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Chaire Modélisation prospective au service du développement durable

Electric vehicles: What economic viability and climate benefits in contrasting futures?

An exploratory essay by

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Summary

This paper presents a study conducted by CIRED which focuses on macroeconomic and macro-energetic aspects of the electric vehicle (EV) deployment, using the hybrid model Imaclim-R. It captures interactions between the dynamics of the world economy and of technical systems. The analysis first conducts an in depth exploration of the uncertainty that surrounds some determinants of future evolutions of the EV, including the time profile of oil prices and the existence of significant climate policies. Results show that EV deployment can positively impact the economy, in particular in scenarios with tensions on oil prices and climate policy scenarios. The EV avoids dependence on oil imports and creates local employment. It avoids the use of carbon-intensive synthetic fuels. The EV also plays a key role when climate policies tend to limit GHG emissions. It reduces the required level of carbon tax to achieve these limitations, by leveraging the technical change in the electricity sector induced by those climate policies. It then allows a significant reduction on emissions from private transport, a segment that is particularly insensitive to economic signals. Finally, an early effort to develop EV-oriented infrastructure networks and industrial coordination entails a net gain on GDP.

Keywords: general equilibrium model, inertia, uncertainty, prospective, electric vehicle, social value, mitigation, climate change

Résumé

Ce papier rend compte d'une étude sur le véhicule électrique (VE) menée au Cired qui se concentre sur les aspects macro-énergétiques et macro-économiques en utilisant le modèle de prospective hybride Imaclim R. Celui-ci associe à la fois une représentation des principaux rouages économiques et des systèmes techniques explicites. L'accent est d'abord mis sur l'exploration de l'incertitude qui pèse sur certains déterminants de l'évolution future du système économie-technologies. L'étude évalue également la valeur sociale, c'est-à-dire les bénéfices ou les coûts, de la pénétration du véhicule électrique au sein d'un spectre de 1024 scénarios. Les résultats montrent que le développement du VE peut avoir un impact positif sur l'économie, en particulier dans les scénarios de forte tensions sur les ressources fossiles et ceux avec politiques climatiques. Le VE évite tout d'abord de recourir à des importations de pétrole et constitue une source d'emploi local. Il réduit le recours à des carburants de synthèse intensifs en carbone. Le VE joue de plus un rôle clé dans la mise en œuvre des politiques climatiques de limitation les émissions de GES. Il participe à la réduction du niveau de la taxe carbone nécessaire pour atteindre ces limitations, en mettant à profit le changement technique dans le secteur électrique induit par des politiques climatiques. Il conduit également à une réduction considérable des émissions liées au transport privé, un segment particulièrement insensible aux signaux économiques. Au final, un investissement précoce dans le développement des réseaux d'infrastructures et la coordination industrielle se traduit ainsi par un gain net sur le PIB.

Mots clefs : modélisation, économie, équilibre général, inertie, incertitude, prospective, véhicule électrique, valeur sociale, mitigation, changement climatique

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1 Introduction

Transportation is known to be a critical sector for climate policies: it is already the second largest source of world greenhouse gases (GHG) emissions (IEA 2006) and there is, so far, no large-scale cheap substitute to gasoline to feed cars, buses, lorries and planes. This is why reducing drastically the contribution of this sector to global warming is expected to involve very high carbon prices and/or public subsidies (IPCC 2007, p.11).

There are four policy variables to cutback GHG emissions from the transportation sector: (i) travel demand management (ii) modal shift (iii) higher share of non fossil fuels and (iv) lower energy intensity/km through more efficient engines and/or change in the power and design of the car. However, these four strategies have intrinsic limitations. The first two involve lumpy investments and their effects on CO_2 releases will be very slow as they are related to urban organization and transport infrastructure. The third one is limited by important competitiveness margins of conventional fuel-powered engines that prevent alternative technologies from entering the market. As to energy efficiency improvements they interact with the mobility demand through mechanisms resulting into a rebound effect (Greening et al. 2000). The issue is that these mechanisms can temporarily mask the long term unsustainability of a transportation system based on high mobility levels and widespread use of refined oil, thus contributing to a lock in carbon intensive trajectories.

As seen in (Fischer et al. 2009), recent progresses on batteries made all-electric vehicles (EV) seem like a viable technology option. They could partially solve the problem of transportation in climate stabilisation. EVs may be able to shift transportation emissions from private vehicles to centralized power generation, where abatements are likely to be easier to achieve. With appropriate electric power supply, EVs may reduce emissions in the home-to-work transportation without changing users' habits and without re-organizing urban dispositions. Nevertheless, at this stage, the economic viability of the EV industry[1] is not guaranteed. Technically, it requires the coordination of many different actors (e.g. battery makers, electric motors producers, conventional car manufacturers and electric power producers and distributors) who might not anticipate equally EVs suitability. Moreover, as batteries have limited ranges, the development of a specific management net[2] might be necessary to enable a massive penetration. Last but not least, EVs must have a reasonable business model to convince consumers in a competitive market.

At the same time, automotive industry is going through heavy losses as a consequence of the financial and economic crises and the recent spike in oil prices. This has led some governments to design rescue plans with a twofold objective: prevent these labour intensive industries from bankruptcy and at the same time induce climate friendly technical change on the vehicle supply side. These plans may include support to R&D, infrastructure development and industrial actors' coordination. The objective of this paper is both to assess the social legitimacy of a wide public support to the electric vehicle and the overall impact of a massive EVs penetration on the energy system and on GHG emissions.

While the existing literature frequently focuses on energy-oriented issues raised by EVs (Anderman 2004) and economic benefits of their penetration obtained through partial equilibrium analyses (Kempton & Tomic 2005; Werber et al. 2009), our study uses a general equilibrium analysis, Imaclim-R. This is a hybrid environment-economy-energy (E3) model, in which natural resources, technology availabilities and

[1] The "EV industry" represents EV manufacturers and their main EV-specific upstream suppliers.

[2] As a battery charge or change network

international economy evolve consistently. This model is meant to encompass the main uncertainties surrounding the evolution of the economy and energy system.

By defining a high number of different contexts based on contrasting assumptions, we compare, for each context, the effect of two public strategies: to grant or not an early support to the EV industry. We then assess the public support opportunity in each of the simulated contexts. Our evaluation is set on the exploration of interactions between energy development patterns, EV economic viability, and households' revenue.

The remaining of this report is structured as follows. In section 2, we explain our methodology: an overview of Imaclim-R is provided in 2.1, and our different assumptions concerning the uncertainty that surrounds the parameters of the energy and economy futures evolution are gather in 2.2. The transportation sector, particularly the car markets ant its calibration is the object of section 2.3, which includes the modelling of a public support to the EV industry (2.3.4.2). We then expose our result regarding the EV economic viability (3) and the macroeconomic evaluation of its massive penetration (4). We conclude in section 5.

2 Modelling framework and scenario development

2.1 The IMACLIM-R model and the dialogue between engineers and economists

IMACLIM-R is a hybrid recursive general equilibrium model of the world economy divided into 12 regions and 12 sectors (see Table 1). It is solved in a yearly time step from 2001 to 2050 (Sassi et al. 2009). The base year of the model is built on the GTAP-6 database, which provides a balanced Social Accounting Matrix (SAM) of the world economy. The original GTAP-6 dataset has been modified to (i) aggregate regions and sectors according to the IMACLIM-R mapping, and (ii) accommodate the 2001 IEA energy balances, in an effort to base IMACLIM-R on a set of hybrid energy-economy matrixes.

Regions	Sectors
USA	Coal
Canada	Oil
Europe	Gas
OECD Pacific (JP, AU, NZ, KR)	Liquid Fuels
Former Soviet Union	Electricity
China	Air
India	Water
Brazil	Other transports
Middle-East Countries	Construction
Africa	Agriculture
Rest of Asia	Energy-intensive industry
Rest of Latin America	Composite (services and light industry)

Table 1 Regional and sectoral disaggregation in IMACLIM-R

As a general equilibrium model, IMACLIM-R provides a consistent macroeconomic framework to assess the energy-economy relationship through the clearing of commodity markets. Specific efforts have been devoted to building a modelling architecture that allows incorporate in a consistent manner technological information coming from bottom-up models and experts' judgement about how final demand and technical systems are transformed by economic incentives. This is allowed by the existence of physical variables that explicitly characterise equipments and technologies (e.g. the efficiency of cars, the intensity of production in transport, etc.). This is made possible through describing the economy is in both money-metric terms and physical quantities, and by linking these two dimensions by a price vector. This dual vision of the economy guarantees that the projected economy is supported by a realistic technical background and, conversely, that any projected technical system corresponds to realistic economic flows and relative prices.

The full potential of this dual representation could not be exploited without abandoning the use of conventional aggregate production functions that, after (Berndt & Wood 1975; Jorgenson 1981), were admitted to mimic the set of available techniques and thus the technical constraints impinging on an economy: it is arguably almost impossible to find mathematical functions flexible enough to cover large departures from the reference equilibrium and to encompass different scenarios of structural changes resulting from the interplay between consumption styles, technologies and localisation patterns (1993). In IMACLIM-R the absence of formal production functions is compensated by a recursive structure that allows a systematic exchange of information between:

- An annual static equilibrium module with a) Leontief production functions (fixed equipment stocks and intensities of intermediary inputs (including energy) and labour b) a flexible utilisation rate of capacities that allows for capturing possible over or undercapacities due to imperfect expectations of markets . Solving this equilibrium at some year t provides a snapshot of the economy: information about relative prices, output levels, physical flows and profit rates for each sector and allocation of investments among sectors.

- Dynamic modules, including demography, capital dynamics (investments and depreciation) and technical change. Sector-specific reduced forms of technology-rich models assess the reactions of technical systems to the previous static equilibriums and these reactions are then sent back to the static module in the form of updated input-output coefficients to calculate year (t+1) equilibrium.

Between two equilibriums, technical choices are fully flexible for new capital only; the input-output coefficients and labour productivity are modified at the margin, because of fixed techniques embodied in existing equipment and resulting from past technical choices. This general putty-clay assumption is critical to representing the inertia in technical systems and the perverse effect of volatility in economic signals.

IMACLIM-R thus generates economic trajectories by solving successive yearly static equilibriums of the economy interlinked by dynamic modules. Within the static equilibrium, in each region, the demand for each good derives from household consumption, government consumption, investment and intermediate uses from the production sectors. This demand can be provided either by domestic production or imports and all goods and services are traded on world markets. Domestic and international markets for all good are cleared by a set of relative prices that depend on the demand and supply behaviours of representative agents of each region. The calculation of this equilibrium determines relative prices, wages, labor, quantities of goods and services, and value flows.

The dynamic modules shape the accumulation of capital and its technical content; they are driven by economic signals (such as prices or sectoral profitability) that emerge from former static equilibriums. They include the modelling of (i) the evolution of capital and energy equipment stock described in both vintage and physical units (such as number of cars, housing square meter, transportation infrastructure), (ii) technological choices of economic agents described as discrete choices in explicit technology portfolios for key sectors such as electricity, transportation and alternative liquid fuels, or captured through reduced form of technology rich bottom up models, and (iii) endogenous technical change for energy technologies (with learning curves).

In this framework, the main exogenous drivers of economic growth are population and labour productivity dynamics that determine a potential growth. The real growth between two points in time results from the interplay between international trade, particularly that of energy commodities, labour markets (through a wage curve), capital flows and the variation of the utilisation rates of productive capacities,

The next subsection describes how we use this model to build prospective scenarios and explore the key uncertainties and it presents the modelling choices for some critical dynamics modules. For more details on these modelling choices, the reader should refer to (Sassi et al. 2009).

