

Sustainable fleet operations: The collaborative adoption of electric vehicles

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We study the impact of collaboration on the adoption of electric vehicles (EVs) among commercial fleets. Using cooperative game theory, we characterize the joint payoffs for the primary stakeholders in the EV adoption decision – the fleet manager, auto manufacturer, and electricity supplier – to determine the conditions under which EVs become economically feasible for commercial fleets. We do so in two settings. We first analyze a scenario where all three stakeholders cooperate in the EV adoption decision, a setting pertinent in regions such as France where a national electricity supplier makes such an arrangement feasible. We next analyze a scenario where the fleet manager and auto manufacturer cooperate but the electricity supplier participates as an independent actor, a setting pertinent in regions such as the United States where no single electricity supplier possesses sufficient market scope to become involved in the EV decision on a national scale. We show that convex per unit EV production costs drive a boundary solution for both the two- and three-party coalition EV adoption decision. We also illustrate the impact of carbon and operating cost advantages of EVs relative to internal combustion vehicles on the adoption of EVs and complementary vehicle-to-grid technology. Comparing the regions of EV adoption within the two coalition settings provides insights into the value of the electricity supplier’s cooperation and the conditions under which intermediation to promote such cooperation can add value.

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1. Introduction

Ground transportation generates approximately 23% of global carbon dioxide equivalent (CO₂e) emissions (International Energy Agency 2009), and electric vehicles (EVs) represent one of the most promising avenues to reduce this impact. EVs can eliminate up to 100% of internal combustion vehicle (ICE) emissions, depending on the technology employed to produce the electricity needed to recharge EV batteries. While current EV performance limitations make them infeasible for some applications such as long-haul operations, they are well-suited for fleets specializing in “last mile” delivery services such as postal operators and short-haul commercial service providers (e.g., DHL, FedEx, TNT, UPS, etc.).

Most of the existing literature on fleet management, including the EV adoption decision, focuses on a given fleet manager’s internal cost drivers, based on the implicit presumption that prices and technology choices will be mediated by the market. In the case of EVs and other “infant” technologies being considered as part of sustainable transportation, the principal challenge in evaluating fleet replacement choices goes beyond these (still important) internal drivers. In many cases, cooperation among external stakeholders is necessary to trigger initiating investments in the new technologies, so one must also understand the hurdles and opportunities of these potential partners. This cooperation among independent stakeholders and the conditions leading to EV adoption are the central problem we address in this paper. We consider the decision of a fleet manager who faces the requirement to replace a fixed stock of vehicles with some combination of EVs and ICEs, while also considering the decision of the auto manufacturer on whether to produce and how to price EVs, and by the electricity supplier on whether to connect EVs to the grid through vehicle-to-grid (V2G) technology. In line with standard fleet practice we assume that vehicles will be leased for a finite period and then resold into the used vehicle market.

The evaluation of EV versus ICE traction systems is of interest to several stakeholders including fleet managers, auto manufacturers, and electricity suppliers. In addition to potential reputation benefits resulting from reduced environmental impacts, EVs also offer fleet managers more measurable benefits relative to ICEs. EVs provide fleet managers an estimated 50% reduction in maintenance costs due to their simpler drive train (USPS-OIG 2009), and reduced operating costs – due to lower estimated per mile electricity costs versus per mile gasoline costs. From the perspective of established auto manufacturers, EVs are emerging as a new competitive frontier due to their environmental benefits. Large auto manufacturers are further motivated to enter the EV market by the threat from new entrants specializing in EV drive-train technologies. Finally, the electricity supplier gains incremental (and typically off-peak) demand through the adoption of EVs, as well as energy storage for frequency regulation and contingent load management through V2G operations.

Despite the advantages that EVs can offer, the technology suffers from a classic catch-22: mainstream EV adoption among profit-maximizing commercial fleets requires the technology to be economically preferred to ICEs; however, for EVs to be economically preferred, the auto manufacturer must see mainstream volumes in order to achieve the necessary learning and scale economies. In such a setting, mainstream EV adoption is unlikely without collaboration. To understand the impact of such collaboration, and the conditions under which EVs could become an economically feasible solution for commercial fleet vehicle replacement, we characterize the joint payoffs for the parties described above using cooperative game theory.

We focus on a cooperative game incorporating three basic elements of the EV decision: production and sales of EVs by the auto manufacturer, their operation by the fleet manager and their

interconnection with the electricity supplier for recharging and V2G services. We first consider a setting where the fleet manager, auto manufacturer and electricity supplier partner in evaluating the feasibility of electric vehicles. Such a setting is pertinent in countries such as France, where La Poste (the national postal operator), Renault (a major auto manufacturer), and Électricité de France (EDF, the national electricity service provider) are currently evaluating the EV opportunity. We then consider a partnership between the fleet manager and auto manufacturer, with the electricity supplier acting independently – i.e., the electricity supplier can benefit from EV adoption by investing in V2G services, but it is not directly involved in the adoption decision. This scenario represents settings such as in the United States where no single electricity supplier possesses the market scope to become involved in the EV decision on a national scale.

