Out with the Pipes, in with the Plugs : On the Economics of the Energy Transition in the Automobile Sector

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- CO_2: carbon dioxide
- DER: distributed energy resource
- DSO: distribution system operator
- EV: electric vehicle
- EVIC: EV incremental cost
- ESS: electric storage system
- FIT: feed-in tariff
- GHG: greenhouse gas
- LCA: life-cycle assessment
- LEZ: low emission zone
- ICE: internal combustion engine
- MAC: marginal abatement cost
- MACC: marginal abatement cost curve
- NO_x: nitrogen oxide
- PHEV: plug-in hybrid electric vehicle
- PV: photovoltaic
- PVCS: photovoltaic charging station
- PM: particulate matter
- SCC: social cost of carbon
- SOC: state of charge
- TSO: transmission system operator
- TV: traditional vehicle
- V2G: vehicle-to-grid
- V2X: vehicle-to-everything

* * *

- Qu'est-ce que tu foutais, nom de Dieu ?

- On a dû s'arrêter deux fois, expliqua Danglard. Le commissaire pour un arc-en-ciel presque complet et moi pour une étonnante grange templière.

Fred Vargas - *Temps Glaciaires*

* * *

Chapter 1

General Introduction

What other item than the automobile could be more meaningful of the 20^{th} Century in Western countries? The automobile has symbolized modernity and individual liberty and has been a key technology of the unique economic development of the last century. However, in the 21^{th} Century, the environmental and health impacts of cars have become unacceptable for Western societies. The automobile system is therefore forced to transform itself. To this extent, the electrification of the automobile is seen as the only technological compromise that would avoid a more fundamental questioning of cars.

Such energy transition brings many challenges. First of all, it requires to remove pollutant thermal cars from the road. Second, electric mobility involves a novel organization of the automobile system as it connects it to the power sector. This linkage brings additional challenge to the power sector that is undergoing its own decarbonization. However, thanks to the storage capacities of their batteries, a fleet of electric vehicles, could constitute a valuable asset for power grids. By focusing on some of these aspects, this dissertation studies the economics of the transition of the automobile system from thermal engines to electric engines.

This introductory chapter aims at exhibiting an overview of the technical, environmental, economic and political elements of this transition. From the ecological dead-end of thermal vehicles to the deployment of electric mobility, the first section gives an overview of the technical and environmental aspects of this transition. The second part discusses the economics and policies that frame the energy transition of

the automobile system. It is composed of a brief review of the academic contributions on environmental policies regarding passenger cars. It illustrates the topic by detailing the main French policies towards automobile pollution. The third part summarizes each of the four chapters of this dissertation.

1 The automobile now and then

This section aims at giving a broad overview of the current automobile system, the pollution it induces and how electric mobility might change it. First, we discuss the main characteristics of the automobile system, with a focus on the French situation. Then we present the different types of automobile pollutions, their technical determinant and the technical option to reduce them. Third, we present the main features of electric mobility. Fourth, we discuss the challenges and opportunities associated with the integration of electric vehicles in the power system.

1.1 The item of the 20^{th} Century

The automobile is ubiquitous in modern societies since is the most used transportation mode in developed countries. It moves passengers wherever roads are, and provides its owners a mean of emancipation as well as a social recognition. Therefore, it has shaped spatial planning and development of cities and territories. A very powerful technical system composed of oil industries and road infrastructures has been built around the automobile world. The automobile industry has been at the vanguard of the main disruptions of the organization of economic production with Fordism, Sloanism, Toyotism and globalization. The industry is also a strong driver of innovation and technological progress. However, feelings about the automobile are ambivalent (Demoli and Lannoy; 2019). The automobile is criticized as a symbol of consumerism and individualism, for the casualties from road accidents, for the alienation caused by its ubiquity and for the urban sprawl and congestions. Moreover, modern criticisms mostly concern the environmental impacts of the automobile.

The evolution of the French automobile sector followed the economic development of the country after the Second World War (Orselli; 2008). In France, the automobile

is used for more than 65% of the number of trips and 80% of the number of kilometers traveled (Armoogum et al.; 2010; Bigo; 2019). 85% of French households own a vehicle. Expenses related to the automobile (car purchase, fuel expenses, insurance, maintenance...) account for 11% of households' budget. Note that these numbers hide a strong heterogeneity between geographic zones, social classes, gender and generations (Demoli; 2015).

The whole French car fleet weights around forty million vehicles, including 32 million passenger cars. The yearly automobile market records registrations of around two million new vehicles and five million second-hand vehicles. These figures have been steady for the last decades. The average lifetime of a car is estimated about fifteen years. Beyond usage, France has a strong manufacturing tradition, with several large car makers (Renault, Peugeot, Citroen...). This leads to a large economic weight of the automotive sector as it gathers more than one million direct and indirect jobs.

European countries, and especially France, developed a very high preference for diesel vehicles. Europe is an exception compared to other developed countries[1]. Originally, diesel was used for industrial purposes (trucks, tractors, trains...). In the 1980's, European car manufacturers transposed this technology for passenger vehicles. Indeed, diesel engines are significantly more fuel-efficient than gasoline engines. As governments were promoting[2] this technology, diesel vehicles were largely diffused in Europe. For instance, between 2005 and 2013 diesel have reached around 70% of new car sales in France and 50% in Europe (ICCT; 2020). Beyond the debates on the efficiency of diesel compared to gasoline, Miravete et al. (2018) show that this domestic preference for diesel constituted a trade barrier that protected European manufacturers.

[1] In comparison, the US and Japan have very low proportion of diesel inside their fleet (Hooftman et al.; 2018).

[2] For instance in France fuel taxes were around two cents per litter lower than taxes on gasoline. Also, European countries have privileged climate policies more than atmospheric pollution policies. Policies targeting CO_2 would favor diesel over gasoline engines, while regulations on air pollutants (EURO norms) are differentiated between diesel and gasoline.

1.2 An unsustainable development

Drawbacks of the development of the automobile are well known. Among them, this dissertation focuses on the consequences that exhaust gas of cars from fuel combustion have. These include greenhouse gases (GHG) and atmospheric pollutants. Other drawbacks such as congestion, noise pollution, accidents or energy security are not considered. This section presents the properties of the exhaust gas of cars, precises the determinant of pollution of an automobile fleet and reviews the options and difficulties of abating this pollution.

Plenty of externalities

Carbon dioxide (CO_2), as the natural outcome of fuel combustion, is the main exhaust gas[3]. CO_2 is the prevailing anthropogenic greenhouse gas that causes climate change. There is now little debate on the seriousness[4] of the impacts of a global warming of more than 1.5 degree Celsius (Rogelj et al.; 2018). Limiting climate change has therefore been a major political issue, that led worldwide governments to announce drastic reduction of GHG emissions. For instance, the European Union aims at a 55% reduction of emissions by 2030, while France has legally committed to reach carbon neutrality by 2050. In France, the transport sector accounts for one third on national emissions, and is the only sector where emissions have not been declining for the recent years (CITEPA; 2020). Although emissions of new vehicles have declined by 30% since 2001 to 120g/km in 2018 (ICCT; 2020), annual emissions of passenger cars have remained steady at 70Mt of CO_2-equivalent since (CITEPA; 2020).

Due to incomplete combustion reactions, exhaust fumes also contain gas and particles such as nitrogen oxides (NO_x), carbon monoxide (CO), sulfur dioxide (SO_2), unburned hydrocarbons (HC), particulate matter and fine particles ($PM_{10}, PM_{2.5}$). These molecules contribute to atmospheric pollution, which has multiple environmental and health impacts. Environmental impacts mostly include acid rains for SO_2 and eutrophication for NO_x. However, public attention has mostly focused on the health

[3]Each liter of gasoline and diesel respectively emit around 750g and 830g of CO_2.

[4]Main impacts on human activities include rising temperatures, sea levels, increased of extreme climatic events (droughts, floods, hurricanes)...

impacts of air pollution. According to the World Health Organization, air pollution causes each year more than four million deaths worldwide. Main risks associated with air pollutant are respiratory diseases. In France, the national Public health institute estimated that $PM_{2.5}$ alone would cause around 50,000 premature deaths each year (Pascal et al.; 2016). NO_x is also of the main precursor of anthropogenic ozone (O_3) which has multiple health impacts[5]. Road transport is a major contributor of air pollutants emissions. In Europe, it accounts for 60% of NO_x emissions and 12% of PM_{10} emissions. Although emissions of NO_x and PM_{10} have respectively decreased by 60% since 1990, this share has remained steady. Passenger cars account for more than half of these pollutants. Emissions of air pollutants significantly differ between gasoline and diesel vehicles. Diesel mostly emits NO_x and PM while gasoline mostly emits CO.

Determinants of pollution

Obviously, pollution depends on the number of cars on the road. Note that denser less fluid traffic increases pollution per car. The quantity of released gases from a specific thermal vehicle depends on the type of cars and how it is used. Main vehicle characteristics include engine type[6] (gasoline, diesel, hybrid...) and power, weight and size[7]. Nevertheless, the way a car is used remains the main determinant of pollution. Utilization includes driving patterns, and driving style of the user. Driving patterns include the mileage of the vehicle (hence the total fuel burnt) and related types of journeys (commuting, holidays...) and the types of roads (streets, country roads, highways). Driving style is related to the acceleration profile of the cars induced during the driver himself, a smooth driving being consuming less fuel.

Abatement options

Abatement options to reduce pollution from passenger cars include behavioral and technological measures, from drivers and car manufacturers.

[5]These include respiratory and cardiovascular diseases, irritation of lungs, eyes and noses, asthma...

[6]Engine types include gasoline, diesel. Under average conditions, diesel engines are more fuel-efficient than gasoline ones. In addition, some fuel may contain biofuels (bioethanol or biodiesel).

[7]Heavier cars require more energy to move. Larger cars face more air resistance, which increase fuel consumption.

Drivers have several means to reduce their environmental footprint induced by their journeys. They may choose to drive less, in lighter, more aerodynamic and more fuel-efficient vehicles. They may also improve their driving skills and increase the regularity of routine maintenance - especially for smog checks (Merel et al.; 2014; Yamamoto et al.; 2004).

Car manufacturers face many technical trade-offs regarding the environmental footprint of their vehicles: on the one hand between costs and fuel economy[8] and between pollutant types on the other hand. First, the most expensive cars which bring the higher margins for manufacturers are the biggest and most powerful cars, which have the highest consumptions[9] (Knittel; 2011). Second, the choice of engine impacts a lot pollution levels. Indeed, everything else being equal, diesel vehicles are more fuel efficient than gasoline vehicles. However, diesel emits more NO_x and PM and less CO and unburned hydrocarbons than gasoline. Third, modifications made on engines by manufacturers rarely decrease all pollutant emissions (Hooftman et al.; 2018). For instance, catalytic converters decrease NO_x,CO,HCs but create N_2O (a strong greenhouse gas), diesel particle filters decrease emissions PM_{10} while increasing NO_x and CO_2, gasoline direct injection decreases CO_2 but increases PM and NO_x emissions. In addition, vehicle emissions are often underestimated. In Europe, it has been reported a growing gap between measurements from approval tests in laboratory conditions and measurements from real-driving conditions by independent institutions (Fontaras et al.; 2017; Zacharof et al.; 2016). Deviations mostly concern CO_2 emissions, and NO_x emissions in diesel cars.

1.3 The rise of electric vehicles

Opposite goals have brought the automobile industry in a dead-end. It appears that significantly reducing the environmental impacts of passenger cars while keeping the current utilization of the automobile constant cannot be achieved by only improving internal combustion engines. As long as sobriety options such as reduced driving and car downsizing will not be politically acceptable, it appears that the electric vehicle is

[8] Note that CO_2 emissions are almost proportional to fuel consumption.
[9] The trend for sport utility vehicles (SUVs) in the US and more recently in Europe (ICCT; 2020).

the only option to achieve depollution in the automobile system. This section presents the main features of electric vehicles.

History and vehicle types

Electric engines are not a new technology and it has known already several bad starts worldwide. Indeed, the first car to drive over 100 km/h was electric (*la Jamais-contente*) (Høyer; 2008). In France in the 1970's, powerful lobbying was made by the national electricity company to develop electric mobility (Callon; 1979). After the 2008 oil shock, electric mobility was believed about to become the "Second Automobile Revolution" (Villareal; 2014). Beyond the historic context of these examples, electric vehicles have been facing the same several technical barriers during the last century: short driving range, need for charging infrastructure, long charging times and high costs.

Vehicle name	Tesla 3	Renault Zoe	Mitsubishi Outlander	Toyota Prius	Toyota Mirai
Release year	2019	2019	2019	2018	2018
Vehicle type	full-electric	full-electric	plug-in hybrid	hybrid	fuel cell
Entry price (€)	49600	32000	37000	32300	78900
Battery size (kWh)	52	50	13.8	1.3	0
Electric autonomy (km)	409	395	0	500	0
CO_2 emissions (g/km)	0	0	46	106	0

Table 1.1: Typical electric vehicles and their main characteristics. Sources : automobile-propre.com and caradisiac.com

Four main types of electric vehicles can be distinguished. Battery electric vehicles (BEV) only have an electric engine and no combustion engine. They rely entirely on the electricity stored in their battery pack. In 2020, most battery packs of new EVs were in the range 50-70 kWh in Europe. The battery is charged with an external charging infrastructure. Plug-in hybrid vehicles (PHEV) are equipped with a smaller battery (5-20 kWh) and an electric engine in addition to a combustion engine. PHEVs typically rely on their electric engine first, and Alternatively hybrid-electric vehicles are equipped with an additional small battery that supports the ICE engine. In opposition with the latter vehicle types, this battery is only charged during driving. This battery allows a significant gain in fuel economy. Last, fuel cell electric vehicles (FCEV) do not have combustion engine or battery, but electrochemical cells that transform hydrogen into power. Table 1.1 shows several details of one of the most famous electric vehicles

models in 2018-2019. In this dissertation, we consider battery and plug-in hybrid as electric vehicles.

Evolution worldwide

There were over seven million electric vehicles worldwide in 2020 (IEA; 2020). Market share of electric vehicles raised from below 1% in 2015 to more than 3% in the US and Europe in 2019. Some countries even had market shares above 10% such as the Netherlands, Sweden and Norway. This take-off of electric mobility stems from a strong public support, and on the spectacular progress in battery technologies. For the latter, prices have dropped from above 1000$/kWh to less than 200$/kWh in 2019 (BNEF; 2019; IEA; 2020).

This progress is a priority for the industry as the battery is the main cost driver of electric vehicles (Nykvist et al.; 2019). It implies a much higher upfront costs compared to conventional thermal vehicles. However, this gap is lower when the total cost of ownership is considered (van Velzen et al.; 2019). Electric vehicles may even be less expensive during their lifetime if oil prices and mileage are high enough (Clinton and Knittel; 2020).

Environmental footprint of EV

BEV, FCEV and PHEV used in full-electric modes do not directly emit CO_2 or air pollutants. Nevertheless, it does not make them pollution-free. First, regarding greenhouse gas, indirect CO_2 emissions from the life-cycle should be accounted. Electric vehicles do not have exhaust pipes and therefore do not directly emit fumes. However, this scope may not be relevant and environmental performance of EVs is appraised using with life-cycle assessments. Main factors influencing the life-cycle CO_2 emissions of electric vehicles are: the carbon content of the electricity used for charging[10], the battery size and its manufacturing and the vehicle mileage (Ellingsen et al.; 2017; Hawkins et al.; 2012; Temporelli et al.; 2020). When it comes to PHEVs, the share of mileage covered by the electric engine become the one of the most relevant driver of

[10]That the carbon content of electricity varies along with electricity mix. As the power mix may varies on several temporal scales (from hour to decades), it has been advised to control charging of EVs could lower their indirect emissions from electricity (Jochem et al.; 2015).

life-cycle emissions (Plötz et al.; 2018). Electric vehicles have also other environmental impacts. They still indirectly emit PMs from erosion of road usage, and brake[11] and types erosion. Several life-cycle assessments (LCA) measure the impact of EVs in term of water and local pollution. Electric vehicles also have consequences in term of metal rarefaction, especially rare earth material. Nevertheless, battery technology is rapidly evolving and substitutes could be found in the next future (Hoekstra; 2019).

1.4 Electric vehicles and the power system

With electric vehicles, oil is replaced by power. This means that the electricity sector is called to play a major role in the development of a sustainable road transport. This section details the main aspects of this new interaction. We first detail the charging infrastructure for electric vehicles, then present the challenge of the integration of this infrastructure in power grids. Finally, we present the opportunities of a smart management of the batteries for electric vehicles.

The charging infrastructure for electric vehicles

Contrary to ICE vehicles that refuel only in fuel stations, electric vehicles can virtually charge in any location connected to the power grid.

Home-charging represents the main location of EV charging, with 80-90% of charging events (IEA; 2020). Home-charging typically uses low charging power (3-7 kW). Although a long charging duration (8-10 hours), home-charging fits energy needs for commuting trips. Nevertheless, households need an individual and easily accessible parking space. This can be difficult for some households in urban areas in cities, especially those who live in collective buildings[12]. Also for commuting needs, workplace charging is an interesting option that can achieve higher charging powers.

Beyond commuting needs, both home and workplace charging are insufficient, and a public charging infrastructure is needed. As discussed earlier, its role has been designated as a key-element for EV large-scale diffusion (Hardman et al.; 2018). Charg-

[11] Thanks to regenerative braking, erosion of brakes is much lower in electric vehicles than in thermal vehicles.

[12] Even if a multi-dwelling building has parking lots, there may be rules that complicate the installation of charging points.

ing stations can be located in streets, commercial areas or highways. Charging stations are composed of parking lots equipped with charging points. These points may deliver electricity at different powers, from slow charging to fast and ultra-fast charging. However, the development of such infrastructure especially for high charging power, is very capital intensive, and requires high adoption of electric vehicles. This so-called "egg and chicken problem" is a major issue in the electrification of passenger cars and has major consequences for the design of support policies (Greaker and Midttømme; 2016; Li et al.; 2017; Meunier and Ponssard; 2020; Springel; 2016; Zhou and Li; 2018).

Beyond the "egg or chicken problem", EV charging gathers a multiplicity of actors, forming an business ecosystem (Madina et al.; 2016; San Román et al.; 2011). Infrastructure operators install charging points and ensure their maintenance. Mobility service providers propose EV owners an interface to use charging points. They can typically provide users phone apps that indicate locations of charging stations and offer roaming services. They can also handle payment aspects. Infrastructure operators may be mobility service providers. Interoperability platforms intermediate mobility services providers and infrastructure operators and allow them to contract roaming agreements. Network operators ensure the connection between charging points and the power grid.

Impacts of electric vehicles in power networks

Growing EV deployment occurs at a crucial moment for power sector (Borne; 2019). First, its decarbonization mostly relies on intermittent and variable renewable power sources, such as wind or solar. While power generation was based on controllable sources (*e.g.*gas, coal, nuclear), maintaining grid stability with renewable energy appears to be a considerable challenge. Second, liberalization of power generation has created complex markets that are interconnecting. Third, the power sector faces a decentralization movement, as individual consumer are getting able to produce their own electricity, for instance with home solar photovoltaic. In this context, EV integration in power grids brings additional challenges.

A large EV fleet would impact power grids in several ways. First, it may require a substantial amount of energy (kWh) to charge EVs. According to the French trans-

mission system operator RTE in (RTE; 2019), at least 15 million vehicles could be easily integrated by the grid in 2035. Then, a more serious issue for the TSO would be in term capacity (kW). It is very likely that a large fleet of commuting EVs would charge in synchronized way. Several authors as Jochem et al. (2015) indicate that current EVs charge in the evening, when usual peak demand of electricity happens. This could cause two issues. Increased peak power may require building additional power plants to meet demand. Then, peak power plants are usually running using fossil fuel, which would increase CO_2 emissions from the power sector. In the same RTE report, no increase of capacity is needed (RTE; 2019). Authors indicate that a mild level of smart charging, *i.e.*modulating charging power of EVs in a coordinated way, would be enough to handle these power issues. Third, EVs may impact negatively the functioning of distribution grids[13] may also be challenged (Wangsness et al.; 2020).

In summary, EV should not represent any problem at the transmission level or at the distribution in France on the middle run. However, situation on the long run with a full-electric fleet may be much more challenging. The traditional way to deal with it would be to engage costly grid reinforcements.

Vehicle-to-Everything

To describe interactions between EVs and the power system, the EV-focused concept of Vehicle-to-Everything (V2X) is useful[14]. Traditional cars are used for a few hours in a typical day. The main principle of V2X is to allow the use of the EV battery while it is not driving and plugged. A key enabler of V2X configurations is the enabling of bi-directional capacity of EV battery. This means that EV are able to deliver electricity from their battery to the grid. This requires dedicated devices, either in the vehicle or in the charging infrastructure. Each configuration presents different opportunities for the EV. Such opportunities strongly depend on market rules and regulations. Value streams can be created through power markets, interaction with network operators and consumers (Thompson and Perez; 2020).

[13] Low and middle voltage networks.

[14] Note that other concepts are possible. For instance, chapter three focuses on the concept of technology interactions. However, for the focus of this general introduction, an EV-focused concept seems more appropriate.

Vehicle-to-Grid is the most famous configuration between EVs and the power grid. It has been proposed by seminal papers (Kempton and Tomić; 2005a,b). V2G consists in using the EV battery flexibility to participate in the power system stabilization. This involves the participation of a decent number of EVs that simultaneously are smart charging. Although smart charging is generally uni-directional, substantial gains from V2G happen when bi-directional capacity is available for EVs. Participating in the power grid stabilization generally requires dedicated markets. Borne et al. (2018) reviews the participation rules of different flexibility markets. In a near future, flexibility markets should also be implemented for distribution systems[15]. A critical point of V2G is that it requires the participation of several actors: car makers and charging station installers (for the hardware), an aggregator of EVs charging, and of course EV driver Parsons et al. (2014). Vehicle-to-building applies bi-directional charging to a lower scale, typically commercial and industrial buildings and to a lesser extent, large residential buildings grouped in a energy community. Vehicle-to-home mainly aims to optimize energy consumption of home. EV battery may be used as an emergency back-up. Finally, Vehicle-to-Load is essentially the same as Vehicle-to-home, but without connection to the grid. It is appropriate in areas with weak or no connection to the grid.

2 Transition pathways and policies

The challenges brought by the energy transition are tremendous for the automobile industry. Its conversion to the electric engine requires huge investments for car manufacturers, change of uses for car manufacturers, and many actors that will face losses. This transition cannot occur without a strong public support. This section presents the economic and political aspects of the energy transition in the automobile system. It starts by reviewing the contributions of environmental economics on the understanding of public policies that aim at shifting the automobile fleet towards low-emission cars.

[15] Several pioneer projects are described in (Schittekatte and Meeus; 2020).

2.1 Environmental economics and automobile pollution regulation

Significantly reducing pollution in a cost-effective way is the key political question of the energy transition in the automobile sector. Economists can help in two ways: assessing the efficiency and effectiveness of ongoing and past policies and proposing alternative better policies. When studying policies, economists also aim at identifying unintended effects of policies such as distributional effects (especially if they are regressive) or interactions with other externalities.

Environmental economics have textbook solutions for regulating automobile pollution. Indeed, pollution from exhaust fumes seems a simple negative externality problem. The first-best solution should then be a pigovian tax on fuel which would make agents internalize the social costs of the fuel combustion by their car (Parry et al.; 2007). The well-known advantages of a carbon tax are numerous. First, a carbon tax would reach every vehicle and should be simple to implement since fuels are already taxed. Then, by making the use of driving thermal cars more expensive, it reduces the costs differential with cleaner technologies such as hybrid, electric or hydrogen cars. Also, it provides a clear signal to manufacturers for the planning of their production and their decisions regarding innovation. However, carbon taxes have been rarely implemented by governments, or at very low level (Kossoy et al.; 2015). This is not specific to the automobile system, as carbon taxes are not higher in other sectors. In general, the political acceptability of carbon taxes is low. This is even more relevant when taxes apply directly to end-use sectors, such as road transport. Indeed, it has been shown that carbon taxes are particularly regressive (Douenne; 2020; Fullerton and Muehlegger; 2019). A minor aspect deals with consumer myopia towards future energy costs which could jeopardize the efficiency of fuel taxation. Indeed, the debate is still open on whether or not consumers undervalue future fuel costs (Busse et al.; 2013; Gillingham et al.; 2019; Grigolon et al.; 2018).

Due to the difficulty of the implementation of stringent fuel taxation, governments have preferred the use of standards on the emission levels (as in the EU), or on the fuel economy (as in the US) of vehicles. Such measures can be seen as complements

of already in place fuel taxes. In principle, these instruments act like a feebate, i.e. a combination of a tax on pollutant vehicles and a subsidy on low-emission vehicles (Davis and Knittel; 2019). Feebates are also themselves implemented by many national governments[16]. Durrmeyer and Samano (2018) compares the two instruments and find that feebates dominate standards in term of global welfare. However, the efficiency of standards and feebates remain highly conditioned by the policy design (d'Haultfoeuille et al.; 2014). Both instruments share similar drawbacks. First, they do not give incentives to reduce vehicle usage. As the policy gives incentives for more efficient vehicles, rebound effects may further reduce the efficiency of the policy (Linn; 2016). Moreover, as standards and feebate deal only with new vehicles, they do not give incentive to retire old pollutant vehicles[17]. An other drawback is that standards and feebates require precise measurements of fuel economy or CO_2 emissions. These measurements are made during approval tests of new vehicles. Numerous studies have pointed out the gap between reported and real-driving emissions or fuel consumption. Tanaka (2020) has noted that the design of feebate or standards could even induce strategic behaviors from manufacturers to falsify the vehicle performance during approval tests. West (2004) finds that feebates on new vehicles are more regressive than fuel taxes, due to high price-responsiveness from low-income households. Davis and Knittel (2019) find that US standards on CO_2 emissions are more regressive than a fuel tax with lump-sum redistribution of tax revenues. Durrmeyer (2018) finds first, the feebate advantage car manufacturers at the expense of consumers. The author also finds that middle-income households are favored by the feebate.

Last, welfare assessments of standards and feebate have been studied in the literature, with, for instance (Anderson et al.; 2011; Dou and Linn; 2020; Goldberg; 1998; Lin and Linn; 2019) in the US, (d'Haultfoeuille et al.; 2014; Durrmeyer; 2018) in France, (Rivers and Schaufele; 2017) in Canada, (Adamou et al.; 2014) in Germany.

We saw that standards, feebate and subsidies would not give incentives to retire old vehicles. Governments have been using scrapping schemes in order to renew the

[16] France for instance has a feebate scheme, in addition to the European standard on CO_2 emissions.

[17] Jacobsen and Van Benthem (2015) even find that as standards have a general increasing effect of new vehicles prices, demand for new vehicles decrease while demand for cars increase in the used car markets. This ends up delaying old car retirement compared to a no policy scenario.

automobile fleet and, in some cases, to support car manufacturers. The principle of these schemes was to offer a rebate on new fuel-efficient cars when retiring an old vehicle. These policies have been studied in (Alberini et al.; 1995; Jacobsen and Van Benthem; 2015; Li et al.; 2013) in the US, (Grigolon et al.; 2016) in Europe, (Adda and Cooper; 2000) in France, (Antweiler and Gulati; 2015) in British Columbia, (Sheldon and Dua; 2019a) in California. Main drawbacks of these policies are that they tend to accelerate vehicle purchases.

Besides emission standards, governments have extensively implemented subsidies towards low-emission vehicles. While subsidies do reduce the price gap between thermal and low-emission vehicles, they do not incentivize to drive less[18]. As for standards, most subsidy schemes apply on new vehicles. Studies regarding subsidies on hybrid and electric vehicles show that these policies have been effective. Such studies include Yan and Eskeland (2018) in Norway, (Clinton and Steinberg; 2019; DeShazo; 2016; Jenn et al.; 2018; Sheldon and Dua; 2019b; Wee et al.; 2018) in the US, (DeShazo et al.; 2017) in California, (Sheldon and Dua; 2020) in China. Others highlight that they show low cost-effectiveness. Others point out the importance of non-financial incentives (Sheldon and DeShazo; 2017). Regarding electric vehicle support policies, several others have shown that discarding the charging infrastructure from the design of subsidies could significantly deter the effectiveness of subsidies[19]. Moreover, (Xing et al.; 2019) have pointed out the importance of consumer heterogeneity[20] in the design of the subsidy. Regarding distributional aspects, it has been noted that subsidies on low-emission - especially electric - were particularly regressive. The main reason is that they stimulate sells of new and expensive cars and therefore large income buyers. Furthermore, Holland et al. (2019) find that including spatial environmental benefits make these subsidies even more regressive. More generally, Bjertnæs (2019); Davis and Sallee (2020) indicate that fuel taxes incorporate other aspects related to road

[18]This is a common trait of subsidies on clean technologies (Tol; 2019).

[19]Meunier and Ponssard (2020) develop a theoretical framework to analyze indirect network effects between car adoption and infrastructure deployment. Li et al. (2017) and Springel (2016) have respectively analyzed policies in the US and in Norway. They show that a more balanced public spending greatly improve the efficiency of the policy.

[20]By evidencing that subsidies on EVs tend to target consumers that would have bought a low-emission (*i.e.*hybrid) even without subsidy, Xing et al. (2019) recommend to implement subsidies that specifically target low-income households.

usage (road maintenance, accidents...) than the only impacts of automobile pollution. Therefore authors argue that as electric vehicles avoid fuel taxes, they should be taxes at purchase at some point.

All these policies are mainly about CO_2 reductions. They generally leaves air pollutant out of the equation. Only a few papers deal with regulation of multiple pollutants (Ambec and Coria; 2013, 2018). This strand of literature highlights the crucial need to understand whether the abatment of pollutants is complementary or not, *i.e.* whether abating one pollutant helps abating the other. Assessing such complementaries is not trivial as there are multiple technical options for depollution. Linn (2019) finds that European policies on CO_2 reduction of new cars have increased the average level of air pollutant emissions of new cars. Indeed, diesel cars (that emits less CO_2 but more NO_x and PM than gasoline cars) have been advantaged by these policies. Moreover, Durrmeyer (2018) finds that the French feebate led to an increase of air pollutant, especially, in areas with good air quality. Holland et al. (2016) have identified that electric vehicles (that do not emit any exhaust gas) were inducing indirect air pollution from the power plants. The authors advice for subsidies that would take into account these indirect air pollution. Durrmeyer (2018) finds that the French feebate policy increased air pollution in zones with initially good air quality.

Literature on the effect regulation of air pollutants on the evolution of the vehicle fleet is much scarser. In the US and in the EU, emissions of air pollutants are regulated within approval tests of new vehicles. As most command-and-control instruments, these norms sets maximal emissions. The result of these regulations are of great importance in the composition of the fleet (Miravete et al.; 2018). Other policies that especially target air pollution are generally part of urban policies. These target air quality along with congestion, road security... Among those policies, only driving restriction policies seem to have modified the composition of the local fleet. These policies restrict city access of a selection of cars. Literature on the topic has shown that policy designs that discriminate cars according to their pollution levels could generate significant fleet renewal (Barahona et al.; 2018; Wolff and Perry; 2010).

2.2 The French case

In this section, we give a brief panorama of the French environmental policies towards pollution of passenger cars. We distinguish between policies on CO_2 and policies on air pollutants.

Policies on green-house gases

In France there are three main policies[21] on CO_2 emissions of cars: a national fuel tax, a European standard on CO_2 emissions of new cars and a national feebate scheme.

French fuel taxes are mostly composed of a value-added tax (VAT) and an excise tax on oil products, the TICPE[22]. The revenues from the TICPE were 24G€in 2017 (around 5% of overall taxes). A carbon component has been included in the tax in 2014. Starting from 7.0€/tCO_2 (before VAT), it was supposed to reach 103.4 €/tCO_2 (before VAT) in 2022. In response to the protest movements of late 2018, the increase of the carbon content has been postponed[23]. Hence in 2020, the carbon tax was 44.6€/tCO_2, which means respectively an additional 10 and 11 cents (before VAT) on gasoline and diesel taxes.

At the European level, the automobile industry is not part of the European emission trading scheme, but an emission standard is implemented. 2020 sees the beginning of the third generation of the European standard on CO_2 emissions. It sets an emission limit for new cars of 95 g/km. Previous standards[24] included voluntary targets[25] with 130 g/km. As average CO_2 emissions of EU new cars went below 130 g/km in 2013 (before the enforcement of the standard), this second standard has not been stringent for car makers. The main features of this regulation are the following[26].

[21] Other regulation worth mentioning are the legal biofuel content in fuels, regional registration taxes...

[22] It exists from 1928 and is collected by the customs. It has been named TIPP (*taxe intérieure sur les produits pétroliers* until 2011. After 2011, its tax base has been modified to incorporate biofuels imports, and became the TICPE (*taxe intérieure de consommation de produits énergétiques*).

[23] In first semester of 2020, an increase of the carbon tax does not seem to appear in political agendas.

[24] https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0001:0015:FR:PDF

[25] https://eur-lex.europa.eu/legal-content/FR/TXT/HTML/?uri=OJ:JOL_2014_103_R_0003&from=FR

[26] https://ec.europa.eu/clima/policies/transport/vehicles/cars_en

For each automaker, the average CO_2 emissions of all new car sold during the year have to be lower than a certain threshold. Such threshold is defined by the average weight of the automaker's sold cars. This rule strongly advantages manufacturers of large cars, as each extra 100kg in the average fleet mass grants them an additional margin of 3.33 g/km on their CO_2 threshold. Since 2019, automakers face penalty payments for excess emissions are 95€ per g/km that exceed their individual thresholds. For the first years of the standard, a "super-credit" mechanism is included for low-emission vehicles (below 50 g/km). For instance, each full-electric vehicle counts as twice in the computation of the automaker's fleet average of CO_2 emissions. Moreover, automakers may group to face the standard as one[27]. Such rule is supposed to allow car makers to reach their threshold in a cost-effective way. Finally, the standard is to be tightened progressively in order to reach emissions levels close to 80 g/km in 2025 and 60 g/km in 2030.

Still on new vehicles, France has been implementing a national feebate schemes since 2008. This feebate is complemented by a scrapping scheme. It took the form of either an independent scrapping premium (*prime à la casse*) or an additional rebate included in the feebate policy (*superbonus*). The feebate scheme has change almost every year since its creation. Along the years, the feebate progressively phased-out rebates on vehicle that were not full-electric or plug-in hybrid, while fees on thermal vehicles have increased steadily. Note that several local authorities have been implementing their own subsidy or scrapping schemes to incentivize adoption of low-emission vehicles.

Policies on air pollutants

French national policy towards air pollution has mostly been in reaction to the directive of the European Commission (CC; 2015). The main regulations on the emission of air pollutants of passenger cars are the EURO norms. These norms come from the effort of standardization of approval procedures of new vehicles within the European Union. EURO norms originate the European directive 70/220/EEC. This one defined among other the NEDC (New European Driving Cycle) in order to assess the fuel economy

[27] For instance Fiat-Chrysler grouped with Tesla Motors.

and pollution levels of passenger cars by simulating a typical car usage in laboratory. Originally, this directive only targeted carbon monoxide and unburned hydrocarbons levels. Euro norms were implemented in the 1990's. Each Euro norm gives absolute maximum thresholds (measured with the NEDC) for air pollutants of vehicles. They are differentiated between passenger cars, light-weight commercial and heavy duty vehicles. Euro norms are differentiated between gasoline vehicles and diesel vehicles. Indeed, Euro norms are less (resp. more) stringent for diesel vehicles than gasoline vehicles in term of NO_x and PM (resp. CO). Such distinction is particular to the EU, as for instance neither the US nor Japan have it[28]. Due to the design of the NEDC, measurements of air pollutants suffers from the same issues as with CO_2. Deviations of measurements between real driving condition and NEDC have even increased since 2000, and mostly with emissions of NO_x of diesels cars (Hooftman et al.; 2018).

As air quality became a public health issue in the 2000's, the European Commission implemented standards for local, especially urban, air pollutants, through the Directive 2008/50/EU[29]. France, as many EU countries including the UK or Germany, repeatedly breached limits for NO_x[30]. Hence, the European commission engaged legal actions at the European Court of Justice in[31]. The court pronounced France guilty in late 2019[32].

There are two main policy levers for local authorities to act on air pollution from cars. These include the regulation to pollution peaks, and low emission zones. Pollution peaks are regulated by regional administrative authorities. When regional pollution observatories detect that pollution of a particular pollutant ($e.g.$$PM_{10}$,$O_3$...) outpaced a threshold, a large set of measures may be undertaken. Temporary measures regarding automobile include driving restrictions based of a national vintage-engine type classification, but also reduction of speed limits, free residential parking, limit transit of heavy-duty vehicles... Low Emission Zones (LEZ) are a local policy developed typically by a municipality, that restrict access of a zone perimiter to a category of

[28] In the US or Japan, diesel penetration has never been higher than a few percents.

[29] https://eur-lex.europa.eu/legal-content/fr/ALL/?uri=CELEX%3A32008L0050

[30] Twelve French cities had annual concentrations of NO_2 around $100\mu g/m^3$ in 2016.

[31] https://ec.europa.eu/commission/presscorner/detail/en/IP_18_3450

[32] http://curia.europa.eu/juris/document/document.jsf?text=&docid=219452&pageIndex=0&doclang=FR&mode=req&dir=&occ=first&part=1&cid=7203078

vehicles. Developing a LEZ needs to define a restricted perimiter inside the municipality, a classification of targetted vehicles, and a calendar of implementation. Perimiters go from the city hyper-center (*e.g.*touristic centers) to the whole urban area. Vehicle classifications generally involve levels air pollution. Calendars define the pace of vehicle exclusion and eventually a broadening of the LEZ perimiter. Compared to other European countries (*e.g.*Germany and UK), France has been particularly late in the implementation of LEZ (ADEME; 2018). The French legislation towards LEZs has changed along with last three governements. In 2010[33], first LEZs started in Paris and Grenoble as experimental programs for three years[34]. Grenoble aimed at banning commercial (light-weight ahd heavy-duty) vehicles, while Paris included all vehicles in its LEZ. This legal framework has been updated in 2015[35]. Municipalities could then implement LEZ[36] indefinetely. This law provides the "Crit'air" classification, described earlier. Under this framework lifetime, only Strasbourg implemented a LEZ in its center for commercial vehicles. In 2018, 12 additional municipalities (as Lyon, Marseille, Toulouse...) made a joined anouncement regarding the creation of a LEZ by the end of 2020[37]. The latest law regarding LEZs was enacted in 2019[38]. LEZ is renamed ZFEm (*Zone Faible Emissions mobilité*). This law makes the implementation of an LEZ mandatory for cities where pollution levels exceed legal threshold values. In 2020, only the Greater Paris[39] had an operationnal LEZ targetting passenger vehicles[40]. The city of Paris restricts access of vehicles with Crit'air 4 and higher, while 5 and higher Greater Paris[41]. The announced calendar plans on banning diesel vehicles by 2024, and gasoline vehicles by 2030. Greater Strasbourg[42] and Greater Lille have announced the operationnal beginning of their LEZ for 2021. Remaining cities that have announced a LEZ, have not yet presented detailed plans.