2.2 Scenarios: neither “best guess” nor arbitrary “storylines”

2.2.1 Articulating three layers of uncertainty

Decisions for large scale technological projects like the EV, the nuclear power or the bioenergy have to be made in a context of radical uncertainty. The approach selected in this study tries and avoids both the traps of the ‘best guess’ or ‘more likely’ scenarios, which come to an illusory reduction of uncertainty and the symmetric trap of defining somewhat arbitrary ‘storylines’ amongst the many possible ones. It aims in some way at giving a structure to uncertainty in order to disentangle the role of a) exogenous uncertainty about critical parameters b) regulatory uncertainty (such as the existence of climate policies) c) endogenous uncertainty created by the interplays between the parameters in the modelling structure.

The detailed representation of the dynamics that drives the energy system and the material content of the economic growth in the IMACLIM-R model allows us to describe in a consistent manner a) the interplay between consumption styles (C), technological choices (T) and localisation patterns (L) (Hourcade 1993) that drive the mobility needs and global energy demand b) critical technical uncertainty (e.g. carbon capture and sequestration (CCS) availability, ultimately recoverable fossil resources availability and accessibility, etc). At each level, uncertainty on fields is translated into a wide set of critical parameters[3]; for CCS for example, these parameters include the date of availability in each region, capital costs, technology learning rate, maximum socially and technically achievable market shares, etc.)

These critical parameters (CPs) take part in the calibration of the model and define the macroenergetic context in which the model run is performed. They must be distinguished from endogenous outputs that results from model runs. For example, the maximum possible share of CCS-equipped coal plants over the whole electric sector is a CP, but the actual CCS equipment rate is an endogenous variable that is consistent with carbon shadow prices, electricity demand, etc. To put it in another way, a scenario defined with optimistic parameters about the ultimate performance of a technology may result in a non penetration of this technology if the economic conditions of this penetration are not met.

Physical constraints and technologies	Oil and gas markets
	Coal markets
	Alternative liquid fuel supply
	Carbon-free options for power generation
	Energy end-uses technologies
Strategic choices and behaviours	Middle-East strategy
	Development patterns
Macro economy	Time length of the current economic crisis

Table 2 The eight subsets of critical parameters that calibrate the baselines

We identified hundreds of CPs, and two practical choices had to be made to avoid combinatory explosion. First, selected parameters are aggregated into fewer consistent subsets. For instance, all the parameters that describe the future availability of oil and gas are aggregated into an “oil and gas markets” scenario variable. These scenario variables are made up with two alternative sets of values for each CP of the subset. As a result, each scenario variable can take two values in the form of two vectors of CPs. Eventually, we distinguish height scenario variable covering the major drivers of macroenergetic contexts as a combination

[3] Explanation of a more complete list of critical parameters is the purpose of section 2.2.2

of assumptions on natural resources, technology availabilities and international economic trends (see Table 2).

All the possible combinations of the modalities in those variables lead to 2^8 (i.e. 256) contexts that we call baselines. In each of these baselines, we assess the effects of climate policies implementations. Therefore, we introduce a ninth critical parameter subset covering the existence of climate policies (encompassed by a carbon tax as we explain later). In the methodology, we do not refer to 'EV support' as a part of climate policies, as the objective of this paper is to consider the opportunity of a massive EV penetration. We then decline the 512 (2^9) contexts into 1024 scenarios, half with an early support to the EV industry, and half without it (we explain how the early investment in EV sector is modelled in section 2.3).

In the next subsection, we detail the content of each parameters subset and shed some light on the underlying modelling principles.

2.2.2 Scenario variables and uncertain parameters subsets

2.2.2.1 Oil and gas markets

The modelling structure of oil supply in IMACLIM-R is based first on a physical description of oil resources with an explicit differentiation of these resources by region and nature (conventional vs. non-conventional) and on the evolution of oil producing capacities described by the dynamic sub-model.

Oil resource availability is based on data from (USGS 2000; Greene et al. 2006; Rogner 1997) and was corrected according to estimations of Total about oil resources and future field production profile. An explicit differentiation is made between fourteen (seven conventional and seven non conventional) categories of resources in each region according to the cost of exploration and exploitation. As oil must be discovered before it can be produced, the temporal availability for production of a given category of oil resource depends on the characteristics of the discovery process, which is submitted to two main effects: the information effect (the more an oil slick is exploited, the more information about the localisation of remaining resources is obtained) and the depletion effect (the more a slick is exploited, the less oil remains in the soil). Following (Rehrl & Friedrich 2006) the resulting inertias in the deployment of oil producing capacities are captured through independent bell shaped curves that give the time-evolution of oil producing capacities for each category of oil in each region.

As to the dynamics of production capacities, IMACLIM-R makes a distinction between 2 types of oil producers according to their investment behaviours. All non Middle-East countries are supposed to be motivated by short-term return on investments, which implies that they will bring a category of oil reserve into production as soon as the selling price on world market exceeds the total cost of exploration and exploitation). The development of production capacities is thus limited by geological constraints and strictly follows the corresponding bell shaped curve. These producers who do not adopt any strategic behaviour are referred to as 'fatal producers'. As to the Middle-East producers they are one of the scenario variables because they exert a market power that enables them to conduct several strategies. For a given year, Middle-East production capacity is still bounded by a bell-shaped curve but its actual value can be below this limit if it decides to restrict production. This 'swing producer' behaviour is consistent with past OPEC production which has no longer fit the discovery trend since the 70's oil shocks (Laherrère 2001).

In addition to the investment behaviour of OPEC which will be analysed later, three major uncertainties are explored in the oil supply module:

- The amount of ultimately recoverable resources in each region: its lower bound at their aggregation at the world level is 3Tbl (*i.e.* 3.10^9 barrels or 134.5 Gtoe) accounting for both conventional and unconventional oil, while it is 30% higher at its upper bound.

- The share of the OPEC's amount of ultimately recoverable resources that can be extracted before depletion begins. At its maximum, it can begin when three quarters of the resources have been extracted – instead of half resources, in the opposite assumption – so that the production follows a tableau-shaped curve more than a bell-shaped curve.

- The shape of the curve for unconventional oil production capacity can differ due to inertias in their deployment This shape is the same as for conventional oil in the optimistic case where development of unconventional oil is easy; it is a more outstretched bell-shaped curves in the hypothesis of a deployment which confronts a higher inertia.

As to the gas, the world production capacities follow the demand until ultimately recoverable resources enter a depletion process. Gas prices are indexed on oil prices via a decreasing coefficient calibrated on the World Energy Model (IEA 2007). In the option 2 this indexation disappears when oil prices reach 80 $/bl[4]: beyond this threshold, the evolution of gas prices only depends on production costs and on the depletion effect, which leads to a sharp price increase. In the option 1 gas prices remain indexed on oil prices. Of course, the sharp increase of gas prices – that is initiated by gas resources depletion process – still stands.

2.2.2.2 The OPEC strategy

The Middle-East countries can use their market power in two polar ways (and any combination in between). The first is to secure high price levels over the short-run by limiting the expansion of production capacities; but this strategy has the drawback of inciting the oil importing countries to accelerate their efforts to develop oil-free technologies and to adopt energy-sober consumption patterns. The second one is a 'market flooding' strategy to maintain rather low prices over the short-term in order to discourage oil importing countries from sustaining such efforts. The basis trade-off is between low revenues in the following decades and higher rents in the long run, the lower price elasticity of the oil demand being due the lack of large scale cheap substitutes to oil. The trade-off between these two options does not depend only on the flows of export revenues, it also depends upon geopolitical considerations and long term objectives of the Middle-East governments, including the way they envisage the preparation of the 'post-oil' area. The conduct of these strategies will depend upon the internal cohesion among OPEC 'members and of Middle-East countries, some countries having less latitude than others to accept lower growth rates in the short term in the name of long term benefits. Because of these political constraints we selected 80 $/bl the oil price target pursued in the first strategy in the following decades and 40 $/bl in the second one.

2.2.2.3 Coal market

The coal is treated in a different way than oil and gas because of the larger amount of available resources which prevents coal production from entering into a depletion process before the end of the 21st century.

[4] USD per barrel.

We describe price formation on the world coal market with a reduced functional form which relates price variation to production changes, in order to capture the cyclic behaviour of this commodity market. In the first option, the coal price is supposed to be very sensitive to the utilisation rate of production capacities whereas in the second option it is supposed to be less sensitive to this parameter.

2.2.2.4 Alternative liquid fuels supply

In the following numerical exercises the biofuels (first and second generation) and Coal-To-Liquid fuels represent the main alternatives to refined oil over the 21st century. The penetration of biofuels is modelled according to worldwide supply curves published by the IEA (IEA, 2006). These curves define the maximum amount of biofuels that can penetrate the liquid fuel market, at a given date and for a given oil refined products' price (including taxes). They evolve over time in function of technical improvements in production processes and within the constraints on land availability and conflicts with food production[5].

These constraints and their feedback on the cost of biofuels are one major reason why synfuels may become a potentially competitive alternative to oil. In the following simulations, the main synfuel is Coal-To-Liquid (rather than Gas-To-Liquid) because of the abundance of coal resources. The decision to initiate CTL supposes to be made at a threshold value for oil price above which CTL producers take the risk of launching large scale production because it is competitive enough with oil refined fuels to reward investment risks. Beyond this threshold a constraint on the penetration rate of CTL is set to account for the inertia due to production investments maturation and the time necessary to deploy distribution network. This constraint is gradually taken off as CTL production increases.

In the following exercises, the upper threshold value is set at 200 $/bl and is associated with a low penetration rate, while the lower threshold is set at 120 $/bl.

2.2.2.5 Carbon-free options for power generation

The electric supply module in IMACLIM-R represents the evolution of power generation capacities over time, depending on the amount of available investment and changes in fuel and other factors prices. The expectations are adaptative; investment decisions are made anticipating ten years forward the future electricity demand and the future fuel prices on the basis of the extrapolation of recent trends. Moreover, the modelling structure accounts for the physical constraints that – in the absence of competitive technology for electricity storage – obstruct the extensive development of renewable capacities within the electrical grid due to their intermittent production, especially for solar and wind energy.

Given that electricity decarbonisation can have a strong impact on the oil sector through electric vehicles development our uncertainty analysis is focussed on carbon-free technologies (renewable energy generators – simply called *renewables* – carbon capture, and sequestration (CCS) and nuclear plants). The social acceptability and the future technical availability of these technologies spark off debates: future development, when technically possible, can be constrained by bottlenecks like the lack of technical skills or political barriers. Our approach implies that we do not pretend settling these debates; rather, we test for

[5] For the treatment of this constraint see Hourcade JC., Crassous R., Cassen C., Saglio S., Gitz V., *Biofuels and the Environment-Development Gordian Knot : Insights on the Brazilian*, Matisse project Working paper ; The numerical calibration benefited from the results from the Agrimonde project developed at Cired under the umbrella of the CIRAD and INRA (Cirad-Inra 2009)

each technology their impact on the effective available dates and the penetration rates, and, ultimately on the energy system and on the global economy.

In the scenarios where such constraints are progressively removed, renewable energies, CCS and nuclear energy can penetrate the markets early and at large scale, and their costs drops quickly thanks to learning-by-doing effects, whereas in the first one they face strong constraints on their development.