We show that the convexity of EV production costs leads to an all-or-nothing boundary solution for EV adoption. Similarly, a comparison of V2G infrastructure costs to grid efficiency gains leads to boundary solutions for V2G adoption. This results in three regions of adoption in both the two- and three-party coalition settings: zero adoption of EVs and V2G services, full adoption of EVs with no adoption of V2G services, and full adoption of both technologies. Contrasting the regions of adoption for the two- and three-party coalition scenarios provides insights on the value of the electricity supplier’s cooperation. Such a contrast also provides insights on the conditions under which an outside player can influence the adoption of EVs by the primary stakeholders. Understanding these conditions is crucial for firms currently betting on the emergence of a mass market of electric vehicles, such as Better Place and Chinese BYD¹, and for national governments interested in mitigating CO₂e emissions.

The remainder of the paper proceeds as follows; within the next section, we position this work relative to the existing literature. Section 3 evaluates the motivation, costs, and revenues for the key stakeholders involved in EV decision: (i) the fleet manager, (ii) the auto manufacturer, and (iii) the electricity supplier. Section 4 solves the cooperative game when the fleet manager, auto manufacturer, and electricity supplier all participate as active players. Section 5 considers the game where the electricity supplier acts in its traditional role as an arm’s length supplier of electric power and connection infrastructure. By contrasting these scenarios, in Section 6 we explore the value of extending the partnership paradigm to include the electricity supplier and the role of potential intermediaries in facilitating EV adoption. Finally, key implications and directions for future research are discussed in Section 7.

¹ For a discussion of the Better Place business model and related research issues, see Avci et al. (2011).

2. Relation to the Literature

The literature underlying this paper comes from several areas. The foundation for this work is the field of sustainable operations (see Kleindorfer et al. 2005 for a review), which expands the study of profit-oriented operations management to encompass the environmental and social impacts of industrial operations. This paper extends the scope of the sustainable operations literature to fleet replenishment decisions. The paper also contributes to the innovation and product/process design literature, and in particular to the area of green innovation (e.g., Day and Schoemaker 2010). This literature makes the basic point that innovation rarely arises from working harder with the same mental model of operations that has driven past success. Rather, what is required is a new lens through which to see new possibilities, enriched by active engagement with customers, suppliers and other external stakeholders (e.g., von Hippel 1988). It is precisely this new lens for managing fleet operations that is provided by the sustainability paradigm, a spark to motivate fleet managers to look beyond the traditional approach to fleet management to new sources of risk and opportunity that they may otherwise overlook. That spark manifests here as an extension of the purchasing paradigm to include the electricity supplier or an intermediary representing diffuse public interests in more sustainable transport.

Pisano and Verganti (2008) provide a framework defining various forms of collaborative innovation based on the openness and hierarchy of the collaborative partners. Within this framework, both flat and hierarchical forms of collaborative innovation are relevant in the current context, but the setting is better suited to a closed collaborative architecture. This combination leads to roles for both a consortium and an elite circle. Pisano and Verganti define a consortium as a closed group of participants who pool a set of assets and share the costs, risks and/or challenges of innovating while collectively selecting a solution. As we will see, there is incentive in the current context for fleet managers to form such a consortium, pooling their demand for new vehicles to facilitate the adoption of EVs by increasing auto manufacturer learning effects and economies of scale. On the other hand an elite circle, as defined by Pisano and Verganti, is a select group of collaborative partners chosen by one member who also selects the solution. Within the current context, the partners of the elite circle include the fleet manager (or consortium of fleet managers), the auto manufacturer, and the electricity supplier or mediating partner(s). Within this framework, the fleet manager sits atop the circle's hierarchy and is ultimately responsible for the EV solution selected, while the auto manufacturer and electricity supplier can choose to opt in or out.

This paper also explores “co-opetition” as an element of the EV-adoption decision (Brandenburger and Nalebuff 1996). This term connotes the nature of strategies in many businesses that are characterized both by the need to cooperate in setting standards and rules of play as well as the need to compete once these rules have been established in order to ensure efficient outcomes.

In the present context, as noted above, collaboration between fleet managers, auto manufacturers, and electricity suppliers is a necessity to define proper vehicle characteristics and their interactions with the electricity grid if EVs are to play a role in commercial fleets. Further collaboration with providers of infrastructure and governmental entities may also be necessary in aligning company strategies with the broader social and environmental objectives and in ensuring that laws and regulations implementing these objectives are economically sensible. Such collaboration is characterized by both elements of sharing and partnership (the cooperative elements) as well as the need to define how the resulting larger pie is to be shared among the actors (the competitive elements). As we will see in the discussion below, the co-opetition framework provides valuable insights in understanding the EV commercial fleet planning problem studied here. This paper adds to the co-opetition literature an example from sustainable operations where the rationale for collaborative innovation is based on the significant start-up costs that are present for multiple players, each of which must contribute an essential and unique asset for the innovation to succeed.