[33] *Loi Grenelle* I and II.
[34] Named ZAPA (*Zones d'Action Prioritaires pour l'Air.*).
[35] *Loi de transition énergétique pour la croissance verte.*
[36] Renamed ZCR (*Zone à circulation restreinte*).
[37] https://www.ecologique-solidaire.gouv.fr/lutte-qualite-lair-gouvernement-et-15-territoires-sen
[38] *Loi d'orientation des mobilités.*
[39] The *Métropole du Grand Paris* includes Paris and its close suburb (around a hundred small municipalities).
[40] https://www.zonefaiblesemissionsmetropolitaine.fr/
[41] However, there are no police controls in the Greater Paris for now.
[42] https://www.strasbourg.eu/zone-faibles-emissions

3 Contributions of this dissertation

3.1 Research questions and scope

This dissertation studies different aspects of the transition towards electric mobility. It contains four chapters that are independent from each other and are organized according to a transition chronology. Chapter one deals with the exclusion of thermal cars, chapter two with the transition from thermal to electric cars, and chapters three and four with the integration of electric mobility in power systems.

Obviously, this dissertation does not pretend to embrace all aspects of the energy transition in the automobile system. It focuses on engine substitution, and does not consider for instance, other abatement options such as car downsizing or modal report. Although these measures have not been privileged by governments, they are likely to be mandatory in the success of the energy transition.

3.2 Description of chapters

Stranded to be? Diesel ban and used car markets

The first chapter focuses on the first side of the energy transition: removing most pollutant thermal cars from circulation. We investigate the effect of a French policy targeting urban air pollution. This policy consists of driving restriction zones based on vintage and engine types (gasoline or diesel) of vehicles. It is important to notice that this policy is particularly discriminates diesel. Such discrimination is part of a turnabout on the perception of diesel in France. Yet, this engine type has been promoted for decades to become dominant in the automobile fleet. Nowadays, diesel is now associated with smogs in cities, and its advantage in term of lower CO_2 emissions compared to gasoline is not clear anymore. Driving restrictions policies, so-called Low Emissions Zones (LEZ), have been widely introduced in Europe during the last decade and brought a lot of attention from scholars. While most studies assess the short term effects of these policies in term of air pollutant concentrations, little work has been done on the impact of low emission on the replacement of pollutant vehicles soon-to-be excluded vehicles. In this empirical chapter, we ask whether and how car

owners anticipate the implementation of low emission zones. To identify the anticipation, we analyze the French used car market. We rely on data from online advertising platforms. Using web-scrapping techniques, we collected about a million of unique ads from all over France. Our data contains information on basic car characteristics (car name, brand, version, year, engine type), the zipcode of the seller localization. We complete our primary data base with a car specs data base that include further technical characteristics of each brand-model-year-version. We also enlarge our data base with socio-geographical information provided by the French National Statistical Institute. Based on announcements of cities, we define three status of the implementation of LEZ. "Ongoing" LEZ are already in place (*e.g.*in Paris). Cities with "planned" LEZ are about to be implemented by 2021, and the practical details of the policy have been disclosed (*i.e.*exclusion perimeter and calendar). "Announced" LEZ will be implemented in the coming years but no practical details have been disclosed. We control for the effect of each type LEZ by introducing indicators on the proximity of cities with LEZ. This indicator depends on the minimal distance between the zipcode of the seller and the closest city center that is implementing a LEZ. Our empirical strategy is a simple linear regression model on the posted price of ads. We control for vehicle technical and utilization characteristics, advertising characteristics and socio-geographic characteristics. Our explanatory variable of interest is the crossed effect of the diesel dummy and the LEZ proximity indicator. We find a significant and negative effect of the proximity of low emissions for diesel cars. This effect is much higher for ongoing LEZ. Planned and announced LEZs have effects that are close. We find similar results by replacing the diesel dummy with the age of the vehicles. Our results were robust on several sensitivity checks. We did several tests by re-sampling the LEZ indicators and could not find any effect on diesel. We tested for a large city effects, or pollution and did not find any effect. Intuitively, urban planning policies that deliberately aim at limiting car use do not discriminate between diesel and gasoline, or older cars. Only LEZ policies include such discrimination. Hence, we interpret the malus on diesel as an anticipation of consumers on the implementation of driving restriction policies. Back-of-the-envelope calculations estimate that diesel vehicles face a malus around one thousand euros in ongoing LEZs, and a few hundred euros in planned and

announced LEZs. Although LEZ often comes with additional scrapping schemes, they only cover the oldest vehicles, while the diesel malus also applies to the other vintages.

Coordinations of abatements and policies with sector coupling technologies

The second chapter[43] analyzes with a theoretical model the transition from thermal to electric vehicles. More precisely, we investigate how this transition should be coordinated with the decarbanization of the power system, in term of allocation of mitigation of efforts across sectors on the one hand, and in term of sectoral policy design on the other hand. In principle, a cost-efficient decarbonization should be achieved through the implementation of a uniform tax that equates the social cost of carbon (Tol; 2019). With such policy, each sector internalizes its externalities. However, almost no government has implemented carbon taxation (Ramstein et al.; 2019), while decarbonization efforts have mainly involved sectoral policies on clean technologies, such as renewable energy in the power support or electric vehicles in the automobile sector. In this case, a crucial point is how to allocate efforts between sectors in a dynamic perspective. Marginal Abatement Costs (MAC) curves have been a powerful and practical tool to support the decision making of such allocation (Gillingham and Stock; 2018). These curves are a ranking of MAC from the cheapest to the most expensive option. Nevertheless, MAC curves have raised several criticisms in the academic field. The main criticism would be that MAC curves are built in a static framework, that fails to take into account technological progress, sectoral inertia and sectoral interactions. Still unaddressed in the literature, the latter is of main interest because electric vehicles create a new interaction between the transport and the power sectors. This is even more relevant since there have been strong debate on the life-cycle ecological footprint of vehicles. Literature on life-cycle assessment of electric vehicles has identified the carbon content of the electricity used to manufacture and charge electric vehicles as a main driver of the lifetime environmental benefit of electric vehicles. LCA considerations hence raise the issue on whether or not promoting electric mobility when the electric sector is not decarbonized. This issue also applies to sectoral transition towards other energy carriers, such as hydrogen or biogas.

[43] This chapter comes from a collaboration with Guy Meunier.

This chapter analyzes the optimal allocation of mitigation effort among two vertically connected sectors, an upstream (e.g. electricity) and a downstream (e.g. transportation) one. In each sector, an homogeneous good is produced by the mean of one clean and one pollutant technology. The clean downstream technology (e.g. electric vehicle) consumes the upstream good as an input and may raise production to that sector. Polluting technologies induce social costs, with idiosyncratic emission rates. In partial equilibrium settings, we study the social optimum and the competitive equilibrium. We work mainly with general convex functional forms, but some results mainly holds with quadratic forms for clean technologies and linear forms for consumer demand and dirty technologies. At equilibrium and in each sector, marginal of clean technologies equates marginal costs of dirty sectors added to the social costs of carbon induced by the latter. Sectoral linkage induces that the marginal downstream clean costs include the upstream good price.

Understanding the allocation of effort between sectors requires to evaluate the precise order of phase-in and phase-out of clean and dirty technologies in all sectors. Assessing the comparative statics of this equilibrium relatively to the social cost of carbon gives unexpected ambiguous results on the monotony of the downstream clean quantity and the upstream dirty quantity. From the analytical conditions driving this ambiguity, we define three types of sector coupling technologies: upstream-driven, downstream-driven and balanced. For low linkage intensities, sector couplings are most likely balanced. For large linkage intensities, coupling types are downstream-driven (resp. upstream-driven) when the emissions rate of the dirty technology is much higher (resp. lower) in the downstream sector compared to the upstream sector. We characterize coupling types according to the concept of consequential life-cycle assessment (cLCA), which computes the life-cycle impact of a marginal unit of a good by taking into account market interactions.

We relate coupling types to the description of transition pathways (*i.e.*the chronology of phase-in and phase-out of technologies). With upstream-driven couplings, the only pathway possible is that the deployment of the downstream clean technology starts after the full decarbonization of the upstream sector. With downstream-driven couplings, it is possible that the upstream sector shows a transient decarbonization,

to restart its dirty technology to follow the deployment of the downstream clean technology. To fully characterize transition pathway, we define "transition" marginal costs that allow us to overcome the endogeneity of marginal costs between sectors due to the sector coupling. We demonstrate that the ordering of technology phase-ins and phase-outs across sectors is explained by the ranking of these transition MACs.

We then study the competitive equilibrium, and assess the optimal policies. Pigovian taxes in each sector implement the first-best, and hence do not require policy coordination across sectors. We then investigate the situation where regulator can not implement first-best carbon taxes, but can use subsidies on clean technologies in addition to taxes each sector. By computing the comparing statics with each sector, we find similar ambiguities as previously. When sector coupling is upstream-driven (resp. downstream-driven), we found that the downstream clean (resp. upstream dirty) quantity would decrease (resp. increase) when the downstream subsidy (resp. upstream tax) increases. Sectoral second-best subsidies depend on the unpriced emissions inside the sector. Second-best subsidies in the downstream sector have a component that is related to the upstream sector. We interpret this as a need of coordination of the downstream subsidy to the policies in the upstream sector. Obviously, this need of coordination disappears in case of a perfect carbon pricing. We show that welfare losses induced by second-best instruments compared to first-best taxes does not depend on the linkage. In order to assess the relative importance of policy coordination across sector, we consider that sectoral policies may be developed by distinct regulators that may not take into account the effect of their policies in other sectors. Such regulators would choose uncoordinated optimal subsidies. Our final result is to show that the welfare losses from incoordination may outweigh losses from imperfect carbon pricing, when linkage were strong enough, which would corresponds to upstream or downstream-driven sector couplings.

Interactions between electric mobility and photovoltaic generation

The third and fourth chapters go deeper in the analysis of the integration of electric vehicles inside the power system. Through a thorough literature review[44]. The third chapter studies the specific interaction between electric mobility and photovoltaic energy. This interaction has recently gathered a of lot attention from scholars (Mwasilu et al.; 2014; Richardson; 2013). Indeed, photovoltaic energy has been the most disruptive power source in the recent years. The motivations of this coupling are multiple. While both technologies should deliver environmental benefits, they strongly depend on public support to be economically viable. Hence, they require to trigger alternative efficiency levers. Moreover, both technologies present characteristics that should jeopardize the stability of power grids. Regarding solar energy, it is its variability and intermittency. EV may induce sudden large power peaks, that may happen in the evening, after drivers have commuted back home and plugged their vehicles. The combination of these effects would result in a power facing almost no or negative net (of renewable) demand during a sunny afternoon, to be followed by a massive consumption peak in the evening. A straightforward solution would then be to displace EV charging during sunny hours. This would increase the environmental benefits of both technologies, improve economic profitability and reduce systems costs in power networks. The aim of this chapter is to investigate the efficiency determinants of systems that combine electric vehicles and photovoltaic generation. We review a wide literature, mainly techno-economic, on the topic and develop a systematic framework to analyze these systems. We organized our framework along technical aspect on the one hand, and economic aspects on the other hand.

We distinguish technical aspects of EV/PV systems, between its spatial configuration, its smart charging strategy of electric vehicles, and its technological environment. Spatial configuration is one of the most determinant aspect as directly set the potential synchronization between EV charging patterns and PV production profiles. EV/PV systems can be constituted inside individual house, buildings, charging stations, or wider territories. Efficient EV/PV system are operated by the mean of a

[44]Published as: Hoarau, Q., & Perez, Y. (2018). Interactions between electric mobility and photovoltaic generation: A review. Renewable and Sustainable Energy Reviews, 94, 510-522.

smart charging strategy. Each strategy gather a singular objective, a control mode and a coordination method. EV/PV systems may be in presence of other energy technologies. Efficient operations of such systems may consist in optimizing the system as a whole across energy carriers. The technological environment may integrate additional storage technologies (*e.g.*batteries), heating systems, other energy sources (*e.g.*wind) and network technologies (*e.g.*DC systems).

Economic aspects of EV/PV systems include three dimensions: the cooperation between technology owners, the interaction between the system and surrounding power networks and the regulatory and political environment. Beside the individual houses, EV/PV system most likely s different stakeholders that own PV systems and EVs. There are two typical configurations where lack of cooperation can prevent a synergy allowed by the technical aspects. First, in charging stations with PV capacities where the station operators have to give incentives to EV drivers to agree for a flexible charging management. Second, in territories where EV fleet managers have to contract large PV producers. Efficient EV/PV systems may generate benefits for power grid, or at least mitigate the respective impacts of each technologies. The literature has identified distinct relations with distribution and transmission grids. The third dimension of economic aspects concerns regulations and policies on both mobility and power sectors. These can be distinguished between pricing regulation, entry conditions in power markets, and support mechanisms.

Network tariff design with prosumers and electromobility

The last chapter[45] addresses one of the open issues identified by the third chapter. It focuses on the issue of power network tariff design with electric vehicles and distributed energy resources (DERs). Indeed, decentralization is one of the ongoing disruption in power grids. With DER such as photovoltaic panels or stand-alone batteries, it becomes possible to produce and consume their own power (Dato et al.; 2020). Such active users are also named prosumers. In parallel, electrification of end-use sectors, such as transport or heat, is an other trend for consumers, which leads them to rely even

[45]Published as: Hoarau, Q., & Perez, Y. (2019). Network tariff design with prosumers and electromobility: Who wins, who loses?. Energy Economics, 83, 26-39.

more on electricity for their basic needs. In this chapter, we focus on electric vehicles. All these technologies now meet in distribution networks, where they pose challenges for grid operations. Indeed, the variability of PV and the high-power charging patterns of EVs should induce voltage drops, increase network losses and decrease transformers lifetimes. In the meantime, grid operations should be enhanced by the usage of digital technologies such as smart metering. The literature has pointed out that DERs raises issues on how grid costs should be recovered. In most European countries, a dedicated component of the electricity bill[46] is allocated to networks operators. The tariff design of this part deals with how users are charged for using the networks. Traditionally, tariffs were mainly based on the energy consumed. Such tariff structures become problematic with the apparition of prosumers. Indeed, as prosumers self-consume, they do not contribute to the operations of a network they still rely on, for instance, when their DER do not produce. As prosumers avoid network charges, operators' revenue to decrease. This would lead regulators to increase network charges for all users in order to ensure the financial stability of operators. As this increases electricity bills for all users, it increases the profitability of investment in DERs. Most studies assume a low user heterogeneity, a clear opposition between prosumers and traditional users and focus on technologies that decrease users' consumption. In this chapter, we contribute to the literature by adding electric vehicle, *i.e.*a technology that substantially increases users' consumption, in this equation. We aim at understanding the distributional effects across network users of different tariff designs. We rely on a numerical game-theoretical model that combines four classes of representative users and a regulator that ensure the financial balance of the network operator, by setting tariff levels. The model is calibrated on European-averaged consumer consumption profiles. The model is solved iteratively. Our model confirms the intuition that higher share of prosumers increases tariff for the other users. More interesting, our results suggest that when the share of electric vehicle owners increases, tariff decreases. Indeed, EV owners induce an opposite mechanism compared to prosumers. As their share grow, more charges are collected by operators, increasing their revenues. This leads the regulator to decrease tariffs for all users. With our calibration, we find that the marginal effect of

[46] Around one third with energy part and taxes.

EV owners outweighs the marginal effect of PV prosumers. An important mechanism is that we assume that driving needs of EV owners were inelastic with respect to electricity prices. Hence when the share of EV owners increase, tariffs lower and DER investment may become less profitable. This mechanism is especially visible regarding battery investments. The key-message is that EV owners could more than compensate the negative effect created by prosumers. Said differently, traditional networks users - with no EV nor DER - won't see their electricity bill raise a lot as long as there are enough EV owners. Furthermore, we discuss how those results differ more with alternative tariff structures than energy based charges, such as flat tariff of capacity-based tariffs. Also, the appendices discuss these results when network costs are not fully sunk but depend on the peak power in the grid. This paper fills a gap in the literature on the interactions between electric vehicles and photovoltaic. It presents a fundamental conflict between those technologies, as one consumes energy while the other produces it.

4 References

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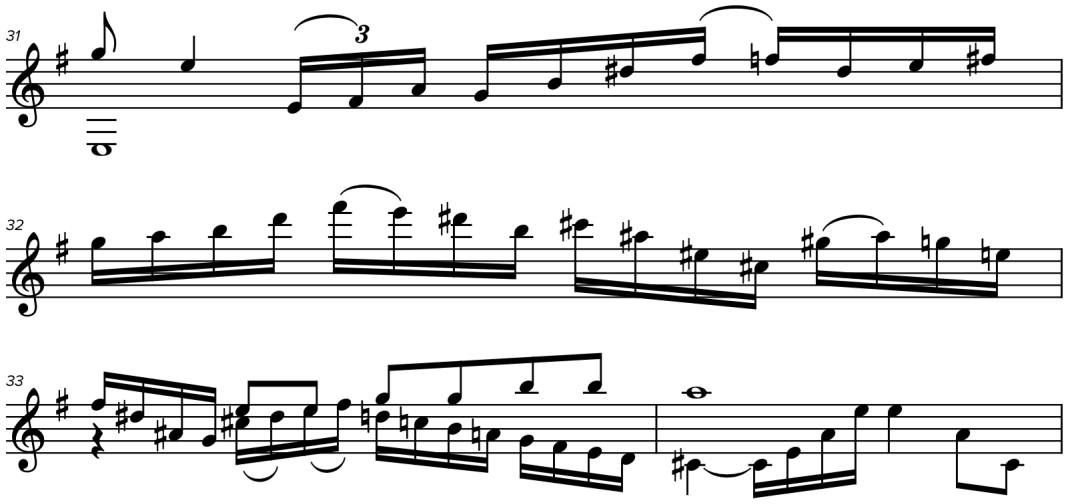

Antoine Boyer - *arrangement de Sound for Silence (Paul Simon).*

* * *

Chapter 2

Stranded to be? Diesel ban and used car markets

* * *

After promoting their development for two decades, European governments are pulling back their support to diesel cars. While those engines were assumed to be "cleaner" than gasoline ones, thanks to lower fuel consumption and reduced CO_2 emissions, they turned out to emit much more air pollutants. In response to growing concerns about the effects of air quality on public health, Low Emissions Zones (LEZs) are gradually implemented by several cities, announcing a progressive ban on diesel cars which could turn those vehicles into stranded assets for households. This is a thorny issue in France where half of passenger vehicles are diesel-fueled. Investigating about one million of used cars ads across France, we find that diesel vehicle sellers located within ongoing and planned LEZs anticipate this change of regulation and lower their asking price for those cars. This effect is robust to the introduction of an air pollution indicator for cities, evidencing a specific effect of this LEZ policy.

* * *

1 Introduction

The Diesel-gate scandal revealed the need for stronger environmental regulations in the road transport sector (Jonson et al.; 2017). It contributed to speed up announcements on the ban of petrol - especially diesel - cars from European countries and cities over the last few years (Plötz et al.; 2019). Indeed, road transport is a major producer of environmental externalities with greenhouse gases[1] and air pollutants[2]. Alongside European and national policies, cities develop local clean air programs. Low Emission Zones (LEZs) are among the most ambitious programs for clean air, and spread quickly across the Member States[3]. A LEZ is an area where some driving restrictions are applied to vehicles, according to their air pollutants emissions. Such programs often enable cities to tighten national targets on their territory[4]. Nevertheless, a major obstacle to diesel bans lies in the important share diesel cars in the vehicles fleets of several European countries, such as Germany or France. Although more expensive to purchase, diesel cars have benefitted both from a competitive advantage towards gasoline cars, as they consume less fuel, and from a favorable tax system inherited from the specialization of several European car makers in diesel engines (Hivert; 2013).

This paper investigates the impact of diesel ban announcements by French cities on the used cars market. More precisely, we determine if ongoing and future LEZs impact prices posted by used cars sellers. Our analysis relies on scraped data containing about one million ads of used cars from online car dealers and market-places. We find that that posted prices for diesel cars are significantly smaller in both ongoing and future LEZs. This impact is about three times larger for ongoing LEZs compared to future ones. Several robustness checks confirm these results.

We relate to two main strands of literature. The first one is the economic analysis of driving restrictions. Due to their recent implementation, only few studies investigate LEZs' efficiency in Europe. Nevertheless, European LEZs have a lot in common with

[1] Road transport contributed 21% of CO_2 emissions in Europe in 2016. Source: https://ec.europa.eu/clima/policies/transport/vehicles_en

[2] According to the European Environment Agency, road transport produces up to 30% of fine particles and NO_2.

[3] There were more than 230 cities with LEZs in 2019 in Europe.

[4] For instance, several French cities, including Paris, aim at prohibiting entrance to diesel cars by 2030, while national target aims at phase out new diesel cars in 2040 (Plötz et al.; 2019).

some driving restriction policies developed in other parts of the world. Such policies in Latin America (Colombia, Mexico, Ecuador, Chile...) and China have brought attention to scholars. Studies mainly focused on two effects of driving restriction policies : on the one hand, their benefits in terms of air quality and health, and on the other hand, their impact on local vehicle fleets composition, congestion and modal choices. Wolff (2014) analyses the effect of German LEZs, finding an average 9% decrease of PM emissions in the treated areas. He also underlines a significant effect on the renewal of the car fleet near LEZs, with more recent low-emission vehicles. Gehrsitz (2017) finds that LEZs significantly improve air quality, but does not isolate a significant related improvement in infant health. Some Latin America cities - as Mexico, Bogota - developed driving restrictions based on licence-plated digits (authorizing alternatively odd and even plated cars to circulate), and not on cars pollution levels. Several authors such as Davis (2008); Gallego et al. (2013); Zhang et al. (2017) have shown that these policies did not improved air quality or decreased congestion. This inefficiency lies in the design of the policy which gave incentives to drivers to buy a second car, generally older and more polluting. , Barahona et al. (2018) indicate that driving restriction policies targeting cars by vintage would be much more efficient. In addition, Carrillo et al. (2016) points out the importance of a strict enforcement by the local police, especially during peak hours. In the case of Beijing, Blackman et al. (2020) evaluate net positive benefits of the driving restriction policy.

The second interesting strand of literature covers empirical studies consumer behavior in car purchase. However, their results are diverse regarding the rationality of consumers. While Sallee et al. (2016) showed that used cars buyers have consistent anticipations regarding energy costs, Lacetera et al. (2012) showed that they rely on heuristics when buying used cars, suffering from a bias in the process of odometer values. Regarding consumers anticipations regarding regulatory changes, the recent papers by Rittenhouse and Zaragoza-Watkins (2018) and Asplund et al. (2019) make interesting contributions by showing how a credible political announcement shifted substantially car buyers behaviors.

The remaining of the paper is organized as follows. Second section describes the French context, presents the data and our empirical strategy. Third section presents

the results of our empirical estimations. Fourth section concludes. Appendices include additional information on the French context, present other descriptive statistics and robustness tests details.

2 Methods

2.1 Background

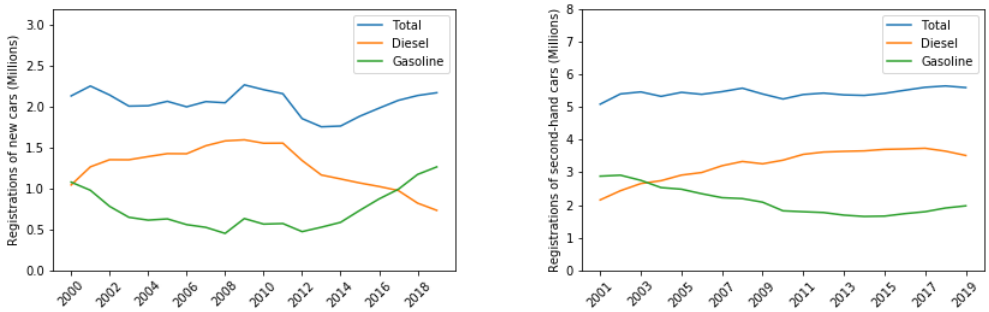

Figure 2.1: Registration of new cars (left) and used cars (right) from 2000 in France, by fuel type (gasoline and diesel). Source: SDES (French minister of ecology).

Since the 1990's, France has developed an important share of diesel cars in its national fleet. In 2013, diesel share was 75% for new car sales and 60% in the whole fleet. Figure 2.1 shows the evolution of registration of new and used cars by fuel types in France. For consumers, diesel were more expensive to buy but with less costly fuel expenses. This trend was sharpened both by a fiscal advantage on diesel fuel over gasoline and by the industrial know-how of French makers in diesel engines (Hivert; 2013). The diesel advantage peaked with the introduction of a national feebate and scrapping scheme targeting CO_2 emission level new cars. Due to their lower CO_2 emissions, new diesel vehicles would receive a substantially rebate. This trend was reversed in the middle of the 2010's. Following the 2008 economic crisis, smaller and cheaper vehicles were favored by consumers, increasing the proportion of gasoline-fueled ones. In the middle of the decade, several fiscal advantages on diesel have begun their phase-out, thanks to a raising awareness of policy makers regarding air pollution hazards. In 2019, new registrations of diesel cars dropped to 30% while national share of diesel has dropped to 50% in the vehicle fleet.

In France, the market for second-hand cars is more than twice the size of new cars, with five million transactions each year. The used-cars market follows the fleet dynamics induced by the new car market. Hence, while there has been an inflection in the market for new diesel car in 2010, the used car market is still dominated by diesel vehicles.

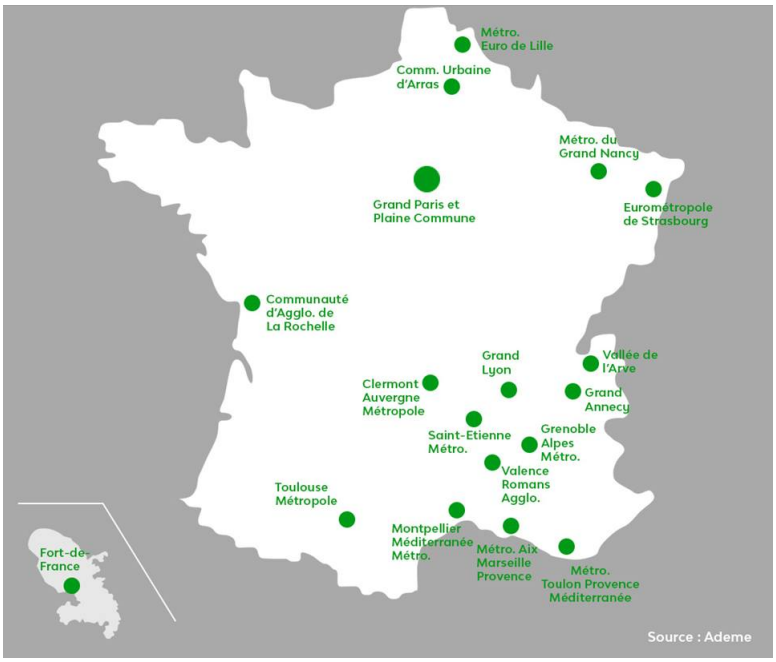

Figure 2.2: Map of French Low Emission Zones that are in place or will be by 2021.

According to the *Cour des Comptes*[5], French policy regarding air pollution has mostly consisted in applying - with some delay - the successive directives from the European Commission. Moreover, France has been condemned several times by the European Commission for non-compliance with air pollution levels.

Four LEZs were in place in 2019 in France[6], and nineteen should be in 2020 [7]. In late 2019, a new general law on mobility created a formal legislative framework for LEZs. This framework makes mandatory the creation of a Low Emission Zone for each city which has repeatedly violated pollution limits. Cities implementing LEZs

[5]French national administrative court in charge of providing financial and legislative analysis.
[6]In Paris, Paris agglomeration (with a less stringent restriction), Grenoble and Strasbourg.
[7]https://www.ecologique-solidaire.gouv.fr/zones-faibles-emissions-19-collectivites-sengagent-qualite-lair

are displayed on figure 2.2. These LEZs consist in excluding most polluting cars from delimited areas, which can cover from a limited zone (such as city center) to the whole agglomeration. Air pollutants of vehicles are classified according to their Air Quality Certificate, named *Crit'Air*. Those certificates are differentiated according to the fuel type and the Euro emission norm of the vehicle (see Table 2.3). Euro norms are mandatory norms on local pollutants emissions (PMs, CO, NO_x) which car makers must comply from a certain year. Nevertheless, compliance generally starts one year before the year of enforcement of the norm. The part of the fleet labelled 4 and above was around 20% in 2019 [8]. Figure 2.5 in the appendices shows the geographical distribution of cars labeled 4 and above in 2019 across France. In January 2020, only the Paris metropolitan area had an ongoing LEZ by restricting access to diesel car labeled Crit'air 4 and more. Cities of Strasbourg and Lille enacted the implementation of their LEZs for January 2021 and detailed that the LEZ perimeter will cover most of the city urban area. In addition Strasbourg aims at banning diesel in 2025.

2.2 Data

Our main dataset comes from the scrapping of online car ads. Ads are recovered from the website which aggregates used car ads from more than fifty online car dealers websites, market places and platforms. From a single recovery in 2020, we collected more than 900,000 unique ads. As a reference, there are about five million transactions of used cars each year in France. Web scrapped data, and more generally big data sources, are a data source of growing interest in the economic research and have been used in diverse fields such as macroeconomics, housing or digital economics (Edelman; 2012). Each ad contains the selling price, the vehicle age and mileage, technical characteristics, zip-code and nature of the seller (professional dealer or private individual), the website of the original dealer, the number of days since the ad has been posted online. Technical characteristics include the vehicle maker, model, year and version, body type, fuel type and gearbox type.

[8] https://www.statistiques.developpement-durable.gouv.fr/une-voiture-sur-deux-est-eligible-la-vignette-critair-1-ou-2?list-chiffres=true

We complete each ad with other characteristics on the car, using a secondary data set, also obtained by scrapping a website gathering more than 100,000 car specs. Additional characteristics include power trains, car dimensions, etc.

We also add socio-demographic information based on a geographic criteria, provided by the French National Statistical Institute (INSEE). Added variables include population density, median income and a classification of areas' urban type defined by INSEE (urban, suburban, rural, remote areas...)[9]. We link each post-code to pollution data collected from the LCSQA, an official laboratory monitoring pollution in France[10]. We link our data set to the number of pollution alerts by region for the last five years.

Finally, we make the following simplifications on the merged data set. We remove ads from rare brands cars (less than 200 ads in our data set), oldest cars (older than 30 years), luxury cars (more expensive than 100,000€), alternative fuel cars (electric, hybrids, LNG...). We also remove ads that have been online for more than one year.

2.3 Descriptive statistics

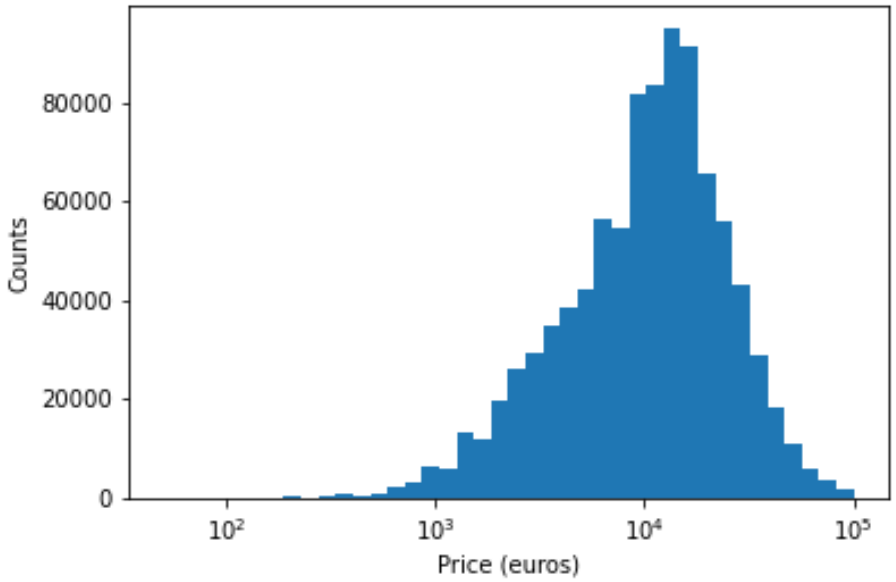

Figure 2.3: Distribution of prices

[9] See https://www.insee.fr/fr/information/2115011 (in French).
[10] https://www.lcsqa.org/fr/les-donnees-nationales-de-qualite-de-lair

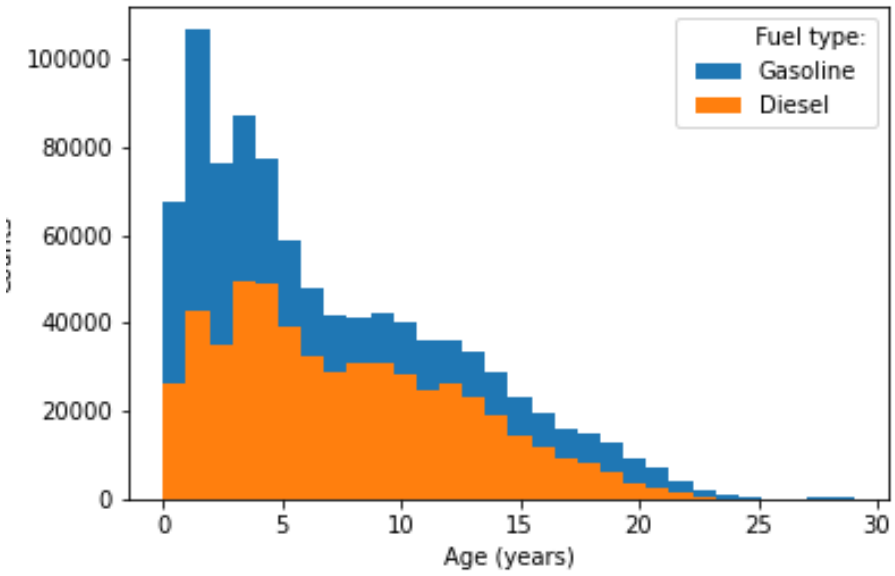

Figure 2.4: Distribution of age by fuel types

Variable	Mean	Std. deviation
Price (€)	14003	12013
Age (year)	6.9	5.6
Mileage (km)	97000	79000
Engine power (kW)	128	52
Weight (kg)	1312	298
Fuel consumption (l/km)	5.2	1.4
Trunk volume (cm^3)	391	224
Fuel type - Diesel (dummy)	58%	-
Gearbox - Manual (dummy)	71%	-
Seller - Professional (dummy)	57%	-
Total : 919,594		

Table 2.1: Main descriptive statistics

Table 2.1 shows main descriptive statistics from our data sets on used car ads. Figure 2.4 shows the distribution of age, for both diesel and gasoline engines. Diesel are more represented than gasoline (60% of our data set), and even more for vehicles aged from 5 to 15 years. This is consistent with the historic trends of the French fleet mentioned earlier. Full electric and other fuel types (as LNG) are present in very low quantities, which is due to their very low share in new cars sales. For ease of understanding, we discard them of our our analysis. The typical car ad shows an average price of about 15,000 euros, and a mileage of almost 100,000 kms. The majority of ads in our data set is posted by professional dealers (60%).

2.4 Empirical approach

LEZ proximity indicator

In our analysis, we differentiate cities along three types of Low Emission Zones. First, cities with an ongoing LEZ that already restricts city access from some diesel passenger cars (only Paris area for now). Second, cities that have planned to implement a LEZ (Strasbourg and Lille) in the coming year and presented a perimeter and/or a precise calendar of vehicle exclusion. Third, cities that have either committed to implement a LEZ without having defined practical details (*e.g.*Toulouse, Marseille, Montpellier) or already implemented LEZ that do not exclude any passenger vehicles yet (as Grenoble, Lyon). We refer to these using the denomination *ongoing*, *planned* and *announced*. Based on this classification, we define the following proximity indicators:

$$PROX_{ij} = e^{-d_{ij}/d_0} \tag{2.1}$$

With i being the index of the ad in our data set, j the type of LEZ considered. d_i is the minimal distance between the centroid of the zip-code of the ad and the coordinates of the centers of an LEZ of type j. d_0 is a characteristic distance supposed to represent the size of the local car market. With this formulation, $PROX_{ij} = 0$ when the distance d_{ij} is much larger than d_0. We motivate the use of such ad-hoc indicators as follows. First, used-car markets are relatively local markets, since transactions costs for buyers increase with distance. Hence, each seller's ads are rather aimed at potential buyers

in a reasonable perimeter. Second, the alternative option of defining a "dummy" LEZ indicator inside sole perimeter of the municipality responsible of the policy remains arbitrary, as some cities have not defined clearly the limits of their area yet, and as these perimeters are likely to evolve in the future. We set d_0 by default at 20 km, and perform sensibility checks around with value. Using this 20 km value, the proximity indicator becomes very small from 100 kilometers.

Econometric model

Our empirical estimation relies on a simple linear regression model. We are particularly interested in the cross-effects of the LEZ proximity indicators with either the fuel type of the vehicle, or its age. Note that we do not include Crit'air labels as treatment variables for the following reasons. Indeed, as shown in the appendices, Crit'air labels are defined in function of age and fuel type, and it would be difficult to disentangle age and fuel types from an hypothetical "label" effect. Our models are :

$$\log(PRICE_i) = \alpha X_i + \beta A_i + \gamma G_i + \sum_j \left[\sigma_j PROX_{ij} + \eta_{ij} PROX_{ij}.Fuel_i\right] + \epsilon_i \quad (2.2)$$

$$\log(PRICE_i) = \alpha X_i + \beta A_i + \gamma G_i + \sum_j \left[\sigma_j PROX_{ij} + \eta_{ij} PROX_{ij}.Age_i\right] + \epsilon_i \quad (2.3)$$

X_i is the vector of car characteristics : energy, age, body types, makers, power, fuel consumption, gearbox type. A_i represents the ad characteristics: the seller type (individual or professional), fixed effects on which type of advertising platform, the duration of the ad at the scraping date. G_i is a vector gathering control variables on the location of the seller at the zip-code of subregion level: median revenues, population density, area type, number of pollution alerts... $Fuel_i$ and Age_i are the fuel type and the age of advertised car i. ϵ_i is the average effect on price resulting from unobserved characteristics (error term). We choose the following references for categorical variables: gasoline for fuel types, sedan for body shapes, French maker Renault for makers, professional for seller types, automatic for gearbox types.

3 Results

	Dependent variable:	
	log(Price)	
	(1)	(2)
Age	−0.076*** (0.0001)	−0.075*** (0.0001)
Mileage	−0.039*** (0.0001)	−0.039*** (0.0001)
Diesel	0.010*** (0.001)	0.005*** (0.001)
Manual Gearbox	−0.123*** (0.001)	−0.123*** (0.001)
Professional Seller	0.051*** (0.001)	0.051*** (0.001)
Ad Duration	0.0002*** (0.00000)	0.0002*** (0.00000)
Engine Power	0.003*** (0.00001)	0.003*** (0.00001)
Weight	0.0003*** (0.00000)	0.0003*** (0.00000)
Fuel Consumption	−0.034*** (0.001)	−0.034*** (0.001)
Trunk volume	0.0001*** (0.00000)	0.0001*** (0.00000)
Median Revenue	0.031*** (0.002)	0.029*** (0.002)
LEZ_ongoing_20	−0.055*** (0.004)	−0.045*** (0.004)
LEZ_planned_20	−0.068*** (0.003)	−0.033*** (0.004)
LEZ_announced_20	−0.012*** (0.002)	−0.0001 (0.002)
Diesel:LEZ_ongoing_20	−0.086*** (0.004)	
Diesel:LEZ_planned_20	−0.022*** (0.004)	
Diesel:LEZ_announced_20	−0.018*** (0.002)	
Age:LEZ_ongoing_20		−0.008*** (0.0004)
Age:LEZ_planned_20		−0.007*** (0.0004)
Age:LEZ_announced_20		−0.003*** (0.0002)
Constant	9.181*** (0.005)	9.183*** (0.005)
Brand	Yes	Yes
Category	Yes	Yes
Geographic controls	Yes	Yes
Ad controls	Yes	Yes
Observations	919,594	919,594
R^2	0.905	0.905
Adjusted R^2	0.905	0.905
Residual Std. Error (df = 919507)	0.281	0.281
F Statistic (df = 86; 919507)	101,836.400***	101,891.400***
Note:		*p<0.1; **p<0.05; ***p<0.01

Table 2.2: Main regression results

Main regressions are shown in Table 2.2. Our econometric model has a high explanatory power, about 91%. Most controls are highly significant and their effects are easily interpretable. As expected, results indicate that age and mileage have depreciating effects on the asked car price by sellers. Diesel cars are more expensive than gasoline cars. As discussed earlier, this result is understandable as new diesel cars are generally more expensive than the gasoline equivalent. Financial advantage of diesel remains in its lesser consumption of fuel and lower fuel taxes. Fuel consumption has a negative effect, meaning that fuel economy is valued by sellers. Car value increases

with the engine power and the size (weight and trunk volume) of the vehicle. Regarding the controls on the add, cars sold by professional dealers are more expensive than by private individual. This can be explained by the additional services, such as warranties, that dealers may provide to their customers.