2.2.2.6 Energy and end-uses technology

The evolution of the final demand for oil refined products is related to the general level of activity but its ability to adjust to oil prices movements is again impacted by inertias on the renewal of equipments and on technical change in the three major oil-consuming sectors (industry, residential and transport[6]). In these sectors, inertias on equipments are captured by a description in capital vintages, each of them being characterized by their energy intensity and a final energy mix. At each point in time, energy prices affect the selection of new equipments (that include technology explicit portfolio for automobile transportation) but not the technical characteristics of the existing production capacities. Since IMACLIM-R relies on an endogenous technical change framework, the costs of equipments and production techniques are related to their cumulative production through the usual learning curves. Because of the embodiment of technical change in equipments, endogenous technical change captured in IMACLIM-R has to be interpreted as encompassing both R&D and learning-by-doing.

2.2.2.7 Development patterns

In addition to the uncertainty surrounding technological changes, the IMACLIM-R model allows to include contrasted views in development patterns. The articulation between consumption styles, technological and localisation patterns is a critical parameter for the energy future with and without climate policies for any region in the world. However, the major uncertainty is about how this articulation will be made by developing countries in the next decades. Even though the economic context will matter in the shaping of development patterns, it will do so together with infrastructure decisions that involve political bargaining, as well with the evolution of households' preferences in various cultural contexts. The first set of related scenario variables will describe a 'mimetic' development pattern, in which developing countries want to catch up with the western lifestyle (vast houses in spread and mobility-intense cities, high calorie intake per capita) and asymptotically the US development pattern. A second set of scenario variables describes an alternative orientation towards, asymptotically, an EU development pattern. This set assumes infrastructure policies (to discourage or not urban sprawls), the agents' preferences for automobile transport and vast individual dwellings (through income elasticities), as well as a lower role of the 'just in time' and distributed industrial processes. The reader must keep in mind that endogenous outputs will be influenced by those parameters, while remaining coherent with the economic context, through the resolution of the economic equilibrium.

2.2.2.8 Economic growth and uncertainty about the current economic crisis

Numerically, one major uncertainty is about the future of the economic growth. The discrepancy in results with a 8% growth rate for an emerging economy instead of a 9% leads to an impressive 1.59 difference over 50 years. But, for today policy decisions one major difference may be the duration of the present economic

[6] See section 2.3.1

crisis. This is why we tested two alternative time ranges: 2 years, which means a recovery in 2010 or 5 years (recovery in 2013).

2.2.3 Implementation of climate policies

Without climate policies, the world economy follows a "business as usual" (BAU) trajectory and carbon shadow prices are null. With climate policies, the model calculates year by year the carbon price associated with a trajectory that leads to emissions consistent with a concentration ceiling of 450 ppm CO2-equivalent. This corresponds to category I of (IPCC 2007) and requires the global emissions to be halved in 2050.

The future of climate policies is very uncertain or, more precisely, there are doubts about the possibility to have a fully fledged carbon market resulting from a Kyoto type framework extended to the entire world. Since the aim of this tentative exercise is not to cover the spectrum of possible climate architectures, we selected one with fragmented markets reflecting the discrepancies in the claimed willingness to act and the prevailing notion of common but differentiated responsibility.

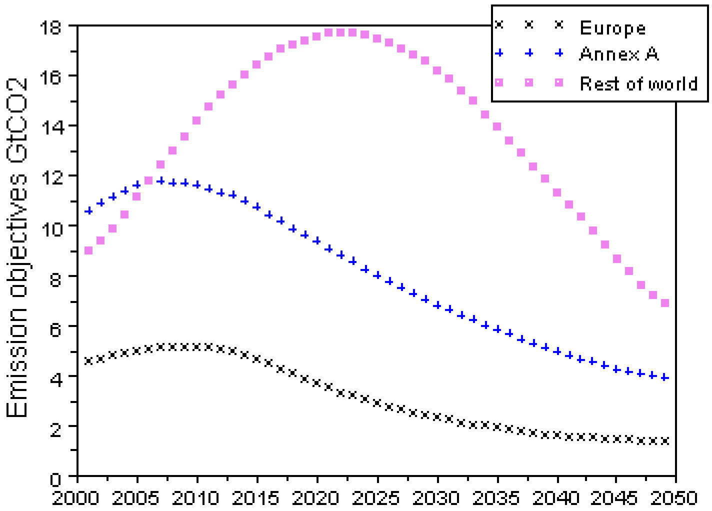

Figure 1 GHG emissions objective of the three carbon markets

In practice, the world is segmented in three markets with no emissions trading between them (segmented policy architecture). Therefore, the endogenously calculated carbon shadow prices differ *a priori* in each group of region.

Europe achieves a 75% reduction of its emissions in 2050 with respect to 2001. Other annex A regions (USA, Canada, OECD Pacific, Former Soviet Union) make a 60% reduction. The rest of the world (India, China, Brazil, Africa, Middle East, Rest of Latin America and Rest of Asia) achieves laxer objectives that are calculated so that the entire world halves its emissions (Figure 1).

Table 3 summarizes the critical parameters subsets and the two modalities of climate constraints.

	Option 1	Option 2
Oil and gas markets	Low amount of resources Inertia on non conventional fuels Gas price always indexed on oil price	High amount of resources No inertia on non conventional fuels Gas price indexed on oil price until 80$/bl
OPEC strategy	Short-term wanted price: 80$/bl	Short-term wanted price: 40$/bl
Coal markets	High sensitivity of price growth with respect to production growth	Low sensitivity of price growth with respect to production growth
Alternative liquid fuels supply	Limited penetration	No constraints on penetration
Power generation decarbonization	Difficult decarbonization	Easy decarbonization
End-uses technologies	Limited penetration	Low constraints on penetration

Development patterns	Mimetic development pattern (transport intensive)	Less carbon-intensive pattern
Time length of economic crisis	5 years	2 years
Climate policies	Business as usual	3 markets leading to 450ppm CO_2-eq.
	Option 1	**Option 2**

Table 3 Summary of the critical parameters subsets and their alternatives

2.3 Modelling personal vehicles market and EV public support

2.3.1 The transportation sector in IMACLIM-R and the rebound effect

Transportation is a typical sector in which we use the IMACLIM-R modelling architecture to include sectoral specificities in a consistent macroeconomic analysis. The transportation modelling is thus an attempt to disentangle specific mechanisms of transportation dynamics:

- The transportation demand described in the static equilibrium allows representing in a stylized way (i) rebound effects (Greening et al., 2000) associated with energy efficiency improvements and (ii) the induction of mobility demand by infrastructure policies (see Goodwin, 1996) that determines the modal break down. To that end, the households' mobility is defined as an aggregate of four imperfectly substitutable travelling modes (air travel, public transportation modes, personal cars[7] and non motorized modes). This aggregate is one of the elements of each region representative household's utility function. Households' choices are made, in addition to a budget constraint under a travelling-time constraint.[8] Each mode's « effective speed » (average distance covered in an hour of travel time) is described as a growing function of the dedicated public infrastructures. As for productive sectors, transport consumption (an intermediate input which includes freight) depends on specific Leontief coefficients (reflecting sectors' transportation intensity), leading to a total "intermediate demand" consistent with the economic activity level. These coefficients evolve in time in function of the scenarios.

- The transportation dynamic module alters the technical constraints that hinge on transportation demand formation in the static equilibrium: it keeps track of and adjusts the energy efficiency of vehicles, households' car equipment, the freight content of economic activity and last but not least transportation infrastructure policies.

More practically, total households' time dedicated to mobility evolves correlatively to total population. The motorisation rate is related to the evolution of *per capita* disposable income with a variable income-elasticity: for very poor people, the access to motorised mobility rests on public modes and income-elasticity remains low; households with a medium *per capita* income have access to private motorised mobility and the motorisation rate becomes very sensitive to variations of income; for the higher *per capita* income levels (those prevailing in the OECD) saturation effects appear and the income elasticity of the motorisation rate declines. Numerical values are adjusted from SMP Model (Fulton & Eads 2004) for comparable GDP per capita growth comparable[9] . As emerging economies may play a lead role in increasing mobility demand, we

[7] Personal cars are also referred to as "own-supplied mobility" in this paper.

[8] Following "Zahavi's law" (Zahavi and Talvitie, 1980) establishing that the daily time spent in transportation is quite stable across time and regions of the world, regardless of the transportation mode—and hence of the distance covered.

[9] Time steps (one year in Imaclim, five in SMP) and regional disaggregation differs in the two models.

encompassed uncertainty on their future own mobility demand by adjusting the income elasticities found in the previous calibration to a higher or lower value in function of the development pattern scenario variable.

Various policies about investment in transport infrastructure can be tested through different routines, but in this paper we stick to the conservative assumption that transportation infrastructure building follows the modal mobility evolution. The freight content of the economic growth evolution is an exogenous scenario

2.3.2 The electric vehicle, in competition with four technologies

Five types of personal vehicles (also referred as "technologies" in this subsection) are considered in this version of Imaclim-R: internal combustion engine standard (ICE_std), efficient ICE (ICE_eff), hybrid (HYB_std) and efficient hybrid (HYB_eff), electric vehicle (EV). Each technology is specified as a set of a capital cost, an energy intensity and an operating and maintaining cost (O&M). Energy consumption (stated in litres of gasoline equivalent by kilometre, lge/km) is related to conventional gasoline and diesel, but also to biofuels and synfuels as CTL or electricity. Instead of having specific car technologies for each liquid fuel type, those are supposed to be mixable with refined oil, and all the modelled vehicles (except EVs) can run equally well on a blend of CTL, biofuel or diesel/gasoline. Electric consumption is typically null except for EVs (we do not explicitly take plug-in hybrid vehicles into account). O&M costs are considered as variable costs and modelled as a quantity of composite sector consumed per unit of travelled distance.

Each year, an endogenous vehicle equipment rate is computed by the dedicated dynamic module of Imaclim-R, as a region-specific function of personal income: this rate derives from annual sales and yearly fleet depreciation (given the vintaged stocks and lifetimes). They are then allocated amongst the different technologies in function of the complete life cycle cost (LCC) of each technology, its capital cost, energy intensity, electricity and liquid fuels prices (including all taxes as well as a hypothetical carbon tax), operating and maintaining (O&M) costs, the annual average travelled distance and a discount rate[10]. Market share of a given vehicle type is then computed trough a logit function on LCCs[11] in order to account for inhomogeneous customers' preferences and diversity of cars uses. Taking into account that only a small part of the fleet is replaced each year we eventually compute the regional fleet input-output coefficient as a mean on all operating car vintages. Thus, energy efficiency improvement is encompassed at a macroeconomic scale: when fuel prices grow, households naturally go over more energy efficient cars.

As for all technologies in the IMACLIM-R model, the car dynamic module lays on a full representation of induced technical change through the broad use of learning curves (Arrow 1962) that link decrease in capital cost to the cumulative sale of a given technology. As far as automobile technologies are concerned, the learning rate is set at a 10% value if technologies are in option 1 (see 2.2.2.6), and at 20% in the option 2 case.

2.3.3 Technical characteristics of the competing technologies;

We modelled five specified technologies: ICE_std, ICE_eff, HYB_std, HYB_eff and EV. Those technologies have different technical properties in each of the twelve regions.

[10] We use a 13% discount rate that is even quite low for the kind of economic choice, reflects consumers' aversion to invest in more expensive but more efficient technologies, unless the financial payback time is short. Consistently with Imaclim-R simulation philosophy, a high discount rate represents better actual consumers' perception rather than optimal economic choices. The reader should keep in mind we do not answer questions like "what should economic agents do?" but "what would economic agents do?"