In terms of fleet operations, capacity decisions, routing decisions, and supporting optimization procedures are well advanced in the transportation literature (see Ghiani et al., 2004, for a survey). Replacement and leasing choices, including those for EVs, have been explored and are based on considerations of total expected life-cycle costs of alternatives. The literature of asset replacement distinguishes between serial and parallel replacement. Most of the research has been tracing the issue of serial replacement where a deteriorating piece of equipment (such as a machine or a vehicle) is replaced with a new one in a manner minimizing total cost of operation. Classical examples include works of Bellman (1955), and Drinkwater and Hastings (1967). Parallel replacement models, such as those of Karabakal et al. (1994) and Keles and Hartman (2004), on the other hand are concerned with replacement schedules of a group of assets that are economically interdependent. It is clearly the latter, parallel replacement models, that are relevant for fleet operations. In the model developed here, two alternatives for replacement (EVs and ICEs) are considered. A more detailed discussion of the asset replacement literature in the context of the EV adoption decision, including the effects of uncertainty (in fuel and battery prices) is provided in Neboian et al. (2010), which builds on the framework developed here using a real options model to solve for near-optimal EV-ICF replacement decisions in a dynamic setting.

Given our focus here, it is appropriate also to note on-going studies related to sustainable transportation and commercial fleet operations. In the postal sector, which serves as the motivating example for this paper, a number of studies have started in this area. These include Buc et al. (2010), Ravnitzky (2009) and USPS Inspector General (2009). These studies make a strong case for the importance of carbon footprinting and the potential contribution of EVs in lowering transportation costs while simultaneously reducing carbon emissions from USPS operations. The analysis of

carbon footprinting and related sustainability value for public organizations is in its infancy. In the postal sector, including fleet operations, work to date is summarized in Buc et al. (2010). Orsato (2009) provides a broader framework for valuing firm-level sustainability strategies. This paper makes a contribution to this stream of literature by framing the commercial fleet replenishment problem in terms that integrate the long-term profit impacts of the EV decision with the hurdles that must be overcome to promote innovation.

In summary, the present paper contributes to the literatures on fleet replenishment and sustainable operations in framing the fleet replenishment problem in terms of the strategic innovation game between the major stakeholders whose co-investments are required for EVs to be feasible. This is a different approach to the standard fleet replenishment problem, which treats the supply and pricing of vehicles and fuels as the result of available competitive markets, and exogenous to the fleet replenishment decision itself. Under these traditional assumptions, the primary concerns for the fleet operator are internal and focus on the optimization of expected costs over a suitable time horizon. The EV decision, like many nascent technology choices, however, requires going beyond these internal cost drivers to encompass the incentives of potential external partners to participate in the launch of the technology. This paper proposes a cooperative game theory framework to capture the principal drivers underlying the collaborative innovation necessary for EV adoption in commercial fleet operations.

3. Principle Stakeholders in Sustainable Fleet Management

In this section, we consider the interests and constraints of each of the major stakeholders involved in the EV versus ICE vehicle decision. These primary stakeholders are denoted $\mathcal{N} = \{F, A, S\}$, with F indicating the fleet manager, A indicating the auto manufacturer and S indicating the electricity supplier. In this cooperative game, the fleet manager has demand for K vehicles (i.e., replacements and/or fleet growth), choosing the vehicle type $v \in \mathcal{V} = \{E, I\}$ for each new vehicle acquired, where E represents an EV and I represents an ICE. Table 1 summarizes this set notation.

Variable	Set	Elements
$n = \text{stakeholder}$	\mathcal{N}	$F = \text{fleet manager}$ $A = \text{auto manufacturer}$ $S = \text{electricity supplier}$
$v = \text{vehicle technology}$	\mathcal{V}	$E = \text{electric vehicle}$ $I = \text{internal combustion vehicle}$

Table 1 Variables, sets and elements for stakeholders and vehicle technologies.

We imagine the following choice setting. A fleet manager must replace K vehicles at a fixed point in time through some combination of EVs and ICEs, where K is exogenously specified by the demand requirements on the fleet. Once the vehicles are purchased or leased, they will be operated

for L periods (where L can be thought of as a fixed leasing period), and thereafter resold in the used vehicle market. We denote the number of EVs leased as $x \leq K$, so the number of ICEs leased is $K - x$. The electricity supplier (or partner) decides to provide V2G infrastructure to connect $y \leq x$ EVs to the grid. The problem that we consider is a static, or one-shot, problem. Framing the problem in this manner corresponds to the recurrent fleet replenishment choice faced in practice, where successive waves of vehicles reach the end of their lease life and come due for replenishment. Each such decision would take the form of the problem stated here.