The central result is that the crossed effect of LEZs and diesel engine is negative and highly significant. The effect is three times higher for ongoing LEZs than for planned LEZs. The effect in planned LEZs is also slightly higher than in announced LEZs. The second regression shows that the LEZ stimulates vehicles depreciation due to aging. The effect is much larger for ongoing and planned LEZ than for announced.

This indicates that car sellers located within cities with a LEZ program anticipate the future effect of these policies - a progressive discrimination and/or ban of diesel - and lower their posted price compared to the ones for the same car in cities without a LEZ. To say it in a nutshell, the perspective of a LEZ implementation decreases the leftover diesel and older car value compared to zones without any anticipated LEZ. The fact that this effect indicate that the eventuality of diesel ban in cities is taken seriously by vehicle owners. This "LEZ" malus on diesel and old cars could also be amplified by a drop of consumer demand towards such cars. Consumers anticipating driving restrictions in the future would avoid choosing those cars. However, as we do not observe transaction prices, we can not conclude on this mechanism.

These results are robust to several checks. First, sensitivity checks on the most crucial hypothesis - the characteristic distance of our LEZ proximity indicator - are shown in the appendices, and show similar results. Then, random re-sampling of the LEZ variable evidences the specific effect of this policy. We also introduce a fourth class of French large cities that did not plan the implementation of an LEZ program. We did not find significant effect of the price of diesel cars. Using the previously defined classification of urban areas from INSEE, we do not find either the evidence of a general "large city" effect on diesel used car prices.

4 Discussion and conclusion

Our results provide a new evidences that a stringent environmental policy may create stranded assets for individuals. From the average posted price of diesel cars in ongoing and planned LEZs, back of the envelope calculations can give the absolute depreciation caused by the implementation of LEZ programs. We find an average depreciation of diesel cars of 1150 € for ongoing LEZs and 350 € for planned and announced LEZs. In comparison, the national scrapping scheme has been completed in 2020 to include an additional rebate for residents in LEZs. A maximum of 2000€[11] can be granted to consumers who scrap their car if it will be targeted by the LEZ. Hence a priori, consumer losses should be compensated. Nevertheless, note that this subsidy does not reach all diesel cars. Hence, relatively new diesel cars could see their leftover value drop with any compensation.

In the discussion of our results, we proposed several explanations that incorporated dynamic aspects, such as the selling rush of old diesel car owners. For further research, we plan to build a panel data of similar ads, in order to track the evolution of the "LEZ malus" in time. Future works should elaborate how those effects may translate into distributional effects. Finally, there are reasons to think that LEZ program may have significant spatial spillovers in local car markets. Potential extensions of this study will be to include more precise geographic specifications in a spatial econometrics framework.

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2.A Introduction to webscrapping

Web-scrapping is a data mining technique, which consists in the automated extraction of the content of web pages. To do so, a bot is programmed with the following components : a processing method of the HTML code of the page that stores needed information, a method for webpage extraction, and an a list of URLs to visit. Such bots can be written in common programming language such as Python or R. (Mitchell; 2018) provides an introduction to the topic in Python, and (Munzert et al.; 2014) in R.

To process the code of an extracted HTML page, several built-in libraries can be used, such as *BeautifulSoup* in Python or *Rvest* in R. These libraries do not prevent a comprehensive preliminary study of the building of the HTML pages. Typically, a bot programmer have to understand which elements of the page contains the right information, which tags refers to the elements etc. Nevertheless, very limited practical knowledge in HTML is required.

There are several methods to extract the HTML code of a webpage. The simplest one is to perform a remote HTTP requests, using the libraries *Requests* on Python[12] or *Rvest*[13] in R. HTTP requests may be insufficient when the webpage contains advanced features, such as JavaScript modules. The user may use a remote-controlled web browser. For both Python and R, the *Selenium* is the appropriate library. Such programmed browser allows actions that are closer to real users', such as stimulating clicking or using keys.

Last, a list of the URLs of web pages must me constituted. This can be straightforward when the URLs wanted pages show a clear pattern that is easily generalizable. When this is not the case, an alternative may be to use the search engine of the website. Search results may be given a series of pages that may be scrapped in order to recover the url of each result. However, the number of results may be limited by the website. This issue may be overcome by multiple filtered searches that maps the whole set of needed pages.

[12] Such library is a simplified version of *urllib2*. *Requests-html* is an alternative version that adds additional features, such as JavaScript support.

[13] *Rcrawler* is an alternative package.

2.B Additional information on French LEZs

Crit'Air label	Gasoline	Diesel	Hybrid	Full electric
0				All
1	Euro 5 and above (>2011)		All	
2	Euro 4 (2006-2010)	Euro 5 and above (>2011)		
3	Euro 2&3 (1997-2005)	Euro 4 (2006-2010)		
4		Euro 3 (2001-2006)		
5		Euro 2 (1997-2000)		
Non-ranked	Euro 1 and below (<1996)	Euro 1 and below (<1996)		

Table 2.3: Definition of "Crit'Air" air quality certificates for light duty vehicles.

City	LEZ type
Paris area	Ongoing
Strasbourg	Planned
Lille	Planned
Lyon	Announced
Grenoble	Announced
Toulouse	Announced
Marseille	Announced
Montpellier	Announced
Toulon	Announced
Clermont	Announced
Nice	Announced
Saint-Etienne	Announced
Rouen	Announced
Nancy	Announced
Valence	Announced

Table 2.4: Classification of city by LEZ type.

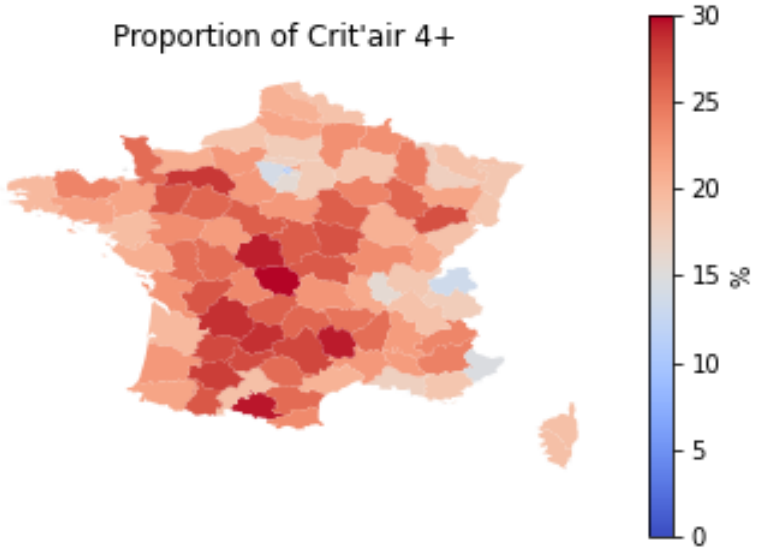


Figure 2.5: Proportion of cars labeled Crit'air 4,5 and NC.

2.C Additional descriptive statistics

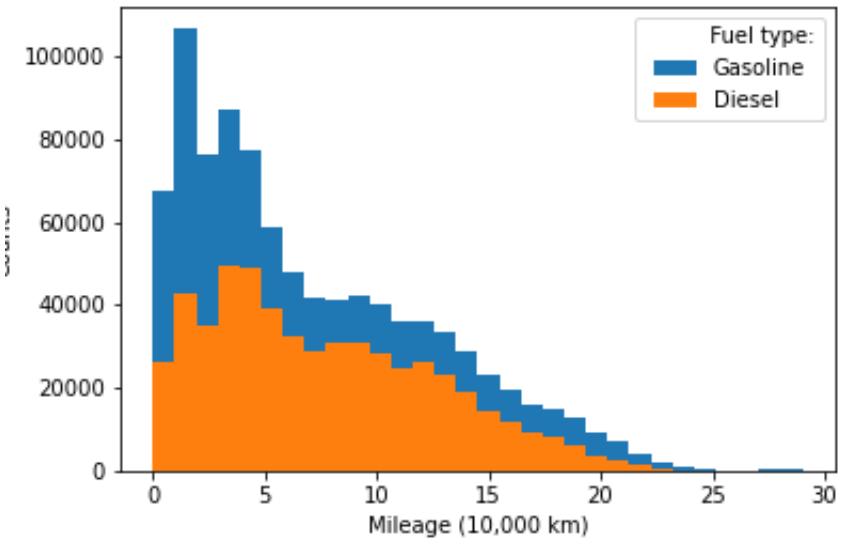


Figure 2.6: Distribution of mileage of used cars with their fuel type.

2.D Additional regressions

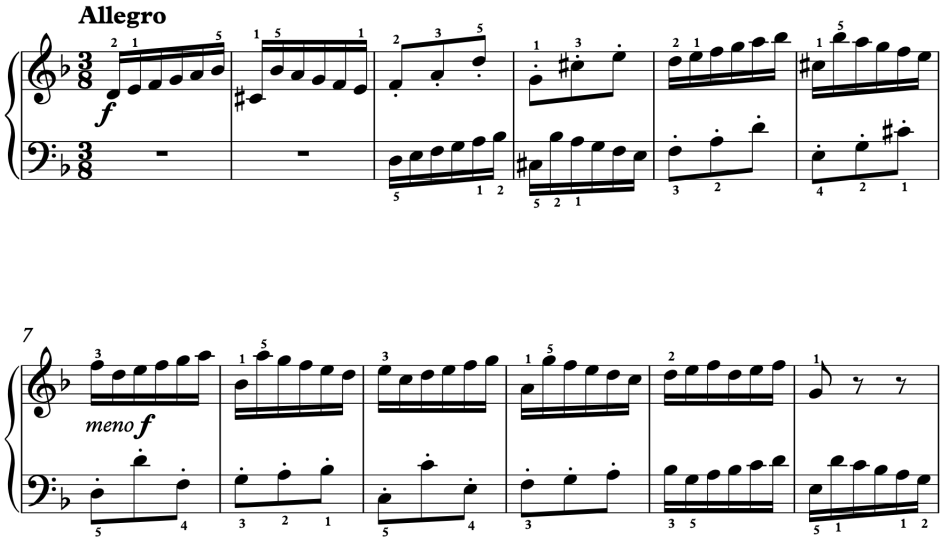
	Dependent variable:	
	log(Price)	
	(1)	(2)
Age	−0.076*** (0.0001)	−0.075*** (0.0001)
Mileage	−0.039*** (0.0001)	−0.039*** (0.0001)
Diesel	0.011*** (0.001)	0.005*** (0.001)
Manual Gearbox	−0.123*** (0.001)	−0.123*** (0.001)
Professional Seller	0.051*** (0.001)	0.051*** (0.001)
Ad Duration	0.0002*** (0.00000)	0.0002*** (0.00000)
Engine Power	0.003*** (0.00001)	0.003*** (0.00001)
Weight	0.0003*** (0.00000)	0.0003*** (0.00000)
Fuel Consumption	−0.034*** (0.001)	−0.034*** (0.001)
Truck Volume	0.0001*** (0.00000)	0.0001*** (0.00000)
Median Revenue	0.033*** (0.002)	0.031*** (0.002)
LEZ_ongoing_25km	−0.054*** (0.003)	−0.044*** (0.003)
LEZ_planned_25km	−0.064*** (0.003)	−0.027*** (0.003)
LEZ_announced_25km	−0.013*** (0.002)	−0.001 (0.002)
Diesel:LEZ_ongoing_25km	−0.077*** (0.004)	
Diesel:LEZ_planned_25km	−0.025*** (0.004)	
Diesel:LEZ_announced_25km	−0.019*** (0.002)	
Age:LEZ_ongoing_25km		−0.008*** (0.0003)
Age:LEZ_planned_25km		−0.007*** (0.0004)
Age:LEZ_announced_25km		−0.003*** (0.0002)
Constant	9.179*** (0.005)	9.181*** (0.005)
Brand	Yes	Yes
Category	Yes	Yes
Geographic controls	Yes	Yes
Ad controls	Yes	Yes
Observations	919,594	919,594
R^2	0.905	0.905
Adjusted R^2	0.905	0.905
Residual Std. Error (df = 919507)	0.281	0.281
F Statistic (df = 86; 919507)	101,876.100***	101,941.200***
Note:		*p<0.1; **p<0.05; ***p<0.01

Table 2.5: Regressions with a 25km characteristic distance for the LEZ proximity indicator

	Dependent variable:	
	log(Price)	
	(1)	(2)
Age	−0.076*** (0.0001)	−0.075*** (0.0001)
Mileage	−0.039*** (0.0001)	−0.039*** (0.0001)
Diesel	0.009*** (0.001)	0.005*** (0.001)
Manual Gearbox	−0.123*** (0.001)	−0.123*** (0.001)
Professional Seller	0.051*** (0.001)	0.051*** (0.001)
Ad Duration	0.0002*** (0.00000)	0.0002*** (0.00000)
Engine Power	0.003*** (0.00001)	0.003*** (0.00001)
Weight	0.0003*** (0.00000)	0.0003*** (0.00000)
Fuel Consumption	−0.034*** (0.001)	−0.034*** (0.001)
Truck Volume	0.0001*** (0.00000)	0.0001*** (0.00000)
Median Revenue	0.028*** (0.002)	0.027*** (0.002)
LEZ_ongoing_15km	−0.055*** (0.004)	−0.046*** (0.004)
LEZ_planned_15km	−0.073*** (0.004)	−0.040*** (0.004)
LEZ_announced_15km	−0.012*** (0.002)	0.002 (0.002)
Diesel:LEZ_ongoing_15km	−0.098*** (0.005)	
Diesel:LEZ_planned_15km	−0.019*** (0.005)	
Diesel:LEZ_announced_15km	−0.016*** (0.003)	
Age:LEZ_ongoing_15km		−0.010*** (0.0005)
Age:LEZ_planned_15km		−0.006*** (0.0004)
Age:LEZ_announced_15km		−0.003*** (0.0002)
Constant	9.186*** (0.005)	9.187*** (0.005)
Brand	Yes	Yes
Category	Yes	Yes
Geographic controls	Yes	Yes
Ad controls	Yes	Yes
Observations	919,594	919,594
R^2	0.905	0.905
Adjusted R^2	0.905	0.905
Residual Std. Error (df = 919507)	0.281	0.281
F Statistic (df = 86; 919507)	101,777.800***	101,822.000***
Note:		*p<0.1; **p<0.05; ***p<0.01

Table 2.6: Regressions with a 15km characteristic distance for the LEZ proximity indicator

* * *



Extrait de: Johann Sebastian Bach, *BWV 775 - 4e invention à deux voix en ré mineur.*

* * *

Chapter 3

Coordination of abatement and policy across interconnected sectors

* * *

To drastically reduce greenhouse gas emissions, numerous specific measures are required in all sectors of the economy. These measures, and the GHG consequences of their implementations, are not independent from each other because of sectoral linkages. For instance, the carbon footprint of electric vehicles depends on the electricity mix, an issue that have received considerable attention but few economic analysis. The present paper addresses the issue of sectoral policy coordination, especially when pigovian carbon pricing is unavailable. It analyzes the optimal allocation of mitigation effort among two vertically connected sectors, an upstream (e.g. electricity) and a downstream (e.g. transportation) one. The clean downstream technology (e.g. electric vehicle) consumes the upstream production and may shift production to that sector. Using a simple partial equilibrium model, we connect the concept of Marginal Abatement Cost and Life-Cycle-Assessment. We propose a characterization that indicates the order of options implementations, which is relevant for policy making. The decentralized version of the model allows us to characterize optimal second-best policy in presence of imperfect GHG taxation.

* * *

1 Introduction[1]

The reduction of Greenhouse Gas (GHG) emissions requires to shift from fossil energy to non-carbon energy. For many energy uses (e.g. transport, industry, heating) such a shift may be achieved through electrification combined with low-carbon non-carbon power sources (e.g. nuclear, renewable). This paper investigates whether mitigation policies need to coordinate the decarbonization of the upstream electricity sector with the electrification of the downstream sector. Indeed, as long as the upstream sector is not fully decarbonized, the decarbonization of downstream activities partly shifts GHG emissions upstream, Life Cycle Assessments (LCA) of electric vehicles have stressed such effect (Archsmith et al.; 2015) raising concerns about their carbon footprint. The purpose of the present article is twofold. First, it aims at analyzing the optimal allocation and sequencing of mitigation efforts between two polluting sectors when the pollution abatement of one sector is done by consuming the production of the other sector. Second, it investigates whether such linkages creates a need of policy coordination across sectors, especially when pigovian taxes are unavailable.

We develop a partial equilibrium model with two sectors: an upstream and a downstream one. In each sector, a dirty and a clean technology are available. The downstream clean technology (e.g. electric cars) consumes the upstream good (e.g. electricity) as an input. We analyze the optimal allocation of production for a given Social Cost of Carbon (SCC), and the optimal sequencing of the deployment of the two clean technologies as the SCC increases. We build discuss policy consequences, notably the optimal second-best subsidy of the downstream clean technology when GHG emissions are imperfectly priced in the economy.

The linkage of the two sectors has two consequences on the optimal allocation. First the upstream sector produces more than with no SCC, its production is clean or dirty. Second, the marginal cost of the downstream technology is endogenously determined and depends on the SCC. We establish a condition under which upstream emissions increases with the SCC because of the demand emanating from the downstream sector. Concerning Marginal abatement cost (MAC) curves, the two conse-

[1]This chapter comes from a collaboration with Guy Meunier.

quences mentioned above translate into: an increased "abatement potential" of the upstream sector, total clean production is larger than the initial size of the sector. We define an adjusted MAC in the downstream sector that incorporates the marginal cost and emission intensity of the upstream sector. This last point contributes to bridge the gap between environmental economics and LCA approaches of industrial ecology.

Regarding the sequencing of decarbonization as the SCC increases, it is relatively easy to determine which sector starts and first finishes based on cost functions and sector sizes. However, the sequencing along the MAC-curve is more subtle and we exhaustively identify conditions for a each possible sequencing. We exhibit a "transient decarbonization" pathway along which, as the SCC increases, the upstream sector is fully decarbonized before recarbonizing and eventually being fully clean again.

Finally, we investigate the policy consequences of sector coupling, in a flexible realistic policy environment. A comprehensive carbon pricing enforces the first best allocation, and policy coordination is not needed. Without carbon pricing and only subsidy to clean technologies, both downstream and upstream, the first best cannot be reached except with inelastic demand. The optimal downstream subsidy depends on the marginal upstream technology. If the marginal upstream technology is dirty, and whatever its market share is, the optimal downstream subsidy is decreasing with respect to the upstream GHG emissions and LCA is relevant. If the marginal upstream technology is clean, the optimal downstream subsidy is decreasing with respect to the upstream subsidy.

The present article is related to several strands of the literature and we organize our review from the applied work (LCA), sometime grey literature, to the more conceptual consideration (second best). Our main contribution is to bridge the gap between economic models on the energy transition and life-cycle assessments approaches in industrial ecology.

The energy transition has been tackled from environmental economists as a optimal management of pollution formulated in a cost-benefit problem. In climate economics, integrated assessment models such as (Acemoglu et al.; 2012; Gerlagh and Liski; 2018; Golosov et al.; 2014) consider an energy sector that combines carbon and non-carbon energy sources. Technology chains are not modeled. However, a criti-

cal question for policy makers is how to allocate effort between technological options across the sector of the economy. Such questions are therefore addressed in more applied works. Marginal abatement costs (MAC) curves rank sectoral mitigation options by their abatement potentials and by their abatement costs (Gillingham and Stock; 2018). The logical recommendation that follows is to schedule investments from the cheapest. MACs can be defined as the value of foregone output due to emission reduction (Boyd et al.; 1996; Färe et al.; 2005). MAC curves have faced several criticisms by scholars (Kesicki and Ekins; 2012; Kesicki and Strachan; 2011). They fail at capturing relevant dynamic effects such as sectoral inertia, technological learning and, in our case, sectoral interactions. If several authors tackled the first two issues (Creti et al.; 2018; Vogt-Schilb and Hallegatte; 2014; Vogt-Schilb et al.; 2018), the third has not been studied to our knowledge.

Sectoral links are a central aspect in Life Cycle Assessments. In public debates, these approaches regularly temper the enthusiasm associated with new "green" technology because of their upstream footprint. Our primary motivation comes from the deployment of electric vehicles and the debates surrounding their total environmental benefits. Several authors have analyzed the upstream carbon footprint associated with electricity production and the battery production (Archsmith et al.; 2015). There are other examples[2]: hydrogen is another vector of energy mostly produced with a carbon emitting technology, and has application to decarbonize downstream energy uses (transport, heating) (Granovskii et al.; 2006); a more prospective example is artificial meat, the production of which requires a lot of energy but would abate cattle emissions (Mattick et al.; 2015; Tuomisto and Teixeira de Mattos; 2011). Consequential life-cycle assessment (cLCA) helps to integrate economic mechanisms in LCA (Earles and Halog; 2011; Rajagopal; 2014). It has been widely used to discuss the carbon footprint of biofuels by integrating various considerations on land-use changes and market mechanisms. However, these works give little recommendations on how to design adequate policies that would include sector interactions.

Economic theory states that pigovian taxes in each sector of the economy would

[2]Note that sector coupling may also designate the interaction of gas and power system through power-to-gas technologies (Roach and Meeus; 2020). We do not consider such situation.

implement social optimum. However, perfect carbon pricing is rarely implemented. Seminal work of Lipsey and Lancaster (1956) establishes how in a second best world, with pre-existing distortion in the economy, optimal formulas should be modified. The analysis of second-best policies with imperfect pricing of externality is well developed in the literature on waste management and recycling (Walls and Palmer; 2001). More recently and applied to the transportation sector Holland et al. (2015) analyze the optimal subsidy of electric vehicle when electricity production is unregulated,[3], they stress that optimal subsidy of electric vehicle should integrate the external costs associated to energy production. However, their contribution remains empirical. They do not consider the impact of electricity regulation, and possibly the joint optimization of subsidies.

The article is organized as follow. The model is introduced in Section 1. Then, in Section 2 we analyze the social optimal and and derive MAC-curves. Policy considerations are described in Section 3. Some numerical illustrations are discussed in section 4. Section 5 concludes.

2 The analytical framework

2.1 The model

We consider a partial equilibrium model with two interrelated sectors an upstream (e.g. electricity) and a downstream (e.g. mobility) sector. There are two goods, $i = m, e$ (m stands for mobility, and e for electricity), consumed both by households. For both goods there is a dirty and a clean technology. The clean downstream technology uses the upstream good (electricity is both consumed by households and by electric cars). As this latter technology develops, a sectoral coupling is created between the two sectors.

For each sector $i = m, e$ the total quantity consumed by households is Q_i, the associated gross consumers surplus is $S_i(Q_i)$, with $S_i' > 0$, and $S_i'' < 0$.

On the production side: in sector $i = m, e$ the total quantity produced is $q_{id} + q_{ic}$

[3]They do not discuss regulation in the electricity sector and only consider NO_x and SO_x permit market in an appendix.

the sum of dirty and clean productions, with production costs $C_{ij}(q_{ij})$, with $i = m, e$ and $j = d, c$. Cost functions are increasing and convex, $C'_{ij} > 0$ and $C''_{ij} \geq 0$.[4] Each clean downstream unit consume θ units of the upstream good so that the total quantity produced $q_{ed} + q_{ec}$ is equal to the quantity consumed by households Q_e and by the downstream clean variety θq_{mc}: $q_{ed} + q_{ec} = Q_e + \theta q_{mc}$. We will denominate θ as the linkage intensity. In sector i, each unit produced by the dirty technology emits α_i tons of CO_2. We denote μ (in \$ per tCO_2) the Social Cost of Carbon (SCC). Total welfare is then:

$$W(\mathbf{q}, \mu) = \sum_i S_i(Q_i) - \sum_{ij} C_{ij}(q_{ij}) - \mu[\alpha_m q_{md} + \alpha_d q_{ed}] \tag{3.1}$$

subject to $Q_m = q_{md} + q_{mc}$ and $Q_e + \theta q_{mc} = q_{ed} + q_{ec}$ and $q_{ij} \geq 0$..

The following two assumptions ensure that without environmental cost ($\mu = 0$) there is no clean production, and that for large environmental cost ($\mu = +\infty$) there is nonnegative clean production and consumers consumption.

Assumption 1 *There are $Q_m^0 > 0$ and $Q_e^0 > 0$ such that*

$$S'_i(Q_i^0) = C'_{id}(Q_i^0) < C'_{ic}(0) \tag{3.2}$$

Assumption 2 *There are $Q_m^1 > 0$ and $Q_e^1 > 0$ such that*

$$S'_e(Q_e^1) = C'_{ec}(Q_e^1 + \theta Q_m^1) \text{ and } S'_m(Q_m^1) = C'_{mc}(Q_m^1) + \theta C'_{ec}(Q_e^1 + \theta Q_m^1) \tag{3.3}$$

The following comments have to be made on the previous modeling choices. First, we consider perfect substitutability between technologies in each sector. Regarding the power sector, this assumption rarely verified (Baranes et al.; 2017). For instance, renewable power is intermittent and variable contrary to gas or coal-based generation. Hence, we consider that the convexity of the upstream costs includes storage costs as in (Coulomb et al.; 2019). Second, as goods are homogenous in each sector, the

[4]The convexity of the clean technology cost are notably due to the increasing storage and transportation costs for renewable energy together with good sites scarcity (notably for wind), in the transportation sector convexity mainly comes from the increasing cost associated with density (urban vs rural) and types of vehicules (weight of vehicules).

downstream clean technology can not choose which the upstream technology. We do not consider the possibility to charge electric cars at night, so that the content of the electricity used to charge is not exactly the same as the total mix of the grid. Third, our framework is static and does not include dynamic aspects such as adjustment cost, learning-by-doing, or sectoral inertia. Transition aspects will be appraised by comparative statics on the social cost of carbon. Fourth, the downstream clean technology creates a vertical sectoral linkage with the *a fortiori* "upstream" sector. A more general and realistic setting would be that each downstream technology induces an idiosyncratic demand on the upstream sector. In this framework, all sectors are already linked before the introduction of the downstream clean technologies. Although both situations are not equivalent, we consider only the former. This can be justified when the clean technology require much more input than the dirty technology. We could also have considered the more realistic situation where clean technologies are only cleaner, and still emits carbon. Nevertheless, both of these situations severely increase the mathematical clarity of our results.

2.2 States, configurations and pathways

Our objective is to understand the allocation of efforts between the upstream and downstream sector as a function of the SCC μ, and qualitatively determine the property of a MAC-curve that integrates the interaction between the clean downstream variety and the upstream sector. We will then consider the policy implications and particularly second best subsidies of clean upstream and downstream technologies, and how they relate to MAC and Life Cycle Analysis.

We have in mind a dynamic context of an energetic transition in which the SCC increases over time, for instance due to a carbon budget consistent with the Paris Agreement, and the economy is progressively decarbonized. At the end of the transition, the whole economy is clean ($q_{ed} = q_{md} = 0$). We are particularly interested by the ranking of the respective starting and ending dates of the transition of each sector. Let us denote $\mathbf{q}^*(\mu) = (q^*_{ij}(\mu))_{i,j}$ the allocation that maximizes welfare (3.1), and we define for each sector the two SCCs at which a sector starts and ends its transition.

Definition 1 *For each sector $i = m, e$ let us define the two SCCs $\underline{\mu}_i$ and $\bar{\mu}_i$ such that*

$$\underline{\mu}_i = \max\{\mu \mid q^*_{ic}(\mu) = 0\} \text{ and } \bar{\mu}_i = \sup\{\mu \mid q^*_{id}(\mu) > 0\} \tag{3.4}$$

		Sector m		
		d	b	c
Sector e	d	D	db	dc
	b	bd	B	bc
	c	cd	cb	C

Table 3.1: Possible Configurations. Each box corresponds to one configuration, the first (second) letter being the upstream (downstream) sector. Each sector can be in three states: only dirty "d", only clean "c", or both "b".

For a given SCC μ, the **state** of a sector describes the technologies used. Each sector has three possible states: only dirty (d, $q_{ic} = 0$), only clean (c, $q_{id} = 0$) and both dirty and clean (b). A **configuration** if the combination of states, there are therefore nine possible configurations summarized in Table 3.1. And a **transition pathway** is the ordering of configurations along the MAC-curve. For instance, if the pathway is {D,bd,cd,cb,C}, as the SCC increases the upstream sector is fully clean before the downstream sector starts its transition. Assumptions 1 and 2 ensure that transition pathways begin in D and ends in C. Pathways are linked to the ranking of the thresholds SCCs defined by (3.4), for instance the pathway {D,bd,cd,cb,C} corresponds to the ranking $\underline{\mu}_e < \bar{\mu}_e < \underline{\mu}_m < \bar{\mu}_m$.

2.3 Quadratic specification

To get explicit formula, some of our results and draw figures, we will make use of the following quadratic specification, in which the cost of dirty technologies is assumed to be linear, gross surplus and clean cost functions quadratic.

Specification 1

$$S_i(Q_i) = a_i Q_i - \frac{1}{2} b_i Q_i^2 \tag{3.5a}$$

$$C_{id}(q_{id}) = c_{id} q_{id} \tag{3.5b}$$

$$C_{ic}(q_{ic}) = c_{ic} q_{ic} + \frac{\gamma_i}{2} q_{ic}^2 \tag{3.5c}$$

with $a_i, b_i, c_{ij}, \gamma_i$ all nonnegative real numbers.

Under this specification, assumptions 1 and 2 imply conditions on parameters: First, there is no clean production initially if $c_{ed} < c_{ec}^0$ and $c_{md} < c_{mc}^0 + \theta c_{ec}^0$. Second, a fully clean situation with nonnegative production and consumption of both goods exists if and only if (see Appendix)

$$(\theta + \frac{b_m + \gamma_m}{\theta \gamma_e})(a_e - c_{ec}^0) > (a_m - c_{mc}^0 - \theta c_{ec}^0) > \theta \frac{\gamma_e}{b_e + \gamma_e}(a_e - c_{ec}^0).$$

The first inequality ensures a nonnegative consumption upstream and the second a nonnegative consumption downstream. The clean upstream production should be sufficiently abundant, γ_e large, to serve both markets. And the size of each market ($1/b_m$ and $1/b_e$) should be relatively small to ensure that neither of them completely absorbs the clean upstream production.

3 Optimal abatement and transitions

3.1 Optimality conditions

The optimal allocation $\mathbf{q}^*(\mu) = (q_{ij}^*(\mu))_{i,j}$ maximizes welfare (3.1). Denoting ϕ_{ij} the Lagrange multiplier of the positivity constraint $q_{ij} \geq 0$, the first order conditions are:

$$S_e'(Q_e) = C_{ed}'(q_{ed}) + \alpha_e \mu \ - \phi_{ed} \tag{3.6a}$$

$$= C_{ec}'(q_{ec}) - \phi_{ec} \tag{3.6b}$$

$$S_m'(Q_m) = C_{md}'(q_{md}) + \alpha_m \mu - \phi_{md} \tag{3.6c}$$

$$= C_{mc}'(q_{mc}) + \theta S_e'(Q_e) - \phi_{ec} \tag{3.6d}$$

$$Q_e + \theta q_{mc} = q_{ed} + q_{ec} \tag{3.6e}$$

$$Q_m = q_{mc} + q_{md} \tag{3.6f}$$

At the optimal allocation in each sector a positive quantity is produced and consumed thanks to Assumption 1 and 2, and the marginal consumer surplus is equal to the marginal costs of each technology used. Note that the marginal cost of the clean downstream technology encompasses the marginal benefit from the upstream good consumption S_e'.

3.2 Increasing SCC and expansion of technologies

Transition pathways can be qualitatively described by considering the consequences of a marginal increase of the SCC on the optimal allocation described by equations (3.6). Indeed, at the aggregate level total emissions are decreasing with respect to the SCC, i.e. the MAC-Curve is increasing. However, the allocation of that change of total emissions among sectors and technologies is not straightforward. The two following lemmas describe the evolution of quantities produced and consumed in each sector as the SCC increases. Most quantity changes can be signed except for the quantity of clean downstream and dirty upstream productions, the monotonicity of which depends on parameter values.

Lemma 1 *In the downstream sector, as the SCC increases, the total quantity consumed, dirty production and emissions decreases. However, until upstream dirty production is phased out, the effect on clean production is ambiguous , as it decreases if :*

$$\frac{\alpha_m}{1+\epsilon_m} < \frac{\theta\alpha_e}{1+\epsilon_e(1+\frac{1}{\nu_e})} \tag{3.7}$$

With $\epsilon_i = \frac{C''_{id}}{-S''_i}$ $\nu_i = \frac{C''_{ic}}{-S''_i}$

In the downstream sector, the linkage with the upstream sector does not impact the monotonicity of consumption and dirty production with respect to the SCC. However, the monotonicity of the clean quantity depends on parameter values. Under condition (3.7), the optimal downstream clean production decreases with respect to the SCC. This condition can be interpreted as a comparison between emissions generated in the downstream (left-hand-side) and the upstream (right-hand-side) sectors from an additional clean downstream unit, with optimal adjustment of the other three quantities. These adjustments are represented by the ratios ϵ_i (resp. ν_i) of the slope of dirty (resp. clean) marginal costs and consumer demands. For instance, with inelastic demands and linear dirty costs the condition (3.7) becomes $\alpha_m < \theta\alpha_e$. In that case, an additional dowstream unit generates more indirect emissions $\theta\alpha_e$ from upstream dirty production than the direct emissions it abates in the downstream sector. In the general case, the comparison between downstream and upstream emission changes is modified by the optimal reduction of consumptions and the re-allocation of production among upstream technologies, encompassed in ratios ϵ_i and ν_i. Once the upstream dirty technology is phased out, indirect emissions from the downstream clean technology go to zero and downstream clean production increases with the SCC.

Lemma 2 *In the upstream sector, as the SCC increases, demand decreases and clean production increases. However, until the downstream clean lock-in, the effect on upstream dirty production (i.e.upstream emissions) is ambiguous, as it increases if:*

$$\alpha_e < \frac{\theta\alpha_m}{\theta^2(1+\epsilon_m) + \eta(1+\epsilon_m(1+\frac{1}{\nu_m}))(1+\nu_e)} \tag{3.8}$$

With $\epsilon_i = \frac{C''_{id}}{-S''_i}$, $\nu_i = \frac{C''_{ic}}{-S''_i}$, $\eta = \frac{C''_{mc}}{C''_{ec}}$

In the upstream sector, consumption decreases and clean production increases with respect to the SCC, while the monotonicity of dirty production depends on parameter values. Surprisingly, upstream dirty production increases with respect to the SCC if condition (3.8) is satisfied. Indeed, condition (3.8) and (3.7) are mutually exclusive,[5] the increase of upstream dirty production occurs only if the downstream clean technology expands.

This unexpected result is due to an other feature of the sector coupling. The deployment of the clean downstream technology calls for an increase of upstream production that is shared between clean and dirty production, together with a reduction of upstream consumption. Whether the net effect is an increase of dirty production depends on emission intensity, the slope of consumer demands and marginal production costs. If upstream demand is inelastic (S_e'' large) and upstream clean marginal cost steep (C_{ec}'') condition (3.8) is more likely to hold. The rise of the clean downstream technology is all the more important that downstream demand is inelastic and dirty downstream production costs flat (ϵ_m small). With a fully clean downstream sector (which amounts to $\epsilon_m = +\infty$), an increase of the SCC is accompanied by a reduction of upstream dirty production.

Condition (3.8) holds for intermediary linkage intensities. With a small linkage intensity the demand for the upstream good emanating from the downstream sector is relatively small and does not hinder the reduction of dirty upstream production. With a large linkage intensity, the downstream clean technology expansion is restrained by the rise of upstream production cost.

Lemma 1 and 2 have identified conditions on parameter values under which sectoral linkage induces counter intuitive monotonicity of either clean downstream or dirty upstream productions. These conditions can be used to define three different types of sector coupling.

Definition 2 *Sector coupling is*

- *upstream-driven if condition (3.7) is satisfied.*

[5] If condition (3.8) then, multiplying both sides of it by θ gives $\alpha_m/(1+\epsilon_m) > \theta\alpha_e$ which is incompatible with condition (3.8).

- *downstream-driven if condition (3.8) is satisfied.*
- *balanced otherwise*

With linear dirty costs, as in Specification 1, $\epsilon_i = 0$, and conditions (3.7) and (3.8) are greatly simplified. Furthermore, with the general formulation, the type of sector-coupling depends on quantities and can vary with the SCC. With a quadratic specification, it is not the case and sector coupling types are fully defined with the above conditions.

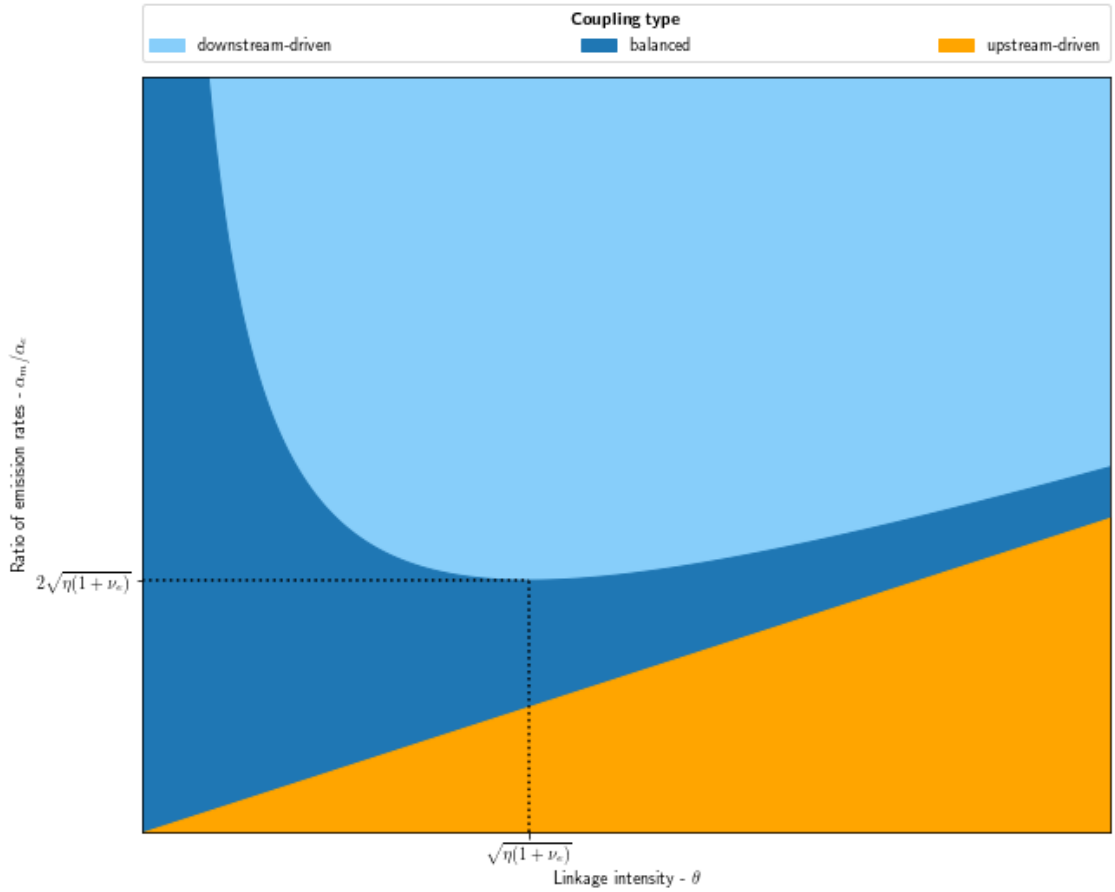


Figure 3.1: A map $(\theta, \frac{\alpha_m}{\alpha_e})$ representing the three possible types of sector coupling (upstream-driven, downstream-driven and parallel).