[11] For an example of consumer's discreet choice model using logit function, see (Horne et al. 2005)

As Imaclim-R is calibrated from year 2001 the initial market share of hybrid and all electric vehicles is less than 1% and we calibrate ICE_std technical properties to stick to the actual automotive sector consumptions in 2001. This way, ICE_stds' energy efficiencies vary from region to region. We then make sure that in the time period from 2001 to 2005, competition between ICE_std and ICE_eff, given the actual energy prices reproduced in the same period, lead input-output coefficients of regional fleets to match up to reality.

Hybrids (HYB_std and HYB_eff) and EVs' technical properties and costs are much more uncertain than for conventional ICE vehicles. Since corresponding vehicles don't widely exist yet in the marketplace, real energy effectiveness and actual capital costs relative to ICE_std cannot be made without explicit incorporation of expert's estimates. For each technology, we consider energy consumptions estimates as the world average consumption, and we reproduce the same regional disparity as noticed when dealing with ICE. We summarize the results for European market in Table 4.

Europe	ICE_std	ICE_eff	HYB_std	HYB_eff	EV
Consumption lge[12]/(100km) kWh/(100km)	9.0	6.7	4.5	2.4	2.0 (18)
Oil world price for market competitiveness[13] ($/brl)	[14]	75	130	270	160

Table 4 European cars consumption and competitiveness limit

2.3.4 EV penetration and maturity of industrial maturity

Section 2.3.2 explains how demand of different car types is formed each year endogenously, consistently with energy prices and economic activity. In this section we see how we relate EVs maximum market to the maturity of the EV industry.

2.3.4.1 Constraints on EVs penetration depend on industry's maturity

For the first years of simulation, we consider that EVs are not available at all, reflecting the fact that battery manufacturers and car builders are not equipped yet. EV's production is triggered beyond a price threshold and it enters an acceleration phase when it exceeds 1% of total sales. But, because of a lack of coordination in the deployment of ancillary infrastructures and institutions, the EV industry faces a "bottleneck phase" which makes the EV's availability growing slowly during 8 years. We encompass here delays from R&D on batteries and corresponding cars progresses, invention of a business model and the spread of a battery management network. Any demand that would be addressed to EV over the limit imposed by these pre-conditions is reported on the other four technologies on a *pro rata* basis.

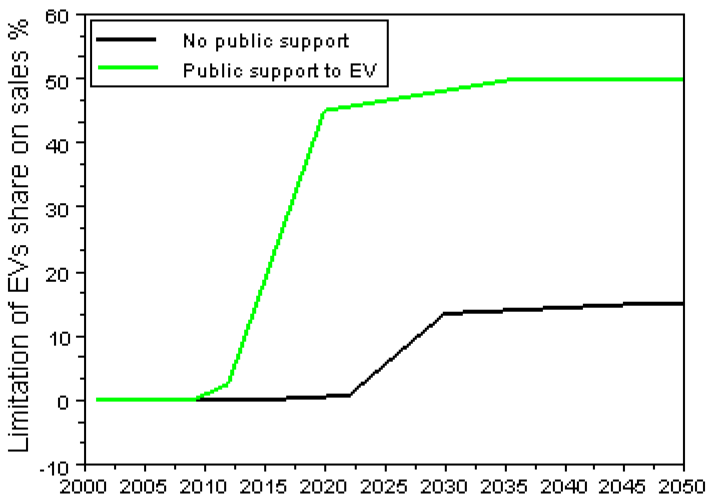

Figure 2 EV availability (maximum possible penetration) evolution, with and without public support to the EV industry.

[12] Litres of gasoline equivalent.

[13] We consider a technology as competitive when its demand market share on sales achieves one fifth (20 %) of total fleet.

[14] ICE_std represents the existent fleet in 2001: the competitiveness definition given in the precedent footnote does not apply.

We assume EVs to be only suitable for peri-urban mobility, as battery autonomy and the potential management net may not allow high autonomy at a reasonable cost everywhere (notably not in rural areas), and long distance trips are out of the question. Since we do not explicitly describe localisation, we take that into account in a macroeconomic approach, by limiting the final maximum market share that EV is able to cover. We set it to 15% when no early investment is directed to the industry (Figure 2).

2.3.4.2 Early support to EV deployment: not necessarily a subsidy

The Imaclim-R model rather conventionally pictures the supply of EV as a response to the demand of EV which results of the overall demand for cars and of the consumers' choice amongst the competing models. Under such a modelling approach, the profitability of investments is secured by a mark-up pricing (production cost plus a margin). But the pace of deployment of production capacities of EVs is conditional upon the tightness and the duration of pre-existing bottlenecks.

The specific economic problem posed by the EV in a public economy perspective is thus on who will accept to bear the costs of overcoming these bottlenecks given the uncertainty involved in the market for EVs. This is a question of better coordination within the EV industry, of a widespread standardized infrastructure for the refilling, maintenance and replacement of batteries availability

In the following numerical exercise the notion of early support refers to the existence of institutional conditions allowing for reducing the duration of the bottleneck to 3 years (instead of 8); and allowing EV for covering up to half of the provided mobility demand (Figure 2). It is worth noting that this does not necessarily account for public subsidies to households to lower the cost of EV ownership and the level of risk uncertainty for the industry, or for public subsidies to reduce the capital costs on infrastructures. Such incentives may be necessary, although their efficiency has been disputed by economic literature, but other types of public facilitation may be mobilized to improve the coordination between the car industry, distribution networks (currently controlled by the petrochemical industry), the electric sector, the local authorities and even the norms to be respected by public car parks.

This is why the following exercise will try and reveal the social benefit of such an early effort, leaving aside the question of the nature a public support of such an effort likely to avoid the risks of a large scale "windfall effect" and of the cost of such an early effort.

3 Three contrasting futures for the electric car

This study is a tentative essay which aims at providing some insights on the spectrum of possible scenarios for the EV more than to deliver a definitive assessment of its social benefits. One reason is that, although we build upon the expertise during prospective exercises conducted with the International Energy Agency, the World Bank and some European research projects[15] we cannot pretend to represent both the decarbonisation pathways and of the potential markets for EV with the same level of scientific control for regions other that European Union. However, since global dynamics are at stake, we venture to publish in the essay the findings for the USA, China and India, in view of demonstrating the likely commonalities and differences between the stylized scenarios found for these large countries by comparison with the EU case. We do so because our numerical results suggest rather robust qualitative insights. We thus describe the EU case in a rather detailed way before presenting an overview of the three other countries.

3.1 The European Case

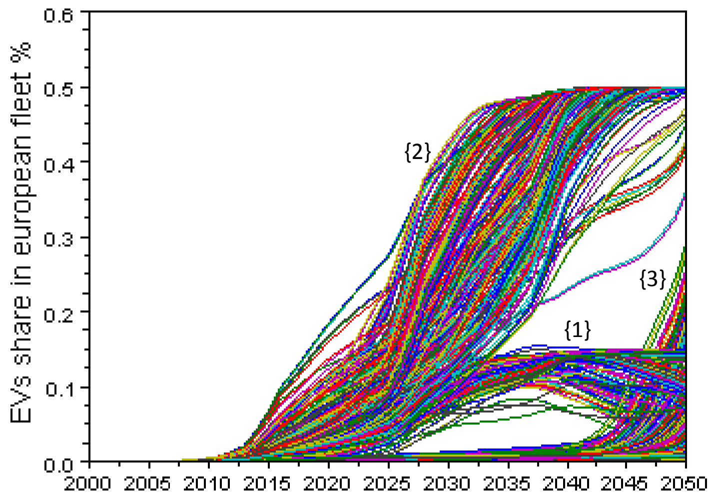

Figure 3 The 1024 simulated trajectories of ECs share in European fleet

A quick glance at Figure 3 shows that the trajectories of EV penetration obtained as a result of our 1024 scenarios have very contrasting end points but that these end points and the corresponding trajectories, instead of being evenly distributed with a normal law around a mean value, can be grouped into three easily distinguishable clusters:

-In the **first cluster**, EV emerge in the second third of the century, reach a maximum of 15% of European automotive park, stabilize at this maximum or decline more or less significantly after 2040. This is a form of *let us benefit from the niche* storyline

-In the **second** cluster, the emergence is quicker than in the first one but its key feature is that, once market shares stabilize at 50% (which results from a pure exogenous asymptote), it does not turn down before the end of the simulation period; this a *dominant technology* storyline

-In the **third cluster,** EV reaches end points often higher than in the first cluster and some of them will likely reach the 50% asymptote of the first cluster between 2060 or 2070 but there is no real take off of this technology before the turn of the century; this is typically a *wait and see* storyline.

Obviously, there are significant differences within each cluster, due to the fact that the simulations encompass a wide range of economical and technological assumptions. These differences matter for investment decisions but less than the existence of bifurcations towards three contrasted storylines. Would indeed one of them be certain, the decision problem would not be too complex: mid-course corrections

[15]World Bank, 2006, *Energy Scenarios for India and China : Implications for Energy Markets, Development and Climate Mitigation*, IEA, 2008, macroeconomic locking and expertise for the du World Energy Outlook 2007 , RECIPE project, 2008, *Long term mitigation scenarios* (with IMACLIM-R) , REMIND (PIK) and WITCH (FEEM) ; Matisse Project, 2008, 'A Novel Hybrid Architecture for Agriculture and Land Use in an Integrated Modeling Framework'

within these storylines can indeed always be operated and a more in depth analysis could reduce the uncertainty margins by attributing different probability weights to some parameters or combination of parameters. More tricky is the existence of bifurcations which makes very misleading any stochastic calculation to define a "more likely" or "best guess" future.

It is thus critical to delineate the parameters behind these three clusters and the surprising behaviour of the first (with a peak and a declining share). An **attribution analysis** shows that three storylines emerge as a combination of two parameters: the **liquid fuel prices** (themselves resulting from a wide set of determinants that we explain below) and **the public support to the** EV industry.