We treat total vehicle demand as determined by the fleet manager's route planning and as exogenous to the problem of vehicle technology choice. Further, we assume that the EV versus ICE decision would only be undertaken for those routes where EV distance constraints (due to battery charge limits) are non-binding. These assumptions are non-limiting for many delivery-type fleets. For example, the average daily usage vehicle route at La Poste is approximately 30 miles per vehicle per day, which is well within the 60-mile per battery charge constraint of existing EV technology (see, for example, The Economist 2009, December 12).

A set of technology-specific prices \mathcal{P} are important, with these prices in period t given by $P_{v,t}^i$ (we suppress t when $t = 0$), where $i \in \{l, r, e\}$, and l indicates the vehicle leasing price, r indicates the vehicle resale price, and e indicates the vehicle electricity/energy price per mile. We assume that the per vehicle leasing price, $P_v^l(z) = P_{v,0}^l(z)$, depends on the number z of each vehicle type leased, x for EVs and $K - x$ for ICEs, but that all other prices are independent of the fleet manager's decisions. Two additional prices are relevant in the context studied here: P_t^c , the CO2e emissions allowance price in period t which represents the value the fleet manager can acquire for emissions improvements; and P_t^b , the price paid to the fleet manager in period t for making EV batteries available as reserve power through V2G services. As we note below, solutions are independent of inter-agent transfer prices, $\mathcal{P} \setminus \{P_{I,t}^e, P_t^c\}$, as long as those prices do not violate the stakeholder participation conditions that follow. Table 2 summarizes each of these prices.

EV relevant prices	ICE relevant prices
$P_E^l(x)$ = Per vehicle EV leasing price for x vehicles	$P_I^l(K - x)$ = Per vehicle ICE leasing price
P_E^r = Discounted EV resale price	P_I^r = Discounted ICE resale price
$P_{E,t}^e$ = Electricity cost per mile	$P_{I,t}^e$ = ICE fuel (i.e., energy) cost per mile
P_t^c = CO2e emissions allowance price	
P_t^b = Battery reserve price (i.e., V2G availability price)	

Table 2 Prices relevant to EVs and ICEs that impact the vehicle replenishment/acquisition problem.

We now consider each of the stakeholder perspectives, their revenue drivers, and their cost drivers with respect to the EV vehicle replacement decision.

3.1. Fleet manager's perspective

For the fleet manager, there are a number of factors that favor the transformation to electric or hybrid vehicles. First and foremost, EVs are an appropriate technology for most “last mile” collection and delivery services (Ravnitzky 2009). Recall the example of La Poste, where the vast majority of daily usage of vehicles routes are well below the 60-mile range that is easily achievable with current technologies. Indeed, due to regenerative braking power, the many required stops in “last mile” delivery services favor EV technology.

In those settings where EV technology is applicable, it offers the fleet manager many advantages over ICE technology. Due to its less complex drive train, EV maintenance costs are estimated to be 50% less than ICE maintenance costs (USPS-OIG 2009). Concerning operating expenses, fuel/electricity cost per mile can be expected to be significantly lower for EVs than for ICEs at current prices, with average cost per mile estimates of 13.7 euro cents for EVs and 15.2 euro cents for ICEs. This difference is likely to grow given the expected increases in gasoline and diesel prices relative to electricity over the coming decades².

Finally, concerning environmental benefits, EVs provide between a 12.5% and 100% decrease in CO₂e relative to ICEs, depending on the mix of electricity generation used to recharge EV batteries. For France, for example, where nearly 80% of electric power produced is generated by nuclear power, a switch to EVs would eliminate an estimated annual 1.8 tons of CO₂e per vehicle for a delivery provider such as La Poste. Over its fleet of approximately 45,000 vehicles, this would amount to an annual reduction of 81,000 tons of CO₂e, or an estimated value of 2.4 million euro per year in Joint Implementation emissions allowances (at a forecasted EU-ETS Phase III allowance price of 30 Euro)³. Further, environmental improvements resulting from a switch to EV technology could yield reputational benefits monetizeable through price premiums or increases in market share.

However, EVs also lead to additional costs relative to ICEs. These costs result primarily from increased lease prices, and battery replacement costs. We capture battery replacement costs in EV maintenance costs, where $M_{v,t}$ is the maintenance cost in period t for vehicle technology v .

In considering the fleet manager's problem, let L represent the leasing or ownership period (typically 5 to 6 years), δ represent the discount factor, α_v represent the emissions intensity (CO₂e emissions per mile) of type v vehicles, and d_t represent the average distance traveled by a vehicle in the consideration set during period t (assumed to be given by the fleet manager's route planning,

² As recorded, for example, in the International Energy Associations reports at <http://www.iea.org/>.

