) \\ \sigma = -\dfrac{c_1}{\varepsilon_d\Gamma_d + \varepsilon_g\Gamma_g} + \dfrac{\Gamma_d}{\varepsilon_d\Gamma_d + \varepsilon_g\Gamma_g} \dfrac{c_{ml} - c_{mc}}{\Gamma_{ml} - \Gamma_{mc}} \Gamma_{mc}\Gamma_{ml} \end{cases}$$

A.2 Stylized complex model

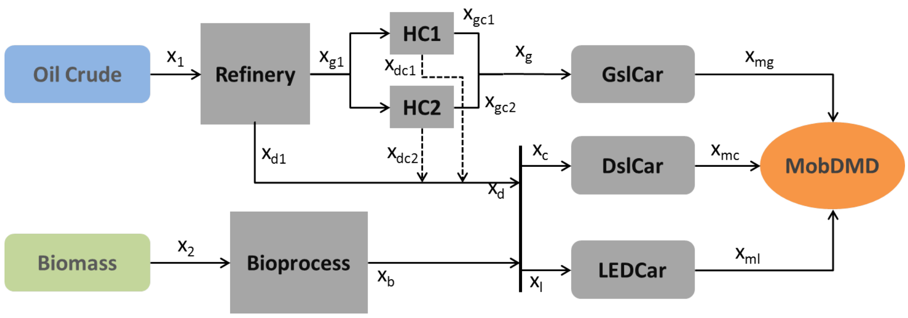

Figure 21: Complexified refinery

A.3 Parameters values

	Case 1	Case 2
Γ_g	0.4	0.7
Γ_d	0.6	0.3
Γ_b	0.4	0.4
γ_c	0.5	0.5
γ_l	1	1
c_1	0.02	0.02
c_2	0.028	0.03
c_{mc}	0.2	0.2
c_{ml}	0.3	0.25
N	0.1	0.1
Mobdmd	4	4
Gdmd	2	2
ε_d	3.16	3.16
ε_g	2	0
cHC1*	0.02	-
cHC2*	0.08	-
Γ_{dHC1}*	0.1	-
Γ_{dHC2}*	0.2	-

Figure 22: Parameters values used for the stylized model (*:Complex case only.)

B Results

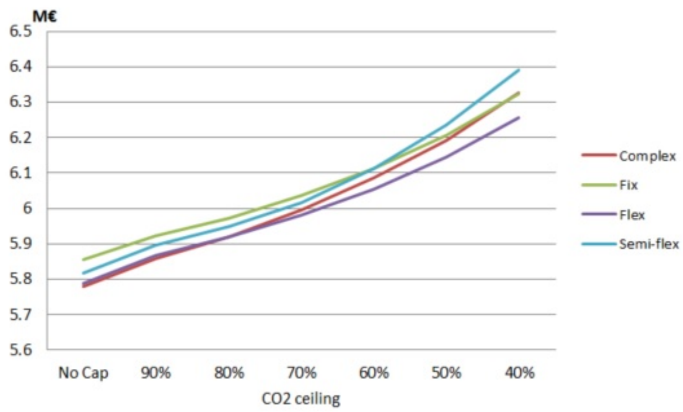

Figure 23: Objective value evolution with different levels of CO_2 emission ceilings

The flexible refinery model adapts logically at the lesser cost since the yields flexibility is free in this case.

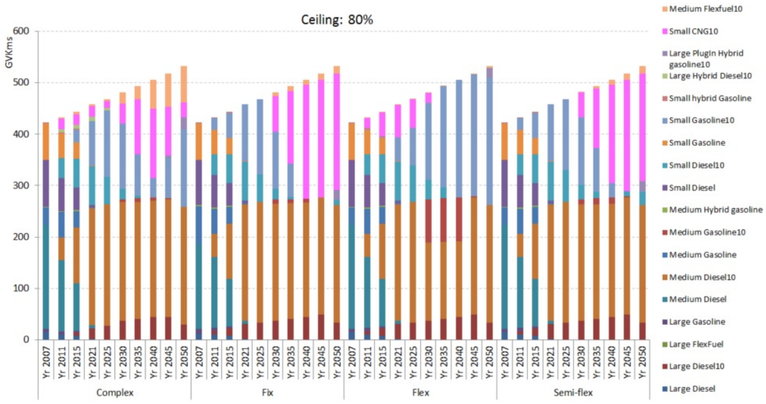

Figure 24: Cars activity : 80% Ceiling

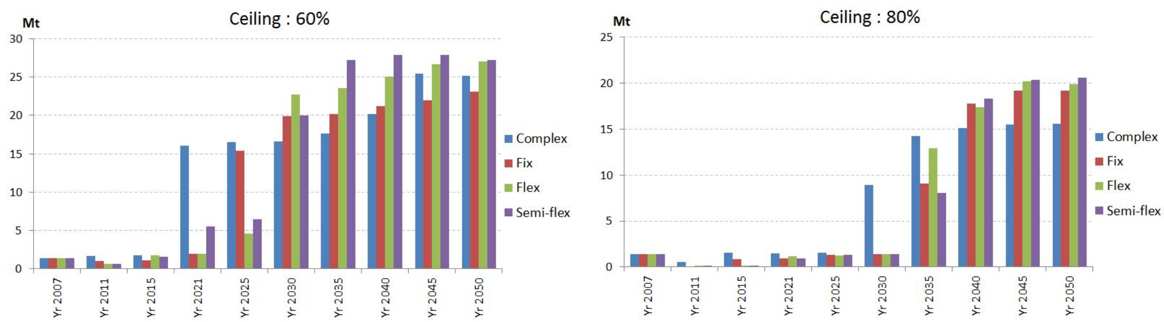

Figure 25: Biofuels in Transportation: 60% and 80% cap

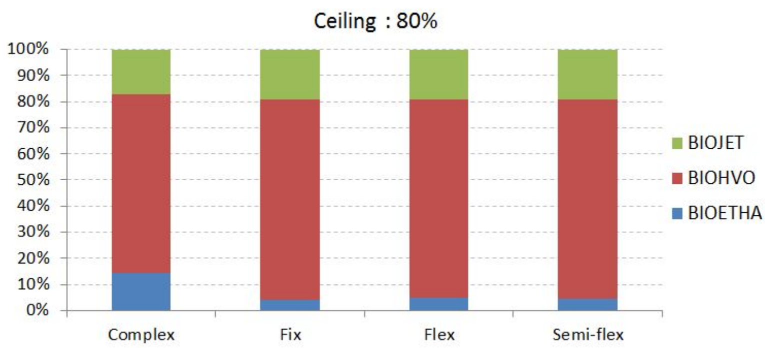

Figure 26: Biofuel use in proportion during the whole period : 80% Ceiling

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