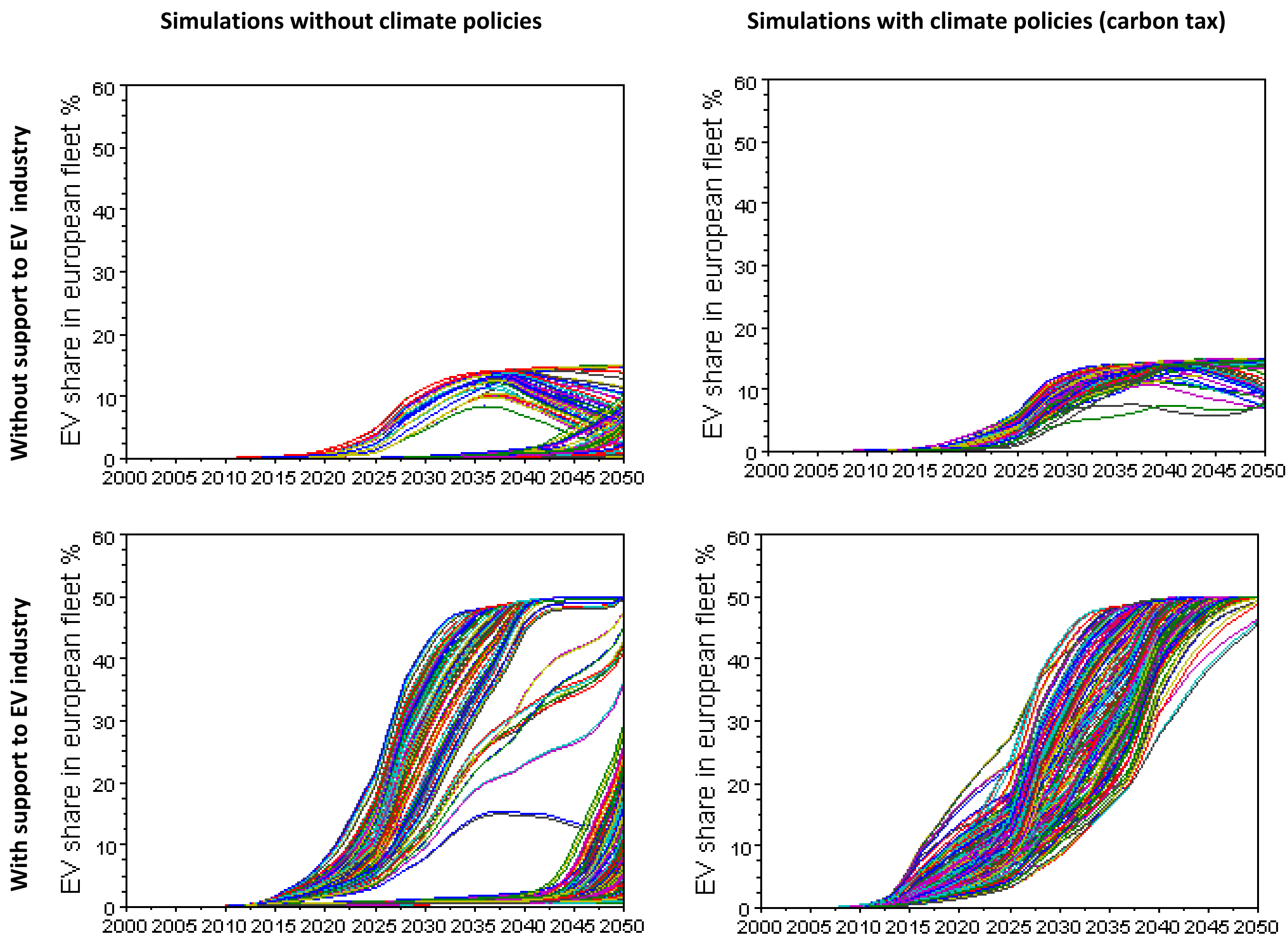

Figure 4 EV share in the European fleet as a function of public policies

Let us first compare the 512 simulations with and without early support. The striking feature that emerges from Figure 4 is that without early support, there is no chance to get a massive penetration (up to 50% of the number of vehicles) of electric cars and, symmetrically, that such an early support eliminates almost all the first cluster. Nevertheless, public support does not guarantee EVs early market success**,** as reflected by cluster-3-shaped market shares trajectories in the subset with a support to EC industry (the above row of Figure 4).

That the same early support ends into very different outcomes is obviously explained by the level of liquid fuel prices. These prices mainly depend on oil prices and carbon taxes. Actually, all our simulations leading to a massive penetration of EVs in the short-run present either one of those characteristics: (i) a world oil price that achieves more than 90$/barrel in 2015 or (ii) climate policies with a high carbon price in Europe[16].

A trail across the four quadrants of figure 4 demonstrates one of the key conclusion of this exercise is that the an early support to the electric vehicle is a necessary but not sufficient condition for a large scale deployment of electric cars after 2020 (which means basically that investment decisions have to be taken within the five following years).

In **the North West quadrant,** there is no climate policies and no specific support of investments and R&D on EVs. Unsurprisingly though, there is no early market penetration of EVs in a subset of scenarios with oil prices around 80 $/barrel in the middle of the twenties; in these scenarios the EV's take off is postponed beyond 2040. An early penetration is conversely triggered in scenarios with a high enough oil price (above 90$/barrel in 2015). Beyond this price, the EV start penetrating the cars market (between 2020 and 2030) because it is competitive but reaches a ceiling, due to the fact that the speed of penetration is too limited and trigger economies of scale and learning high enough to prevent the decline of the EV by the end of the mid-century when the overall context is less favourable and when more technical substitutes, such as the 2nd generation of biofuels, are available. Actually the start of a massive penetration of electric vehicles generates its own countervailing mechanism: it raises the pressure on electricity prices and lowers the pressure on liquid fuel prices. This allows for alternative techniques to cumulate technical change, including biofuels, unconventional oil and coal to liquid. This leads to a market share decline after 2040 in most cases of this cluster.

In the **North-East quadrant**, when climate policies allow for the emergence of a carbon price, there is no more any non penetration scenario. This is mainly due to the fact that, even if OPEC countries react by temporarily cuts in oil prices in order the OECD Countries to pursue climate policies, they cannot do so to a point at which the total of oil prices and carbon prices make the EV non competitive. Contrary to the dominant trend in the North-East in which the share of EV declines after 2035 in all but two scenarios, 33% of them stabilize at the peak level up to 2050 and, in other the market share, declines significantly less. One disappointing result however is that the penetration of the EV in 2035 is only a few percentage points higher than in the previous quadrant. The underlying mechanism behind this apparent ceiling is that a high price of gasoline has a mixed impact on EV: it avoids a significant decline of the market share of EV because it rules out a lot of carbon based alternatives to conventional oil but it also favours all the other carbon alternative technologies. It comes across that the pace of technical change is not sufficient to win definitely the race against 2nd generation bio-fuels and fuels-to-liquid plus sequestration.

The **South-East quadrant** is the only one in which the EC penetration is irreversible and reaches the 50% ceiling imposed by exogenous technical assumptions. There are large discrepancies amongst scenarios but a fifteen years delay between the most favourable and the most pessimistic scenarios to reach a 33% market share does not change the fact that investment decisions made over the following five years are not utmost risky. This means that, an early action on infrastructure investments to prepare the penetration of EC helps the EC to win the technological race against all its competitors.

[16]The fact that electricity prices do not affect electric deployment can be explained by (ii the fact that electricity prices have lower variations than liquid fuel price in our simulations (i) car market is not much sensitive to electricity prices variations *per se*. ECs energy efficiency is indeed more than two times higher than –per example– HYB_std efficiency. Therefore, a 10 % variation in electricity price is expected to have about the same effect (in EC *vs.* HYB_eff competition) than a 5 % variation in liquid fuel prices, as they have the same outcome in effective costs for households..

The **South-West quadrant**, although it seems not to correspond to consistent policies is worth analysing first to better understand the mechanisms at play, second because it may correspond to a political context in which public support is given to the EC and the post Copenhagen process fails in delivering worldwide climate architecture within the ten following years. In this quadrant, is remarkable that there is no room for an intermediary 'pick the niche' storyline and that there is a bifurcation between two very contrasted story lines, the "wait and see" option and the "dominant technology storyline". There are only a few intermediary trajectories between these two contrasting scenarios, which correspond to gasoline's prices just around the limit value which separates the two scenarios (90$/barrel in 2015). What matters in this result is less the exact value of this separating price than the very instability of a medium position between an early take-off and a "wait and see" policy. Obviously, in this quadrant, the early support to investments allows for a post 2040 take-off which leads in most cases to a 'dominant technology' position and the absence of a carbon price makes a far lower number of scenarios leading to a 'dominant technology' position as soon as 2030.

Any numerical experiment of this sort can obviously be criticized for being conditional upon the choice of the numerical values. In this case we have in particular to underline our rather conservative assumptions around the biofuels potentials. However, given the large spectrum of hypothesis we cover with our 1024 scenarios, the existence of bifurcation points seem to be a very robust result which has a very important policy implication, i.e. the necessity of a consistency between long run price signals and early support to investments to trigger in an irreversible manner the take-off of EV.

3.2 An outlook in other regions

We show in figures 5, 6 and 7 the same quadrants as in Figure 4 for the USA, China and India respectively. It is remarkable that the same types of clusters as in the EU appear in almost all cases, but in a less contrasted way and with a different weight.

For these three countries, the North-West quadrant (no climate policy and no early support) demonstrates a) the same let us benefit from the niche storyline as for the EU but with a decline of the EV market shares beyond 2040 that occurs in more scenarios than in the EU case b) only a very few scenarios with a wait and see storyline, or more precisely, almost no take-off before 2050. The basic reason is the low level of gasoline prices in these three countries; in case of unchanged pricing practices for gasoline, the rise of oil prices in the scenarios without early tensions on oil comes too late and is not high enough to make the EV competitive, whereas it is competitive in the EU in a significant number of scenarios after 2042.

In the South-East quadrant (no climate policy and early support) the USA, India and the EU demonstrate almost the same profiles. The differences are in consistency with the information of the NW quadrant about the role of baseline gasoline prices: the late take-off occurs, later and in fewer scenarios in the USA and in India and the *dominant technology storyline* cluster is less dense. The *niche* storyline disappears for China because most of the *niche* storylines of the NW quadrant are turned into dominant storylines (with a certain delay for many of them which makes this cluster less dense as for the other three countries) but no 'no take-off' storylines are transformed into a niche or late take-off storyline. This means that even an early support to EV, *coeteris paribus*, does not compensate for the learning by doing in conventional techniques and, at the end of the period, for the penetration of coal to liquid.