³ We refer readers unfamiliar with Joint Implementation allowances or the phases of the EU-ETS to Mansanet-Bataller and Pardo 2008 for a discussion.

and to be less than the EV limit per battery charge). To simplify notation, let ε^c be the per vehicle value of emissions improvements resulting from a switch from ICEs to EVs, where

$$\varepsilon^c = \sum_{t=1}^L \delta^t (P_t^c d_t (\alpha_I - \alpha_E)).$$

We define $R_n(x, y, \mathbf{P})$ as the revenues stakeholder n earns through the vehicle replenishment decision, where \mathbf{P} is the vector of prices. For the fleet manager, we can imagine various forms for reputation benefit and revenues from carbon markets resulting from the purchase of EVs. Such reputational benefits are likely to require a minimum-sized investment in EVs to be visible, which perhaps implies that reputational benefits are convex in x until a minimum size is reached and then concave. However, for the present analysis, we treat only revenues from carbon credits and from V2G services provided by the fleet manager's EVs. Therefore, the fleet manager earns

$$R_F(x, y, \mathbf{P}) = \varepsilon^c x + \sum_{t=1}^L \delta^t (P_t^b y). \quad (1)$$

Denoting by $C_n(x, y, \mathbf{P})$ the cost stakeholder n incurs as a result of vehicle replenishment, the fleet manager incurs

$$C_F(x, \mathbf{P}) = \left(P_E^l(x) - \delta^L P_E^r + \sum_{t=1}^L \delta^t (d_t P_{E,t}^e + M_{E,t}) \right) x + \left(P_I^l(K - x) - \delta^L P_I^r + \sum_{t=1}^L \delta^t (d_t P_{I,t}^e + M_{I,t}) \right) (K - x). \quad (2)$$

3.2. Automotive manufacturer's perspective

Current levels of performance make EVs suitable for specialized applications, particularly for applications requiring multiple stops within a short range. Indeed, niche markets for EVs have always existed and, because the volumes are on the order of a few thousand cars, they have been supplied by specialized manufacturers. Large auto manufacturers have mostly ignored such markets because their systems of production have been designed for break-even points at above 100,000 vehicles per year (Nieuwenhuis and Wells 1997). Put simply, in order to make money, *volume* manufacturers need to sell cars on the order of hundreds of thousands a year. Therefore, for EVs to become a viable mainstream option, auto manufacturers need a level of market presence and business longevity that small niche customers are not able to guarantee. Satisfying the levels of volume necessary for the required economies of scale will require the formation of customer consortia, as even the largest commercial fleets could not provide the required volume alone⁴. However, auto manufacturers are motivated to see EVs become a viable mainstream option.

⁴ In this regard, a buying consortium has been established in France to solicit bids from qualified automotive manufacturers. This consortium established after a first feasibility study under the management of the CEO of La Poste includes several major fleet operators in France. It will act both to coordinate standardized design features for EVs purchased by members of the consortium as well as to assure an order of sufficient size for the winning suppliers (of both autos and batteries) to act as a major stepping stone to achieving minimum production volumes. For details, see Barneoud (2010).

Over the last quarter century, auto manufacturers have faced significant pressure to reduce the environmental impact of their vehicles. Perhaps as a consequence, by the late 2000s, the environmental advantages of EVs started to be seen as a potential source of competitive advantage for the next generation of cars. Carlos Ghosn, the CEO of both Renault (France) and Nissan (Japan), has been a prominent advocate of this view (Autonews 2010, December 15), but he is not alone. Most carmakers have made public their intention to have several EVs in their vehicle portfolios within the next five years (Autonews 2010, December 13). After substantial efforts to improve the environmental performance of ICEs, the most promising avenue for further advances seems to be the electric power train. In terms of environmental performance, a lightweight electric vehicle outperforms a conventional automobile in almost every aspect. In addition to the environmental advantages of EVs over ICEs during their use, Whitelegg (1993) points to their reduced energy requirements during production and greater recyclability as further environmental benefits.

In addition to the environmental advantages of EVs over ICEs, executives in the car industry further justify investments in EVs on the basis of a potential breakthrough in battery technology. If EV range per charge can be improved dramatically, it will not only solve the problem of automobile emissions but it would also help auto manufacturers reduce their dependency on oil – a recognized weakness for the long-term survival of the industry (Orsato and Wells 2007). As a result, battery technology could represent a major *first mover advantage* for car companies.