Figure 3.1 depicts parameter values, with Specification 1 under which the three different types of sector coupling hold. Linkage intensity θ is represented on the x-axis and the ratio of emission rates $\frac{\alpha_m}{\alpha_e}$ on the y-axis. Delimitation of types are $\frac{\alpha_m}{\alpha_e} = \theta$

between the balanced and the upstream-driven sector couplings, and $\frac{\alpha_m}{\alpha_e} = \theta + \frac{\eta(1+\nu_e)}{\theta}$. This latest function has a minimum in $\left(\theta, \frac{\alpha_m}{\alpha_e}\right) = \left(\sqrt{\eta(1+\nu_e)}, 2\sqrt{\eta(1+\nu_e)}\right)$. Such minimum will be used as a central point in what follows. Balanced sector coupling mostly happens when linkage intensity is small ($\theta \ll \sqrt{\eta(1+\nu_e)}$. Importantly, when linkage is very high ($\theta \gg \sqrt{\eta(1+\nu_e)}$), sector coupling are almost exclusively either downstream-driven or upstream-driven.

Proposition 1 *Coupling types relate to transition pathway as follow:*

- *If sector coupling is upstream-driven then as the SCC increases, the downstream clean technology is not developed until the upstream dirty technology is phased-out:*

$$\underline{\mu}_e < \bar{\mu}_e < \underline{\mu}_m < \bar{\mu}_m$$

- *If sector coupling is downstream-driven then as the SCC increases, the upstream sector can neither start nor end its transition during the transition of the downstream sector.*

  Moreover, the upstream sector may fully decarbonize, before recarbonizing once the downstream clean technology develops.

3.3 MAC and Life Cycle Assessment

Let us relate the previous findings with LCA and consequential LCA (cLCA). First, at the optimal allocation the SCC is equal to the MAC in each sector computed with direct emissions only (quantities are omitted to alleviate notations):

$$\mu = \frac{C'_{ec} - C'_{ed}}{\alpha_e} = \frac{C'_{mc} + \theta S'_e - C'_{md}}{\alpha_m}$$

At first glance, LCA of the downstream clean technology does not intervene in those formula since upstream emissions do not appear in its MAC. However, the marginal cost of the downstream clean technology encompasses the marginal value of the upstream sector which depends upon the SCC. Injecting equations (3.6a) or (3.6b) gives

:

$$\mu = \frac{C'_{mc} + \theta C'_{ec} - C'_{md}}{\alpha_m} = \frac{C'_{mc} + \theta C'_{ed} - C'_{md}}{\alpha_m - \theta \alpha_e}.$$

This relationship tells us that the emissions at the denominator of the MAC should be consistent with the upstream cost at the numerator. Indeed, it works with any weighting of the two technologies as long as marginal costs and emissions rates are similarly weighted.

Concerning the evolution of technologies with respect to the SCC and our coupling typology, these can be related to cLCA. While conventional LCA focuses on the physical flows that composes the lifecycle of a product, cLCA aims at including the marginal adjustment of equilibrium quantities (Rajagopal; 2014; Rajagopal and Zilberman; 2013). Here, we do not consider a market equilibrium but the optimal allocation. However, in that context, one can define the cLCA of a good as the environmental consequences of the addition of a unit of that good with optimal adjustment of the three other quantities. The following corollary makes the link between the coupling type and cLCA.

Corollary 1 *The sector coupling type could be described in terms of consequential life cycle emissions:*

- *If sector coupling is balanced, then clean (resp. dirty) technologies has negative (resp. positive) consequential life cycle emissions.*
- *If sector coupling is upstream-driven, the downstream clean technology has positive consequential life cycle emissions ($cLCA_{mc} > 0$).*
- *If sector coupling is downstream-driven, the upstream dirty technology has negative consequential life cycle emissions ($cLCA_{ed} < 0$) .*

It is worth stressing that our coupling typology aims at characterizing a dynamic mechanism. While LCAs are linked to MACs and the optimal static allocation, cLCAs are linked to the MAC-Curve and an optimal dynamic transition that we next further characterize.

3.4 Optimal transitions and marginal abatement cost curve

As discussed earlier, marginal abatement costs curve (MACC) have been a key operational tool for policy makers to plan transition and allocate in time abatement efforts between sectors. They notably indicate at what SCC a sector should start its transition (phase-in of the clean technology) and end it (phase-out of the dirty technology), and thus the ordering of the transitions of several sectors. MAC-curves are built by ordering MACs obtained by substituting dirty technology by clean ones in carbon emitting sectors. The standard MACC ignores sector coupling and thus the two following interelated issues: the MAC of the clean downstream technology depends upon the technology used in the upstream sector and the size of the upstream sector depends upon the technology used in the downstream sector. Because of these two issues, it is not a priori evident which MACs should be used in each sectors as a guide to determine the ordering of the two sectoral transitions. In this section we will determine the "transition MACs" (t-MACs) that should be used to fully characterize the ordering of the transition of the two interconnected sectors.

We defined the thresholds SCCs $\underline{\mu}_i$ and $\bar{\mu}_i$ as the SCCs at which a sector $i = m, e$ respectively starts and ends its transition. Without linkage $\theta = 0$, it is straighforward to link these threshold SCCs with two MACs computed with the Q_i^0 and Q_i^1 defined in Assumptions 1 and 2: the quantities consumed in sector $i = m, e$ in its starting state (fully dirty) and its ending one (fully clean).

Lemma 3 *When there is no sectoral linkage, transition pathways follows the ranking of marginal abatement costs.*

$$\underline{\mu}_i = \frac{C'_{ic}(0) - C'_{id}(Q_i^0)}{\alpha_i} \tag{3.9a}$$

$$\bar{\mu}_i = \frac{C'_{ic}(Q_i^1) - C'_{id}(0)}{\alpha_i} \tag{3.9b}$$

$$\tag{3.9c}$$

In the rest of this section we will consider Specification 1, the main characteristic of which is the linearity of the dirty technology costs which greatly simplify the compu-

tation of MACs since the marginal cost of the dirty technology does not depend of the quantity used. Furthermore, we will consider that the coupling type is not upstream driven, since in that case the transition pathway is known, that is $\theta\alpha_m < \alpha_e$.

With sectoral linkage, MACs are endogeneous along the transition pathway and the threshold MACs cannot be easily expressed as a function of sectoral parameters. The precise expressions of $\underline{\mu}_i$ and $\bar{\mu}_i$ in sector i depend on whether the other sector has started or finished its transition. However, only five MACs are necessary to qualitatively describe the transition pathway, even though they might not coincide with the thresholds SCCs, and are computed in situations that might never be reached along the transition.

Definition 3 *We designate* $\left(M_e^0, \tilde{M}_e, M_e^1\right)$ *and* $\left(M_m^0, M_m^1\right)$ *as the transition MACs of the upstream and downstream sectors:*

$$M_e^0 = \frac{C'_{ec}(0) - c_{ed}}{\alpha_e} \tag{3.10a}$$

$$\tilde{M}_e = \frac{C'_{ec}(\tilde{Q}_e) - c_{ed}}{\alpha_e} \tag{3.10b}$$

$$M_e^1 = \frac{C'_{ec}(Q_e^1 + \theta Q_m^1) - c_{ed}}{\alpha_e} \tag{3.10c}$$

$$M_m^0 = \frac{C'_{mc}(0) + \theta c_{ed} - c_{md}}{\alpha_m - \theta\alpha_e} \tag{3.10d}$$

$$M_m^1 = \frac{C'_{mc}(\tilde{Q}_m) + \theta c_{ed} - c_{md}}{\alpha_m - \theta\alpha_e} \tag{3.10e}$$

In which, for $i = m, e$, Q_i^0 *is defined in Assumption 1 and* Q_i^1 *in assumption 2. The quantity* $\tilde{Q}_e$ *is such that* $S'_e(\tilde{Q}_e) = C'_{ec}(\tilde{Q}_e)$ *and* $\tilde{Q_m}$ *such that :*

$$(1 - \theta\frac{\alpha_m}{\alpha_e})S'_m(\tilde{Q}_m) = C'_{mc}(\tilde{Q}_m) + \theta(c_{ed} - \frac{\alpha_e}{\alpha_m}c_{md})$$

These MACs are computed at specific quantities, for each sector they are ordered:

$$M_e^0 < \tilde{M}_e < M_e^1 \text{ and } M_m^0 < M_m^1.$$

The two M_i^0 correspond to the MACs associated with the first clean unit in sector i and corresponds to the SCC where the sector starts its transition if it is the first to do so.

The MAC M_e^1 is the MAC of the very last clean upstream unit if the upstream sector ends its transition after the downstream one. The other two MACs are computed for specific intermediate quantities: In the upstream sector $\tilde{Q}_e$ is the quantity produced in a fully clean upstream sector without coupling. In the downstream sector, $\tilde{Q}_m$ is the quantity where the sector ends its transition using the dirty upstream technology as an input. The MAC M_m^1 is the SCCs where this hypothetical transition ends, so that M_m^1 and $\tilde{Q}_m$ jointly solve the couple of equations:

$$S'_m(Q_m) = C'_{mc}(Q_m) + \theta(c_{ed} + \alpha_e \mu) = c_{md} + \alpha_m \mu.$$

Therefore, M_m^1 corresponds to $\bar{\mu}_m$ if the downstream sector ends its transition while the upstream sector did not end its own transition. How the MACs M_m^0 and M_m^1 compare with the MAC M_e^0, M_e^1 and $\tilde{M}_e$ completely characterize the transition pathway:

(i) the upstream clean phase-in happens before the downstream clean phase-in ($\underline{\mu}_e < \underline{\mu}_m$) iff $M_e^0 < M_m^0$

(ii) the upstream dirty phase-out happens before the downstream dirty phase-out ($\bar{\mu}_e < \bar{\mu}_m$) iff $M_e^1 < M_m^1$

(iii) the upstream clean phase-in happens before the downstream dirty phase-out ($\underline{\mu}_e < \bar{\mu}_m$) iff $M_e^0 < M_m^1$

(iv) the upstream dirty phase-out happens before the downstream clean phase-in ($\bar{\mu}_e < \underline{\mu}_m$) iff $\tilde{M}_e < M_m^0$

Figure 3.2 illustrates this result.The two axis corresponds to the t-MAC in the downstream sectors, the x-axis for M_m^0 and the y-axis for M_m^1, along each axis the three t-MACs of the upstream sector are indicated. A set of parameters value will correspond to a point on that figure and a corresponding pathway. That M_m^0 is lower than M_m^1 explains that only the upper side of the figure, above the diagonal, is relevant.

There is a peculiar ranking that is only feasible if coupling is downstream driven:

$$\tilde{M}_e < M_m^0 < M_m^1 < M_e^1$$

it corresponds to a case of *recarbonization*, along the transition the upstream sector is fully clean before the downstream starts its transition and then recarbonizes and eventually ends its transition after the downstream sector does. That situation corresponds to a triangle on the Figure that is then only relevant for a downstream-driven coupling.

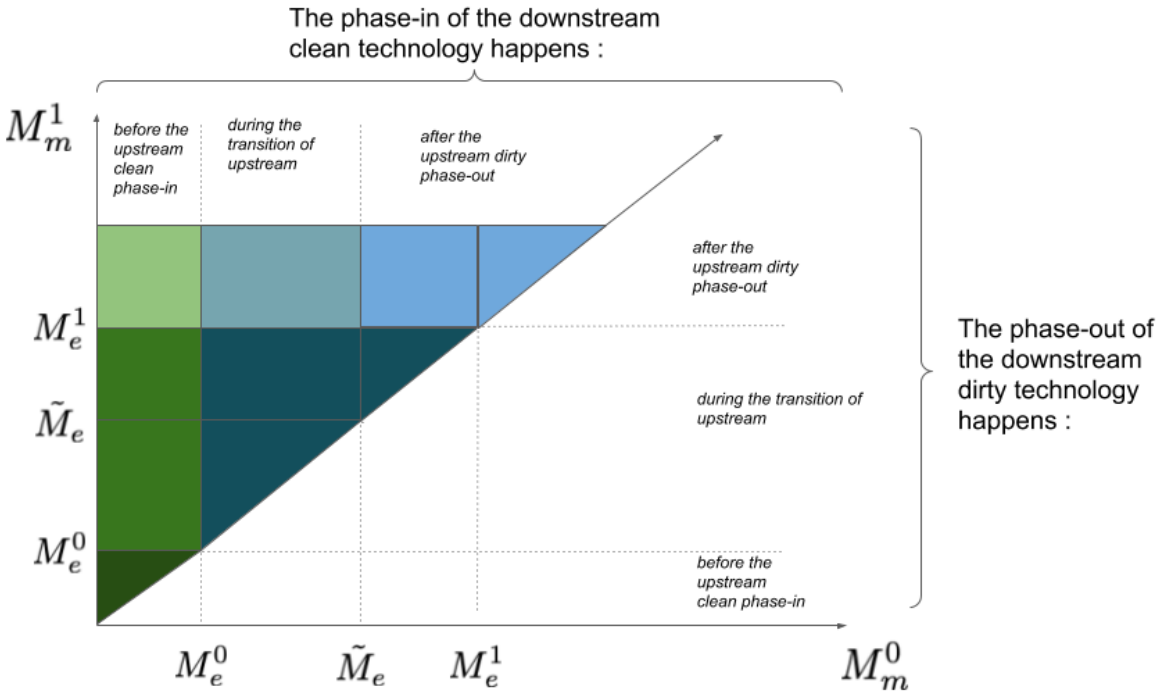


Figure 3.2: Description of transition pathways relatively to the ranking of the effective marginal abatement costs of the downstream sector (M_m^0, M_m^1) and upstream sector $(M_e^0, \tilde{M}_e, M_e^1)$

4 Policies under imperfect carbon pricing and coordination

In the previous section we investigated how sectoral linkage influence the allocation of emissions among sectors and its evolution along the MAC-curve. In this section we analyze the policy implications of sectoral linkage in a decentralized version of the model. First, for the sake of realism, we will consider optimal subsidies with imperfect carbon pricing. Indeed, pigovian taxes, or the equivalent quotas, are rarely

implemented in practice and subsidies are much more common.For instance, few carbon emissions are taxed at a level consistent with estimates of the SCC (Bank; 2015), and multiple other policies are deployed (Fischer et al.; 2017). Second, we will investigate the need of, and the benefit from coordination of these subsidies. Sectoral policies are often developed by distinct regulators, even in the same country, and we will determine the welfare loss associated by the lack of coordination.

4.1 Market equilibrium, pigovian taxation, sector coupling types

Let us denote P_e and P_m the selling prices of the upstream and downstream goods, t_i the tax on dirty units and s_i the subsidy on clean units of good $i = e, m$, both can indeed be negative. The market equilibrium is obtained with two representative consumers and a representative firm, all being price takers. In each sector $i = e, m$, a representative consumer maximizes the net surplus $S_i(Q_i) - P_i Q_i$, and the representative firm maximizes

$$\Pi(t, s, P_e, P_m, \mathbf{q}) = \sum_i \left[P_i(q_{id} + q_{ic}) - t_i q_{id} + s_i q_{ic} - C_{id}(q_{id}) - C_{ic}(q_{ic})\right] - \theta P_e q_{mc} \tag{3.11}$$

subject to positivity constraints $q_{ij} \geq 0$ and $q_{ed} + q_{ec} \geq \theta q_{mc}$. Market equilibrium prices and quantities satisfy the equations, denoting ψ_{ij} the Lagrange multiplier of the positivity constraint $q_{ij} \geq 0$:

$$S_i'(Q_i) = P_i = C_{id}'(q_{id}) + t_i - \psi_{id} \qquad \text{for } i = m, e \tag{3.12a}$$

$$P_m = C_{mc}'(q_{mc}) + \theta P_e - s_m + \psi_{ec} \tag{3.12b}$$

$$P_e = C_{ec}'(q_{ec}) - s_e + \psi_{ec}. \tag{3.12c}$$

Lemma 4 *The first-best can be decentralized with pigovian taxes $t_i = \alpha_i \mu$ and $s_i = 0$*

This textbook results helps clarify two important points: if all emissions are taxed when emitted, then LCA considerations are not required to design the optimal policy. Furthermore, there is no need to coordinate policies, each local regulator sets

the same tax level. However, both of these points only hold when taxes are optimally set at the pigouvian level, a case rarely met in the real world, so it is worth investigating consequences of departure from this situation.

Before analyzing optimal couple of subsidies, let us look at the impact of each instruments on total emissions. Indeed, one would expect that taxes on dirty goods and subsidies on clean good both reduce total pollution, but it is not so when coupling is either upstream-driven or downstream-driven defined in 2. In the former case, increasing the subsidy on the clean downstream quantity increases emissions because of the consequences on the upstream market. In the latter case, raising taxes on dirty upstream production increases total emissions because it reduces the adoption of the clean downstream technology.

Lemma 5 *At market equilibrium:*

- *Total emissions always decrease with upstream subsidies or downstream taxes.*
- *When sector coupling is upstream-driven, total emissions increase in configuration B with downstream subsidies.*
- *When sector coupling is downstream-driven, total emissions increase in configuration B with upstream taxes.*

4.2 Second-best policies

Let us start with a discussion of the optimal downstream subsidy for a given tax on the dirty downstream technology and regulation (both tax and subsidy) in the upstream sector. We will next look at the joint optimization of downstream and upstream subsidy. Indeed, in the case of electric mobility, the question is whether emissions associated with electricity production should influence the optimal subsidy on electric vehicle. Even though the subsidy is initially justified by the unpriced negative externality from the dirty downstream technology, it should also be adjusted to the suboptimal upstream regulation.

Lemma 6 *For given downstream tax t_m and upstream tax and subsidy t_e and s_e, the optimal downstream subsidy, in configurationB, is:*

$$s_m = (\alpha_m \mu - t)\frac{1}{1+\epsilon_m} - \theta\left[(\alpha_e \mu - t_e)\frac{1}{\epsilon_e} + s_e \frac{1}{\nu_e}\right]\frac{1}{1+\frac{1}{\epsilon_e}+\frac{1}{\nu_e}} \tag{3.13}$$

The optimal downstream subsidy is justified by unpriced externality, indeed, if the externality is taxed at the pigovian level, so $t_i = \alpha_i \mu$ and $s_e = 0$, the optimal subsidy is null. In the downstream sector, an increase of clean production reduces dirty production by an amount determined by the slopes of consumer demand and of dirty marginal cost. If either the demand is inelastic or dirty cost are linear the rate of substitution is equal to minus one [6]. Concerning the influence of the upstream sector regulation: first, if the externality is perfectly priced in the upstream sector, ($t_e = \alpha_e \mu$, $s_e = 0$) the emission intensity of the upstream sector does not intervene in the formula. It is so because the environmental cost is already encompassed in the upstream price. Second, the optimal downstream subsidy does not depend on the average mix in the upstream sector but on the emission intensity of the marginal unit which is a weighted sum of dirty and clean production, the weights depending on the slope of the respective marginal costs. With a linear dirty cost that marginal unit is dirty as long as there is some dirty production.

A similar result to Lemma 6 could be established for the upstream subsidy. The optimal upstream subsidy incoporates terms related to the suboptimal regulation of the downstream sector. The following Proposition provides the formula of optimal subsidies that are jointly optimized..

Proposition 2 *For given taxes t_m and t_e, the optimal two second-best subsidies s_m and s_e are*

$$s_m^{SB} = \frac{1}{1+\epsilon_m}\Big(\mu\alpha_m - t_m\Big) - \theta\frac{1}{1+\epsilon_e}\Big(\mu\alpha_e - t_e\Big) \tag{3.14a}$$

$$s_e^{SB} = \frac{1}{1+\epsilon_e}\Big(\mu\alpha_e - t_e\Big) \tag{3.14b}$$

[6] The formula could be generalized to take into consideration that dirty and clean downstream goods are not perfect substitute on the consumer side.

with $\epsilon_i = C''_{id}/(-S''_i)$.

While the optimal downstream subsidy still encompasses elements from the upstream sector, it is not so for the upstream subsidy.[7] The optimal upstream subsidy is only determined by substitution between clean and dirty production in the upstream sector but not in the downstream sector. The ratio ϵ_e only encompasses such local sector substitution and not the adjustment of demand emanating from the upstream sector. It is so because the downstream subsidy optimally adjusts and absorbs change of the upstream price. There is an asymmetry between the two sectors because a subsidy on the clean downstream good rises the demand for the upstream good whether clean or dirty, whereas a subsidy on the clean upstream good has only an impact on the supply of the clean downstream technology, and not the dirty one. That asymmetry explains that the regulation of the upstream sector does not need to consider downstream regulation (and it could easily be extended to several downstream sectors), whereas the downstream regulation should take into account upstream considerations.

Finally, we can compute differences in welfare between first-best and second-best.

Lemma 7 *Given specification 1, welfare losses between first-best pigovian taxes and second-best subsidies is given by*

$$W^{FB} - W^{SB} = \frac{1}{2}\frac{(\alpha_e\mu - t_e)^2}{b_e} + \frac{1}{2}\frac{(\alpha_m\mu - t_m)^2}{b_m} \tag{3.15}$$

Welfare loss are quadratic in the absolute mispricing of carbon emissions in each sector $\alpha_i\mu - t_i$. Less elastic demands decrease welfare losses.

4.3 Cost of incoordination

The previous section highlighted that an optimal second-best policy of a given sector may have to acknowledge its own impact in other sectors, and integrate this impact in its policy design. Including the impact may be very difficult and uncertain for a regulator. In this section, we investigate the conditions where benefits from policy

[7] It is not exactly true in full rigor since the upstream sector characteristics indirectly influence ϵ_i in the general model, but not in a quadratic specification.

coordination are high. By defining a set of uncoordinated policies, we are investigating the quantify the social benefits of coordination relatively to the social benefits of improving carbon taxation.

Causes of lack of coordination are multiple. Typically, policies could be developed by distinct regulators, each one with her own political agenda. Also, regulators could show limited understanding on the functioning of the other sector. Such limitations could prevent regulators to anticipate the impact of their policies on the other sector. This condition could even exagerated by considering regulators that see no linkage at all when designing their policies. Additionally, one could consider regulators from distinct jurisdictions that design their policies strategically.

We consider the following ad-hoc set of policies:

$$s_m^{Inc} = \frac{1}{1+\epsilon_m}\Big(\alpha_m \mu - t_m\Big) \tag{3.16a}$$

$$s_e^{Inc} = \frac{1}{1+\epsilon_e}\Big(\alpha_e \mu - t_e\Big) \tag{3.16b}$$

The only difference with second-best policies is that the downstream subsidies do not have a component in θ. Such set of instruments can be formalized easily when upstream dirty costs are linear. With this hypothesis, it is possible to demonstrate this choice. More precisely, assuming each regulator i has her own welfare function, given as follows. Upstream welfare is given $W_e = S_e(q_{ec} + q_{ed} - \theta q_{mc}) + \theta P_e q_{mc} - C_{ec}(q_{ec}) - C_{ed}(q_{ed}) - \alpha_e \mu q_{ed}$. Downstream welfare is : $W_m = S_m(q_{mc} + q_{md}) - C_{mc}(q_{mc}) - \theta P_e q_{mc} - C_{md}(q_{md}) - \alpha_m \mu q_{md}$. The set of uncoordinated policies 3.16 can be derived assuming non-cooperative regulators. Similarly, it can also been derived assuming that the upstream regulator is myopic towards the downstream quantity (*i.e.*taking q_{mc} as constant), and that the downstream regulator is myopic towards the upstream good price (*i.e.*taking P_e as constant).

The downstream regulator sees the price of the upstream good P_e as constant. It does not take part in her choice of subsidy. Hence, she sets a higher subsidy level compared to the second-best subsidy: $s_m^{Myo} > s_m^{SB}$.

The key point of uncoordinated policies is that the downstream regulator do not integrate the indirect emissions caused by the downstream clean technology in the

upstream sector. Compared to the second-best situation, $s_m^{Inc} \geq s_e^{SB}$. This should lead to a larger development of the clean downstream technology.

Lemma 8 *Given specification 1, welfare benefits from between second-best and myopic policies are given by*

$$W^{SB} - W^{Myo} = \frac{\theta^2}{2} \frac{(\alpha_e \mu - t_e)^2}{\gamma_{mc}} \tag{3.17}$$

Welfare losses increase with the linkage intensity, with upstream carbon mispricing and decrease with steeper costs. It is relevant to compare the magnitude of the welfare benefits from improved carbon taxation (raising taxes towards their pigovian levels) and from coordinated sectoral policies.

Proposition 3 *Social benefits from coordination are higher than social benefits from improving carbon taxation when the linkage intensity is sufficiently high:*

$$\theta^2 > \left(\frac{\alpha_m}{\alpha_e}\right)^2 \tau \nu_m + \eta \nu_e \tag{3.18}$$

With $\tau = \frac{\mu - \frac{t_m}{\alpha_m}}{\mu - \frac{t_e}{\alpha_e}}$

Trivially, social gains from coordination are negligible when linkage intensity is very small. However, coordination begins to seriously matter when downstream clean costs are particularly flat, linkage intensity is high and when the emission rate of dirty technology is much higher in the downstream sector.

5 Quantitative illustration

This section aims to illustrate the two previous parts on social optimum and on the coordination of sectoral policies with numerical examples. First, we describe the evolution of quantities during the transition with first-best, second-best and uncoordinated policies. Second, we derive the marginal abatement curves for those three situations.

We consider the specified version of the model. We choose to focus on a situation with a downstream-driven coupling. We let realistic calibrations for future works. We

	upstream (e)	downstream m
Q_i^0	100	100
b_i	100	100
c_{ic}	40	80
c_{id}	20	22
γ_{ic}	20	1
α_i	1	1
β_i	0.1	0.1
θ		0.9

Table 3.2: Parameter values

simulate our model for increasing values of the social cost of carbon until all sectors have been decarbonized. For each value of the SCC, we solve the market equilibrium resulting from the first-best taxes, second-best subsidies or uncoordinated subsidies. In the case of second-best and uncoordinated policies, we assume that the taxes increase proportionally to the SCC in each sector with a rate β_i. Values of the parameter are displayed in table 3.2. Our parametric setting includes relatively inelastic demands, a high linkage intensity, much higher cost-slopes for the upstream clean technology than for the downstream clean technology, and equal emission rates in both sectors. Importantly, with such values the coupling is downstream-driven.

Quantities evolutions are shown in figure 3.3. With pigovian taxes in each sector, we saw earlier that social optimum was ensured. When the SCC increases, demand decreases in both sector, clean quantities increase, downstream quantity decreases. As shown previously, as the coupling technology is downstream-driven, upstream dirty production increases until the downstream dirty technology is phased-out. With second-best policies, clean technology develops similarly to the first-best case. However, as demands decrease much slower, full decarbonization happens for higher SCC compared to the situation with first-best taxes. With uncoordinated policies, subsidies for the downstream clean technology are higher than in the second-best case. Hence, the downstream clean technology increases much faster with the SCC than under the two previous policies. This leads to a much wider expansion of the upstream dirty technology. Nevertheless, once the downstream dirty technology has phased-out, those two situations converge.

Marginal abatement costs curve can be built by plotting the social cost of carbon versus the total abatement. Total abatement is defined by $\sum_i \alpha_i \Big(q_{id}(0) - q_{id}(\mu) \Big)$.

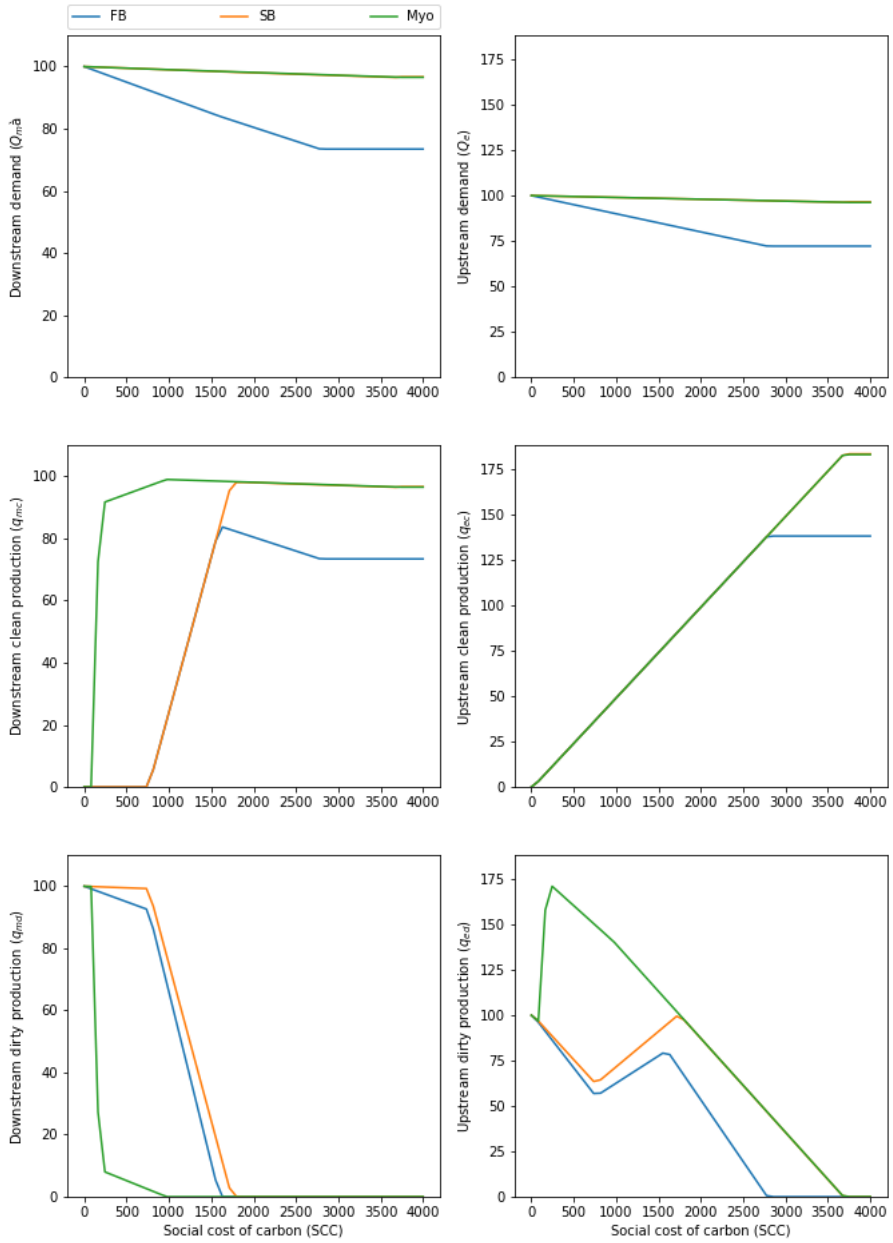


Figure 3.3: Evolution of main quantities for first-best (FB), second-best (SB) and uncoordinated (Myo) policies

Figure 3.4 shows the MAC-curves for the three policies. It shows that the MAC-curve resulting from second-best subsidies is always higher than the one of first-best taxes.

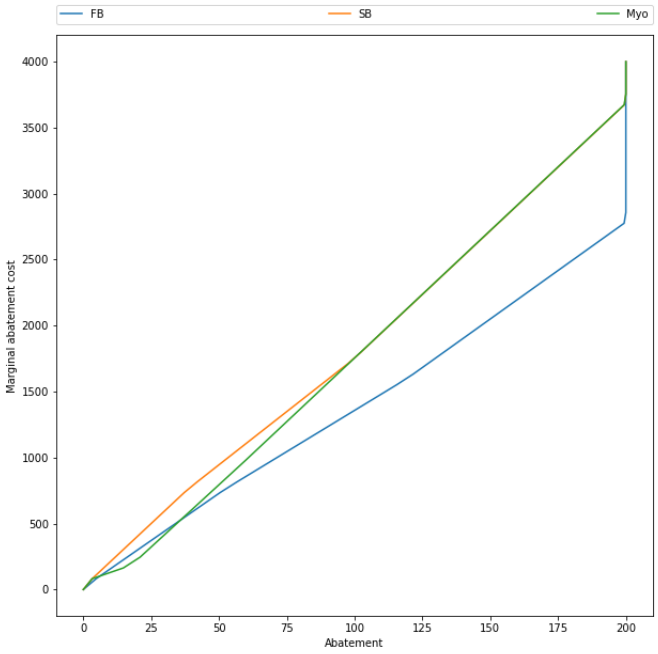


Figure 3.4: Marginal abatement costs curves

Indeed, higher taxes reduce demand which decreases marginal abatement costs. MAC-curve from uncoordinated policies is below the MAC curve from second-best subsidies, and even below the MAC-curve of pigovian taxes for low abatements. Indeed, overall subsidies are higher in uncoordinated policies, which decrease the abatement cost of firms.

Figure 3.5 shows the evolution of welfare losses from second-best subsidies, and from uncoordinated policies relatively to the social welfare given first-best taxes. Losses from lack of policy coordination dominates the loss from second-best subsidies for low SCC. This range of SCC correspond to the the transition in the downstream sector. This results tells that coordinating policies is particularly beneficial at the early stages of the transition, less after. This last result was found in many other simulations.

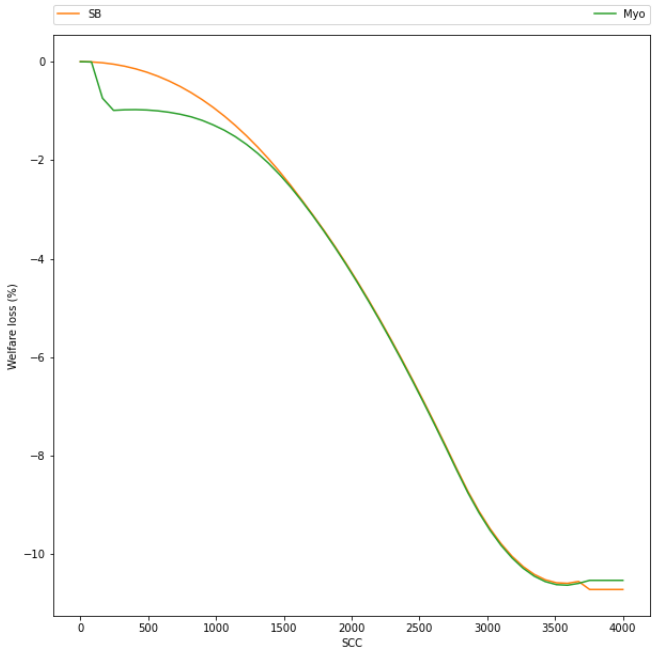


Figure 3.5: Evolution of welfare losses

6 Conclusion

Our simple model allowed us to consider transition in an economy with interconnected sectors. We established that it is indeed optimal to shift emissions from a downstream to an upstream sector, and that along an optimal trajectory upstream emissions can well be increasing because of that induced demand.

We showed that Marginal Abatement Costs Curves could be easily corrected by integrating sectoral interactions. However, the endogeneity between the downstream and upstream transition could make MACCs more difficult to interpret as it could hide transient decarbonization (even with a quadratic simple specification).

The analysis of second-best subsidy in the downstream sector stressed three main points: only unpriced externalities influence the optimal subsidy, the marginal upstream unit and not the average one influence the optimal downstream subsidy, along a decarbonization transition the optimal downstream subsidy should evolve depending on the state of the upstream sector.

This work could be improved in several ways. First, our model could be extended

to an economy with multiple sectors and with more complex structures. This would allow to build real-world MAC curves based on Input-Output Matrices. Second, our second-best analysis could be applied to a situation where different regulators (different agencies, federal versus state regulators) would decide based on their own objectives.

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3.A Equilibrium quadratic specification

In the initial dirty state :

$$Q_i^0 = \frac{1}{b_i}(a_i - c_{id}) \tag{3.19}$$

and in the fully clean state, the two quantities Q_m^1 and Q_e^1 if positive satisfy the couple of equations

$$\begin{aligned} a_e - b_e Q_e &= c_{ec}^0 + \gamma_e(Q_m^1 + \theta Q_e^1) \\ a_m - b_m Q_m &= c_{mc}^0 + \gamma_m Q_m + \theta(c_{ec}^0 + \gamma_e(Q_e + \theta Q_m)) \end{aligned}$$

the unique solution of which is, after some manipulation:

$$\begin{aligned} Q_e^1 &= \frac{1}{\Delta_1}\left[(b_m + \gamma_m + \theta^2\gamma_e)(a_e - c_{ec}^0) - \theta\gamma_e(a_m - c_{mc}^0 - \theta c_{ec}^0)\right] \\ Q_m^1 &= \frac{1}{\Delta_1}\left[(b_e + \gamma_e)(a_m - c_{mc}^0 - \theta c_{ec}^0) - \theta\gamma_e(a_e - c_{ec}^0)\right] \\ \text{with } \Delta_1 &= (b_e + \gamma_e)((b_m + \gamma_m + \theta^2\gamma_e) - \theta^2\gamma_e^2 \end{aligned}$$

the conditions in the main text ensures that these are both non-negative which then ensures that they indeed correspond to the couple Q_e^1 and Q_m^1 by uniqueness of the solution.