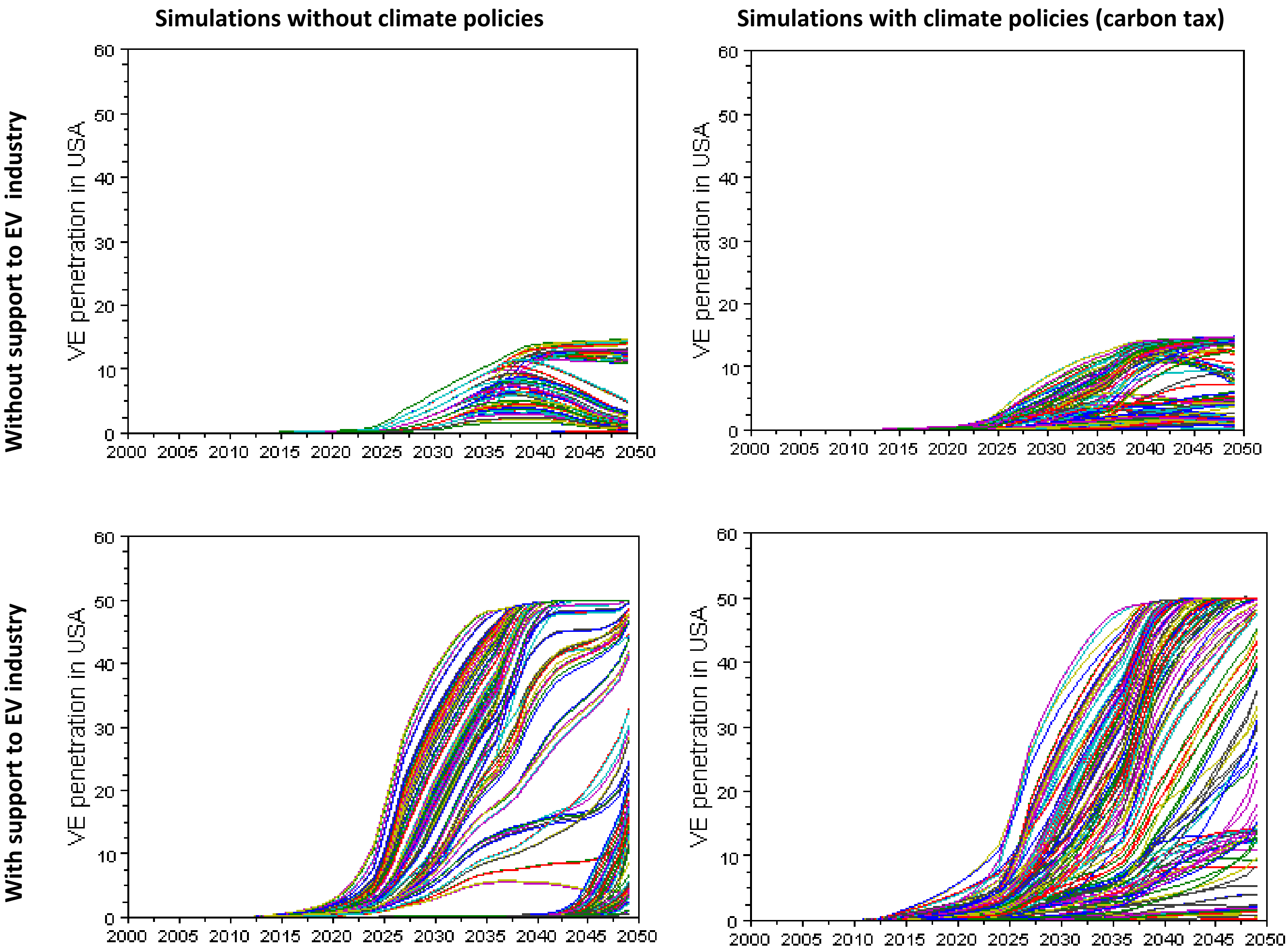

Figure 5 EV share in the American fleet as a function of public policies

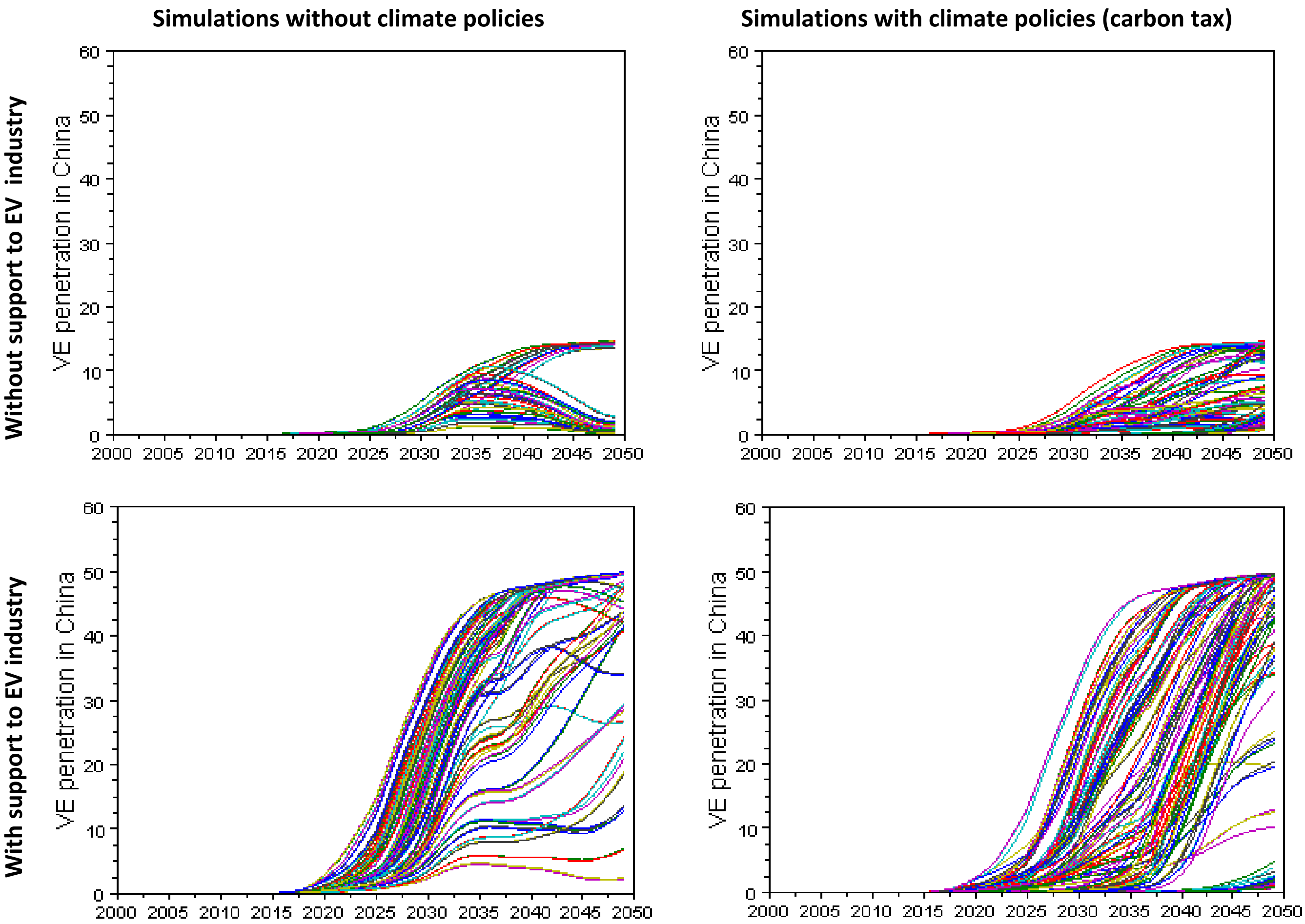

Figure 6 EV share in the Chinese fleet as a function of public policies

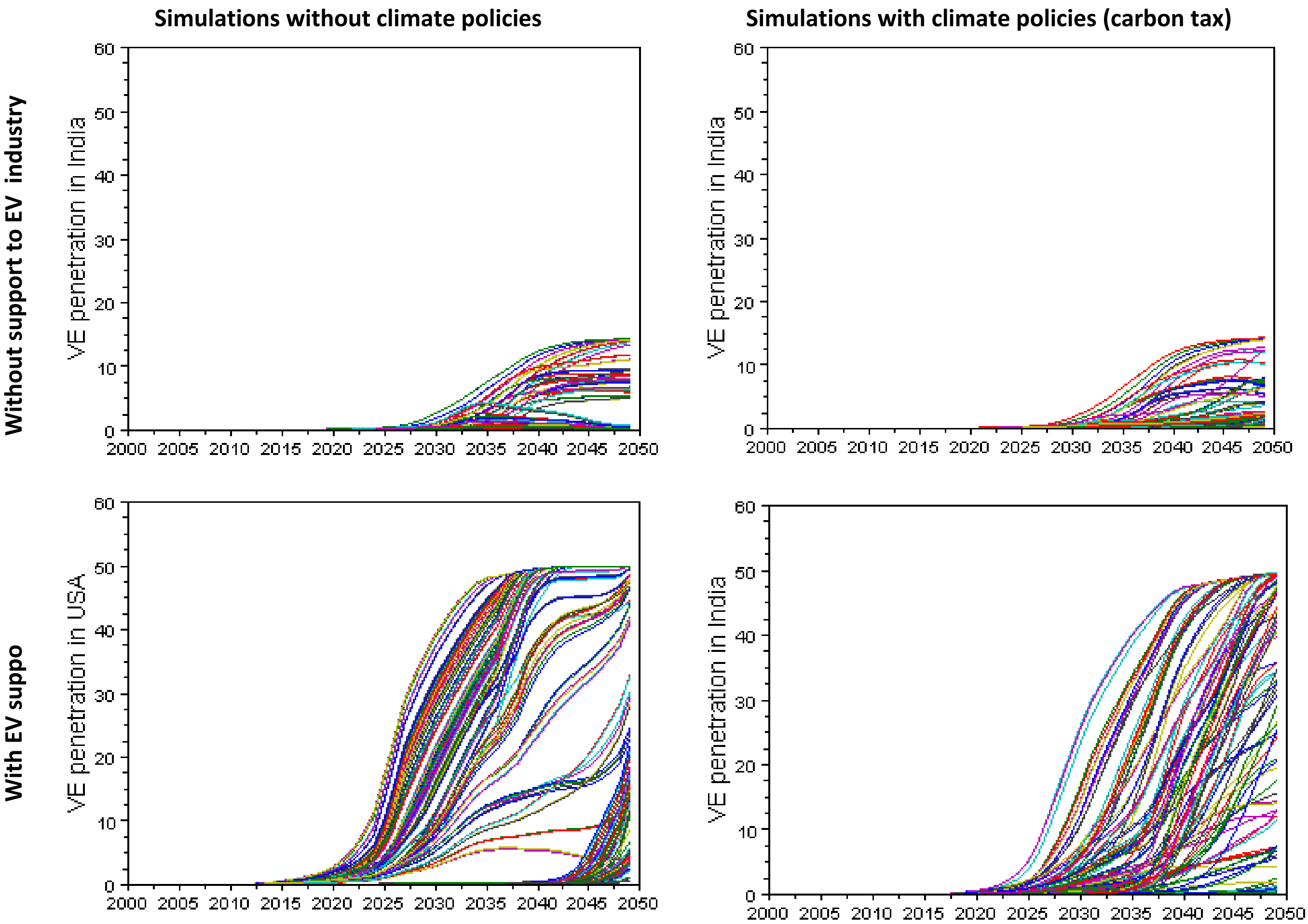

Figure 7 EV share in the Indian fleet as a function of public policies

The results of the climate policy scenarios displayed in the North-East and South-East quadrants can thus be straightforwardly interpreted. In the North-West quadrant, the emergence of a carbon price make a niches storylines to appear in many scenarios but a significant number of late take-off (and some absence of take-off) scenarios can still be found while they disappear in the EU. This is basically due to the fact that, on top of a lower gasoline price in the reference scenarios for the three countries, the carbon prices are lower in the US than in the EU and even more in China and India. In the early support and climate policy scenarios of the South-East quadrants the three regions tend to resemble the EU profile but with some delay, which makes the dominant technology cluster less dense in 2050, specifically in China and India.

These results are obviously very conditional upon the climate scenarios adopted in these exercises; but they confirm the fundamental mechanisms at play and the importance of early support in the emerging economies.

4 From the social value of EVs to the legitimacy of its public support

A public support to EV, in addition to the setting of a carbon price, is necessary to secure the large scale penetration of EVs. Nevertheless, it does not mean that it is economically justified in a public welfare maximizing perspective. To respond this question demands a prior understanding of **the macroeconomic benefits (or costs) of the penetration of EV.** To do so we compare the impact of early support on economic growth with and without climate policies in Europe. We then and assess what could be the social value of EV and discuss briefly the main issues about the content and level of a public support.

4.1 Social benefits of EV with and without climate policies

Figure 8 shows, for the EU, that a massive penetration of electric vehicles has, on average, a positive impact on the economy with and without climate policies. In the latter scenarios benefits are higher at the end of the period (from $ 40 billion to $ 500 billion instead of $ -90 billion to $ 280 billion) and none of them generates GDP losses. However, its discounted[17] gains over the century are not that different from scenarios without climate policies (in average, $ 630 billion to be compared with $ 570 billion). This is due to the fact that the discounted value of the main differences between the two sets of scenarios (higher peak of GDP gains in climate policy scenarios and the GDP losses in without climate policy scenarios) are low because they come very late (the first occurs in the 2030s, the second in 2040/2050).