For the auto manufacturer’s problem, we assume that the same firm supplies both EVs and ICEs for the fleet manager. We also assume that the auto manufacturer buys back the vehicle after the leasing term. Therefore, the auto manufacturers revenues are

$$R_A(x, \mathbf{P}) = \left(P_E^l(x) - \delta^L P_E^r \right) x + \left(P_I^l(K - x) - \delta^L P_I^r \right) (K - x). \quad (3)$$

We define $\gamma_E^p(z)$ as the average cost to produce an EV when the auto manufacturer produces z EVs, and γ_I^p as the average cost to produce an ICE (we assume scale economies for ICEs have been exhausted). We assume $\gamma_E^p(z)z$ is increasing and concave in z (i.e., marginal cost is less than average cost). EV economies of scale to be determined not only by the fleet manager’s EV demand, x , but also by EV demand from others, D_E . Therefore, the auto manufacturer’s costs are

$$C_A(x, \mathbf{P}) = \gamma_E^p(D_E + x)x + \gamma_I^p(K - x). \quad (4)$$

3.3. Electricity supplier’s perspective

For the electricity supplier (ES), the electrification of major commercial fleets offers new sources of demand of a particularly favorable variety, namely off-peak demand. In addition, under vehicle-to-grid (V2G) operations, batteries connected for recharging can also provide backup power for a number of purposes, including contingent load (in the event of failure of a generating unit

connected to the grid), regulation (fine tuning the necessary instantaneous balance between supply and demand on the grid), reactive power (providing local phase-angle corrections important in AC networks), and load-following reserves (necessary in particular to back up and absorb variations in power provided by renewables such as wind and solar).

Since the earliest days of major grids in the late 19th century, electricity has remained essentially a non-storable commodity. Some sources of power, such as hydro, can be varied within wide limits, however it is primarily gas turbines running as spinning reserve that provide the reserve energy for contingent power and regulation. The appeal of major commercial EV fleets in this regard is the possibility of using the batteries of such vehicles when they are not on the road as a source of reserve power and buffering for the grid. This entails some costs in connecting and controlling these batteries for bidirectional flows, and the challenges of doing so are non-trivial. However, given current objectives to introduce massive amounts of renewable energy into the grid, the economies of scope between providing both transportation services as well as battery reserves when EVs are not in use are very appealing and are under close scrutiny in several countries. They represent, in fact, a means of adding significant energy storage to the grid, thus alleviating some of the intermittency drawbacks associated with many renewable sources of energy, as well as the well-known peak load challenge associated with electric power demand⁵. In this respect, EVs provide two sources of potential reserve for the grid operator. First, is the use of EV batteries as energy storage and reserve power during the non-use periods of EV life (through V2G services). Second, after batteries have ceased to have the requisite power for effective EV use, they can still provide up to 50% of their rated power for several years thereafter, so that banks of used batteries can provide useful reserves beyond their economic life as the power source for EVs.

We capture this effect by defining $A_{E,t}$ as the value of avoided power generation costs in period t resulting from the availability of the fleet manager's EVs for V2G services. Therefore, the electricity supplier earns revenues from the vehicle replacement problem given by

$$R_S(x, y, \mathbf{P}) = \sum_{t=1}^L \delta^t \left(d_t P_{E,t}^e x + A_{E,t} y \right). \quad (5)$$

Finally, we define $\gamma_{E,t}^e$ as the average kWh production cost in period t , and $\beta_E(z)$ as the total cost when connecting z vehicles to the grid. We assume linear V2G connection costs, so that

⁵ Since the work of Gravelle (1976) and Nguyen (1976), it has been recognized that storage flattens peak prices and leads to significant efficiency benefits by helping to avoid the use of the highest variable cost plants during peak hours. The same economic argument applies to batteries.

$\beta_E(z) = F_E^b z$, where constant $F_E^b > 0$ is the capital recovery and operating cost for a V2G connection over the leasing period⁶. In light of these considerations, the electricity supplier's costs are

$$C_S(x, y, \mathbf{P}) = \sum_{t=1}^L \delta^t \left(d_t \gamma_{E,t}^e x + P_t^b y \right) + \beta_E(y). \quad (6)$$

4. Three-party Partnership and Technology Choice

The stakeholders analyzed in the previous section – the fleet manager, auto manufacturer, and electricity supplier – are all essential players/agents in the strategic game that may give rise to a solution that is a continuation of the status quo or, alternatively, to a switch of the fleet manager's fleet to EVs. We will deal in this section with the simplest version of this problem, assuming risk-neutral preferences and ignoring the role of the Government and the associated public benefits of EVs (we discuss the Government as a potential intermediary in Section 5). The central issues that are highlighted here are the economies of scale in automotive manufacturing and infrastructure costs for harvesting V2G benefits. We deal with the deterministic setting to present and discuss the foundational structure of the problem. We will note extensions of this formulation to capture efficient risk-sharing issues in Section 6 (risk-sharing is not relevant in the context of risk-neutral agents that do not face significant risks of financial distress or other transaction costs affecting their valuation of realized cash flows).

We imagine the following decision or choice context. The fleet manager (possibly together with a consortium of fleet owners) is about to make an irrevocable choice of vehicles on lease with the auto manufacturer for the next leasing period. The number of such vehicles to be replaced is dictated by a fixed requirement of K vehicles in total that must be replaced to meet operational needs.