3.B Proofs of lemma 1 and 2

This section provide for a full derivations of results of lemmas 1 and 2. Specifically, we aim at deriving the comparative statics $\mathbf{dq} = (dq_{ec}, dq_{ed}, dq_{mc}, dq_{md})^T$ of the stage "B". We start by differentiating 3.6:

$$S''_e dq_{ec} + S''_e dq_{ed} - S''_e \theta dq_{mc} = C''_{ed} dq_{ed} + \alpha_e d\mu \tag{3.20a}$$

$$C''_{ec} dq_{ec} = C''_{ed} dq_{ed} + \alpha_e d\mu \tag{3.20b}$$

$$S''_m dq_{mc} + S''_m dq_{md} = C''_{md} dq_{md} + \alpha_m d\mu \tag{3.20c}$$

$$C''_{mc} dq_{mc} + \theta C''_{ed} dq_{ed} = C''_{md} q_{md} + (\alpha_m - \theta\alpha_e) d\mu \tag{3.20d}$$

Such system can be converted in a matrix system : $M\boldsymbol{dq} = \boldsymbol{\alpha} d\mu$

$$M = \begin{pmatrix} S''_e & S''_e - C''_{ed} & -\theta S''_e & 0 \\ C''_{ec} & -C''_{ed} & 0 & 0 \\ 0 & 0 & S''_m & S''_m - C''_{md} \\ 0 & \theta C''_{ed} & C''_{mc} & -C''_{md} \end{pmatrix}, \ \boldsymbol{\alpha} = \begin{pmatrix} \alpha_e \\ \alpha_e \\ \alpha_m \\ \alpha_m - \theta\alpha_e \end{pmatrix} \tag{3.21}$$

A tedious[8] inversion of the system gives:

$$dq_{ec} = \frac{1}{H}\Big[- S''_e(-S''_m(\alpha_e(C''_{mc} + C''_{md}) + \alpha_m C''_{ed}\alpha_m) + \alpha_e C''_{mc}C''_{md})\Big] \tag{3.22a}$$

$$dq_{ed} = -\frac{1}{H}\Big[- S''_e(-S''_m(\alpha_e(\alpha_m^2 C''_{ec} + C''_{mc} + C''_{md}) - \alpha_m C''_{ec}\alpha_m) + \alpha_e C''_{md}(\alpha_m^2 C''_{ec} + C''_{mc})) + \alpha_e C''_{ec}(-S''_m(C''_{mc} + C''_{md}) + C''_{mc}C''_{md})\Big] \tag{3.22b}$$

$$dq_{mc} = \frac{1}{H}\Big[- S''_e(-S''_m(\alpha_m(C''_{ec} + C''_{ed}) - \alpha_m\alpha_e C''_{ec}) - \alpha_m\alpha_e C''_{ec}C''_{md}) + -S''_m C''_{ec}C''_{ed}\alpha_m\Big] \tag{3.22c}$$

$$dq_{md} = \frac{1}{H}\Big[- S''_e(-S''_m(\alpha_m(C''_{ec} + C''_{ed}) - \alpha_m\alpha_e C''_{ec}) + \alpha_m(C''_{ec}(\alpha_m^2 C''_{ed} + C''_{mc}) + C''_{ed}C''_{mc})) + C''_{ec}C''_{ed}\alpha_m(-S''_m + C''_{mc})\Big] \tag{3.22d}$$

With the common denominator $H = -S''_e(-S''_m(C''_{ec}(\theta^2 C''_{ed} + C''_{mc} + C''_{md}) + C''_{ed}(C''_{mc} + C''_{md})) + C''_{md}(C''_{ec}(\theta^2 C''_{ed} + C''_{mc}) + C''_{ed}C''_{mc})) + C''_{ec}C''_{ed}(-S''_m(C''_{mc} + C''_{md}) + C''_{mc}C''_{md})$

As $H \geq 0$, only the numerator of dq_{ij} matters for the sign of comparative statics.

3.C Transition marginal abatement costs

When $\theta > 0$, the value of thresholds $(\underline{\mu}_e, \bar{\mu}_e, \underline{\mu}_m, \bar{\mu}_m)$ depend the transition pathway, and hence on their respective ranking. Our concept of transition marginal abatement costs aims at bypassing this endogeneity issue. We start by computing thresholds $(\underline{\mu}_e, \bar{\mu}_e, \underline{\mu}_m, \bar{\mu}_m)$ in every possible pathways. To exhibit the transition-MAC, we find the induced conditions by given by the pair of $\underline{\mu}_i < \bar{\mu}_j$, $\underline{\mu}_i < \underline{\mu}_j$,$\bar{\mu}_i < \bar{\mu}_j$.

- $\underline{\mu}_e = \frac{C'_{ec}(0) - c_{ed}}{\alpha_e}$
- $\bar{\mu}_e = \begin{cases} \frac{C'_{ec}(\tilde{Q}_e) - c_{ed}}{\alpha_e} \text{ if } \bar{\mu}_e < \underline{\mu}_m \\ \frac{1}{1+\nu_e - \theta(x-\theta)\frac{\gamma_e}{\gamma_m}}\Big(\frac{C'_{ec}(Q_e^0) - c_{ed}}{\alpha_e} - \theta(x-\theta)\frac{\gamma_e}{\gamma_m}\frac{C'_{mc}(0) + \theta c_{ed} - c_{md}}{\alpha_m - \theta\alpha_e}\Big) \text{ if } \underline{\mu}_m < \bar{\mu}_e < \bar{\mu}_m \\ \frac{1}{1+\nu_e + \theta\frac{g}{1+\nu_m}}\Big(\frac{C'_{ec}(Q_e^0 + \theta Q_m^0) - c_{ed}}{\alpha_e}\Big) - \frac{g}{1+\nu_m}(x-\theta)\frac{C'_{mc}(Q_m^0) + \theta c_{ed} - c_{md}}{\alpha_m - \theta\alpha_e}\Big) \text{ if } \bar{\mu}_m < \bar{\mu}_e \end{cases}$

[8] Mathematica or similar is recommended!

- $\underline{\mu}_m = \begin{cases} (1-\frac{\theta}{x})\frac{C'_{mc}(0)+\theta c_{ed}-c_{md}}{\alpha_m-\theta\alpha_e} + \frac{\theta}{x}\frac{C'_{ec}(\tilde{Q}_e)-c_{ed}}{\alpha_e} \text{ if } \bar{\mu}_e < \underline{\mu}_m \\ \frac{C'_{mc}(0)+\theta c_{ed}-c_{md}}{\alpha_m-\theta\alpha_e} \text{ if } \underline{\mu}_m < \bar{\mu}_e < \bar{\mu}_m \\ \frac{C'_{mc}(0)+\theta c_{ed}-c_{md}}{\alpha_m-\theta\alpha_e} \text{ if } \bar{\mu}_m < \bar{\mu}_e \end{cases}$

- $\bar{\mu}_m = \begin{cases} \frac{1}{1+\nu_m+\frac{\theta g}{1+\nu_e}}\left((1-\frac{\theta}{x})\frac{C'_{mc}(Q^0_m)+\theta c_{ed}-c_{md}}{\alpha_m-\theta\alpha_e} + \frac{\theta}{x}\frac{1}{1+\nu_e}\frac{C'_{ec}(Q^0_e+\theta Q^0_m)-c_{ed}}{\alpha_e}\right) \text{ if } \bar{\mu}_e < \underline{\mu}_m \\ \frac{1}{1+\nu_m+\frac{\theta g}{1+\nu_e}}\left((1-\frac{\theta}{x})\frac{C'_{mc}(Q^0_m)+\theta c_{ed}-c_{md}}{\alpha_m-\theta\alpha_e} + \frac{\theta}{x}\frac{1}{1+\nu_e}\frac{C'_{ec}(Q^0_e+\theta Q^0_m)-c_{ed}}{\alpha_e}\right) \text{ if } \underline{\mu}_m < \bar{\mu}_e < \bar{\mu}_m \\ \frac{C'_{mc}(\tilde{Q}_m)+\theta c_{ed}-c_{md}}{\alpha_m-\theta\alpha_e} \text{ if } \bar{\mu}_m < \bar{\mu}_e \end{cases}$

Where we noted $x = \frac{\alpha_m}{\alpha_e}$, $\nu_i = \frac{\gamma_i}{b_i}$, $\eta = \frac{\gamma_m}{\gamma_e}$ $Q^0_i = \frac{a_i-c_{id}}{b_i}$. $\tilde{Q}_e = \frac{a_e-c_{ec}}{b_e}$ and $Q^*_m = \frac{\alpha_m(a_m-c_{mc}-\theta c_{ec})-\theta\alpha_e(a_m-c_{md})-\theta\alpha_m(c_{ec}-c_{ed})}{\alpha_m\gamma_m+(\alpha_m-\theta\alpha_e)b_m}$.

* * *

Dans une ferme du Poitou
Un coq aimait une pendule
Tous les goûts sont dans la nature...
D'ailleurs ce coq avait bon goût
Car la pendule était fort belle
Et son tic tac si doux si doux
Que le temps ne pensait surtout
Qu'à passer son temps auprès d'elle
Dans une ferme du Poitou
Un coq aimait une pendule
De l'aube jusqu'au crépuscule
Et même la nuit comme un hibou
L'amour le rendant coqtambule
Des cocoricos plein le cou
Le coq rêvait à sa pendule
Du Poitou

Claude Nougaro - *Le Coq et la Pendule.*

* * *

Chapter 4

Interactions between electric mobility and photovoltaic energy

* * *

Photovoltaic generation and electric mobility are two disruptive technologies in the power and transport sectors that are raising several issues regarding power grids. Numerous studies have been indicating that a synergistic potential exists between these two technologies. This special interaction would alleviate their burden on power grids and at the same time, would empower one technology with the other's specifities. Indeed, electric vehicles could use photovoltaic energy to benefit of a low-cost and carbon-free electricity to charge. In return, photovoltaic systems would use the bi-directional flexibility of electric vehicles battery to maximize their self-consumption. With such synergy, business cases of both technologies improve and therefore their joint development could be stimulated. The objective of this paper is to develop a framework in order to analyze technical and economic aspects of this synergy. We tackle these issues with a literature review on systems including electric vehicles and photovoltaic energy. This literature mostly describes technical aspects of these interactions. There is a lack of knowledge on the economic conditions of the implementation of such synergy. We identified several open issues about these conditions that should be worth further investigation.

* * *

1 Introduction[1]

Electric vehicles (EV) and photovoltaic generation (PV) are two independent technologies disrupting their respective sectors. In 2017, the world EV fleet reached two million units, while solar energy boasted the largest growth of all energy sources (IEA; 2017a,b). Both technologies meet in power grids, in a distributed way, and tend to overlap geographically (Delmas et al.; 2017; Li et al.; 2017). Numerous studies have pointed out that the flexibility of EV batteries would be an excellent complement for renewable energy integration (Kempton and Tomić; 2005). This potential synergy should provide individual and systemic benefits by decreasing both technology costs and ecological footprints (Chaouachi et al.; 2016; Nunes et al.; 2015; Tushar et al.; 2016), and could even stimulate the development of each technology.

Nevertheless, there are several barriers to mutually beneficial interactions. EV and PV bring various technical and economic problems to power grids, problems that create added costs for power grid managements and that increase with increasing penetration of each technology (Baker et al.; 2013; Eid et al.; 2016). Moreover, a disorganized EV/PV system may even compound these costs. A growing literature has therefore studied the combined integration of EV and PV (or other renewable energies) in power grids. Several authors have written reviews on the subject (Liu, Kong, Liu, Peng and Wang; 2015; Mwasilu et al.; 2014; Nunes et al.; 2016; Richardson; 2013) and identified the main technical features of such integration. Assessing the properties of EV/PV systems is a complex task as they depend on various technical, meteorological, behavioral, economic and political parameters. Moreover, the benefits of EV/PV synergy are often mixed with other benefits captured by a single technology (energy trading outside the system for instance). Therefore, the purpose of this paper was to build a systematic framework for assessing the properties of EV/PV systems and the conditions for synergy.

This framework allowed us to identify the main conditions for synergy to lend EV/PV systems better economic and technical efficiency with a smaller ecological footprint. This synergy is determined by a smart control strategy aiming at optimizing

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the power flows in the system, mostly by adapting EV charging to variable photovoltaic generation. The spatial configuration of the EV/PV system is a major aspect of the synergy. EV/PV couplings were particularly efficient at intermediate scales (large workplace buildings and charging stations). During the day, these configurations host a moderate number of EV, which facilitates the predictability of charging demand. In addition, this demand is adapted to the PV generation profile, which makes smart control very efficient. However, the specificity of EV/PV couplings is less obvious at other scales (households, territories) and in technologically diversified systems.

The literature in general has not assessed the economic conditions for EV/PV synergy in a primary concern. Nevertheless, we were able to identify the key aspects of these conditions. First, it emerges that the efficiency of most EV/PV systems is driven by a certain level of cooperation between the different participants of the system, and this cooperation becomes even more crucial where the potential EV/PV synergy is the highest. Then, EV/PV system-power grid interdependencies could be leveraged to bring further efficiency gains for both the EV/PV systems and the different grids. Finally, the economic context (electricity pricing, barriers to entry, support mechanisms) in which EV/PV systems operate plays a major role in the synergy.

The paper begins by outlining the rationale and components of our systematic framework. We then go on to detail the elements of our analytical framework. Next we explore the different technical aspects and then the economic aspects of EV/PV systems. We conclude the review by summarizing key elements of EV/PV interactions and giving potential leads for future research.

2 Description of the systematic framework

Future smart grids will harness an array of technologies such as distributed generation, distributed storage, and flexible loads. Combining them optimally requires precise knowledge on the intricate interplays between technologies. Due to the vast diversity of possible systems and the numerous exogenous factors (meteorological, behavioral, technical, economic and regulatory) that influence their performances, the system

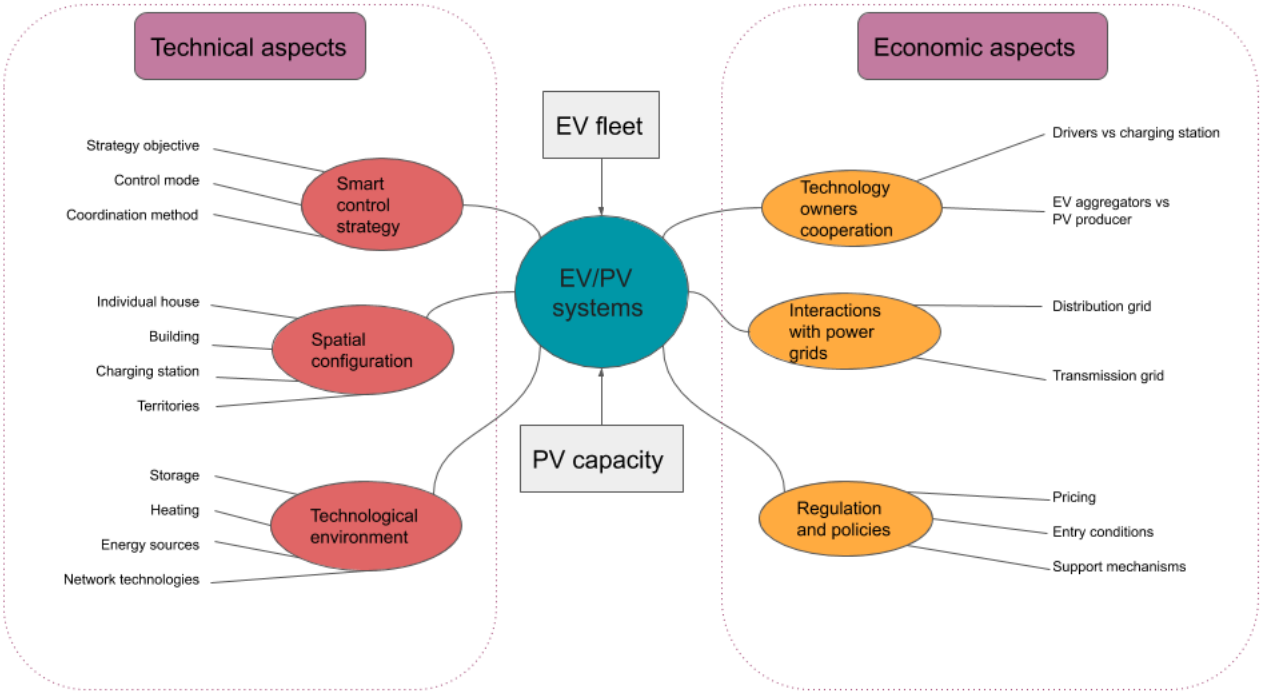

Figure 4.1: Analytical framework of EV/PV interactions. For each section, some of the most relevant references are indicated.

complexity involved means that analysis has to mobilize different perspectives. Such perspectives could focus on a typical technology or on a typical configuration with multiple links between various technologies. We feel it relevant to focus on single links between two technologies (here EV and PV) as an alternative perspective to help gain understanding on future power systems.

We employ the artificial term "EV/PV systems" to designate a technical entity that combines a specific quantity of electric vehicles and a specific capacity of photovoltaic generation. Our literature review found that the constellation of EV/PV systems brings out several key aspects influencing the potential for synergy between EV and PV. Figure 1 describes these key aspects in detail. They can be split between technical aspects and economic aspects. Technical aspects consist in a spatial configuration (house, building, charging station or territory) in a technological environment (storage, heat systems, additional energy sources or special network components). The performance of the EV/PV system hinges on a smart control strategy that optimizes the charging (and discharging if V2G available) with PV generation and the various

constraints of the spatial and technological environment.

Beyond technical aspects, the EV/PV systems, like most future power systems, are also largely dependent on economic and regulatory aspects. More precisely, we identified the main feature of the economic context as the emergence of cooperative behaviors inside EV/PV systems, interactions between EV/PV systems and the power grids (distribution and transmission grids), and regulatory and policy factors (pricing, barriers to entry, and support mechanisms).

3 Technical aspects of EV/PV synergy

An EV/PV system is set in a particular spatial configuration and technological environment. The spatial configuration shapes the technical and organizational conditions where EV and PV technologies meet. The technological environment gathers the other main relevant technologies that coexist and interact with EV and PV capacities inside the spatial configuration. Finally, both technologies in their spatial and technological environment are combined with a smart control strategy. This section details these three components: smart control strategies, spatial configuration and technological environment.

3.1 Smart control strategies for EV/PV systems

Smart control strategies are the core of EV/PV systems and the main leverage for potential synergy, which is why they have been the most investigated aspect of EV/PV couplings. Here we give a broad review of the defining features of smart control strategies, i.e. the strategy objective and the coordination method (optimization, heuristic, hybrid) with their data requirements, and the mode of control (centralized or decentralized). A key element in these strategies is the ability of EVs to use bidirectional flow (from and to the power system), namely vehicle-to-grid (V2G)[2].

[2]For more detailed information, a technical review of electric vehicle fleet management can be found in (Hu et al.; 2016)

Strategy objective

Defining a strategy objective is generally the first step of a smart strategy. Liu, Kong, Liu, Peng and Wang (2015) provide a review of EV and renewable energy couplings by strategy objective, which can be distinguished by the quantity considered, whether monetary or physical. An objective is generally specific to a particular organization of agents, the spatial configuration in which it operates, and the technical means of coordination it uses. A monetary objective can be to increase the revenues of an entity (*e.g.*a charging station), or to decrease total energy costs (*e.g.*for a building), electricity costs (*e.g.*for a charging station), charging costs (*e.g.*for an EV driver), or electricity generation costs (*e.g.*for a system planner). Alternative objectives may be energy efficiency or ecological footprint. An energy efficiency objective may be to improve the system's self-consumption or to reduce grid power imports, power losses in the system, or total system energy demand. An ecological footprint objective may be to reduce direct or indirect emissions of carbon dioxide or a combination of pollutants. As we will see later, a smart strategy can also aim to combine several of these objectives.

Control mode

In smart grids, the control mode defines the level of coordination of flexible charges, which in EV/PV systems means almost exclusively EVs. This control can be either centralized or decentralized. A detailed introduction to these concepts is presented in (García Villalobos; 2016).

In a centralized mode, a special agent (the so-called "aggregator") manages the scheduling of EV fleet charging. An aggregator can be the manager of an EV fleet, a charging station, or a district microgrid. The pros of this mode are that it provides good results, with good utilization of network capacities and ancillary services. The cons are that it requires a heavy communication architecture handling large amounts of data. In a decentralized mode, EV drivers organize their charging themselves by reacting to incentives offered by aggregators, who may be the same as for centralized control but also include larger actors like distribution system operators (DSO). Typically, drivers are incentivized by dynamic electricity prices. Compared to centralized

control, decentralized control requires less complex communication systems and has better consumer acceptance, but it offers lower gains and requires a sharp idea of user reaction to incentives.

Coordination methods

A coordination method is the mathematical formulation of the control strategy. It articulates the strategy objective, the control modes with the diverse constraints on EV (charging demand needs, battery availability), PV generation, other available technologies and other technical constraints (e.g. imposed by power grids). Here we distinguish coordination between optimization methods, heuristic methods, and hybrid methods.

Optimization methods One of the most common methods for energy management in EV/PV systems is to optimize an objective function (based on cost, energy efficiency or ecological footprint). This function is typically the imported power from the grid (in cost or energy) over a given time, but can also be power losses, system total lifetime cost, direct and indirect pollutant emissions, and more. It can also be a combination of different objectives. As we will see later, multi-objective optimization methods are a good way to simulate cooperation between different actors. As an illustration, we formulate a simple problem for a system with an independent load, several charging EVs, and PV power. The system manager wants to minimize grid power costs over a certain time under the following constraints: balance between energy produced (PV and grid) and consumed (load, EVs and losses), EV charging dynamics, EV battery limits (minimal and maximal state of charge), power limits for charging, possibility of bidirectional EV flows (V2G), and the state of charge required by drivers. Such a problem would require data on power grid prices, PV generation profiles, load profiles, and charging efficiencies. Solving an optimization problem depends mostly on the functional forms. Linear, quadratic and more generally most convex problems are easily manageable with numerical solvers. When functions are not convex, genetic algorithms and particle swarm optimization algorithms can achieve near-optimal results in a reasonable computation time. As the problems contain several uncertainty sources (here, for solar irradiance, EV charging demand, electricity prices, among others), stochastic modeling

can be used. An objective function would then be the expected sum of the objective functions over the different deterministic scenarios. Several authors have incorporated stochasticity in their smart strategies. Guo et al. (2016) show that the difference in microgrid revenue between a strategy with perfect forecast and a stochastic optimized strategy was 1-9%. In this case study, this range was comparable to the range of improvement of a stochastic optimized strategy compared to the uncontrolled strategy. Similarly, Karan et al. (2016) show that a stochastic algorithm decreases forecast error by 15-30% compared to a deterministic algorithm. Finally, it is possible to use statistical methods to get a prediction of EV arrivals, PV power, or grid electricity prices (Ghofrani et al.; 2014; van der Meer et al.; 2016).

Heuristic methods Energy management schemes for EV/PV systems often need simple logical rules to react instantaneously to new events (plugging/unplugging of an EV, decrease of PV power, grid price). Ruled-based decision-making provides a simple heuristic method to manage the system with predictions requiring little data. Typical example of such a method can be found in (Byeon et al.; 2013; Liu, Chen, Liu, Lu, Li, Lei and Zhang; 2015). Liu, Chen, Liu, Lu, Li, Lei and Zhang (2015) show that it can even provide results almost as good as optimization problems, while reducing the energy management system computation time by a factor 300.

Hybrid methods Optimization methods and heuristic methods can be combined into hybrid approaches. Liu et al. (2016) define a smart control strategy by a two-level approach. Before each day of service, an offline deterministic optimization gathers data on EV charging needs, PV power and grid prices and a database of past optimal strategies. A parallel real-time approach uses a machine learning algorithm (based on the database of past events) and rule-based decision-making. The authors demonstrate that such methods do not require any forecasts on future PV power and charging demand to get near-optimal results. The hybrid strategy in (Chen, Wang, Hodge, Zhang, Li, Shafie-khah and Catalao; 2017) consists of a dynamic price forecasting algorithm and a rule-based decision-making algorithm.

3.2 Spatial configuration of EV/PV systems

Smart control strategies are designed for particular spatial configurations where EV and PV technologies meet. These configurations bring specific constraints. We distinguish the following spatial scale levels: individual house, commercial building and workplace, charging station, or territory. In addition to spatial level features, the number of EVs (or fleet size), PV capacity and aggregation level all play an important role.

Individual household

The smallest scale for EV/PV coupling to operate is in residential households. Several works have shown that EV/PV coupling could improve utilization of the two technologies aiming at taking houses towards the objective of zero net emissions over a year. EV charging typically becomes less costly as solar panel self-consumption increases. Coffman et al. (2017) set out the conditions, based on a case study in Hawaii, that would make total cost of EV ownership lower than their plug-in hybrid EV or internal combustion engine vehicle competitors. Integrating EV in an electricity mix with a high penetration of PV makes EV much more attractive. Ritte et al. (2012) study EV home-charging in houses equipped with solar panels. The authors find that the effectiveness of smart control strategies is highly dependent on the driver's mobility uses. Indeed, a long-range commuter does not take advantage of PV charging while private users with several daily trips around their home benefit from almost 70% of PV energy in their EV charging. Short-distance commuters use around 40% of PV energy in their EV charging. The electricity bill savings are fairly low (around €100 per year) for everyone. Two case studies carried out in Sweden (Munkhammar et al.; 2013) and the UK (Munkhammar et al.; 2015) develop a Markov chain stochastic models of energy consumption in EV-owning households equipped with PV systems using real data. Both studies show poor EV/PV synergy. Indeed, most EVs come back home and plug in the evening, when household load is at a peak. As the authors do not define smart charging, the EVs only increase energy consumption and its standard deviation. In both cases, they point out that EV disturbances on the local grid

(measured by consumption standard deviation) are attenuated at large scale by statistical effects. Salpakari et al. (2017) seek to minimize total operational power costs for a microgrid serving a residential district (from one to a dozen buildings) equipped with 10kWp solar panels. These costs compile EV charging, V2G use, other types of electricity consumption, and heating. By solving the linear programming problem, the authors find a 8-33% cost reduction per building. Cooperation between buildings through direct power exchanges improves cost reductions. Moreover, V2G use extends self-consumption but has very little effect on overall operational costs due to battery degradation costs.

Wu et al. (2016) formulate a mobility model (with Markov chains) and a predictive model for household load and PV electricity generation. The authors then develop a stochastic optimization model minimizing grid energy purchases. Considering a Tesla S and a Nissan Leaf, the annual cost reductions came to -493% and -175%, respectively. Note that these huge cost reductions are due to V2G utilization with high feed-in tariffs and without taking into account potential cost on the battery. Note too that there was next to no coordination of optimal charging with PV generation profile. Ancillotti et al. (2014) combine a mobility model and a building electricity consumption model to simulate the energy management of a "zero net-energy building". The authors quantify the benefits of vehicle-to-house (V2H) for ten houses running one EV each, and then determine the sensitivity of their results to PV capacity (20-90 kWp) and the degree of cooperation of the EV owners (*i.e.*their chosen state-of-charge fraction available for V2H). Two scenarios are simulated, with and without an electric storage system (ESS). Depending on the installed capacity, solar panels provide 20-30% of household loads, and depending on the pre-set state-of-charge fraction for V2H, EV can provide up to 30% of house power. An ESS further reduces grid power imports. Alirezaei et al. (2016) model the electricity system of a residential household (consumption, PV generation, ESS and EV). Once consumption is optimized, a rule-based decision-making algorithm is used to manage EV and battery storage charging as a function of PV generation and electricity time-of-use tariffs. The proposed algorithm leads to 62% lower electricity bills. The individual effect of EV on total strategy efficiency is difficulty tractable compared to the stand-alone battery effect,

but its role gets even greater with a higher initial state of charge. Bedir et al. (2010) use empirical data on residential consumption and PV generation to assess the effect of a combination of house loads, EV charging, and solar panels. Using a commercial energy management system, the authors find a 30-50% reduction in electricity bills.

Having an EV almost doubles the electricity consumption of a household, so having an own energy source (like PV) makes sense. Nevertheless, it appears through the literature that while coupling EV with PV inside households can be beneficial, the benefits are bounded by the EV utilization for mobility. Indeed, EV are usually away from home during the day and therefore cannot benefit from maximal PV generation. As we will see later, an additional energy flexibility source (like battery storage or thermal systems) is beneficial to household energy management.

Buildings

In the case of individual houses, we saw that the benefits of EV/PV coupling could be limited by the absence of EV at maximal PV generation hours. EVs will be parked at this time, whether at workplaces or in other car parks. Given that these places should be able to host more EV, which would allow a better predictability, EV/PV coupling should be more efficient to improve self-consumption in commercial or workplace buildings. In a commercial building equipped with 50kWp capacity solar panels, Wi et al. (2013) seek to optimize the charging of 12 EV by minimizing total electricity costs. EV mobility is modeled simply with times of arrivals and departures, and with arrival states of charge as fixed parameters. Smart charging defined on PV power predictions can reduce electricity purchases by 6% to 15% compared to uncontrolled charging. van der Meer et al. (2016) formulate an optimization problem for the charging management of 6 EV at a workplace equipped with 9kWp of PV capacity. Compared to an uncontrolled charge, optimized charging allows to improve self-consumption by 20-30%, while generating profits. Van Roy, Leemput, Geth, Salenbien, Buscher and Driesen (2014) test different EV charging strategies on a large residential building. Depending on the number of EV parked, self-consumption can be improved by up to 20%. van der Kam and van Sark (2015) use a linear programming algorithm to define EV smart charging on a microgrid of a residential neighborhood in a case study

based on Dutch data. The microgrid has 31kWp PV capacity and 2-5 EV for which charging demand is estimated using probabilistic methods. The authors find a 13-38% improvement in microgrid self-consumption. Soares et al. (2015) formulate an optimization problem to minimize the operational cost of an eco-district microgrid with EV and PV systems. Compared to an uncontrolled scenario, optimal management lowers operational costs by 70%. For a university campus microgrid, Zhang et al. (2016) develop an energy management scheme with two levels: the first one deals with energy exchanges with the grid while the second one coordinates EV charging. This system can reduce imported power by 73% and improve self-consumption by 50%. Roselli and Sasso (2016) develop a simulation model of power management for a workplace. By comparing a "classical" system (with a classical vehicle and gas and electricity heating) with a "green" one (with an EV, a PV system and a heat pump), the authors find a 40% decrease in primary energy consumption and 40% decrease in CO_2 emissions. Byeon et al. (2013) simulate the DC electric system of a building with 6kWp PV capacity and a car park hosting 8 EVs. Energy management follows a rule-based decision-making algorithm allowing V2G. Compared to a dumb charging case, smart charging leads to a 43% decrease in charging costs. Tulpule et al. (2013) assess the economic feasibility of a workplace charging station with solar capacity. The authors use a stochastic dynamic optimization problem to define the smart charging EV scheme that minimizes imported power from the grid. EV arrival and PV power are estimated using probabilistic methods. Compared to uncontrolled charging with and without PV, smart charging with PV reduces imported power by 80% and 90%, respectively. The authors then develop an investment model to determine the payback time of the station depending on user tariff and regulatory instruments. They carried out two case studies in two US states with different solar irradiation and subsidy frameworks. The authors find that optimal charging matters when PV capacity is low. (Kuang, Chen, Hu and Yang; 2017) contains an interesting study on power loads for different categories of buildings. Based on 16 building categories (*e.g.*offices, hotels, hospitals, schools...), the authors show that the smart control strategy of a EV/PV building system brings costs reductions of between 4% and 18%. Moreover, the coupling performance is highly dependent on building type and its typical load profile.

For instance, warehouses, fast-food restaurants, hostels and supermarkets benefit the most of EV/PV synergy, whereas hospitals and healthcare centers benefit the least.

Charging stations

This section focuses on the study of EV/PV complementarity in the case of charging stations with on-site PV capacities (PVCS) or off-site PV power stations, for either commercial or professional purposes (*e.g.*included in the workplaces). PVCS management spans a broad range of fleet numbers, since charging stations go from small workplaces to large carpark complexes. Nunes et al. (2016) provide a review of the main technical-economic features of PVCS technology and its environmental benefits.

In a Monte-Carlo simulation, Brenna et al. (2014) show that the potential share of PV energy in EV charging ranges from 1% to 72% without smart charging. Season and charging power are shown to be the main determinants of the efficiency of PV-based charging. Indeed, lower power increases charging duration and thus PV self-consumption. Chen, Liu, Hu, Wang and Zhang (2017) consider a novel technology of solid-state transformers to enable flexible management of a PVCS. The authors develop a rule-based decision-making model in order to participate in ancillary services for the grid. In their case study of a PVCS hosting 60 EVs with a 200kWp PV capacity, the authors find an increase of 200% of revenues from ancillary services compared to their uncontrolled case without PV. Chen, Wang, Hodge, Zhang, Li, Shafie-khah and Catalao (2017) propose an architecture for a PVCS with a hybrid control strategy. The authors' smart control strategy reduces charging costs by 50-75% while increasing PV self-consumption by 20%. The strategy does not particularly improve charging completion which stays stable at 85%-92%.

Awad et al. (2016) seek to maximize the profits of a PVCS investor while factoring in grid constraints. By optimizing the net present value of the PVCS revenues and costs, the authors find that smart charging a fleet increases owners' benefits by 10% while reducing peak load by 40%. In their study of a small charging station equipped with up to 10kWp PV capacity for a single EV (Nissan Leaf or Tesla Roadster), Chukwu and Mahajan (2014) develop a technical model to introduce a smart strategy. The results show that V2G capabilities can be enhanced by 60% for ancillary services.

For a PVCS able to host 300 EVs, Guo et al. (2016) develop an operational framework in two steps to maximize the PVCS profits. A first stochastic algorithm calculates day-ahead grid power need and marginal electricity cost for the PVCS. A second algorithm optimizes the charging scheduling of EVs. This smart strategy increases the revenues of the PVCS operator by 3% in summer and 10% in winter. Seddig et al. (2017) consider a charging station hosting up to 650 EVs and equipped with 100kWp of solar capacity. The EVs are divided into 3 categories that define their charging profile: commercial (night charging), commuter (long day charging) and opportunity parkers (short day charging). The authors minimize the grid power purchases using different optimization algorithms (deterministic and stochastic). Compared to the uncontrolled strategy, the smart strategies double the PV utilization while reducing grid power costs by 86%-95%.

Figueiredo et al. (2017) study the technical and economic feasibility of a PVCS from an investor point of view. The authors investigate various PVCS management system designs (control strategies, storage). From real parking data, the daily correlation between occupancy profile and PV generation is found to be between 36% and 59%. In every case, the PVCS is found to be profitable with a 7% interest rate on the period covering the PV modules lifetime. Gil et al. (2015) study the management of an EV parking lot in ancillary markets (regulation and reserve). PVCS revenues are defined by the addition of participation of EVs in various ancillary markets (energy, spinning reserve, regulation up and down) and the charging and parking fees of EVs. Costs gather the purchased power from the grid, penalties in markets, payment to EVs owners for their V2G services, and battery degradation costs. In one of their case studies, the distribution system handles a 200kWp solar farm. In this situation, the authors find 5.3% higher expected profits than in the case without renewable energy. In this scenario, PV and EV systems interact indirectly in energy markets. Noticeably, regulation market revenues decrease (-2.6%), while reserve revenues remain steady and energy market revenues increase (+10%). Mouli et al. (2017) develop a management model in which the PVCS is able to use V2G capabilities, trade energy, and offer reserve services to the grid. The optimal strategy leads to a 250% decrease in the PVCS energy costs on average through the year.

Territories

This section reviews papers dealing with EV/PV synergy at a far larger scale territories, which can be cities, islands, regions, or countries, and can host large numbers of EV and high PV capacities. The power grids considered are large distribution grids and transmission grids. The issue of coupling EV and PV matters to companies with substantial transport and electricity needs.

De Schepper, Van Passel and Lizin (2015); De Schepper, Van Passel, Lizin, Vincent, Martin and Gandibleux (2015); Tang et al. (2014) look at joint investments possibilities in EV and PV. For a Chinese taxi company, Tang et al. (2014) use an energy optimization model to assess the net present cost and carbon footprint of combinations of technologies (including grid and PV power, EV and battery storage). The authors find that grid-powered EV are a more economical option than PV-powered EV but emit twice as much carbon. Nevertheless, high carbon taxes, higher feed-in tariffs and lower interest rates are all parameters that can make PV-powered EV more profitable. In every case, PV-grid power is always less costly than PV-battery power as single power source, but PV -battery power emits two-fold less CO_2 than PV-grid power. develops a detailed decision model to calculate the economic payoffs of investments in EV and/or PV technologies. EV/PV synergy is defined by the difference between net present value of an optimal EV/PV combination and the sum net present value of optimal investment in separated technologies. In the scope of managing a company fleet and electricity provision, the authors find a synergy of investment in EV or PV. The key parameter appears to be grid electricity price. Indeed, EV/PV synergy only exists in a specific grid electricity price range. Below the lower bound of this range, investing in EV only is more beneficial, while above the upper bound, it is better to invest in PV only. In a case study focused on Singapour, Huber et al. (2012) model an aggregator controlling a large EV fleet (up to 600,000 vehicles) recharge. The aggregator formulates a unit commitment problem in order to organize power generation of conventional plants with renewable energy sources and different ancillary services. EV charging is incorporated with different levels of complexity. Although the authors conclude that smart charging only has marginal effects on overall mix of CO_2 emissions, they also

show that it is crucial to cover the regulation power needed by strong PV capacity penetration. An increased EV share in the automobile fleet enables larger penetration of PV energy. For EV owners, smart charging reduces individual charging cost, as well as decreasing CO_2 emissions by 30%. In the US context, Denholm et al. (2013) plot prospective load curves for a power system with a large penetration of plug-in hybrid EV (currently outselling battery EV in the US) and PV capacities (up to 10%). Smart charging, synchronized with maximum PV generation times is evaluated by the peak load reduction and PV energy curtailment (due to over-generation). A 50% penetration of plug-in hybrid EV in the automobile fleet reduces curtailments by 5-6% and enables smart charging to add a further 1-2% reduction. Ghofrani et al. (2014) determine a collaborative strategy between PV energy producers and EV fleets. PV generation is scheduled in day-ahead with the system operator. The producer sends its generation forecast and is penalized depending on its error of prediction. V2G support from EVs allows producers to diminish their penalties. A particle swarm optimization algorithm uses the V2G capacity of an EV fleet to fill the gap between scheduled and actual PV power. Over a year, the authors penalties are reduced for PV producers by a factor of 2 to 10. Nevertheless, this strategy does not seem to bring any benefits to V2G participants, who are left to bear the cost of their own battery degradation.

Chaouachi et al. (2016) seek to maximize EV and PV penetration in a mid-sized city. Maximal penetration is defined by the distribution grid's technical limits. The authors develop a control strategy in a case study simulating a smart grid for a mid-sized city and find 64% more EV penetration and 18% more EV penetration compared to an uncontrolled charge, and 28% lower joint CO_2 emissions from transport and the power sector. Aachiq et al. (2016) investigate the large-scale effects of EV/PV couplings in households by extrapolating the results of a study of 51 Japanese households equipped with PV systems and EV. Based on a rule-based decision-making algorithm including optimization tools, the authors demonstrate a global cost decrease of 17% in the power system. Fattori et al. (2014) determine the effects of a large combined deployment of EV and PV (up to 2M and 620MWp, respectively) in a province of northern Italy. The authors consider three charging strategies (uncontrolled, controlled with V2G and controlled without V2G), and formulate a unit commitment problem in the

new electricity mix. They demonstrate beneficial effects in terms of peak load and ramping reductions.

Vithayasrichareon et al. (2015) run Monte-Carlo simulations to estimate the different determinants of joint EV/PV development in Australia. The simulations use inputs technology costs, fossil fuel prices and carbon price as inputs. The authors demonstrate that beyond a certain level of carbon tax (typically $\$50/tC$) and with a high EV fleet size, PV become economically viable in the electricity mix. Yan et al. (2016) study the behavior of an aggregator in two ancillary markets (demand-side management and outage management). 15000 EVs and 140MWp PV capacity are included into a distribution system composed of variable weather-sensitive zones. The demand-side management strategy is found to reduce 94% of the customer cost increase induced by weather changes.

At large scales, EV fleets can also interact with other renewable energy sources such as wind power. As EVs and PV capacities are aggregated at high level, aggregators or virtual power plant managers could include these supplementary capacities. Multiple studies have investigated the possible synergies of wind power and EV (Liu, Kong, Liu, Peng and Wang; 2015; Mwasilu et al.; 2014; Richardson; 2013), in which case EV/PV synergy seems less specific at these scales. Given their high electricity costs and their lesser energy security, islands would appear to be good candidates for EV/PV systems, but there are no island-specific studies on EV/PV integration to date, although the integration of EV in islanded power systems has received some coverage (Díaz et al.; 2015; Marrero et al.; 2015).