Three main factors, macroeconomic in nature, explain why the EV generates GDP gains on average: (i) European countries oil import bill is lowered. (ii) As a result, those countries are less forced to balance their current account by exportation; this allows for higher terms of trade and higher real wages which in turn generates higher domestic demand, less unemployment and more production. (iii) In climate policy scenarios, an early and massive penetration of electric vehicles lowers the costs of climate policies. Indeed, as we will see later, they alleviate the leading-to-450ppm carbon tax, leading to GDP gains from their arrival in the market and over the long run.

The same order of magnitude of discounted GDP gains is found for the USA (550G$ and 700G$ for no climate policies and climate policy scenarios respectively), confirming that a major part of the benefits from early support policies are independent from climate policies. That additional benefit under climate policies which are higher in the USA than in the EU confirms that, despite a lower carbon price, the USA is more impacted by a transition towards a low carbon society because of their amount of carbon intensive capital stock in the reference scenarios. These gains are very low in India (around 10 G$ on average) because of the very high carbon intensity of its electrical system which starts declining drastically only beyond 2020. This explains why there is several Indian scenarios with no take-off of the EV even under climate policy scenarios and why, in these scenarios the penetration of the EV does not alleviate the overall carbon constraint before the end of the period. With a 6.4% discount rate (consistent with the high growth of this country) the present social value of the EV in India cannot but below. The same mechanism is at play for China but the discounted benefits of the EV are significant (130 G$ and 115 G$) for this country because its oil and fossil energy dependency is higher than this of India given its higher income level which makes the carbon constraint on China binding far sooner.

[17] We calculated the appropriated discount rate for each scenario as the sum of the pure preference for present, (2% in annual rate), and the average growth rate of GDP in the 2000-2050 period.

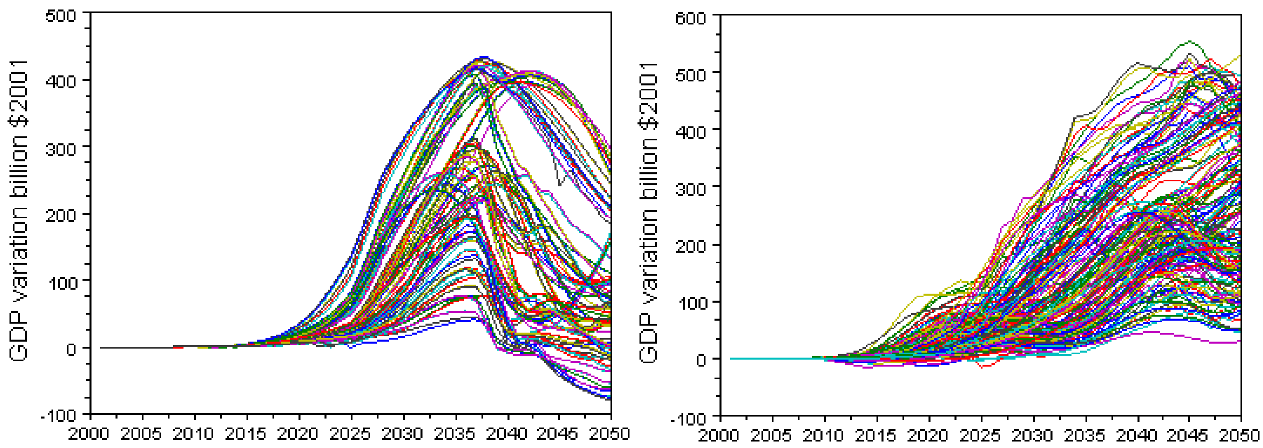

Figure 8: Variation of European GDP induced by a massive penetration of electric vehicles. Left: *baselines (BAU)*. Right: scenarios with climate policies.

4.1.1 EV as a component of an hedging strategy against high oil prices

As seen in Figure 9, world oil prices in the scenarios without climate policies follow time profiles that can be grouped in three clusters[18]:

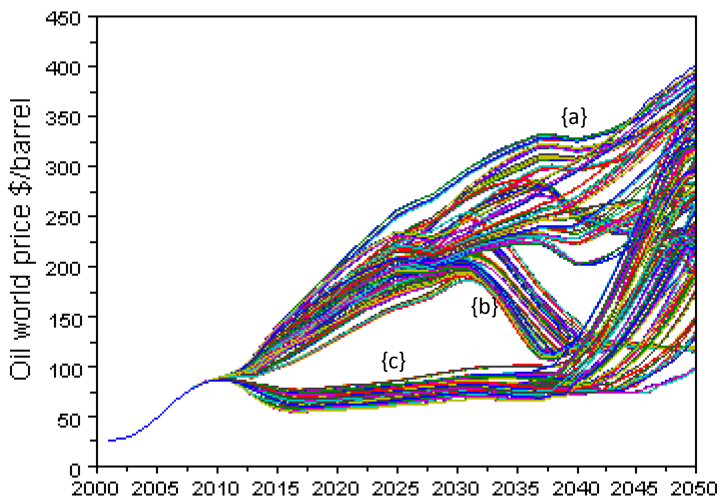

Figure 9 Oil world price in *business as usual* contexts

-In **cluster a,** world oil prices continuously grow, increasing from 250$/barrel to 400$/barrel in 2050. This cluster is composed of scenarios where fossil resources are scarce, alternative fuels availability limited and where OPEC targets high oil prices in the short term (see 2.2.2.2 or Table 3).

-In **cluster b**, middle term prices evolution is the same as in the first one since fossil fuels are still scarce but a larger availability of alternative fuels stabilizes prices to 100 $/barrel after 2030.

-In **cluster c**, Middle East producers target low prices in the short and middle terms. OPEC masks the scarcity of oil with low prices in the short-term in order to discourage efforts of importing countries to lower their dependence. As a consequence, as oil-importing countries are still deeply dependent on fossil fuels, prices skyrocket when depletion starts.

The correlation between oil prices trends and the macroeconomic impact of EV support is straightforward: fast penetration and high macroeconomic benefits in cluster {a}, whereas in cluster {c} long-during low oil prices impede the development of EV before the turn of the century; a public support has therefore no macroeconomic benefit. In the intermediate cluster {b} the first rise in oil prices is followed by a decrease after 2030 as synfuels become available. Those time profiles lead to moderated-in-the-middle-term gains followed by brutal declines in macroeconomic benefits and even GDP losses in some scenarios: when EVs

[18] The three trends of oil prices identified do not directly correspond to the three EC development clusters.

are massively present, the inertia of the automotive park (reinforced by learning effects) prevents householders from quickly adapting to new regime of liquid fuels.

In the climate policies scenarios, the existence of a carbon price causes a dramatic drop in the demand for oil. World prices do not exceed $ 250 in the middle term and are lowered in all the simulations to less than 120 $/barrel in 2050 (). But, as carbon prices offset decreasing oil prices, fossil fuel prices remain high. In those conditions, EV-related GDP gains mainly depend on consumptions patterns and availability of other energy-effective technologies: the more insensitive-to-price is the consumption, the faster, wider and more beneficial is EV penetration. Similarly, the less available are energy- effective technologies, the more valuable is EV.

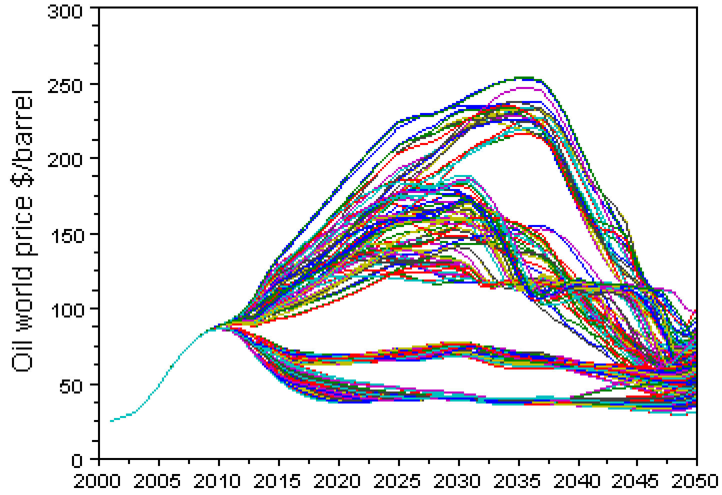

Figure 10 Oil world price in the emissions-constrained contexts

4.1.2 The electric vehicle and the control of climate change

Lower cost of decarbonization…

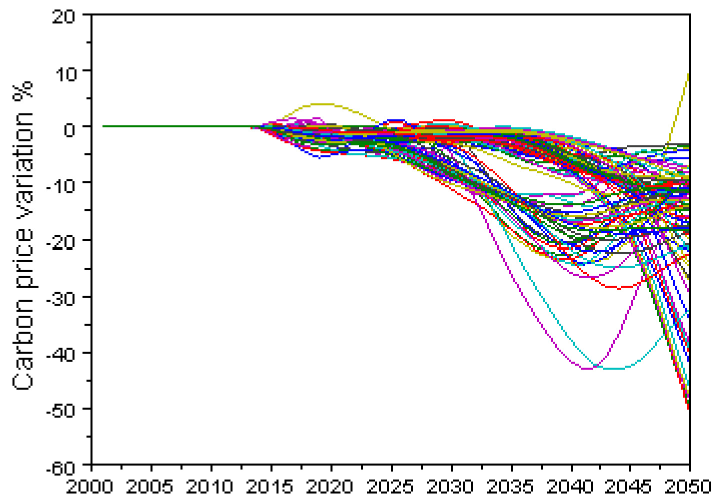

Figure 11 Variation of European carbon price due to a massive penetration of electric vehicles

In scenarios with climate policies, the massive EV penetration in Europe leads to average decreases in European carbon prices required to achieve a 450ppm constraint: 2% in 2020, 10% in 2035 and 17% in 2050 (Figure 11). A lower carbon price than in scenarios without EVs is indeed needed to achieve the same emissions target because, one can take benefit from the decarbonization of power generation to decarbonise the transportation sector.

At a macroeconomic level, the lower carbon prices, the lower the pressure on production costs and on the employment. The result is a GDP increase in all scenarios with climate policies[19], as seen on Figure 8.

[19] Again, our study focuses on gross earnings. In Figure 6 some simulations show a very low gain. One can imagine that in this case, a heavy investment for the technology industry is losing, in the sense that its benefits may not outweigh its costs.

… despite higher emissions in the scenarios without climate policies

Two main arguments are put forward against the EV. First, the transfer of the current fleet's energy consumption in the electric power sector would imply to increase by a half the current electricity production (Box 1 page 31). Second, the well-to-wheel emissions of EV would be higher than those of the conventional cars. But this last argument is only true in the short and middle terms when **no climate policies** are implemented.