4.1. 3-party cooperative Nash equilibrium

From the discussion in Section 3, and given the existence of monetary transfers among all parties, any Pareto-efficient solution to the problem of replacing the K vehicles at the present lease period requires the joint maximization of benefits across the three stakeholders, with participation (or individual rationality) constraints determined by existing outside options. Thus, the Pareto-optimal or First-Best problem of choosing the best fleet composition can be stated as

$$\begin{aligned} \max_{x,y} \pi(x, y, \mathbf{P}) &= \max_{x,y} \sum_{n \in \mathcal{N}} R_n(x, y, \mathbf{P}) - C_n(x, y, \mathbf{P}) \\ \text{s.t.} \quad R_n(x, y, \mathbf{P}) - C_n(x, y, \mathbf{P}) &\geq B_{n,0} \quad \forall n \in \mathcal{N} \\ x, y, \mathbf{P} &\geq 0 \\ y &\leq x \leq K, \end{aligned} \quad (7)$$

⁶ If the economic life of the V2G connection exceeds L periods, the capital costs in $\beta_E(z)$ would be determined as those allocated to the periods 1 through L using the principles of depreciation accounting.

where $B_{n,0}$ represents the value of agent n 's alternative or default option.

The reader will note that (7) is the standard Pareto condition associated with the Nash bargaining problem (Nash, 1950) when side payments are possible. Given side payments, the only efficient choice is one that maximizes total net benefits, with the standard Nash solution then determined by choosing transfers among the agents to assure equal payments above their default options. The role of the prices \mathbf{P} is simply to effect the side payments to assure the satisfaction of the participation constraints (i.e., default options). Joint profits $\pi(x, y, \mathbf{P})$ are independent of the inter-agent transfer prices, $\mathcal{P} \setminus \{P_{I,t}^e, P_t^c\}$. To see this, we rewrite the objective function in (7) by substituting (1) through (6) to obtain

$$\max_{x,y} \pi(x, y) = \max_{x,y} \eta x + \lambda y - \psi K - \gamma_E^p(D_E + x)x - \beta_E(y), \quad (8)$$

where

$$\begin{aligned} \eta &= \varepsilon^c + \sum_{t=1}^L \delta^t \left[(M_{I,t} + d_t P_{I,t}^e) - (M_{E,t} + d_t \gamma_{E,t}^e) \right] + \gamma_I^p > 0, \\ \lambda &= \sum_{t=1}^L \delta^t A_{E,t} > 0, \quad \text{and} \\ \psi &= \sum_{t=1}^L \delta^t \left[(M_{I,t} + d_t P_{I,t}^e) \right] + \gamma_I^p > 0, \end{aligned}$$

which is clearly independent of the inter-agent transfer prices, $\mathcal{P} \setminus \{P_{I,t}^e, P_t^c\}$.

Note that $\eta > 0$ results from the presumed superiority of EV maintenance and operating costs (see Section 3.1). The solution to (7) is found by maximizing (8), subject to the constraint $0 \leq y \leq x \leq K$, and then adjusting inter-agent prices, $\mathcal{P} \setminus \{P_{I,t}^e, P_t^c\}$, to assure that individual rationality constraints are satisfied at the solution found. Of course, this can only be accomplished if the optimal solution (x^*, y^*) to (8) satisfies: $\pi(x^*, y^*) \geq \sum_{n \in \mathcal{N}} B_{n,0}$.

There are two regions of interest in the constrained optimization: either $y < x$ and a separable optimization results, given the structure of (8), or $x^* = y^*$. Based on our previous assumptions, $-\gamma_E^p(D_E + x)x$ in (8) is convex. Therefore, the separable optimization of $\eta x - \gamma_E^p(D_E + x)x$ over the interval $[0, K]$ occurs at the boundary, and it is clear that the optimal solution is characterized by the following mutually exclusive conditions:

$$\begin{aligned} [x^* > y^* \geq 0] &\Rightarrow [x^* = K; y^* \in \arg \max_{y \in [0, K]} \lambda y - \beta_E(y)] \\ [x^* = y^* \geq 0] &\Rightarrow [x^* = y^* \in \arg \max_{x \in [0, K]} (\eta + \lambda)x - \gamma_E^p(D_E + x)x - \beta_E(x)]. \end{aligned} \quad (9)$$

As an example, assume the average cost function for EV production, $\gamma_E^p(D_E + x)$, is of the form

$$\gamma_E^p(z) = \begin{cases} \frac{F_E^p}{z} + f_E^p & \text{if } z > 0 \\ 0 & \text{if } z = 0, \end{cases} \quad (10)$$

where F_E^p and f_E^p are positive constants. Then $\pi(x, y)$ in (8) is convex in both arguments and a boundary solution results under either condition in (9). The result is a solution with either $x^* = y^* = 0$; $y^* = 0 < x^* = K$; or $x^* = y^* = K$. Assuming (10), and defining $\chi(z)$ as an indicator equal to 1 if $z \geq 0$ and 0 otherwise, then the optimal solution to (7) is determined as follows:

$$\begin{aligned} \left[F_E^b > \sum_{t=1}^L \delta^t A_{E,t} \right] &\Rightarrow \left[y^* = 0; x^* = K \chi(\pi(K, 0) - \pi(0, 0)) \right] \\ \left[F_E^b \leq \sum_{t=1}^L \delta^t A_{E,t} \right] &\Rightarrow \left[x^* = y^* = K \chi(\pi(K, K) - \pi(0, 0)) \right]. \end{aligned} \quad (11)$$