3.3 Technological environment of EV/PV systems

Some of the literature on systems with combined EV mobility and PV generation reviewed here also covers additional technologies. These technologies were either included in the system (*e.g.*heating system in buildings) or added to it (*e.g.*standalone batteries). When taken into consideration in the system smart control strategy, these technologies have a more or less essential role that is important to characterize in EV/PV systems. This section reviews the effects of adding technologies in EV/PV systems. The technologies considered in the selected literature span standalone-battery

ESS, heat-ventilation-air-conditioning (HVAC) in buildings, other energy sources (wind power, combined heat and power units...) and innovative network technologies (DC systems, solid-state transformers, reactive power control).

Electric storage systems

Standalone-battery ESS is an obvious technology option when it comes to distributed variable renewable energy. It allows a system equipped with variable energy capacities to increase its self-consumption. In the selected literature, EV/PV systems often incorporate an ESS as an additional flexibility source. We already pointed out that ESS can be beneficial in EV/PV systems, especially when EV charging demand and PV generation profile were uncoordinated or when EV demand was not flexible (Chaudhari et al.; 2017). A few papers give us some insights on the actual added value of ESS in these systems.

Zhao and Burke (2014) study the influence of adding an ESS in a PVCS. The authors maximize PV self-consumption using an optimization algorithm. Among their results, they show that the ESS could increase charging completeness and decrease overall grid electricity exchange by a factor of two. Alharbi and Bhattacharya (2016) build a PVCS architecture from several modules estimating EV arrival and charging need and maximal PV capacity and charger power respecting grid constraints. The authors then minimize the facility net investment costs. Operational functioning is designed to minimize the power losses of the PVCS. One of the main findings is that an optimal charging station with battery storage achieves a two-fold better ROI than a station only equipped with PV. Using the EV charging demand profiles of Islam et al. (2016) for PVCS as a comparison, the authors analyze the sensitivity of their strategy performance to a 50% decrease ESS and PV costs. Results show that as EV charging demand gets more desynchronized with the PV generation profile, the ESS cost reductions appears to get more advantageous to the EV/PV system than the PV cost reductions. Mouli, Bauer and Zeman (2016) study the influence of an ESS capacity on the performance of the smart control strategy of a building EV/PV system. The authors show that ESS efficiency decreases exponentially: 13% of the power grid reduction is achieved with a 10kWh capacity ESS capacity whereas the

maximal reduction is about 25% and is achieved with a 30kW ESS. Lu et al. (2014) co-optimize charging costs and ESS use (*i.e.*number of ESS discharges) for a DC PVCS with standalone ESS, and show how there is a trade-off between the two objectives. Disregarding ESS use leads to a 50% cost reduction while disregarding cost minimization lowers ESS energy use by up to 90%. As already discussed earlier, Figueiredo et al. (2017) study a PVCS from an investor point of view and shows a 58% profit loss on stationary storage due to its high investment costs. Nevertheless, as battery prices are expected to decline in the future, the authors find that delaying the ESS installation makes it profitable.

Heat-ventilation-air-conditioning systems

Heating, ventilation and air-conditioning (HVAC) accounts for more than half of building energy consumption (Lucon et al.; 2014). As a distributed energy resource, heat pumps are meant to play a role in smart grids (Protopapadaki and Saelens; 2017). Among other factors, their interaction with PV energy has attracted attention due to their peak shaving potentia (Fischer and Madani; 2017). While studying EV/PV systems, Alirezaei et al. (2016); Roselli and Sasso (2016); Salpakari et al. (2017); Zhang et al. (2012) considered additional residential heat pumps as part of the smart energy management scheme. In (Alirezaei et al.; 2016), building energy performance is at first optimized, so the influence of its thermal system on the EV/PV smart strategy is not visible. Along with smart control of household EVs, Salpakari et al. (2017) utilize a HVAC-optimized management strategy and ran comparisons against an uncontrolled case to review the performance of their EV charging and HVAC management separately. The optimal HVAC strategy only brings a 8-16% reduction in yearly energy costs, while smart EV charging only brings a 12-20% reduction. Then, combining the HVAC and EV strategies reduces the energy bill by 19-33%. In this case, HVAC and EV charging have comparable benefits when controlled smartly. Moreover, their performance seems almost additive, showing that one management scheme has little effect on the other. In (Zhang et al.; 2012), authors show that a large EV penetration could alleviate a high portion of PV curtailment. They simulate a similar scenario with as many heat pumps as EVs. Compared to the EV-only case, this new scenario

shows that the heat pumps enable a further reduction of curtailed PV energy. Heat pumps may have lower impact than PV, but seasonal heat pump patterns follow an opposite demand curve to PV profiles, with higher use of heat pumps in winter, which is why they offer an interesting potential complementarity with EV.

Other energy sources

We mentioned earlier that there have a big effort to investigate the combination of EVs with renewable energy systems in general, and especially interactions between EV and wind power. EV/PV systems studies have also included micro-CHP (combined heat and power) generators or small fossil-fuel generators. Micro-CHP units could have promising seasonal complementarity with PV energy. As CHP power depends on heat generation, its power is highest in winter, contrary to PV power. Micro-CHP units could show an interesting seasonal complementarity with PV energy. As CHP power depends on heat generation, its power is the highest in winter, contrary to PV power. Van Roy, Leemput, Geth, Büscher, Salenbien and Driesen (2014) study the energy management of a workplace equipped with PV and CHP units and an EV parking. It was not possible at first to discern respective effects of both technologies on the global system performance, because of the magnitude of the CHP power (one tenth of PV peak power) and its synchronization with PV power.studies the energy management of a workplace equipped with PV and CHP units and an EV carpark. It was not possible at first to discern the respective effects of the technologies on global system performance due to the magnitude of the CHP power (one tenth of PV peak power) and its synchronization with PV power. Small dispatchable electric generators are included in (Honarmand et al.; 2015) in a PVCS management study, as they can provide an additional energy source if grid power price is high enough or in an islanded mode. Wind power, as the other major renewable source for electricity generation, is often considered in tandem with PV energy (Liu, Kong, Liu, Peng and Wang; 2015; Mwasilu et al.; 2014; Richardson; 2013).The major differences with PV energy are that wind power generally peaks at night (Ackermann; 2005), and is generally part of large energy systems, which offer large flexibility needs and therefore only concern large coordinated EV fleets. In these situations, the EV fleet could charge with both

PV (in day charging) and wind energy (night charging). Nunes et al. (2015) present a comparison of charging strategy based on wind at night and PV at midday. The authors develop an energy scenario for Portugal with, among others, large deployment of PV capacities, wind power and EV fleets. They highlight that with a smart EV charging strategy, PV reduces curtailed renewable energy and CO_2 emissions better than wind.

Innovative network technologies

Some innovative features of electrical network components can be incorporated into EV/PV systems, namely DC networks, solid-state transformers, and reactive power exchange. While current power grids almost exclusively use AC current, low-voltage DC distribution grids are regarded as the appropriate framework for microgrids (Justo et al.; 2013) , on the grounds that they will mainly host DC distributed energy resources (like PV panels, fuel cells, batteries...). EV batteries run on DC current and are therefore equipped with an AC/DC inverter that causes the bulk of charging/discharging losses Apostolaki-Iosifidou et al. (2017). DC systems should therefore be beneficial to EV/PV systems. Lu et al. (2014),ElNozahy and Salama (2015) and Byeon et al. (2013) also studied EV/PV systems in DC networks, but made no comparison with AC networks. Kineavy and Duffy (2014) show that for a small PVCS using a smart charging strategy, a DC system increases energy efficiency of EV charging from PV panels by 5%. DC networks would intuitively be useful in larger EV/PV systems using V2G technology. Vagropoulos et al. (2014) show that within a DC EV/PV system, revenues are increased by 0.5-1%.

4 Economic context of EV/PV systems

In the literature describing technical features of EV/PV systems, economic aspects are mostly taken as fixed parameters (pricing, forecasting errors, drivers' behaviors...). This is consistent with the technical-economic approaches used, but it misses several issues that seem crucial for characterizing the full potential of EV/PV synergy. First, the practical realization of such synergy remains tied to the willingness of several

agents to cooperate, especially when EV/PV coordination comes at some cost. These costs include investments for the energy management system hardware enabling smart control strategies, but also learning and transaction costs. Such requirements can be related to the well-known economic concept of the "energy efficiency gap", where technical energy efficiency is held back by a series of non-technical barriers (Jaffe and Stavins; 1994). Therefore, the economic context of the development of EV/PV coupling warrants careful analysis. Keeping this is mind, we re-reviewed the EV/PV systems literature through the lens of economic interactions and conditions (the right side of our systematic framework in Figure 1).

This section reviews mutually beneficial strategies in EV/PV systems and between EV/PV systems and power grids (distribution and transmission). We then discuss regulation and policy issues that promote EV/PV synergy. As the selected literature does not address these issues directly, we will interpret it in order to address those questions.

4.1 Economic behaviors inside EV/PV systems

Several agents can share the ownership of an EV/PV system. Two possible cases of cooperation can be distinguished. First, where EV drivers interact with a charging station equipped with PV capacities (PVCS). Second, where an EV aggregator (*e.g.*company fleet manager or charging station manager) contracts with a PV energy producer. As we saw in the section on technical aspects, these EV/PV systems are located in intermediate spatial configurations (buildings and charging station) where synergistic potential was highest. How cooperation will happen at these levels is therefore crucial. After presenting how cooperation is described in the selected literature, we will review these two cases of cooperation.

Cooperation in smart strategies

To enable a smart control strategy, cooperation between participants in the EV/PV system is often required. Smart control strategies have introduced implicit methods that take such behaviors into account. The issue of control mode has been widely

studied in new energy systems with cooperative and non-cooperative game theory approaches (Camarinha-Matos; 2016; Saad et al.; 2012) and agent-based models (Ringler et al.; 2016). This literature has mainly studied distributed generation and storage, as in (Atzeni et al.; 2013), but could readily be applied on EV/PV systems. When an EV/PV system control strategy uses such methods, it typically seeks to optimize its own objective function, along with that of another agent. The most common multi-objective method is the weighted-sum method. For instance, let us consider two agents in EV/PV systems with objective functions X_1 and X_2. Without cooperation, each agent defines its strategy by maximizing (or minimizing) its own objective function independently from the other agent. With cooperation, the agents agree to define their strategy by maximizing (or minimizing) $w_1X_1 + w_2X_2$. As pointed out in (Dai et al.; 2015), w_1 and w_2 can be interpreted as the decision-maker's preference towards the related objective. Alternatively, this method can be interpreted with game theory. By posing $W_i = \frac{\alpha_i}{\underline{X_i}}$, this problem can be considered as the linearized Nash bargaining solution in cooperative games theory. The following Nash bargaining problem would be to maximize $(X_1 - \underline{X_1})^{\alpha_1}(X_2 - \underline{X_2})^{\alpha_2}$ under both constraints of agents 1 and 2. In this framework, α_i and $\underline{X_i}$ can be interpreted as the agents' bargaining power and non-cooperative payoff (Binmore et al.; 1986). Of course, weighted-sum method can be extended to multiple objectives without loss of generality. A Pareto frontier is the optimal solutions set defined by all the combination of w_i. An alternative method is the $\epsilon-$constraint multi-objective optimization, as used in (Zakariazadeh et al.; 2014). As it less easy to interpret in terms of cooperation and much less used than the weighted-sum method, we do not expand on this method. Cooperation between agents requires a value sharing scheme. This issue has been practically unaddressed in the selected literature, the only exception is (Zou et al.; 2015) where a Shapley value method is used in a cooperative game theory model to distribute the total benefits from the EV/PV synergy. More generally, the literature lacks analysis of the business models.

Cooperation between EV drivers and a PV charging station

An issue raised by studies in the framework of PVCS is cooperation between PVCS managers and EV drivers. Indeed, if uncontrolled strategies at least satisfy drivers'

charging needs, efficient smart charging requires basic input from EV drivers, who should renounce some of their charging needs. A driver may be relatively flexible on their mobility needs, environmentally friendly, or willing to participate in power system stabilization [3]. Hence, charging station managers need to incentivize drivers to make a trade-off between their own needs and the PVCS needs. In the literature, no behavioral assumptions were made on EV drivers in terms of reactions to incentives to cooperate in EV/PV systems. Beyond the technical-economic nature of the selected literature, this point remains largely unaddressed as there has been no attempt to characterize the typical behavior of EV drivers.

Liu and Cheng (2017) point out the importance of EV driver preferences for their charging needs. From a PVCS investor's perspective, the authors simulate a smart control strategy in two scenarios where EV drivers expect the PVCS to handle all or only half of their charging needs. The PVCS operates with a rule-based decision-making algorithm that prioritizes vehicle recharge according to parking duration and aims to maximize PV self-consumption. Results show that full charging service leads to operator's profits that are almost fifteen times higher than when drivers' demand is only half of their charging needs.

Tushar et al. (2016),Liu et al. (2016) and Zou et al. (2015) define several charging modes at different tariffs, and each time the users who require charging need to indicate a departure time to the PVCS. In (Liu et al.; 2016) and (Zou et al.; 2015), there are two types of mode: premium and general. Premium mode offers maximum charging power at high tariff while general mode follows the PVCS smart control strategy to define power delivered to the EV. Tushar et al. (2016) define a more detailed business model proposing three types of mode: premium, conservative and green. Premium mode offers maximal power at the highest price. Conservative mode offers slightly but not significantly cheaper charging than premium. Green mode only ensures that the driver's selected state of charge is reached at departure time, and in the meantime the PVCS can freely organize the charging schedule of the green EV. In return, the tariff offered is 15% lower than the premium tariff. Green mode also allows the PVCS to use

[3] On the issue of willingness of of EV and PV users to create flexibility, Kubli et al. (2018) provide an interesting first study

the vehicle's V2G capacity as desired, in exchange for remuneration to the EV owner (here at 85% of the green tariff). Green mode can be interpreted as a cooperative behavior from EV drivers. The only drawback for the green-mode driver is that if he decides to leave before his indicated departure time, his state of charge may be even lower than when he first plugged. Committing to the indicated departure time is therefore a form of additional cooperation with the PVCS. The authors' simulations ultimately show a cost reduction of around 48% for green users compared to premium and conservative users. For the PVCS, a 100% proportion of green drivers leads to an 80% reduction in total operational cost.

Zhang et al. (2016) propose an alternative way to promote cooperation between drivers and the PVCS to maximize PV energy utilization. It defines a "solar-friendliness index" for each driver that measures the correlation between the power consumed by the EV driver for charging and the PV generation profile. A queuing algorithm is then used to organize the charging of a set of EVs based on their solar-friendliness index. As discussed earlier, Tulpule et al. (2013) address the issue of trade-offs between PVCS owner revenues and EV driver costs of charging in the PVCS. Indeed, a PVCS owner has the dilemma of whether to raise its parking fees to improve its profitability. On the other hand, if the parking fees are too high, the EV owners will prefer charging at home or somewhere else. The authors show, using a parametric analysis, that payback time appears to be concave with parking fees, meaning that the marginal benefits of increasing the fees decrease. The authors are able to determine a maximal parking fee against the charging costs of uncontrolled home charge at night. Figueiredo et al. (2017) test different customer tariffs for a PVCS and shows that a flat fee (*e.g.*monthly fee with unlimited free power for EV in the month) is much less profitable than a power-based fee.

As already discussed in (Kuang, Chen, Hu and Yang; 2017), finds that benefits of the defined collaborative strategy depend on building types. Moreover, the authors show that the driver's behavior has a major effect on the optimization of building energy costs. Typically it is shown that long and day-time availability of EV is not always a necessary condition for reaching the best strategies. For instance, a short duration of availability fits best for a small hotel. In this case, the smart control

strategy cuts total costs by 18%. Moreover, optimal energy needs for charging vary across building types from 20% to 70% of the vehicle's state of charge.

Along with these papers, the literature on EV/PV interactions lacks a proper realistic study on PVCS tariffs from both the station-manager's and power-user's perspective.

Cooperation between an EV aggregator and a PV energy producer

An EV aggregator manages the charging of an EV fleet. It is typically a charging station manager, or a company fleet manager. It can contract with a PV energy producer to form an EV/PV system.

When it comes to designing a coalition of cooperating agents, it is important to assess the optimal dimension of this coalition. Latimier et al. (2014) seek to determine the best sizing possible of a collaborative EV/PV system. The system is defined by a coalition of an EV aggregator and a PV energy producer. The authors found that the added value of an EV/PV system depends strongly on the ratio of the average aggregated vehicle capacity to the peak power of the PV energy producer. They find a clear space of this ratio that makes the collaborative system globally profitable, but the length of this space is strongly dependent on PV generation forecast.

Zou et al. (2015) studies a cooperative game theory model where the charging station and PV capacity owners are different agents. In the non-cooperative case, the PV producer sells its power to the grid, and the charging station also buys power from the grid. The authors then propose a cooperative scheme that brings the two entities into one coalition that maximizes the overall profits. Total profit is then shared according to the Shapley value method. Cooperation ultimately raises total profits by 20%.

Kuang, Hu, Dai and Yang (2017) tackle the cooperation issues between a workplace building and a charging station. The building energy system includes solar panels, a fixed battery, workplace load, and a heating system. The charging station is equipped with PV panels. The authors compare the cases without cooperation (separated optimization) and with cooperation. Without cooperation, both parties optimize their cost independently. With cooperation, the authors formulate a multi-

optimization approach with a weighted-sum on each agent's costs (as described in section 4.1.1) and plot the resulting Pareto frontier. The optimal weighting for the global system leads to a cost decrease of 22%. It is interesting to note that global optimum is not the optimum for either agent. For the building owner, global optimum leads to 23% higher costs compared to its own optimum, while for the charging station, costs are 16% lower at its own optimum compared to the global optimum. Note too that the building optimum leads the charging station to a worse outcome than in a non-cooperative strategy. As stated in 4.1.1, weights can be linked to bargaining power in the negotiation. These results show that it is vital to share the benefits of cooperation fairly.

4.2 Interactions between EV/PV coupling and power grids

In the previous section, we reviewed collaborative schemes that would enable EV/PV synergy. Nonetheless, both EV and PV are constrained by their environment, *i.e.*distribution and transmission power grids. Integration of electric mobility in these grids has been widely studied in the literature (Codani; 2016; García Villalobos; 2016), and benefits of collaboration between EV entities (driver, aggregator...) and grids have been demonstrated. Here we address the issue of the integration of EV/PV coupling in the power grids.

Interaction with distribution grids

The purpose of distribution systems is to bring electricity from transmission grid to end-users. Therefore, Distribution System Operators (DSO) design distribution grids and organize investments in grid reinforcements in order to optimize power distribution. These heavy investments in equipment are made to cover several decades. Regulation is then designed to remunerate the DSO on the basis of its costs. As EV and PV units are generally directly connected to the distribution grid, the combined effects of EV and PV should be the most visible there. To study the impact of EV/PV coupling, we start by recapping the individual effects of each technology on the distribution grid, then analyze how beneficial the coupling could be.

Pérez-Arriaga (2014) provide an overview of the technical and economic effects of distributed generation on the distribution grid. Technically, PV generation in distribution grids leads to trouble in grid operations (with congestion and over-voltage issues) and difficulties in maintaining power quality (with increased harmonics) and keeping power losses low (losses are proportional to power variations). For the DSO, this results in additional grid upgrading and missing revenues at short and medium terms. As Eid et al. (2014) point out, any additional costs for the DSO will drive distribution fees up, which under current regulations will mean higher costs for non-PV users while PV users are not paying their fair share of the impacts on the grid. EV create much the same technical issues: more difficult grid operations (phase unbalances, over-voltage, congestion), worse power quality (harmonics), and higher power losses. EV impact is strongly dependent on charging power (from 3kW at home to 50-150kW with fast chargers) (Codani; 2016).

As an effect of EV/PV synergy is to increase the system's self-consumption and reduce grid power imports, wealth transfers should logically be reinforced. Nonetheless, EV charging could create the reverse effect. As an EV substantially raises the owner's power consumption, the DSO's revenues could be increased. These new revenues could offset the DSO's missing revenues due to PV self-consumption in the grid. To our knowledge, the resulting trade-off and the appropriate network tariff designs have not yet been investigated.

Knezović et al. (2017) distinguish EV services in distribution grids between load services (congestion management and power loss reduction) and voltage services (magnitude regulation and unbalance reduction). A part of the EV/PV coupling literature deals with improving its integration in distribution grids by diminishing its grid stress. Although this literature is mainly technical, it underlines the beneficial effect of EV/PV coupling on distribution grids.

Local peak load has to be firmly controlled in order to stabilize the grid. Some authors have studied local solutions for smoothing load curves (Mahmud et al.; 2016). Due to the high initial cost of a transformer (millions of euros), DSOs have to be very watchful of transformer aging. Congestion problems at transformer level (provoked either by PV or EV) tend to shorten transformer lifetime, which erodes the profitability

of the investment. (Dang et al.; 2015; Gray and Morsi; 2017; McBee; 2017; Santo et al.; 2017) develop strategies for an EV/PV coupling to fulfill charging requirements and self-consumption with a softer impact on the transformer. Lagares et al. (2011) propose a smart strategy based on technical constraints that aims to smooth EV/PV-coupling stress on the distribution grid. A smart strategy manages EV charging to better synchronize PV and EV profiles, which leads to a smooth transformer load curve. Voltage-driven EV charging can avoid overload issues and serve a larger number of EV. Smoothing the curve leads to lower power losses as there is less power variation and a lower current peak.

A decentralized method of smart control strategies is to measure directly voltage profile of the system, in order to schedule EV to smooth it (Knezović et al.; 2014; Yang et al.; 2016), which results in less power losses in the grid (Gandhi et al.; 2016). Gandhi et al. (2016) is one of the rare studies to consider technical-economic aspects like exchanges of reactive power between EVs, PV systems and the distribution grid. The authors' method leads to a 50% decrease in power losses in the grid, but only a 3% decrease in costs for the EV/PV system. Gandhi et al. (2016) and Zhang et al. (2017) inject EV reactive power into the system, as it does not cause damage to the EV battery. Tovilović and Rajaković (2015) point out that there may be limits to the benefits of an EV/PV system for the distribution grid. The authors provide a technical study of the EV/PV system effects on several aspects of power quality (voltage profiles and harmonics/voltage distortions). They show that joint effect of PV and EV can reduce the load while improving voltage profiles on the grid, but does not really improve power quality (harmonic distortions).

For larger scales, Yan et al. (2016) and Islam et al. (2016) suggest that EV/PV synergy would be particularly beneficial in weak parts of the distribution grid, and could alleviate the need for distribution grid reinforcements. Nonetheless, it could also require specific contractual cooperation between DSO and EV/PV system manager. In a study on a PVCS system, Islam et al. (2016) consider a grid in which grid strength (based on voltage magnitude) differs across areas. Results show that the influence of a smart strategy is even more beneficial in the weakest areas of the grid. Indeed, high power flows due to EV charging and PV power cause higher losses in a weak

grid area, and maximizing self-consumption in this area manages to improve EV/PV system efficiency. This result offers a DSO's a strong rationale to promote smart control strategies in EV/PV systems. Yan et al. (2016) study coordinated EV and PV strategies in a distribution system focused on demand-side management and outage management. The distribution system faces weather change, and risk is diversely distributed in the fed zones of the grid. The demand-side management strategy appears to be more efficient in the riskiest part of the grid, where costs were reduced by more than 94%, whereas cost reductions in the safest parts of the grid were in the range 76-90%. Figueiredo et al. (2017) show that allowing voltage support from the PVCS (with a regulation price of 25.6/MW/h) increases PVCS profits by 27%. As pointed out earlier, novel power grid components like solid-state transformers or DC microgrids are well geared to EV/PV systems, and as they offer a valuable solution for distribution management, DSOs could be tempted to install them, which would indirectly create an incentive to exploit EV/PV synergy.

We can see through the literature that an EV/PV system can interact with distribution in a mutually beneficial way. There are obvious technical advantages for the grid, but the literature lacks a quantified study of these benefits. Recognition of this systemic benefit should influence the potential regulation for EV/PV systems in terms of entry conditions, pricing, etc.

Interaction with transmission grids

EVs can provide services to the transmission system, mainly frequency regulation and peak load mitigation. Large penetration of intermittent and variable power like PV brings the opportunity for EV fleets to contribute by smoothing the PV generation at large scale. The first issue is control of the global load curve. In many regions, PV generation peaks during low demand periods and is low during high-demand periods. As PV capacity increases, this leads to high power ramps in mornings and evenings, called the duck curve (Denholm et al.; 2015), and large penetration of commuter EVs that charge during the evening would increase this effect. Denholm et al. (2013) study a duck curve effect added by a large EV fleet charging and shows that a smart charging strategy displacing all EV loads from the global peak load could diminish it by up to

8% with 10% PV.

Zhang et al. (2017) present a method for designing a cost-optimal locations and capacities planning scheme for EV charging stations and PV plants in a territory. With a case study considering a transmission grid including 200,000 EVs charging in around 35 charging stations and 5 PV plants with a total capacity 90MWp, the authors show that PV energy managed to reduce the EV impact on the grid, thus enabling substantial deferral of investments.

In (Ghofrani et al.; 2014), PV producers are penalized for their forecasting errors. Penalties are defined by the product of the real-time electricity price, forecasting error, and a penalty factor that varies between three deviation band errors. We already saw that the EV/PV coupling could reduce PV power imbalances by a factor of 10 and penalties by a factor of 15. Moreover, an interesting sensitivity analysis is made over forecast accuracy. Transmission system operators would rather deal with participants with good prediction accuracy and low forecasting deviations. A smart strategy would erase total penalties in an even more efficient way when forecast error is low. Nonetheless, more money is saved when forecast error is high. Moreover, with an uncontrolled strategy, total cost penalty over accumulated forecast error is not dependent on the accumulated forecast error, whereas with the smart strategy, it increases quickly. Therefore, once a smart control strategy is used, it helps get the smallest forecast error. In (Mouli et al.; 2017), authors compare the different effects of allowing a PVCS to trade energy and offer reserve service with and without V2G. They show that without V2G, once reserve services are offered, trading energy on the power market brings comparatively little advantage. On the other hand, once V2G is enabled, trading energy becomes much more interesting. Another issue to be investigated is the possibility of competition between the participation of EV in ancillary services and in the EV/PV synergy. Generally, frequency regulation is needed most when the transmission system is facing sudden large variations, such as during the daily peak load. Our insight is that the correlation of peak load with peak PV generation is an important factor for assessing whether EVs can participate in frequency regulation while profiting from synergy with PV energy. This case of conflict can be related to those identified in (Zecchino et al.; 2017) between TSO and DSO services.

On the other hand, frequency markets are likely to be quickly saturated as soon as there are millions of potential EV participants. As PV stabilization needs will keep on increasing, this hypothetical competition issue may be irrelevant in the long run.

4.3 Regulations and policies for efficient EV/PV coupling

The earlier sections showed that EV/PV synergy holds strong cooperative potential and could reduce the total costs and respective impacts of both technologies, and even help stabilize the power system at both distribution and transmission. In power systems, regulation and policies have a huge impact on technological development. Recent studies show that regulatory and policy components have a prominent influence on distributed energy business models (Burger and Luke; 2017), as for the electric mobility development (Vazquez et al.; 2018). This makes it crucial to identify the appropriate regulatory and political tools and frameworks to efficiently exploit the potentialities of EV/PV coupling. To our knowledge, only (Popiolek and Thais; 2016)provides a framework for analyzing policies to promote solar-powered electric mobility. Such policies, like carbon taxes, are not necessarily specific to EV/PV synergy (Vithayasrichareon et al.; 2015).

Pricings

It is generally accepted that dynamic pricing leads to better economic efficiency, particularly in demand response studies (Schreiber et al.; 2015) that give a more realistic picture of the different costs. In our literature, (Vagropoulos et al.; 2014) provides a comparison of the efficiency of an EV/PV system with different tariff structures. The authors find that revenues of an EV/PV system are increased by 0.5-1% with dynamic tariffs compared to flat tariffs, while power losses decrease by 10-20%. Kaschub et al. (2016) study the effectiveness of different electricity pricings on the profitability of a PV-ESS system for German households. First, the high price of electricity in Germany makes investments in self-consumption more profitable. Then, the authors study different network tariff designs, which account for 22% of the electricity price in Germany. These tariffs are a base-rate volumetric tariff and the following alterna-

tive tariffs: a fixed charge, a maximum peak load tariff, and a tariff combining the two. The authors find a comparable decrease in net present value of the installation for all impacts between the alternative tariffs and the volumetric tariff. Nevertheless, this decrease in net present value is mitigated by a smart charging strategy for EVs. In addition, the authors find that time-of-use tariffs do not significantly improve the performance of the smart EV control strategy.

Entry conditions

Regulation of the power system needs to adapt to facilitate the spread of new technologies (distributed renewable energies and information and communication technologies) (Pérez-Arriaga et al.; 2017). Regulation reforms need to be designed to encompass lots of factors yet with dynamical architectures. The EV/PV literature has rarely addressed regulatory reform formally addressed, but we can tease out some insights for appropriate regulation tools.

The literature has often singled out a new actor, the aggregator, to jointly manage EV fleet charging and distributed PV generation. Burger et al. (2016) define the different types of aggregators in evolving power systems. The authors distinguish fundamental, transitory and opportunistic values of aggregation. A fundamental value comes from intrinsic economies of scale of the aggregator services. A transitory value is an aggregator service that could potentially be replaced by appropriate regulation. An opportunistic value comes from inefficient or inappropriate regulation, and is more likely to disrupt the power system rather than help it. EV/PV aggregators require a new regulation geared to whether they operate at transmission level (frequency regulation) or at distribution level. Aggregated EV/PV systems in energy and ancillary markets require new regulation at both transmission level and distribution level that include all distributed energy resources. The entry conditions of such systems should be similar to those required by EV aggregators in order to participate in those markets. The frequency market is thought to be the most realistic market for EVs involvement (Borne et al.; 2018). For many countries (France, USA), this would require a deep reform of energy markets design (Borne et al.; 2018). Nonetheless, allowing an EV aggregator to contract with a PV power station to lower its forecast error could be an

alternative and/or complementary solution with EV participation in ancillary markets.

We saw that EV/PV coupling could be particularly beneficial for the distribution system and its operator. EV/PV systems in households, buildings and charging stations may have barriers to entry, as the site manager is in charge of the power system for this spatial configuration. For larger configurations, there is not yet any framework enabling DSOs to contract flexibility services (Eid et al.; 2016). Knezović et al. (2017) propose a regulation framework and a road-map for EV integration in distribution systems.

Support mechanisms

Feed-in tariffs and other subsidies are commonly used by governments to stimulate PV technology development, while EV is also heavily subsidized in many countries.

By taking different levels of FITs, van der Meer et al. (2016) show that EV/PV coupling gets more efficient with lower FITs. Indeed, high FITs incentivize PV capacity owners to sell their whole output to the grid instead of cooperating with an EV fleet, which would then have to charge exclusively via the grid. Mouli, Leendertse, Prasanth, Bauer, Silvester, van de Geer and Zeman (2016) show that low FITs make it more profitable to invest in PV and EV than PV and petrol.

In a Belgium context, De Schepper, Van Passel, Lizin, Vincent, Martin and Gandibleux (2015) use a multi-objective framework (investment costs and ecological footprint under the constraints of transport and power needs) for company transport fleet and power system in Belgium. The authors plot the Pareto of combined-technology investments as a function of life-cycle CO_2 emissions and either initial required investments (bounded rationality) or life-cycle economic cost (complete rationality). They show that without subsidization, there is a clear trade-off between economic (classical vehicle and grid electricity) and ecological (EV and PV electricity) options. Applying the current government subsidies on both PV and EV makes the EV/PV coupling both economically and ecologically optimal for an investor with complete rationality, but not so (or less so) for an investor with bounded rationality. In a similar way, Figueiredo et al. (2017) study the influence of investment subsidies on the payback time of a PVCS. And finds that payback time decreases linearly with level of

subsidization, from 14 years without subsidization to 6 years with a 50% investment subsidy.

Synergy between EV and PV raises an issue for the efficiency of public policy. Many countries subsidize both technologies but their policies rarely consider the synergy between them. The efficiency of policies combining separate subsidies thus seems debatable, especially as the two technologies are increasingly likely to be acquired jointly, as pointed out in (Delmas et al.; 2017). It is equally possible that subsidizing features of the EV/PV synergy, such as PVCS, smart buildings, or energy management systems, would be particularly efficient for both EV and PV development. Either way, this issue warrants more detailed investigation.

5 Conclusion and recommendations

The forthcoming energy transition should bring complex technological systems in which the component technologies develop interdependently. The nature of these interactions and the understanding of their technical and economic determinants will influence the pace of transition towards more sustainable industrial systems. This paper focuses on one of these links between two apparently independent but effectively synergistic technologies: electric mobility and photovoltaic generation. These EV/PV systems were described in detail based on a thorough literature review.

We showed how one technology could benefit from the other. This synergy has been analyzed in a framework differentiating EV/PV systems in terms of three core components: smart control strategy, spatial configuration, and technological environment. Our analysis finds it difficult to emerge a general effect of EV/PV synergy on both technologies' lifetime costs due to the many and diverse influencing parameters. A specific study is needed.

We then investigated the economic context of EV/PV synergy. Although the literature that we reviewed was mainly technical, we managed to tease out insights on how EV/PV is reinforced by cooperation between technology owners inside EV/PV systems, on mutually beneficial interactions between EV/PV systems and power grids (transmission and distribution), and on appropriate regulations and policy.

Our systematic framework allowed us to deeply explore the main aspects of the constellation of EV/PV couplings. In particular, it helped us to address economic issues that were poorly studied in the literature. We anticipate that this framework can usefully serve to analyze other systems where several technologies meet. For instance, it would be possible to apply this framework to the articulation of power generation technologies with heat systems (*e.g.*PV and combined heat and power) or with other transport systems (*e.g.*biogas or hydrogen-powered vehicles). In addition to the technical aspects and economic context of a smart grid system, this framework could include the equally vital social acceptance aspect (Wolsink; 2012).

This review led us to emerge as-yet-unanswered questions that warrant further investigation. First, the literature we reviewed is unable to indicate a realistic typical decrease in lifetime EV costs in a territory covered by EV/PV systems. Second, the issue of cooperation between stakeholders involved in EV/PV systems still needs clarifications. In particular, the various participant behaviors that would enable EV/PV synergy (transaction costs, reaction to pricing incentives, and so on) requires a precise study. Along with this, the sharing of the added value of the synergy between system participants remains a key issue. In practice, it requires knowledge of the appropriate business models best suited for the car industry to incentivize car owners to adopt smart charging. More generally, the regulatory and policy context is likely to favor the deployment of some of the technical aspects of EV/PV systems over others. In particular, spatial configuration and technological environment seem very sensitive to economic context. This issue should therefore be studied. Also, the combined effect of EV and PV integration in a distribution grid on the operator's revenue is another crucial issue that warrants investigation. The natural extension of this issue would be to determine which tariff design would be appropriate for a distribution system with joint EV and PV systems. Finally, as both electric mobility and photovoltaic generation are subsidized separately, public policy could be made more efficient by accounting for their synergy. It is time to define a practical regulation policy that specifically targets this synergy.

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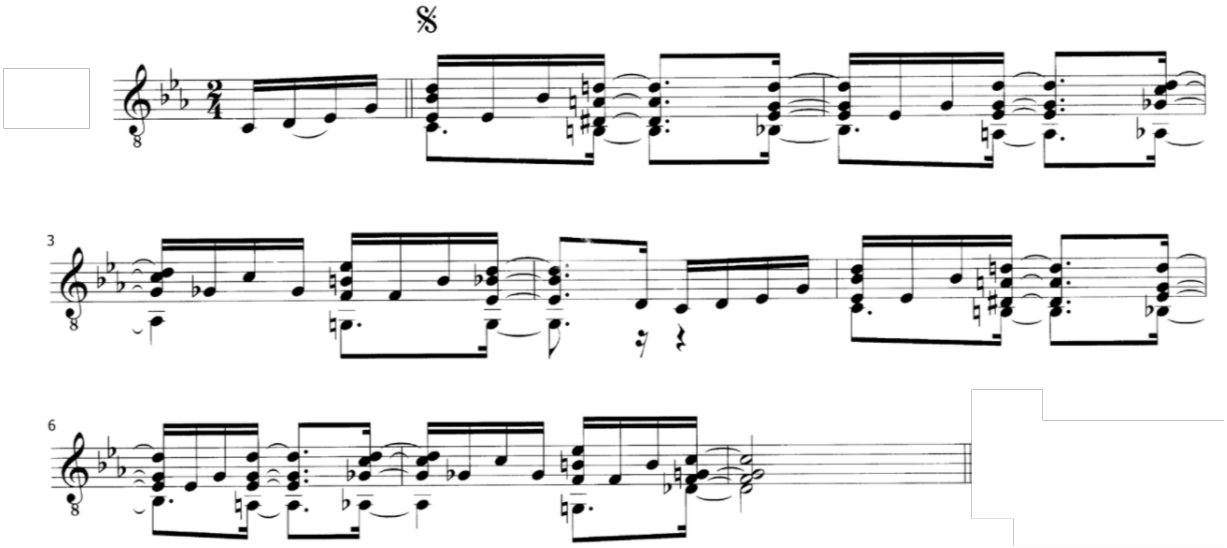

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Chapter 5

Network tariff design with prosumers and electromobility

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Distributed Energy Resources (DERs), mostly in the form of solar photovoltaic (PV) or lithium-ion batteries, and electric vehicles (EVs) are emerging as three disruptive innovations in power grids. Recent studies have pointed out the potential synergies between these technologies, while others have studied the difficulty to design adequate network tariff when consumers can adopt DERs. In this paper, we fill gaps in both strands of the literature by investigating the combined effect of DERs and EVs on tariff design. To study these effects, we use a bi-level model that captures the conflict between a regulator and the network users. In the lower level, prosumers can react to tariff changes by installing DERs and adapting their EV charging. In the upper level, the regulator designs network tariffs by enforcing the total grid costs recovery and anticipating the prosuming behaviors of network users. We study the tariff variations with different levels of EV penetration level and prosuming. The influence of the tariff structure is also investigated. First, we found that the increase of network charges caused by DERs can be balanced by the diffusion of EVs in the network. Second, we highlight that EVs adoption and DERs adoption are conflicting through the network tariff design. Third, we found that the more a tariff structure gives incentives for DERs, the less advantageous it is for EVs, and vice-versa.

* * *

1 Introduction[1]

The power sector faces deep transformations, motivated by environmental reasons and led by disruptive technologies. Within these transformations, energy self-supply and electrification form two of the main trends. On the one hand, distributed generation and storage allow some consumers[2] to produce and self-consume electricity with flexibility. On the other hand, the electrification of sectors (transport, heating) should significantly increase consumers' power consumption. To this regard, solar photovoltaic (PV) and lithium-ion batteries for the first trend and electric vehicles for the second are the main representative technologies. Indeed, both solar PV and lithium-ion batteries have had a spectacular decline in costs (IEA; 2018; Schmidt et al.; 2017). Simultaneously, solar PV and EVs have been supported by strong public policies and regulations (IEA; 2018; MIT; 2015).

In this context, the traditional organization of grids is being moved by these new technologies and network uses. This paradigm shift of electricity use is challenging the current economic rules of power grids, with fears of system efficiency losses and fairness matters between consumers (Eid et al.; 2014). Nevertheless, smart association of these new technologies should bring economic gains for users as for the power system (Hoarau and Perez; 2018; Richardson; 2013). Therefore new regulations are needed to cope with this issues while ensuring a well-functioning power system. Among these, the design of network charges is a particularly crucial issue (Pérez-Arriaga et al.; 2017).