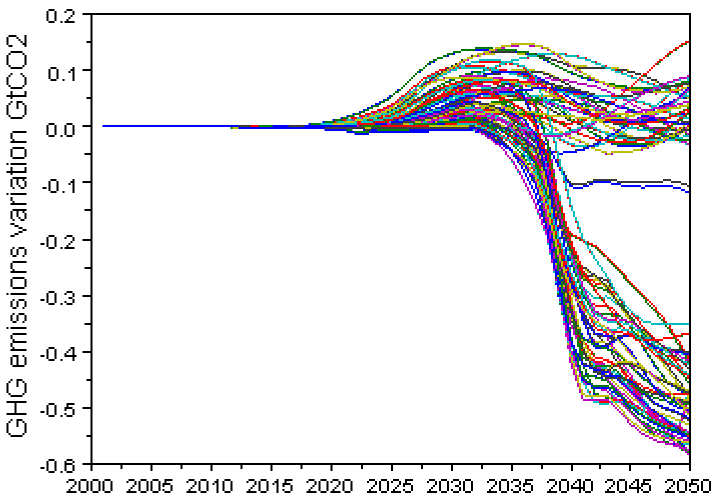

Figure 12 Variation of total emissions in Europe induced by EC in the 256 contexts with no climate policies

Indeed, in about the half of the no climate policies scenarios, an EV massive penetration increase 2025 GHG releases up to 500 $MtCO_2$ per year (Figure 12**Erreur ! Source du renvoi introuvable.**), which amounts to a 1% increase in total European emissions. GHG releases do decrease in the transportation sector (-150 MtCO2 in average in 2035, which is 30% of car emissions), but at cost of higher emissions in the electric sector.

The net increase in total emissions is first due to the fact that the well-to-wheel emissions are not significantly lower than those of the efficient liquid-fuel-powered cars, and this for two reasons: losses in electricity generation and distribution offset the better tank-to-wheel efficiency of Table 4 (page 16) and, the penetration of carbon free options for power generation (see Table 3), specially carbon capture and sequestration (CCS), is limited if there is not a carbon price. Then, the carbon intensity of personal vehicles is not considerably modified; but lower mobility prices and higher income generates higher mobility demand than in the scenarios without EV. In addition to this classical rebound effect, a more general macroeconomic rebound effect occurs since the higher economic growth increases the GHG releases from all the economic sectors.

However, Figure 10 also shows that, in the other half of the scenarios, the EV does contribute to cut GHG emissions up to 600 $MtCO_2$ in 2050 (which represents up to 12% of European emissions). Those trajectories correspond to simulations with a high CTL and biofuels availability (see Table 3 page 14): when they are available at low price, the final liquid fuel blend is cheaper and households unsurprisingly choose more energy intensive cars, leading to more liquid fuel consumption in the automotive sector and a higher increase in emissions since the CTL turns the average liquid fuel blend more carbon intensive. This explains the general advantage of EV availability, but which makes this availability critical to control the carbon emissions is when it takes place *before* synfuels maturation; in this case, EVs' competiveness against synfuel-powered cars is preserved by progress in the capital costs (due to *learning by doing* effects), thus preventing a long term growth in the own-provided transportation sector.

4.2 Hedging benefits of EV with and without climate policies

The above results show that an early penetration of the EV has in most cases positive macro economic impacts over the century because it acts as a hedge against bad surprises about oil prices and it contributes to lower the bill of climate policies. However, from an industrial perspective, investing today in a large scale deployment of electric vehicles is a risky business because of the uncertainty about the strength of climate policies and even in cases of certain climate target because of the uncertainties about a large set of parameters which include the cost of other low carbon technical options, the time profile of oil prices, the economic growth and the changes in consumption patterns.

This context cannot but lead to a penetration of EV which may be proven *ex-post* suboptimal, and the question though is to what extent and on what bases some forms of public supports can lower investment risks. To respond this question, one piece of information from our scenarios is the gross social value of the EV. In economic terms, this social value is the difference between the consumer welfare reached at each point in time in an "early EV" scenario by comparison with a corresponding "non early EV scenario". Then, these flows can be aggregated in a net present value through the use of a discount rate.

This calculation can be interpreted as giving the maximum level of investment at the date t0 that would be paid back in a social welfare perspective through the flow of additional social value over half a century. On average, it gives $ 16 000 per vehicle, but, as shown in Table 5, this figure is very conditional upon the assumptions about fossil fuel reserves and about the ambition of climate policies. Interestingly, the benefit is lower in scenarios with high fossil fuel reserves and low oil prices; in this case the adoption of climate policies makes a huge difference with an average benefit multiplied by 3,7. With low reserves, oil prices and the benefits of EV are high even without climate policies, entailing a high price of the gasoline and the decarbonization of the electric supply; this explains why the increase of the net benefit of EV is only 20 % in climate policies scenarios.

	High fossil fuels reserves	Low fossil fuels reserves	Average
Simulation without climate policies	$ 5 000[20]	$ 18 500	$ 12 000
Simulation with climate policies	$ 18 000	$ 22 000	$ 20 000

Table 5 Average discounted GDP gain per EV in function of assumptions in fossil fuels availability and climate policies in Europe

Even though these results are less robust than for the EU, it is worth noting that the same calculation made for the US gives the same order of magnitude. On average, it gives $ 19 200 per vehicle, and GDP gains are still higher with climate policies ($ 26 000 on average).

	High fossil fuels reserves	Low fossil fuel reserves	Average
Simulation without climate policies	$ 7 200	$ 17 500	$ 12 350
Simulation with climate policies	$ 19 000	$ 33 000	$ 26 000

Table 6 Average discounted GDP gain per EV in function of assumptions in fossil fuels availability and climate policies in USA

Obviously, it is interesting to compare this value to the few assessment of upfront investments that have to be made prior to the development of the EV for both vehicle overcost and batteries-management infrastructures production such as $ 15 000 calculated from (Becker 2009). Nevertheless we should first refrain from going to far in that direction without precise understanding of the time schedule of investment. The above calculation indeed hypothesizes that all the necessary investment was made from the beginning

[20] We show in the previous section that in scenarios without climate policies and with high amount of oil resources, EC generally does not penetrate before the middle of the century.

in one year, and the discounted costs of the same amount of investment are very conditional upon the timing of the deployment of these investments.

In the same way, one should refrain from using such a value to translate directly the social value of EV in terms of maximum subsidy to be given to the industry. This calculation indeed simply gives the social surplus yielded by the EV but does not say what share of the surplus has to be given to the consumers, to the industry and to the government. This sharing is not irrelative from the very nature of the public support. At one extreme, the government subsidizes all the upfront investment in infrastructures and let the market operate. At the other extreme, the government subsidizes the purchase of EV and let the firms taking their own risks.

The assessment of the pros and cons of these two polar archetypes and of any combination in between cannot be made without a better understanding of the risk perception by the industry and a better description of the nature of the direct and indirect investment necessary to a large scale deployment of EV.

Nevertheless, the magnitude of the social value is high enough to demonstrate the social interest in developing an incentive framework in which the industry could take the risk of an early deployment of this technology. It is also worth noting that this social value, specifically for China and India should incorporate the no carbon benefits of the abatement of black carbon aerosols which occur in the short and medium term.

Box 1 : EC's impact on electricity production is limited

In our simulations, a massive penetration of electric vehicles in Europe does not represent more than a 5% variation of total electricity consumption in average (and 14% as a maximum).

The average variation in European production adds up to 2.3Mtoe (+0.7% in relative terms) in 2020, 15Mtoe (+3.7%) in 2035 and 21Mtoe (+5.2%) in 2050. At the same time, in the personal transportation sector, the electricity demand variation amounts in average to 1.4Mtoe in 2020, 12Mtoe in 2035 and 24Mtoe in 2050 (Figure 13). The difference between the growth in the own-provided transportation sector demand and the variation of electricity supply are explained as follows:

-The economic growth produced by ECs tends to induce more electricity demand in all the other economic sectors (a macroeconomic rebound effect).

-On the other hand, general equilibrium effects may weaken variation of total electricity demand. Tensions on electricity market and releases of liquid fuels prices delay indeed the substitution of fuel for electricity in all the other economic sectors. This effect may be predominant in the long term in some contexts. Figure 13 shows for instance that in 2050 relative variation of electricity production in Europe may be limited to 7Mtoe.

-Finally, the electricity production increases in all ways during five decades of the simulations, reducing the *relative* impact of the EC.

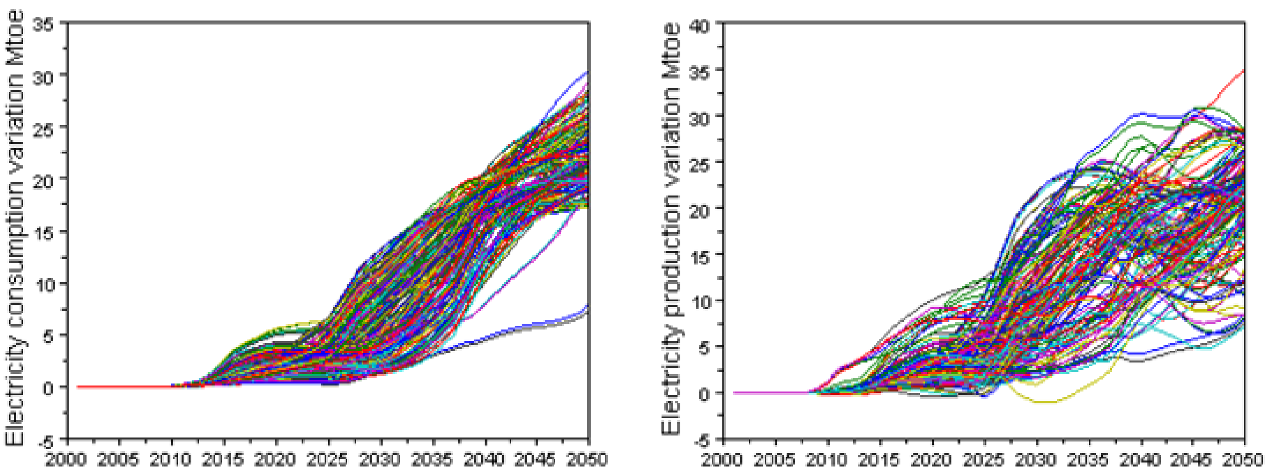

Figure 13 Variations induced by a massive EV penetration in electricity consumption in the self provided mobility sector (left) and electricity total production (right).

5 Conclusion: about the next steps

In this study, we tried and assess the macroeconomic benefit of accelerating technical change in the automotive sector in direction to a massive switch to electric vehicle (EV). We show that this benefit is important in case of climate policies but also that in the absence of such climate policies as it constitutes a hedge *vis-à-vis* the surprises in the evolution of oil prices.

In Europe, its discounted positive impact by vehicle represent an average of $ 16 000 (an average of $ 20 00 in case of climate policies) and this without consideration of the benefit beyond 2050.

To pass from this assessment to public policy decisions about the level and the content of a support which is legitimate in social welfare maximization perspective, further research is needed to incorporate:

- A better description of the time schedule of the investment in infrastructures, battery network and vehicle, the decrease of investment through learning by doing mechanism and network externalities,

- Households purchasing behaviour and perhaps more importantly the risk perception by the different nodes of the industrial chain,

- The distribution of the social surplus between producers, buyers and other households.

Despite these limitations, the magnitude of the social value we find, covering a larger range of scenarios is high enough to demonstrate the social interest in developing an incentive framework in which the industry could take the risk of an early deployment of this technology.

Actually, the case of the EV is archetypical of one of the key challenges faced by the international community in the post-Copenhagen context: how to transform the social value of limiting carbon emissions into a practical tool, in the absence of fully-fledged international carbon markets, to shift investment decisions in direction to carbon saving investments. This suggests a strong link between climate policies and the reform of the financial system. Perhaps, the time has come to ground what Pierre-Noël Giraud calls *the trading of promises* on an agreed upon value of this major public good which is the climate in order to socialize not the ‘bad debts’ by part of the industrial risks of technologies that are critical for the mitigation of climate change.

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