This paper investigates the tariff design of low-voltage distribution grids with high levels of DERs (solar PV and batteries) and electric vehicles (EVs), which is still a rather unexplored issue in the literature (Pollitt; 2018). More precisely, it studies the interactions of the behavior of active prosumers that are able to invest in distributed energy resources (DERs)[3], with the adoption of electric vehicles that significantly increases the electric consumption of their owners[4]. The tariff design

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[2] In this paper, such consumers will be designated by the term *prosumers*.

[3] By investing in DERs, prosumers may seek to minimize their electricity costs and are hence able to react to changes in network tariffs

[4] For instance, (Andersen et al.; 2017) has shown that for an household from the EU, charging an electric vehicle at home can increase power consumption almost by a factor two.

process is modeled as a non-cooperative game between various classes of network users and a regulator who enforces the network cost recovery. Numerical case studies are conducted with different penetration scenarios of EVs and DERs and different tariff structures. The impacts on network tariffs of increased proportions of prosumers and electric vehicle owners in the network with different tariff structures are investigated. We describe precisely how network costs are shared between the different users. Along with this, we provide evidences of conflicts between DER adoption and EV adoption through the grid costs recovery enforcement by the regulator. These conflicts generally translates into either cross-subsidy from EV owners to prosumers or by decrease of the profitability of DER investments. Also, we determine how tariff structure drives those conflicts. We found that the more a tariff structure gives incentives for DERs, the less advantageous it is for EVs, and vice-versa. In addition, the appendices of this paper provide results on the robustness of the previously described mechanisms to (1) alternative tariff structures and (2) variable components in the grid costs structure.

The paper is organized as follows. First, the motivation of these research questions are presented with a literature review on three related research topics. Then, the modeling framework and the assumptions of the associated simulations are described. Results are presented on section 4 and discusses (1) the impact of EV and prosuming on tariff design, (2) the spillovers between EV and DER adoption through tariff design. Last section concludes the paper and discusses policy implications of this study.

2 Literature review

The contribution of this paper is at the intersection of three strands of literature. The first body of literature deals with designing network tariffs when grid users acquire DERs. The second one studies the integration of EVs in power grids. The interaction between electric vehicles and DERs constitutes the third body of literature. In this section we briefly present these three bodies, and we review the elements of modeling needed to study the interactions between tariff design, electric mobility and prosuming.

Volumetric tariff with net-metering have been the traditional way of recovering distribution network costs. However, many scholars have evidenced that under such

tariff structure, DERs and especially solar PV, leads to inefficiencies and fairness issues between network users (Eid et al.; 2014; Jenkins and Pérez-Arriaga; 2017; Simshauser; 2016). Indeed, prosumers become able to react to electricity prices to minimize their bill by investing in solar PV. With a volumetric with net-metering tariff, they save on energy costs as well as network costs. At some point, this should lead to threaten the financial balance of network operator. To prevent this, regulators would have to increase tariff levels and this for all users. This results in an increase of passive users' bill and hence a sensible fairness issue between network users. Numerous studies have investigated alternative tariffs that would integrate solar PV both efficiently and fairly. For instance, (Simshauser; 2016) has argued that capacity tariffs should remove the over-incentives on solar PV brought by volumetric tariffs. However, adoption of low-cost lithium-ion batteries could also create similar fairness and efficiency issues (Brown and Sappington; 2018; Kubli; 2018; Schittekatte et al.; 2018). This strand of literature mainly focus on tariff design with technologies that allows users to reduce their consumption (energy or peak power). However, no study has considered adoption of technologies that would significantly increase power consumption of users, such as electric vehicles.

Although EVs represent a potential huge source of revenues for electric utilities (Kempton and Letendre; 1997), numerous studies have pointed out that a disorganized deployment of EVs in power grids could severely affect the stability of networks[5] and hence increase network total costs (Clement-Nyns et al.; 2010; Fernandez et al.; 2011; Muratori; 2018; Verzijlbergh et al.; 2012). Nevertheless, such effects are dependent on the robustness of the network (Neaimeh et al.; 2015). Moreover, the flexibility of the EV battery provides a wide range of options to mitigate these impacts on grids, thanks to so-called smart charging strategies (García Villalobos; 2016). Assessing the economic and regulatory incentives to make EV drivers and fleet managers to such uses is therefore a crucial issue for efficient integrations of EVs (Eid et al.; 2016; Knezović et al.; 2017). Among these regulations, electricity prices can give strong incentives to adopt smart charging. Network tariffs can therefore play a significant role in this, that

[5]Typical effect of massive uncoordinated EV charging in distribution network are increased power loss and reduction of transformers lifetimes.

yet needs to be described. We contribute to this research field by assessing how the electricity costs of EV owners vary with the network tariff design and how large EV development could affect the tariff design.

Finally, we contribute to the literature on the interaction between EVs, solar PV and distributed storage, which has gathered much attention recently (Hoarau and Perez; 2018; Richardson; 2013). This research topic is motivated by the following reasons. Electric vehicles need low-cost power for charging and require a low-carbon energy to have a significant environmental advantage against internal combustion vehicles (Doucette and McCulloch; 2011). PV generation needs flexible storage to face its variability and intermittency. Moreover, local PV generation could alleviate electric vehicles' impact on power grids (Islam et al.; 2016). Nevertheless, (Munkhammar et al.; 2015) have pointed out that since EV charging should be synchronized with PV generation hours, there should not be much synergy between EV and PV in residential areas, where EVs are away most of the day. However, (Alirezaei et al.; 2016; Kaschub et al.; 2016) have shown that low-cost home batteries could bypass this issue and ensure significant economic and environmental gains. Generally, there is a lack of studies that integrate economic and regulatory aspects of couplings between EVs and DERs (Hoarau and Perez; 2018). Hence this paper fills one gap in this strand of literature by investigating the effects of network tariff design on the interactions between EVs and DERs. There are few papers that simultaneously take into account EVs, DERs and network tariffs. (Kaschub et al.; 2016) studies how the profitability of home systems comprising solar PV and batteries was affected by EV charging and retail tariff, but there is no feedback on the tariff design. In a recent paper, (Küfeoğlu et al.; 2018) developed a case study of tariff study for British distribution grids and assessed that EVs were counterbalancing the increasing effect on tariffs induced by solar PV, but the authors neither consider batteries or load flexibility.

A difficulty in the modeling of tariff design with EV and DERs is to take into account key-elements of the three fields that have been previously discussed. Studying the integration of EVs in power grids require to model the effect of the EV charging patterns on the single EV owner's load profile and aggregate effect of EVs on the network peak power and network costs. Similarly, investigating the interactions be-

tween EVs and DERs needs to model precisely the consumption of users and how they invest and optimize their consumption (in energy and power) with electricity prices. Designing efficient and fair network tariffs requires to consider the newly conflicting aspect of this problem. One of the main missions of the regulator is to ensure the cost recovery of utilities in charge of distribution systems operations. In the network, some users are now able to react to changes in their electricity costs by investing in DERs. Such conflicting situation is usually modeled by non-cooperative games. More precisely, a non-cooperative game between the regulator and network users would be the appropriate methodology. Such games have been applied for the studies of smart grids organized by an aggregator such as in (Tushar et al.; 2012; Yu and Hong; 2016). Such modeling methods allow to evaluate both distributive aspects and welfare aspects of the tariff design (Brown et al.; 2017; Schittekatte and Meeus; 2018). In the closest study to this paper, (Küfeoğlu et al.; 2018) models different penetration of solar PV and EVs and their implications on the network tariffs. But the authors neither model the precise load profiles of users, nor the reaction of some users to network tariff to optimize their consumption, nor emit welfare considerations.

3 Methods and data

This section presents the methodology adopted in this paper. A detailed exposition of the modeling of tariff design is followed by the description of the data used in the numerical case study.

3.1 Model

Overview

This paper models a regulator that designs tariffs in a low-voltage residential grid in a stylized framework by maximizing social welfare. As pointed out earlier, one of his main missions is to design tariffs paid by network users that will remunerate the DSO so that it recovers its costs. In the previously defined context, he needs to anticipate the behavior of some grid users that would push back by installing DERs at home in

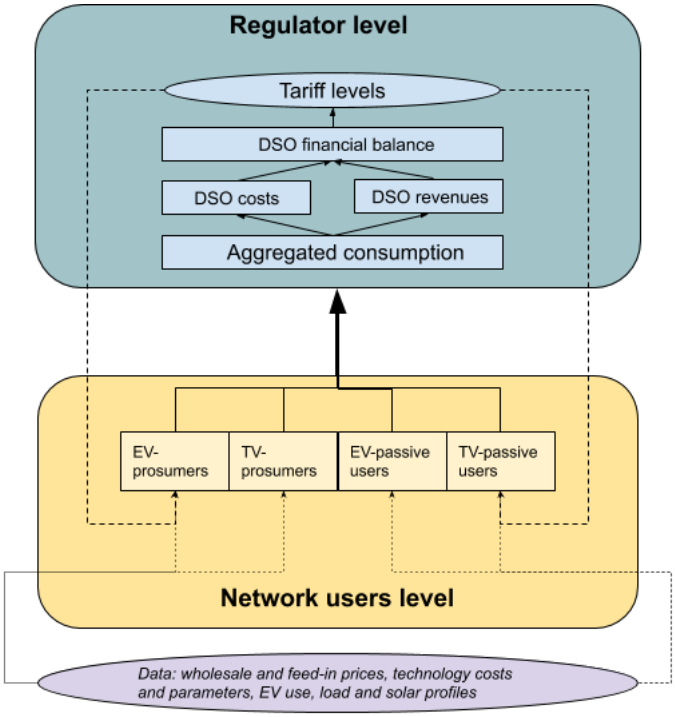

Figure 5.1: Model structure

	Passive network user	Prosumer
Traditional vehicle owner	TV-passive user - *"Traditional user"* • do not minimize electricity costs • may not invest in DERs • proportion: $(1-p^P)(1-p^{EV})$	TV-prosumer - *"Regular prosumer"* • minimize electricity costs • may invest in DERs • proportion: $p^P(1-p^{EV})$
Electric vehicle owner	EV-passive user - *"Green commuter"* • do not minimize electricity costs • dumb charging of EV • may not invest in DERs • proportion: $(1-p^P)p^{EV}$	EV-prosumer - *"Full innovator"* • minimize electricity costs • smart charging of EV • may invest in DERs • proportion: $p^P p^{EV}$

Table 5.1: Description of the different network users with their attributes

reaction of increased electricity prices. Moreover, the regulator takes into account the precise effect of the adoption of other new technologies by users (namely EVs in this paper).

The chosen approach of this paper is a game-theoretical model which is similar to the one used in (Schittekatte and Meeus; 2018; Schittekatte et al.; 2018; von Appen and Braun; 2018). The model is summarized in Figure 5.1. More precisely, the interaction between the regulator that design network tariff and users of grid users is modeled by a non-cooperative game. As different tariff structures are considered by the regulator, typical load profiles of network users need to be precisely modeled. Four kinds of representative network users are considered, depending on whether they are prosumers or passive users, and whether they own an EV or a traditional vehicle (TV)[6]. A description of user types is shown on table 5.1. Importantly, rational representative users are considered. Prosumers are able to minimize their electricity consumption by investing in DERs and to optimize the energy flows of their houses. On the contrary, passive users are not able to do so[7]. Such differentiation has been widely used in the literature (Brown et al.; 2017; Gautier et al.; 2018). The proportion p^P of prosumer is assumed to be independent of proportion p^{EV} of EV owners[8]. To simplify, we assume that all network users have the same typical electric consumption and that this consumption is strictly inflexible. It is important to note the asymmetry between EVs and DERs in this approach. EV adoption is uncorrelated to electricity prices, mainly because electricity prices represent a small part of EV total ownership cost (Breetz and Salon; 2018; Palmer et al.; 2018). On the contrary, DER adoption is mainly motivated by electricity prices (Karakaya and Sriwannawit; 2015). The model is solved numerically[9] by an iterative procedure[10], where each level takes in argument the output of the other level until the algorithm converges[11].

[6]The user type "TV owners" includes more generally all users that do not own a private EV at home.

[7]This inability has several causes, such as lacks of space for DER installation, cash access for investing, unavailable information etc...

[8]However, some correlation of adoption both DERs and EV has been evidenced in some regions (Delmas et al.; 2017).

[9]Note that this model can not be solved analytically, unless a simple ad-hoc DER investment function is assumed

[10]The model is solved in Python/CVXPY

[11]For most of the simulations, less than 10 iterations were needed

Regulator level

In the upper level, the tariff design process is simplified. The only objective of the regulator is to balance the budget of the DSO. The DSO only reports its costs and the aggregated consumption of the whole network[12]. Beside this reporting, the DSO is passive in the tariff design process. The tariff design is defined as follows. The regulator first chooses a tariff structure. This structure is a policy choice and is therefore exogenous in the model. Network tariffs are usually decomposed in three parts : volumetric (in €/kWh), capacity (in €/kW) and fixed (in €). In the case where users are able to self-consume and/or feed-in power back to the grid, net-metering has been generally applied. With net-metering, the volumetric part of the tariff applies to the net electricity consumed (*i.e.*electricity consumed minus electricity produced)[13]. Network tariff design is described in the model with three types of structure are considered (volumetric, capacity and fixed). This allows a precise understanding of the particular effect of each part of the tariff[14].

$$C_N = R_V + R_C + R_F \tag{5.1a}$$

$$R_V = \epsilon_V \sum_i p_i t_V \sum_t (F_{i,t}^{G,+} - \delta_m F_{i,t}^{G,-}) \Delta T \tag{5.1b}$$

$$R_C = \epsilon_C t_C \sum_i p_i \bar{P}_i \tag{5.1c}$$

$$R_F = (1 - \epsilon_V - \epsilon_C) \sum_i p_i t_F \tag{5.1d}$$

Equations 5.1(a-d) describe the DSO cost recovery constraint[15]. The regulator enforces that the overall networks costs C_N should match the revenues of the DSO. These revenues are composed of volumetric (energy) charges revenues R_V, capacity

[12]Among others, the regulation can incentivize the DSO to certain efficiency practices regarding grid reinforcements or renewable curtailment (Abdelmotteleb et al.; 2018; von Appen and Braun; 2018). Such considerations are beyond the scope of this paper.

[13]Without net-metering, the volumetric tariff applies to the total electricity that went through the house power lines (*i.e.*consumed electricity plus produced electricity). We consider this tariff structure only in the appendix

[14]Note that if most countries implemented a mixed structure, pure tariffs are adopted by several countries such as Holland (100% power) or Romania (100% energy) in the EU. Other tariff structures are considered in 5.C.

[15]All parameters and variables are described in the 5.A.

charges revenues R_C and fixed charges revenues R_F. With net-metering ($\delta_m = 1$), the user is charged on its net consumption, meaning that her self-production (*e.g.*from solar PV) is subtracted from its consumption. Without net-metering, volumetric charges apply to the total power flows of the user (consumption added to self-consumption). With capacity tariffs, the user is charged based on its annual peak load $\bar{P}_i$. p_i is the proportion of user i in the network. Parameters $\epsilon_V, \epsilon_C, \delta_M$ describe the composition of the tariff. For pure volumetric tariff, $\epsilon_V = 1, \epsilon_C = 0$. For pure capacity tariff $\epsilon_V = 0, \epsilon_C = 1$. For fixed tariff, $\epsilon_V = 0, \epsilon_C = 0$.

Network users level

In the lower level, network users minimize their electricity costs depending on their user class as follows:

$$\text{Minimize (electricity costs)}_i = \text{(energy costs)}_i + \text{(network charges)}_i + \text{(DERs costs)}_i + \text{taxes} \tag{5.2}$$

With:

$$\text{(energy costs)}_i = \sum_t \left(c^{G,-} F_{i,t}^{G,-} - c^{G,+} F_{i,t}^{G,+} \right) \tag{5.3}$$

$$\text{(network costs)}_i = \epsilon_V t_V \sum_t \left(F_{i,t}^{G,+} - \delta_m F_{i,t}^{G,-} \right) + t_C \bar{P}_i + t_F \tag{5.4}$$

$$\text{(DER costs)}_i = c^S S_i + c^B B_i \tag{5.5}$$

Equation 5.3 describes the energy charges component of the user's bill. It is composed of the total power bought from the grid at cost $c^{G,-}$ minus the total power sold to the grid at price $c^{G,+}$[16]. Equation 5.4 refers to the network charges component of the user's bill. Note that in the case of a volumetric net-metering tariff, network charges cannot be negative by regulation, which imposes an additional constraint.

[16]Note that although they could be easily included, dynamic tariffs are not considered in this paper.

Investments costs in PV and batteries of the prosumer constitutes the DER costs in equation 5.5. PV capacity and battery annualized cost are c^S and c^B. Calculation of these technology costs are described in the section on data.

$$L_{i,t} = F_{i,t}^{G,+} - F_{i,t}^{G,-} + S_i y_{i,t}^S + F_{i,t}^{B,-} - F_{i,t}^{B,+} + F_{i,t}^{EV,-} - F_{i,t}^{EV,+} \tag{5.6a}$$

$$F_{i,t}^{G,-} + F_{i,t}^{G,+} \leq \bar{P}_i \tag{5.6b}$$

$$\sum_t \left(F_{i,t}^{G,+} - F_{i,t}^{G,-} \right) \geq 0 \tag{5.6c}$$

Equations 5.6(a-c) represent the physical constraints on power flows at the house level. The first constraint consists in power conservation at the house level (equation 5.6a), that enforces the equality between the user's regular load, and solar PV self-production and the energy balances from the battery and the EV. Equation 5.6b defines the peak power $\bar{P}_i$ of the user, which is the maximum total power (sum of grid power injection and withdrawal). To prevent having negative network charges, the total net electricity called from the network is assumed to be positive (equation 5.6c)[17].

$$S_i \leq \bar{S}_i \tag{5.7}$$

Equation 5.7 adds an upper bound on prosumers' solar PV capacity. This hypothesis is motivated by practical constraints that users face when installing solar PV.

[17]Note that this constraint only matters in when volumetric and especially with net-metering, is implemented.

Indeed, users may have insufficient space for installing solar panels.

$$B_i \leq \bar{B}_i \tag{5.8a}$$

$$SOC^B_{i,t} = \eta^{B,+} dt F^{B,+}_{i,t} - \frac{dt}{\eta^{B,-}} F^{B,-}_{i,t} + (1 - \varphi^B dt) SOC^B_{i,t-1} \tag{5.8b}$$

$$SOC^B_{i,1} = \eta^{B,+} dt F^{B,+}_{i,1} - \frac{dt}{\eta^{B,-}} F^{B,-}_{i,1} + (1 - \varphi^B dt) SOC^B_{i,0} \tag{5.8c}$$

$$SOC^B_{i,t_{max}} = SOC^B_{i,0} \tag{5.8d}$$

$$SOC^B_{i,t} \leq B_i \tag{5.8e}$$

$$F^{B,+}_{i,t} \leq \nu^{B,+} B_i \tag{5.8f}$$

$$F^{B,-}_{i,t} \leq \nu^{B,-} B_i \tag{5.8g}$$

Equations 5.8(a-g) refer to the battery constraints. As for solar PV, the battery capacity is bounded by $\bar{B}_i$, representing the constraint on space or cash limitations for battery investments. Equations 5.8(b-c) describes the battery dynamics that comprises bidirectional flows and leakage. A periodic condition is imposed in equation 5.8d, and the initial battery SOC is set to zero. This enforces the user to extract the maximal value from its battery. Equations 5.8(e-g) refer to physical constraints on the SOC

and the bidirectional flows of the battery.

$$SOC_{i,t}^{EV} = \eta^{EV,+} dt F_{i,t}^{EV,+} - \frac{dt}{\eta^{EV,-}} F_{i,t}^{EV,-} + (1 - \varphi^{EV} dt) SOC_{i,t-1}^{EV} \tag{5.9a}$$

$$SOC_{i,1}^{EV} = \eta^{EV,+} dt F_{i,t}^{EV,+} - \frac{dt}{\eta^{EV,-}} F_{i,1}^{EV,-} + (1 - \varphi^{EV} dt) SOC_{i,t_{max}}^{EV} \tag{5.9b}$$

$$SOC_{i,t}^{EV} \leq K_i^{EV} \tag{5.9c}$$

$$F_{i,t}^{EV,+} \leq h_{i,t}^{EV} \nu^{EV,+} K_i^{EV} \tag{5.9d}$$

$$F_{i,t}^{EV,-} \leq h_{i,t}^{EV} \nu^{EV,-} K_i^{EV} \tag{5.9e}$$

$$SOC_{i,t_d}^{EV} = SOC_i^{EV,d} \tag{5.9f}$$

$$SOC_{i,t_a}^{EV} = SOC_i^{EV,d} - \frac{\chi^{EV} d}{K_i^{EV}} \tag{5.9g}$$

$$SOC^{EV} \geq SOC_{min}^{EV} \tag{5.9h}$$

To simplify the modeling, the following assumptions are made regarding EV charging. The EV battery dynamics, described in equations 5.9(a-h), are roughly similar to the stand-alone battery dynamics. It is assumed that all EVs have the same travel patterns. They travel every day the distance d, which translates into an additional electricity need of $\chi^{EV} d$ for the user. Every day, the EV unplugs and leaves at t_d and come back and plugs at t_r. As drivers are supposed to be commuting every day, EVs are away from home most of the day. In addition, it is assumed that EV mainly charges at home. The boolean function $h_{i,t}^{EV}$ return 1 when the EV is plugged at home and 0 else. This assumption is motivated by empirical evidences on early EV adopters (Langbroek et al.; 2017). Similarly to the standalone battery dynamics, a periodic condition is also imposed in equation 5.9c. Passive EV owners plug their vehicle at maximum power as soon as they have come back home (*dumb charging*). Note that this dumb charging of the EV happens most likely happens during the house peak load. The plugging power is assumed to be modest (3kW), which is consistent with the current plugs provided by EV manufacturers for domestic use (García Villalobos; 2016). EV-prosumers include the vehicle battery in their process

of electricity costs minimization. In this case, the EV charging is flexible (*smart charging*) and in addition it is assumed that EV-prosumers are able to discharge their EV battery to power their house, without any damage on the battery[18]. It is likely that EV owners could charge their vehicle smartly without being able to invest in DERs. To limit the number of agents' behaviors, such option is not considered in this paper. It is assumed that the EV battery has the same technical parameters as the stand-alone battery. It is assumed that EV owners require a minimal state-of-charge SOC_{min}^{EV} for their battery.

Finally, all variables of the model are positive :

$$F_{i,t}^{G,+}, F_{i,t}^{G,-}, F_{i,t}^{B,+}, F_{i,t}^{B,+}, F_{i,t}^{EV,-}, F_{i,t}^{EV,+}, S_i, B_i, \bar{P}_i \geq 0 \tag{5.10}$$

Evaluation methods

Proxy	Description
Tariff variation	network tariff variation relatively to the reference case (no EV nor prosumer)
EVIC *(prosumer)*	cost difference between EV-prosumers and TV-prosumers
EVIC *(passive)*	costs difference between passive EV owner and passive TV owner
DER payback time (TV)	payback time of DER investments made by TV-prosumers
Solar PV capacity (TV)	solar capacity installed in the network by TV-prosumers
Battery capacity (TV)	battery capacity installed in the network by TV-prosumers

Table 5.2: Proxies used to evaluate tariff designs

The interaction of tariff design with the different network users' behavior are analyzed with different proxies. In this study, we focus on three aspects. First, the impact of EV and DER penetrations on network tariff levels, is computed with the variation of network tariff. This tariff variation has been interpreted in term of fairness between network users in the literature on tariff design with DERs (Schittekatte and Meeus; 2018). The reference case is defined by the scenario with 100% TV-passive users (with neither EV nor prosumers).

$$\text{Tariff Variation } = \frac{\text{Tariff}(p^P, p^A)}{\text{Tariff}(0,0)} - 1 \tag{5.11}$$

[18]This assumption may be strong, but several studies have demonstrated that discharging the EV battery is far from being strictly costly for the battery (Apostolaki-Iosifidou et al.; 2017; Thompson; 2018).

To quantify the spillovers of DER adoption on EVs ownership costs, we define as proxies EV incremental costs for prosumers and passive users as follows:

$$\text{EV incremental cost}(prosumer) = \frac{\text{Bill}^T(EV\text{-}prosumer) - \text{Bill}^T(TV\text{-}prosumer)}{\text{Bill}^{ref}(EV\text{-}prosumer) - \text{Bill}^{ref}(TV\text{-}prosumer)} \tag{5.12a}$$

$$\text{EV incremental cost}(passive) = \frac{\text{Bill}^T(EV\text{-}passive) - \text{Bill}^T(TV\text{-}passive)}{\text{Bill}^{ref}(EV\text{-}passive) - \text{Bill}^{ref}(TV\text{-}passive)} \tag{5.12b}$$

EV incremental costs (EVIC) of prosumers (resp. passive users) are first defined by the difference of electricity costs of EV-prosumers (resp. EV-passive users) and TV-prosumers (resp. TV-passive users). These differences are then normalized by the same cost difference using the tariffs of the reference case[19]. For passive users, EVIC can be identified as the EV charging costs. Oppositely, for prosumers, EVICs may also include additional costs or revenues due to additional DER investments.

Third, the impacts of EV diffusion on DERs adoption and profitability are assessed with the characteristic of prosumers without EV. DER adoption is directly measured by the installed capacities in solar PV and battery of the prosumer. DER profitability is assessed by the payback time[20] of the DER investment, defined by the ratio of the initial DERs investments costs, over the saving in the electricity costs brought by these investments. Such savings are defined by the difference between the TV-passive user's bill with the TV-prosumer's bill :

$$\text{DER Payback time} = \frac{\text{Total DER initial investment cost}}{\text{Bill}(TV\text{-}passive\ user) - \text{Bill}(TV\text{-}prosumer)} \tag{5.13}$$

3.2 Data

As the goal of this paper is to analyze the links between the design of network tariffs and grid users behaviors and technologies, generic numerical examples are computed, based

[19] Note that for this proxy, the network tariffs of the reference case are the tariffs with a fixed tariff structure.

[20] Other proxies are possible to consider as the net present value, internal rate of return...

on stylized facts on power consumption in Europe, technologies costs and technical parameters.

Cost types	Proportion in bill	Cost per year
Energy costs	45%	520€/year
Network costs	35%	400€/year
Other charges	20%	230€/year
Total electricity cost	0.18€/kWh	1150€/year

Table 5.3: Electricity bill of a TV-passive user in the reference case

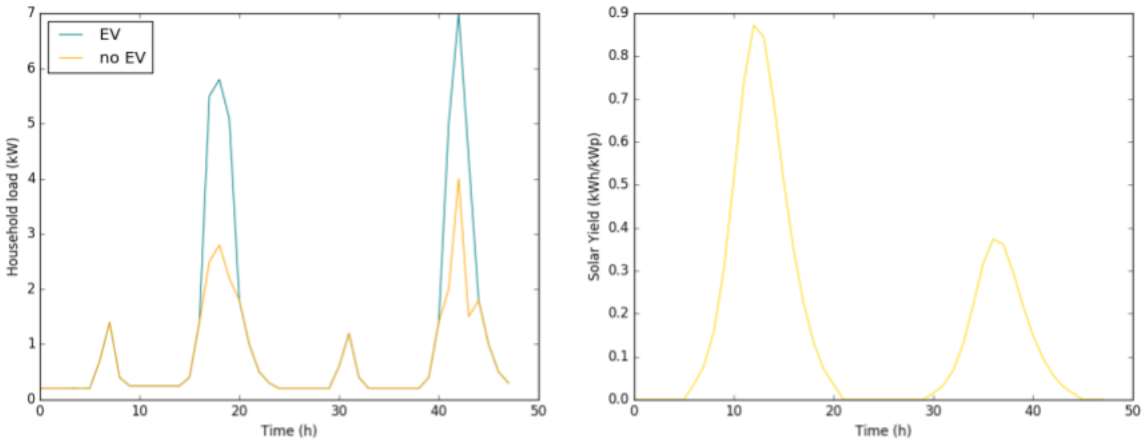

Figure 5.2: Daily demand load profile of TV users (left, in kWh) and solar yield (right, in kWh/kWp)

The basic load of users represented with typical two-day load profile designed for this numerical experiment (shown in Figure 5.2-left). Each daily profile incorporates one low peak in the morning and a high peak in the evening. The two days are chosen to capture seasonal consumption pattern. The whole profile is calibrated to reach an annual consumption of 6500kWh/year and a peak power of 4kW, which are medium estimates between yearly household consumption in Europe and the US (ACER; 2016).

The default electricity bill is defined by the situation without any prosumer or EV owner in the network. Parameters are shown in Table 5.3. The bill is computed over one year, which leads to an annual factor ΔT of 182.5. The default bill is decomposed as follows : 45% for energy purchases, 35% for network utilization and 20% for other charges and taxes. Such decomposition is close to the one used in (Schittekatte and Meeus; 2018) and reflect an average composition of European electricity based on

(ACER; 2016). It is assumed that the regulator has complete information regarding network costs. Network costs are assumed to be sunk, which is the case for a over-dimensioned network, or for a short-term analysis. This hypothesis will be relaxed in the appendix. It is assumed that taxes on electricity are fixed independent from energy consumtion. The final electricity cost is 0.18€/kWh, which is between the average European prices (0.21€/kWh) and the average US prices (0.125 €/kWh).

A two-day solar yield per kWp of PV installed, shown in Figure 5.2-right, is calibrated to a yearly production of 1160kWh/kWp and to capture winter/summer patterns. In line with (Schittekatte et al.; 2016) the efficiency of standalone and EV battery charging and discharging is set at 90%. As EV battery quality is much higher than stand-alone home batteries, we assume that there is no leakage in the EV battery while the standalone battery has leakage rate of $2\%/h$.

We assume relatively low investments costs of solar PV and lithium-ion batteries, which is in line with studies on the short-term future development of these technologies (Schmalensee; 2015; Schmidt et al.; 2017). Investment cost of PV and batteries are set to be respectively 1300€/kWp and 200€/kWh based on (Schittekatte et al.; 2018). Lifetimes of PV panels and batteries are respectively 20 and 10 years. With a usual discount rate of 5%, annual costs for solar PV and batteries capacities are 104 €/kWp/year and 26 €/kWh/year. To avoid over-incentives on solar PV caused by excessively high feed-in tariffs combined with low price of PV panels, feed-in tariff is set at low enough level (4c/kWh in the simulations) to exclude significant investment in solar PV or battery with null network tariff.

As already stated earlier, EV adoption is assumed to be exogenous in the model. In the case study, EVs leave home at 7am and come back at 5pm[21]. The daily travel distance of EV owners is set at 40km, which is a typical order of magnitude for Europe (Pasaoglu et al.; 2014). It can be also considered that EV owners drive over longer distances, but charge more frequently at workplace or at a commercial charging station. Note that in this setting, a passive EV owner consumes 45% more energy and has a 75% higher peak load compared to a traditional passive TV owner.

[21]Several studies have pointed out that early evening charging is currently the most common way (Langbroek et al.; 2017).

Finally, four scenarios of penetration of EVs and prosumers will be considered. Low penetrations will be modeled as 5% of users and 25% for high penetration. If "low" (resp. "high") penetrations can be identified to short (resp. long) term, high penetrations (of EVs and/or prosumers) can potentially occur in specific locations despite low penetrations on larger scales (eg in California, Norway...).

4 Results

4.1 Impacts of DERs and EVs on network charges

This section focus on tariff variations caused by prosumers or EV owners. Table 5.4 shows the variations of tariff levels relatively to the reference case with neither prosumers nor EV owners. Four major highlights are described in what follow.

First, for both tariff structure and for both EV penetration scenarios, increased proportions of prosumers have an increasing effect on network tariff. With volumetric tariff structure and for both EV penetration scenarios, an increase of 20% in proportion of prosumers results in an increase in tariffs by 24-27%. Under capacity tariff, such increase is in the range 13-14% for an increase of proportion of prosumers by 20%. Such results are well-identified and have been discussed in section 5.3. Indeed, both tariff structures give incentives to invest in DERs. As shown in 5.B, volumetric with net-metering tariff incentivizes prosumers to invest in solar PV to save on network charges. Capacity tariffs incentivize both solar PV and battery capacities to lower prosumers' peak load. For both tariff structure, prosumers' DERs results in a decrease of DSO's revenues. As grid costs stay constant, the regulator have to increase tariff levels to enforce DSO's budget constraint.

Second, for both tariff structures and for both prosuming scenarios, increased EV penetration have a decreasing effect on network tariffs. Under volumetric tariff structure, and for both prosuming scenarios, an increase of 20% in proportion of EV owners leads to a tariff decrease by 12-14%. With capacity tariff, the same increase in EV penetration leads to a decrease by 12-13%. This result, can be interpreted as follows. Getting an EV significantly increases its user' energy consumption and peak

Tariff structure	Proportion of EV owners	Proportion of prosumers	**Tariff Variation (%)**
Volumetric	5%	5%	2.6
		25%	29.2
	25%	5%	-9.4
		25%	15.2
Capacity	5%	5%	-0.61
		25%	13.5
	25%	5%	-12.9
		25%	0.63

Table 5.4: Network tariff variation relative to the reference case. Variations are given for capacity and volumetric with net-metering tariff structure, 5-25% EV owners and 5-25% prosumers.

load (in our setup, respectively by 45 and 75%). Hence higher penetration of EVs in the network increase the DSO's revenues. Again, as grid costs are all sunk, the regulator lowers tariffs to minimize electricity costs of network users while ensuring DSO's cost recovery.

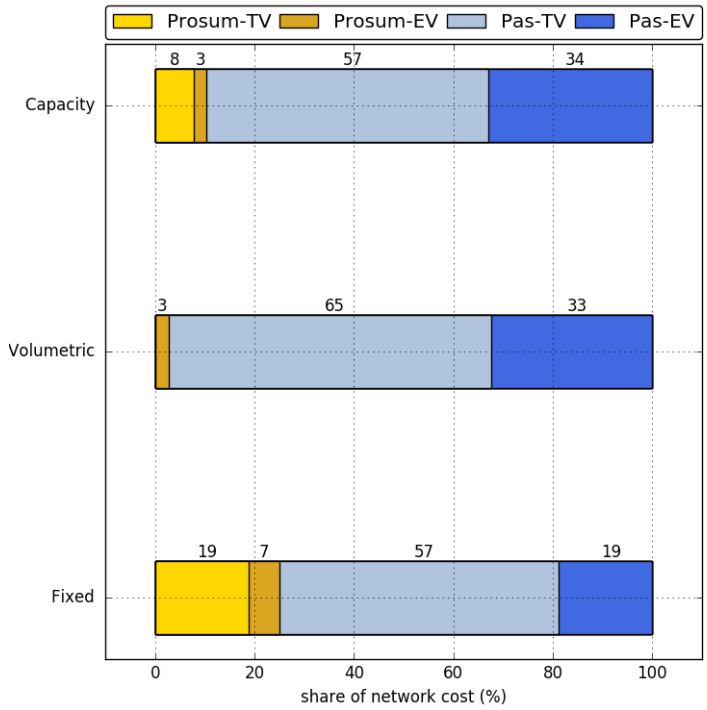

Figure 5.3: Distribution of network revenues between network users classes for the case with 25% EV owners and 25% prosumers. Three tariff structure are considered : volumetric, capacity and fixed.

Third, these two previous effects seem to balance each other. With capacity tariff, same proportions of EV owners and prosumers in the network leave tariffs almost unchanged compared to the reference situation. Indeed, in the 5%-5% as in the 25%-25% scenarios, network tariffs only deviate by 0.6%. With the volumetric tariff structure, network tariff deviates slightly in the 5%-5% scenario, but by 15% in the 25%-25% scenario. However in this scenario tariff has increased by 15% compared to the reference case. Although, this partly contradicts the previous results, it is important to note that the decrease of tariff induced by EV is larger when proportion of prosumers is large. Indeed, the decreases of tariff induced by 20% additional EV owners are respectively 12% and 14% in the 5%-5% and in the 25%-25% scenarios.
An other way to analyze the effects of EVs and prosuming on network tariffs is to represent how grid costs are shared between users. Figure 5.3 shows this distribution for the 25%-25% scenario. Three network tariff structures are considered with a pure fixed tariff in addition to the pure volumetric and capacity tariffs. With fixed tariff, every user pays the same fee for grid access regardless of their power consumption. Hence the proportion of the user class is equal to the share of this user class in grid costs recovery. Importantly, in our set-up fixed tariff does not give incentives neither for solar PV nor for batteries since network charges cannot be avoided by prosumers. With volumetric tariff, prosumers, especially TV-prosumers have withdrawn their contribution to grid costs recovery. Indeed solar PV investments allowed these users to completely escape the network charges they were paying without their solar panels. The resulting gap in grid costs recovery is then filled by passive users. TV-passive and EV-passive users respectively bear 65% and 33% of grid cost, while 57% and 19% under the fixed tariff structure. Under capacity tariff, similar results are found with a reduced share of prosumer and an increase share of passive users in grid costs recovery. These latter results illustrates clearly the non-cooperative aspect network user in grid costs recovery. Indeed with both capacity and volumetric tariff, prosuming leads to free-ride network access, at the expense of passive users.

Fourth, it is important to assess how network tariff structures affect the combined effects of EV and prosuming on network tariffs. In this study, we focused on volumetric with net-metering and capacity tariff structures as they are the most characteristic of

current network regulations. The results described in Table 5.4 have shown that tariff variations are smaller under capacity tariff structure than under volumetric tariff, for all EV/prosuming scenarios. These results can be interpreted as follows. On the one hand, volumetric structure gives higher incentives to adopt DERs. As shown in the 5.B, prosumer invest in their maximal possible[22] solar PV capacity event for low tariffs level. On the contrary, solar PV and capacity investments are much more progressive under capacity tariffs. Hence volumetric tariff structure results in higher missing revenues for DSO than with capacity tariffs. On the other hand, EV owners are more sensitive to capacity tariffs as in our setting, their peak power is increased by 75%[23] while energy consumption is increased by 45%. Hence electric vehicles represent a larger source of revenues for the network operator under capacity tariff. Also, note that fixed tariffs is the less costly tariff structure for passive EV owners, while they do not give incentives for DERs.

This last result highlights a crucial issue. Depending on the tariff structure, EV owners get advantaged and prosumers get disadvantaged and vice-versa. Next section will detail this highlight by investigating the conflicts between EVs and DERs adoption through tariff design. Finally, it is important to note that the numerical results shown in this section are dependent on several assumptions. The appendix provides results that demonstrates that the mechanisms described in this section are robust to (1) other tariff structures, (2) variable grid costs structure.

4.2 Conflicting effects between EVs and DERs adoptions

As discussed earlier, EVs and DERs are identified as crucial technologies in the energy transition. While these technologies will meet in power grids, their economic characteristics are asymmetrical in several ways. First, the adoption of DERs is strongly dependent on electricity prices, contrary to the current EV adoption patterns. Second, DERs adoption is even more incentivized by high electricity prices, while high electricity prices will increase the cost of EV ownership. In the context of tariff design, such asymmetry leads to a conflicting situation between EVs and DERs adoptions. In this

[22]Note that solar PV capacity is constrained in our model by equations (7c) and (8).
[23]Note that standard plug power can be much higher (eg 7kW, 22kW (Codani et al.; 2016)).

section we extend the previous analysis to investigate (1) how EV incremental costs are affected by prosuming and (2) how DER adoption and profitability is affected by EV adoption.

Tariff structure	Proportion of EV owners	Proportion of prosumers	**EVIC (%)** (prosumer)	**EVIC (%)** (passive)
Volumetric	5%	5%	178	179
		25%	194	199
	25%	5%	170	170
		25%	186	189
Capacity	5%	5%	73.0	215
		25%	73.2	231
	25%	5%	72.8	200
		25%	73.0	216

Table 5.5: EV incremental costs (EVIC) for EV-prosumers and EV-passive users.

First, EV incremental costs are increased by DER adoption. In Table 5.5, EV incremental costs (defined earlier) for passive users and prosumers are represented for the four scenarios of EV diffusion and prosuming, and for the two tariff structures. For both volumetric tariffs and whichever the proportion of EV owners and prosumers, there are no significant differences in incremental costs between active and passive EV owners. For instance, with the increase of 20% in prosumers, EV incremental costs increase 16-20%. On the contrary, the capacity tariff shows huge differences of EV incremental costs between EV-prosumer and EV-passive users. EV-passive users face a 15% increase in their EVIC for all scenarios when the proportion of prosumer increases. Results show differences for EV-prosumer costs. For all scenarios, the EV incremental costs of a EV-prosumer are almost three times higher than for passive EV owners. Indeed, smart charging of EV-prosumer allows them to significantly lower their peak for free, even without investing in stand-alone batteries. Nevertheless, in our scenarios, EV-prosumers represent a small fractions of all users. Although we assumed EV adoption to be independent from charging costs, these latter represent a rather small part in the total cost of ownership of EVs (Wu et al.; 2015). The increase can be interpreted as a cross-subsidy from EV owners to all other users through network tariffs, and especially prosumers.

Tariff structure	Prosumer proportion	EV owners proportion	**DER payback time (y)**	**Solar PV capacity (kWp)**	**Battery capacity (kWh)**
Volumetric	5%	5%	10.52	4.48	0.0
		25%	8.82	1.83	0.0
	25%	5%	9.92	4.48	0.0
		25%	9.64	4.48	0.0
Capacity	5%	5%	6.17	1.19	2.93
		25%	6.73	1.19	2.93
	25%	5%	5.63	1.19	2.93
		25%	6.12	1.19	2.93

Table 5.6: DER payback time, solar PV and battery capacity of the TV-passive user.

Second, DER adoption and profitability are affected by EV diffusion. Table 5.6 shows the different proxies defined earlier, *i.e.* solar PV and battery capacities installed by TV-prosumers, and the payback time of TV-prosumer's investments in DERs. With the capacity tariff structure, increases of the proportion of prosumers have similar effects for both EV penetration scenarios. When the proportion of prosumers increase by 20%, the payback time of DER investments increase by 0.6 year while solar PV and battery capacity stay constant. With volumetric tariff, same increase in EV penetration has different effects. In the 5% EV penetration, solar PV adoption decrease from 4.5kWp to 1.8kWp while the related payback time decrease. In the 25% EV scenario, solar PV adoption stay unchanged, but solar PV payback time increase by 0.8 year. The interpretation of the following results are similar. In every case, the increase in EV penetration has a lowering effect on network tariffs. As DER adoption is determined by electricity prices, the effect results in reducing the prosumer's valuation of DER investment.

5 Conclusion

This paper has studied several aspects of network tariff design with DERs (solar PV and batteries) and EVs (with flexible and dumb charging) adoptions within a stylized non-cooperative game including four types of network users. It enlightened several mechanisms that have some relevance for policy design. First, EVs and DERs adop-

tions show counterbalancing effects through the grid costs recovery problem. When grid costs are sunk, EVs decrease the risk of the death spiral of distribution utilities. Then, through the process of network tariff designs, DERs and EVs induce spillovers on each other. These are mainly due to the asymmetrical characteristics of both technology uses. High electricity prices are the main driver of DER adoption. On the other hand EV adoption would be facilitated by low electricity prices, although it is currently largely independent from them. This study has shown that with the main tariff structure (volumetric and capacity), EVs and DERs may be conflicting by inducing negative externalities on each other. This latter finding contradicts a part of the literature on EV/DERs synergies.

Changing regulation makes winners and losers. In this study, winners (or free riders in this case), manage to escape to network charges, leaving the losers to bear the cost of the whole network. Regulation of network charges mainly consists in choosing a tariff structure. It has been shown that with volumetric tariff with net-metering, EV owners are the losers as they pay much more than what they would have had with other tariffs. Oppositely, prosumers are the winners. Depending on the proportion of EVs in the network, the lowering trends on equity can be compensated. With capacity tariffs, DERs are less incentivized for prosumers, but EV owners are much more sensitive to peak load charges. The fact that the situation EV owners may worsen needs to be discussed in term of public acceptance. Moreover, it may disadvantage a technology which is currently strongly pushed by policies. Nevertheless, EV adopters are generally affluent and therefore could perceive this situation lightly.

The implications of these mechanisms for policy making are twofold. First, by focusing only on the impacts of DER diffusion, the debate on network tariff design has eluded the trend of electrification. As including electrification leads to less dramatic outcomes, this could incite regulators to be less willing to modify tariffs promptly. Second, a precise investigation of the winners and losers (in term of both user groups and technologies) of a tariff design change should be made. Indeed, the evaluation of tariff designs in term of efficiency and equity may hide the existence of conflicting effects between some technologies that are deemed valuable for society.

Finally, this paper calls for several future works. This study assumed that EV and

DERs were the only drivers of power consumption of network users. Other flexible or inflexible consumption sources would be added by electrification of other sectors (heating) or removed with sobriety or energy efficiency of appliances. A realistic case study on specific distribution grids should include these consumption sources to compute the DSO's revenues, and hence the effect of DERs and electrification (EVs, heat pump) on tariff design. Such case studies could also include other grids than only low-voltage residential grids, as considered in this study. Indeed, as such distribution grids would include large buildings and workplaces, EV charging profile and solar yields could be more synchronized. This would allow to include the appropriate conditions for EV/DER synergies Then, we assumed that simple roles for the regulator and for the DSO. Our framework could be enhanced by making the tariff structure endogenous based on the regulator's preferences and by an active management of the grid by the DSO. Finally, the conflicts between policies that promote EVs and policies that incentivize DERs should be studied in detail. Taking into consideration other support mechanisms of DERs that also end up increasing the retail price of electricity would therefore be appropriate.

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5.A Notations

Notation	Set
i	User index
t	Time slot

Notation	Variable
t_V	Volumetric tariff (€/kWh)
t_C	Capacity tariff (€/kW)
t_F	Fixed tariff (€)
$\bar{P}_i$	Maximum peak power of user i (kW)
S_i	installed solar PV capacity by user i (kWp)
B_i	installed battery capacity by user i (kWh)
$F_{i,t}^{G,+}$	power flow from the grid of user i at t (kWh)
$F_{i,t}^{G,-}$	power flow to the grid of user i at t (kWh)
$F_{i,t}^{B,+}$	power flow in the fixed battery of user i at t (kWh)
$F_{i,t}^{B,-}$	power flow from the fixed battery of user i at t (kWh)
$F_{i,t}^{EV,+}$	power flow in the EV battery of user i at t (kWh)
$F_{i,t}^{EV,-}$	power flow from the EV battery of user i at t (kWh)
$SOC_{i,t}^{B}$	state of charge of the fixed battery of user i at t (kWh)
$SOC_{i,t}^{EV}$	state of charge of the EV battery of user i at t (kWh)

Notation	Parameter
dt	time step (h)
ϵ_V	volumetric tariff fraction (%)
ϵ_C	capacity tariff fraction (%)
δ_m	net-metering indicator
ΔT	annual factor
$L_{i,t}$	regular load of user i at t (kWh)
$y_{i,t}^{S}$	solar yield at t for user i (kWh/kWp)
$c^{G,-}$	grid electricity price (€/kWh)
$c^{G,+}$	feed-in tariff (€/kWh)
$\eta^{B,-}$	efficiency of battery discharging (%)
$\eta^{B,+}$	efficiency of battery charging (%)
$\eta^{EV,-}$	efficiency of EV discharging (%)
$\eta^{EV,+}$	efficiency of EV charging (%)
$\nu^{B,-}$	ramp down ratio of the battery (%)
$\nu^{B,+}$	ramp up ratio of the battery (%)
$\nu^{EV,-}$	ramp down ratio of the EV battery (%)
$\nu^{EV,+}$	ramp up ratio of the EV battery (%)
φ^{B}	stand-alone leakage rate (%)
φ^{EV}	EV battery leakage rate (%)
$\bar{S}_i$	maximum solar capacity available to user i (kWp)
$\bar{B}_i$	maximum battery capacity (kWh)
K_i^{EV}	capacity of the EV battery of user i (kWh)
c^{S}	annualized cost of solar PV (€/kWp)
c^{B}	annualized cost of stand-alone battery (€/kWh)

5.B Optimal investment of prosumers

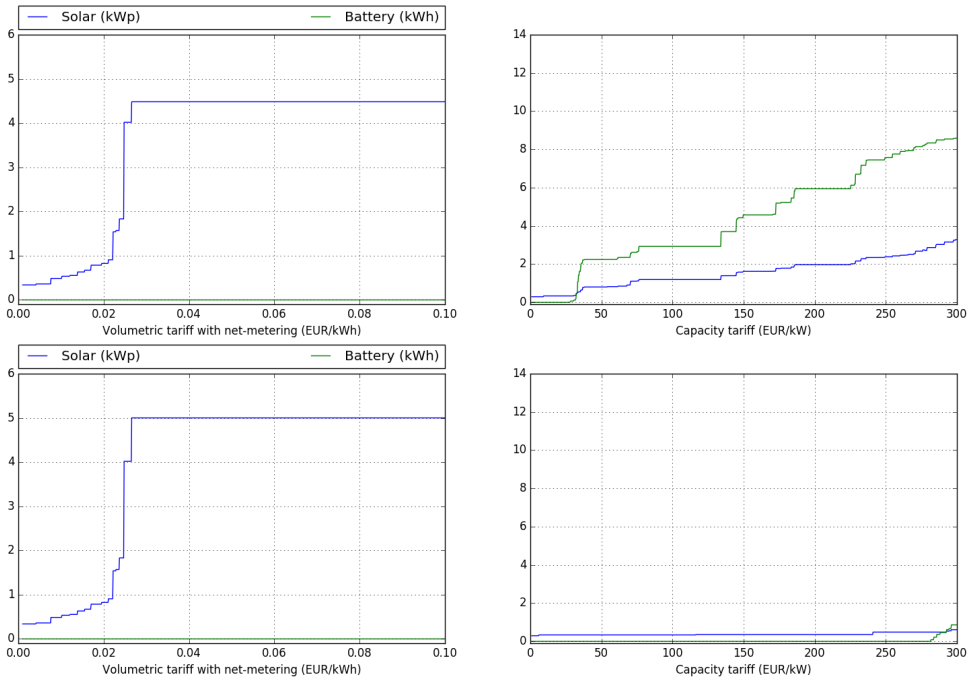

Figure 5.4: Optimal solar PV and battery investment functions of TV-prosumers (up) and EV-prosumers (down) function of the tariff level for volumetric (left) and capacity (right) tariff structures.

In our bi-level framework, the regulator (upper level) has to anticipate the reaction of prosumers (lower level) to set network tariffs. Such tariff level corresponds to the equilibrium of the non-cooperative game. These optimal investments functions of EV-prosumers and TV-prosumers are shown on Figure 5.4 for volumetric and capacity tariff structures. With volumetric tariff, only solar PV is incentivized and the reaction function has almost a threshold. With capacity tariff, both solar PV and batteries are incentivized. Contrary to the volumetric tariff, the optimal investment function is much more smoother. Also, with the volumetric structure, prosumers with EV have similar investment decisions to TV-prosumers. Under capacity tariff, EV-prosumers only invest in DER if capacity tariffs are high enough. Indeed, a smart charging of the EV is sufficient to avoid much of the network tariff.

5.C Impacts of alternative tariff structures

Previously, we only considered pure tariff structures. In this section, we consider different tariff structures. First, we consider another type of pure tariff structure, the volumetric tariff without net-metering. Second, we investigate the impacts of mixed volumetric/capacity tariffs.

5.C.1 Volumetric tariff without net-metering

Tariff structure	Proportion of EV owners	Proportion of prosumers	**Tariff Variation (%)**
Volumetric	5%	5%	-1.95
		25%	-10.7
	25%	5%	0.05
		25%	-9.04

Table 5.7: Network tariff variation relatively to the reference case, under volumetric without net-metering tariff structure. Variations are given for C and VNM tariff structure, 5 and 25% EV owners and 5-25% prosumers.

Another possible tariff is the volumetric tariff without net-metering. With this tariff, prosumers are charged for their feed-in to the grid. Table 5.7 shows the tariff variation of the model with the four scenarios of prosuming/EV penetration. These results indicate that the effects of EV become dominant, as prosumers invest in little DER capacities. Indeed, such tariff gives incentives for solar PV only if the produced power is self-consumed.

5.C.2 Mixed energy-capacity tariffs

In our framework, mixed tariff structure can be modeled with parameters ϵ_V, ϵ_C. Mixed volumetric/capacity tariffs are then $\epsilon_V = 1 - \epsilon_C$. Figure 5.5 shows the evolution of tariff variation with the capacity component ϵ_C. Three observations are made about these results on mixed volumetric/capacity. First, scenarios with small proportion of prosumers show small tariff variations for the whole range of mixed tariff structures. Tariffs decrease with higher capacity components as EV owners pays more for their

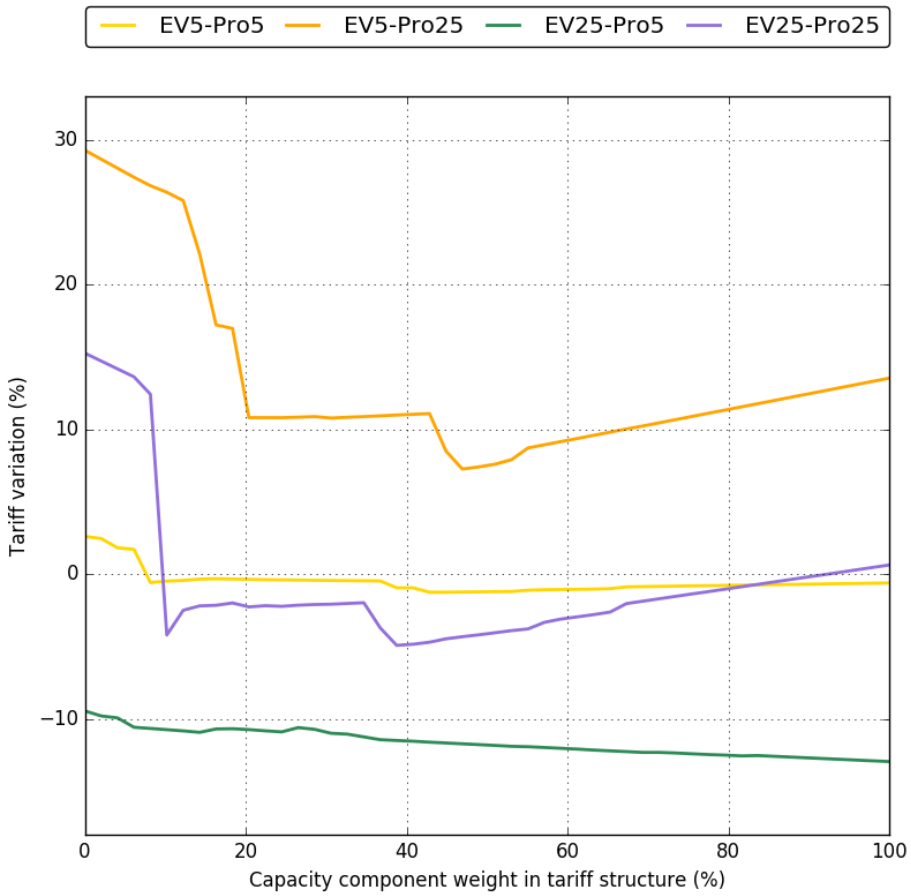

Figure 5.5: Evolution of tariff variations with the share of capacity tariff in the tariff structure. The usual four scenarios of prosuming and EV penetration are considered.

peak load. On the other hand, scenarios with high proportion of prosumers shows non-linear dependence with the capacity component. A minimal tariff variation is achieved for capacity components in the range 20-40%. Indeed, this range is enough to limit both over-incentives for solar PV and for battery.

5.D Impacts of variable grid costs

In the previous sections, we assumed that grid costs were only sunk costs. This hypothesis is adopted by several studies in the field (Schittekatte et al.; 2018). Nevertheless some other studies consider a variable cost component such as (Schittekatte and Meeus; 2018). Moreover, several works have inferred that large electric vehicles diffusion, by increasing the network peak load, could significantly increase grid costs

(Clement-Nyns et al.; 2010; Muratori; 2018). We discuss this consequences of such possibility in this section.

$$C_N(P_{tot}) = \alpha_S C_{sunk} + (1 - \alpha_S) C_{var}(P_{tot}) \tag{5.14}$$

Grid costs function is defined in equation 5.14, with C_{sunk} and C_{var} the sunk and variable components of grid costs. C_{var} depends on the network peak load. α_S is the fraction of sunk grid costs. It is assumed that the variable component of network costs is linear and calibrated with the reference level where there are neither prosumers nor EVs in the network:

$$C_{var}(P_{tot}) = C_{sunk} \frac{P_{tot}}{P_{tot}^{ref}} \tag{5.15}$$

With P_{tot}^{ref} the network peak load of the reference case. This way, we have $C_N(P_{tot}^{ref}) = C_{sunk}$.

We focus on a situation where a network has variable costs (20%), which is in line with several studies in the literature. Such variable component represents the additional costs due to increased damages in the grid or the additional reinforcements that have to be made to the grid. For instance, (Pollitt; 2018; Simshauser; 2016) estimate the variable component of network costs to 20%. (Fernandez et al.; 2011) estimates the worst case scenario to 15% grid costs increase due to high EV penetration. In our model formulation, load peaks of network users are exactly coincident. Remember that getting an EV leads to a 75% increase of the EV owner's peak load. Hence a 25% penetration of EVs with no prosumers leads to an increase of network peak load of 19%. This increase in peak load then results in an increase in grid costs by 4%.

Two main highlights can be drawn from results shown in table 5.8. First, as EVs increase the peak load of their user, they increase the network peak load. This increase leads to higher grid costs, which are then reflected on network tariffs. However, this increase in grid costs is not transmitted on tariffs since they decrease by 6-14% in both prosuming scenarios. Again, as EV owners consume much more power than TV owners, they also pay much more network charges. In this settings, EV owners increase more the financial revenues of the DSO than they increase grid costs. Oppositely,

Tariff structure	Proportion of EV owners	Proportion of prosumers	**Tariff Variation (%)**
Volumetric	5%	5%	10.3
		25%	38.3
	25%	5%	3.7
		25%	26.9
Capacity	5%	5%	6.2
		25%	17.5
	25%	5%	-3.7
		25%	7

Table 5.8: Tariff variations for variable grid costs (20%). The previous prosuming/EV scenarios are considered. The reference is still the 0%-0% EV/prosumers case

tariff variations caused by prosumers are larger with this variable grid costs structure. Indeed, DSO missing revenues because of prosumers is even more severe that grid costs are higher due to EV penetration, which leads to even higher tariffs. In summary, a grid costs structure with a variable component do not change significantly change our previous results.

* * *

El número de ríos no es infinito; un viajero immortal que recorra el mundo acabará, algún día, por haber bebido de todos. Nos propusimos descubrir ese río.

Jorge Luis Borges - *Los Immortales* in *El Aleph*

* * *

General Conclusion

This dissertation has explored several key aspects of the energy transition in the automobile industry. This transition is motivated both by climatic aspects (reduce greenhouse gases) and by health aspects (decrease local pollutants). We also considered that the phase-out of internal combustion engines cars and their replacement by - mostly - electric vehicles were the two sides of the transition. While several policies act on both sides, each side represents distinct and complex challenges. One side is about dismantling and banning of an already in place system, while the other side is about developing a novel industrial ecosystem. On the one hand, the phase-out of internal combustion engines induce high losses for a various actors. On the other hand, the development of electric mobility couples the transport sector with a power sector that faces its own energy transition. A key aspect of this linkage is to develop synergies between technologies and across sectors. This conclusive section is composed of three parts. The first summarizes the content of each chapter of the dissertation. The second revisits the findings of each chapters, and attempts to link them across transversal dimensions. The final section proposes several leads for future research.

Summary of contributions

Chapter 2

The second chapter investigated the first side: removing polluting vehicles from the fleet. Several national bans of new thermal vehicles have been announced for 2035-2040, European cities have developed more stringent policies in order to cope with urban air pollution. Within the so-called Low Emission Zones (LEZs), selected pollutant cars are forbidden. An ultimate version of these policies is the total ban all thermal cars. In France, diesel and old cars are particularly discriminated in the political framework that defines LEZ. This is motivated by their much higher rates of air pollutant emissions. Hence, such policies provide a relevant natural experiment of the removal of fossil fuel cars. Focusing on the French situation, which mostly made announcements on soon-to-be implemented LEZ, we investigated how vehicle owners could react to these policies. We empirically analyzed the French used-car market. We relied on scrapped data from online advertizing platforms, which we enriched with secondary data related to car specs and geographic information. We found a statistically significant decrease in the value of diesel and old cars nearby cities that have announced a low emission zone. These effects were stronger in ongoing LEZs than in planned or announced LEZs. These results indicated that owners of vehicles that should be targeted by driving restriction would respond by lowering their asked price. Such behavior could be motivated by the decision to accelerate the sell of their vehicle, or to adapt to a lower demand. We estimated that this example was a new identification of the creation of stranded assets by the implementation of stringent environmental policies.

Chapter 3

In the third chapter, we tackled the transition from thermal to electric vehicles from a theoretical perspective. We considered that the carbon footprint over the life-cycle of electric vehicles were one of the most debated aspect of the technology. However, there were little work from environmental economics able to formulate adequate policies that

would take into account indirect emissions from a clean technology.

In a partial equilibrium two-sector model, we generalized the concept of sector coupling technologies. Unlike pure abatement technologies, those would cut emissions in one sector, but in an other sector, they would induce additional production and hence, potentially increase emissions. We studied the optimal allocation of mitigation effort across sectors. We adapted the concept of Marginal Abatement Costs Curves to integrate life-cycle considerations.

We then investigated the related optimal policies and asked whether sectoral policies should be coordinated in presence of sector coupling technologies. While pigovian taxes in each sector ensure the first-best, we found that second-best optimal sectoral subsidies needed were coordinated. We derived and compared welfare losses from imperfect carbon pricing and from policy incoordination. We were able to relate that analytical properties of sector coupling technologies to the conditions where policy coordination was the most socially beneficial.

Chapter 4

As the transport sector electrifies and the power sector decarbonizes, a new technological landscape rises. Chapter 4 studies the interaction between electric vehicles and photovoltaic energy (PV). Both are disruptive technologies which have seen their costs fall dramatically in the last decade. However, both of them face serious challenge in their development. PV energy is intermittent and variable, and therefore sees its market value decrease with larger penetration, unless supported by storage capacities. Electric vehicles need decarbonized electricity to minimize their carbon footprint. Hence, many authors have identified several synergistic potential in the coupling of these two technologies. By the mean of a thorough literature review, we developed a systematic framework in order to assess a technological interaction that exhibit many technical and economic dimensions.

We found that the synergy between electric mobility and PV energy was not granted. It mainly depended the synchronization of PV production and vehicle charging profiles, which was determined by several key features, such as the geographical scale (house, neighborhoods or territories) and the technological environment of the

EV/PV coupling. Such framework exhibited a lack of studies on the economic conditions that could favor this synergy. These conditions include the users behaviors, links with the network operators, and political and regulatory contexts.

Chapter 5

Following the findings of the fourth chapter, the fifth one investigates an unaddressed issue of the literature on the interactions between electric vehicles and photovoltaic generation. Distribution tariff design is a hot topic in power system economics due to the emergence of prosumers. Such grid users are able to invest in distributed energy resources (*e.g.*PV or battery) and to optimize the use of these resources to minimize their electricity bills. Many experts have warned that current tariff structures were giving incentives for prosumers to invest in DERs, which could then jeopardize the recovery of grid costs. This would lead to substantial losses for network operators or to an increase of tariffs for all users. Such equity issue is important in a context where climate policy has to incorporate social justice issues. Our contribution to this debate is to integrate other technologies and specific grid users - electric vehicles owners. We showed that electric vehicle owners were counterbalancing the negative effect of prosumers. Indeed, electric vehicles substantially increase power consumption of their owner, which therefore increase their contribution in grid cost recovery. In general, this study highlighted that the electricity price exhibited a fundamental divergence between the interest of PV and EV owners. The first needing high prices of electricity to increase their profitability, while the other needing low prices to reduce total cost of ownership. Such finding came in opposition with literature on the complementarity between EV and PV.

Transversal considerations

The chapters of this dissertation are broadly independent and heterogenous in their topics and methods. However, they share common dimensions beyond the articulation of the energy transition in the automobile sector. We identified: the unintended consequences of environmental policies, the energy system integration and the distributional

effects induced by the energy transition.

Unintended effects of policies

Unintended effects of policies are one of the most common themes in environmental economics. As economic systems are complex, policies may trigger mechanisms that were ignored or underestimated before the implementation of the policy. Most common examples are the Green paradox, carbon leakage, windfall profits or waterbed effects. In this dissertation, the unintended effects were due to agents anticipations (chapter 2), sectoral linkages (chapter 3 and 4) and strategic behaviors (chapter 5). In each of these examples, unintended effects revealed an inadequate policy design. In chapter 2, we saw that the implementation of low emission zones would devaluate all diesel cars in the used car market, while complementary policies would only help owners of the oldest cars. In chapter 3, we saw that if uncoordinated, policies on one sector could significantly affect the performance of the policy in an other sector. Similarly, chapter 4 highlighted that anarchic deployments electric vehicles and photovoltaic energy could be more detrimental than each one taken separately. In a similar trend, chapter 5 underlined that changing tariff structure to restore equity could be vain if enough user heterogeneity is taken into account. Chapter 5 also highlighted that strategic behaviors makes regulations more complex to design. Policy makers would have to know the precise incentives they give to regulated agents, while anticipating the behavioral changes of these agents.

Energy system integration

Instead of a using a technological perspective, the energy transition can be seen as a substitution of energy carriers. It would consist in replacing carriers that cannot be decarbonized (*e.g.*oil, coal, natural gas), by others that may be (*e.g.*electricity, hydrogen, biomass). However, technologies used for the decarbonization of these latter energy carriers (*e.g.*renewable power, storage, electric vehicles) dramatically require performance improvements. Energy system integration is the holistic planning and operation of the energy system across sectors and energy carriers. Such optimization

is made possible by the reduction of the number of energy carriers and by the introduction of sector coupling technologies. This dissertation focused on electric vehicles, but others are power-to-gas (couples power and gas networks), fuel cells (couples hydrogen and transport sectors), heat pumps (couples power and heat)... We contributed to the literature on energy system integration by exhibiting the properties of several couplings. Chapter 3 exhibited the theoretical properties of sectoral coupling such as the one induced by electric mobility on the power sector. These results could also be applied to other energy carriers such as hydrogen. Chapter 4 and 5 studied the interaction between electric vehicles and distributed energy resources, especially photovoltaic generation. Although these technologies interacts at least through economic mechanisms, smart grids could reveal their complementarities.

Distributional effects of environmental policies

Social justice is a core aspect of the energy transition and environmental policies. It is a major barrier for the implementation of ambitious carbon taxes. On the other hand, it has been noted that most policy supporting clean technology, such as direct subsidies or tax rebates could also be regressive. Distributive aspects have been an indirect dimension of this dissertation.

Our study on the reaction of the used car market on the implementation of low emission zone in a striking example. The design of the policy - *i.e.*the selection of the vehicles to be forbidden - affects certain types of consumers. Indeed, low-income households are more likely to own old cars, as they may have limited possibilities to purchase a more recent and better car, or limited alternative for other transport modes. We identified a more general distributive effect, pointing out that diesel cars may face, in average, a significant devaluation in areas that are within or close to LEZs, compared to gasoline-equivalent vehicles. Chapter 5 deals with distributional effects from the network tariff design induced by the apparition of novel class of network users, such as prosumers and electric vehicles owners. While the literature on the topic warns that the increase of prosumers that could make the electricity bills higher for traditional users, we highlighted that including electric vehicles complicate this conclusion. By assessing the winners and losers of different changes of regulation, we concluded that

fair tariff are very contextual to the heterogeneity of network users.

Future works

LEZs, used car markets and scrapped data

Chapter 2 is still preliminary and several additions are needed. First, data collection must be repeated. It would allow to follow the implementation of Low Emission Zones in the coming years. Indeed, the 2019 LOM act makes mandatory the implementation of LEZ in cities whose pollution levels exceed legal thresholds by 2021. This would allow to assess an "LEZ" effect on car prices from a causal perspective, by using differences-in-differences methods. Moreover, having more data would allow to track the liquidity of ads, and how this liquidity varies with old and diesel cars close to LEZs. It would be also interesting to replicate this work in other countries such as Germany, Belgium.

The utilization of scrapped data is still rare in environmental economics. Concerning automobile data, many websites gather interesting information . In the second chapter, we worked on data of advertising platforms and vehicle specs. In our website choice, we choose quantity over details. There are some platform that gives further details on sellers or on the vehicle history. Other websites allows users to display their actual car consumption. Such information could be valuable in order to understand how the fuel economy gap affects new vehicle prices.

Strategic environmental policy in vertical value chains

The third chapter assumed that each sectors were under a single authority. However, upstream inputs could come from an other country than the country where the downstream good is consumed and regulated. If this it hardly the case for electricity and electric vehicles, one could consider the case of batteries of electric vehicles. As discussed in the introduction of this dissertation, batteries are the most emitting part of the vehicles once the electricity of the vehicle use has been decarbonized. Reducing life-cycle emissions of electric vehicles have to tackle battery processing, which depends

on a few countries in the world (China, Japan, Korea...). As such countries may have an energy mix with a high carbon content, the ones promoting electric vehicles may find interesting to relocate battery production as a part of both their industrial and their climate policy.

Integration of electric vehicles in power networks

Finally, our work on interactions between electric mobility and distributed energy resources could be translated inside the framework of peer-to-peer power markets. Indeed, we saw that the association of electric vehicles and distributed energy resources such photovoltaic generation was constrained by several factors. First, the spatial configuration was one of the most limiting factor, since it could make the coupling of the two technologies. Peer-to-peer markets would be a way to connect multiple small producers to multiple small consumers. Alternatively, it could also implies for households with both electric vehicles and photovoltaic to use the grid in order to charge their vehicle away from home with the power generated by their photovoltaic installation. Hence, peer-to-peer markets should significantly alter the results from literature on interactions between electric mobility and photovoltaic generation.

Résumé en français

Cette thèse traite de la transition énergétique dans le secteur automobile et en analyse plusieurs aspects économiques. Elle est composée de quatre chapitre indépendants, encadrés par un chapitre introductif (chapitre 1) et un chapitre de conclusion.

Chapitre 2 : Interdiction du diesel et marchés de véhicules d'occasion

Après avoir encouragé leur développement pendant plusieurs décennies, les gouvernements des pays européens retirent leur soutien aux véhicules diesel. Alors que ces moteurs étaient supposés être plus "propres" que ceux à essence, grâce à une consommation de carburant plus faible et à des émissions de CO_2 réduites, ils se sont avérés particulièrement émetteurs de polluants atmosphériques. En réponse aux préoccupations croissantes concernant les effets de la qualité de l'air sur la santé publique, des zones à faibles émissions (ZFE) sont progressivement mises en place par plusieurs villes, annonçant une interdiction progressive des voitures diesel. De tels politiques pourraient transformer ces véhicules en actifs échoués pour les ménages. Il s'agit d'une question épineuse en France où la moitié des véhicules particuliers roulent au diesel. En analysant jusqu'à un million d'annonces de vente de voitures d'occasion dans toute la France, nous constatons que les vendeurs de véhicules diesel situés dans les ZFE en cours et prévues anticipent ce changement de réglementation et baissent le prix demandé pour ces voitures. Nous quantifions cet effet pour les différents types de ZFE.

Chapitre 3 : Coordinations d'efforts d'abattement et de politiques entre secteurs en interaction[1]

Pour réduire de manière drastique les émissions de gaz à effet de serre (GES), de nombreuses mesures spécifiques sont nécessaires dans tous les secteurs de l'économie. Ces mesures, et les conséquences de leur mise en œuvre en matière de GES, ne sont pas indépendantes les unes des autres en raison des liens intersectoriels. Par exemple, l'empreinte carbone des véhicules électriques dépend du mix électrique, une question qui a fait l'objet d'une attention considérable mais de peu d'analyses économiques. Ce chapitre aborde la question de la coordination des politiques sectorielles, en particulier lorsqu'une tarification du carbone pigouvienne n'est pas réalisable.

Il analyse la répartition optimale des efforts d'abattement entre deux secteurs connectés verticalement, un secteur en amont (*e.g.*l'électricité) et un secteur en aval (*e.g.*les transports). Chaque secteur produit un bien homogène avec deux technologies, une polluante et une propre. La technologie propre en aval (*e.g.*le véhicule électrique) consomme une partie de la production en amont et peut déplacer la production vers ce secteur. À l'aide d'un modèle d'équilibre partiel, nous relions le concept de coût marginal d'abattement à celui d'analyse de cycle de vie. Nous proposons une caractérisation indiquant l'ordre de mise en œuvre des options. La version décentralisée du modèle nous permet de caractériser le niveau et la coordination de politiques optimales de second rang en présence d'une taxation imparfaite des GES, et de caractériser les pertes sociales provoquées par des politiques non coordonnées. Enfin, nous illustrons nos résultats analytiques avec une illustration numérique.

[1]Collaboration avec Guy Meunier

Chapitre 4 : Interactions entre mobilité électrique et énergie photovoltaïque[2]

Le solaire photovoltaïque et le véhicule électrique sont deux technologies disruptives dans les secteurs de l'électricité et des transports. Toutes deux créent de nouveaux enjeux dans les réseaux électriques. De nombreuses travaux ont indiqué qu'il existe un potentiel de synergie entre ces deux technologies. Celle-ci permettrait d'alléger leur effets potentiellement négatifs sur les réseaux électriques et, dans le même temps, d'apporter à chaque technologie des spécificités de l'autre. Par exemple, les véhicules électriques chargés avec de l'énergie photovoltaïque bénéficieraient d'une électricité à faible coût et bas-carbone. En retour, les systèmes photovoltaïques pourraient profiter de la flexibilité bidirectionnelle des batteries des véhicules pour maximiser leur autoconsommation. Grâce à cette synergie, la rentabilité des deux technologies s'amélioreraient et leur développement conjoint pourrait donc être stimulé. L'objectif de ce chapitre est de développer un cadre systématique afin d'analyser les aspects techniques et économiques des sytèmes accueillant les deux technologies. Nous abordons ces questions à l'aide d'une revue de littérature et mettant en évidence les conditions pouvant mener à une synergie.

Chapitre 5 : Tarification des réseaux d'électricité en présence de consommateur actifs et de mobilité électrique [3]

Les ressources énergétiques distribuées (RED), principalement sous la forme du solaires photovoltaïques ou des batteries lithium-ion, et les véhicules électriques (VE) apparaissent comme trois innovations perturbatrices des réseaux électriques. Des études récentes ont mis en évidence les synergies potentielles entre ces technologies, tandis

[2]Hoarau, Q., & Perez, Y. (2018). Interactions between electric mobility and photovoltaic generation: A review. Renewable and Sustainable Energy Reviews, 94, 510-522.

[3]Hoarau, Q., & Perez, Y. (2019). Network tariff design with prosumers and electromobility: Who wins, who loses?. Energy Economics, 83, 26-39.

que d'autres ont étudié la difficulté de concevoir un tarif de réseau adéquat lorsque les consommateurs peuvent adopter des RED. Dans ce chapitre, nous comblons les lacunes des deux pans de la littérature en étudiant l'effet combiné des RED et des VE sur la conception des tarifs. Pour étudier ces effets, nous utilisons un modèle à deux niveaux qui saisit le conflit entre un régulateur et les utilisateurs du réseau. Au niveau inférieur, les consommateurs actifs peuvent réagir aux changements de tarifs en installant des RED et en adaptant la recharge de leur VE. Au niveau supérieur, le régulateur conçoit les tarifs du réseau en imposant le recouvrement total des coûts du réseau et en anticipant les comportements des utilisateurs du réseau. Nous étudions les variations du niveau des tariffs en fonction des différents niveaux de pénétration des VE et de la proportion de consommateurs actifs. L'influence de la structure tarifaire est également étudiée. Premièrement, nous avons constaté que l'augmentation des redevances de réseau causée par les RED peut être compensée par la diffusion des VE dans le réseau. Deuxièmement, nous soulignons que l'adoption des VE et celle des RED produisent des incitations négatives l'un sur l'autre. Troisièmement, nous avons constaté que plus une structure tarifaire offre des incitations pour les DER, moins elle est avantageuse pour les VE, et vice-versa.

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ÉCOLE DOCTORALE N°630
DEM pôle Économie - Management

Titre : Du pot à la prise : économie de la transition énergétique du secteur automobile

Mots clés : Transition Energétique, Economie de l'Environnement, Politiques Publiques, Pollution Automobile, Véhicule Electrique, Ressources Energétiques Distribuées

Résumé :
Le développement de la mobilité électrique est le principal compromis technologique qui peut permettre au secteur automobile de réduire drastiquement ses émissions de gaz à effet de serre et de polluants locaux. Du retrait des véhicules thermiques à l'intégration des véhicules électriques dans le système électrique, cette thèse étudie plusieurs aspects économiques de cette transition énergétique.
Le premier chapitre étudie empiriquement les effets des politiques urbaines de restriction de circulation des véhicules les plus polluants, en analysant les comportements des vendeurs de voitures sur les marchés locaux de l'occasion.
Le second chapitre étudie théoriquement la coordination optimale de l'électrification du parc automobile avec la décarbonisation du système électrique. Il donne notamment des recommandations quant à l'alignement de politiques sectorielles.
Le troisième poursuit en détaillant les interactions entre mobilité électrique et énergie photovoltaïque. Il développe un cadre d'analyse mettant en évidence les conditions techniques et économiques de ces interactions donnant lieu à une synergie.
Le quatrième chapitre discute des effets distributifs de la tarification de l'accès aux réseaux électriques en présence de développement conjoint de la mobilité électrique et sources de production d'électricité décentralisées.

Title: Out with the Pipes, in with the Plugs: on the Economics of the Energy Transition in the Automobile Sector

Keywords : Energy Transition, Environmental Economics, Public Policies, Automobile Pollution, Electric Vehicle, Distributed Energy Resources

Abstract:
The development of electric mobility is the main technological compromise that will allow the automobile sector to drastically reduce its emissions of greenhouse gases and air pollutants. From the ban of thermal vehicles to the integration of electric vehicles in the power sector, this dissertation investigates several economic aspects of this transition.
First, it empirically studies the impacts of urban policies that limit the access of most polluting vehicles by analyzing the behavior of car sellers on second-hand markets.
Then, it theoretically precises the optimal conditions for governments to support the electrification of the automobile fleet concomitantly to the decarbonization of power system.
Third, it investigates the interaction between electric mobility and photovoltaic energy. It develops a systematic framework that enlightens technical and economic conditions of synergy.
Fourth, it discusses the distributional effects from tariff design of power networks with both distributed energy resources and electric mobility.

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