Define $\pi^x = \eta - \frac{d}{dx}(\gamma_E^p(D_E + x)x)$ as the marginal profit earned by replacing an ICE vehicle with an EV, excluding the value of V2G benefits. Further, define $\pi^y = \lambda - \frac{d}{dy}\beta_E(y)$ as the marginal value of connecting a vehicle to V2G services. Then Figure 1 illustrates three EV adoption regions.

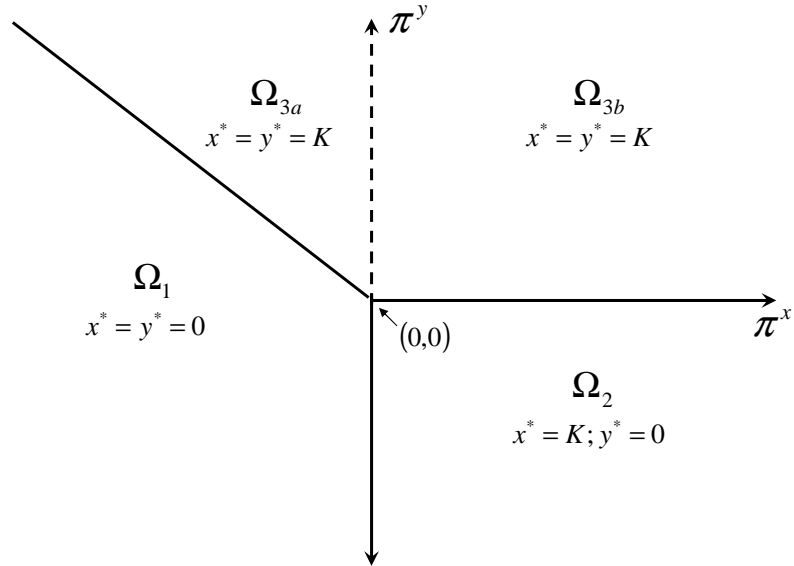


Figure 1 Regions of EV and V2G adoption when all three parties cooperate.

In region Ω_1 marginal benefits from EV replacements and V2G services are not sufficient to motivate adoption. Within Ω_2 , however, the marginal gain from replacing an ICE vehicle with an EV is positive, and the fleet manager would replace all of the vehicles under consideration with EV technology. V2G services are positive, and sufficient to motivate connection of EVs to the grid within Ω_3 , with V2G benefits sufficient to overcome negative direct EV adoption value within region Ω_{3a} . Both the direct value from adoption of EVs and the value of V2G services are positive in region Ω_{3b} . We will revisit these regions when comparing partnership paradigms in Section 6.1.

Consider the upper quadrants of Figure 1 – i.e., the second of the cases in (11) – so that there are some potential benefits from V2G services. Then the condition under which $x^* = y^* = K$ (rather than 0) is

$$\gamma_E^p(D_E + x) - \gamma_I^p \leq \varepsilon^c + \left[\sum_{t=1}^L \delta^t \left[(M_{I,t} + P_{I,t}^e) - (M_{E,t} + d_t \gamma_{E,t}^e) \right] \right] + \left[\sum_{t=1}^L \delta^t A_{E,t} - F_E^b \right], \quad (12)$$

which is a straightforward comparison of the per vehicle benefits of EVs, when $x^* = y^* = K$. The LHS of (12) represents the EV production cost disadvantage, and ε^c represents the monetizeable present value of emissions reductions. The second term on the RHS represents the EV present value advantage in operating and maintenance costs, and the third term represents the present value of V2G services. It is clear from (12) that x^* is increasing (i.e., more likely to be K than 0) whenever $\eta + \lambda$ increases or whenever D_E increases or F_E^b decreases. A similar interpretation is readily apparent for the other terms, all of which comports well with intuition.

5. Two-party Partnership and Technology Choice

There are two practical factors that could inhibit the formation of a partnership between the three stakeholders described above. First, the opportunity to incorporate the electricity supplier into the partnership might not be recognized. Although this may seem trivial (especially under economic rationality), the reality is that the fleet manager and auto manufacturer might have a long history of collaboration with respect to fleet purchases, while the broader partnership including an electricity supplier would be novel, and therefore potentially overlooked. Second, even if the opportunity to incorporate the electricity supplier into the partnership is realized, there might not be a suitable partner within the market. In France, for example, that partner exists with EDF supplying electricity throughout the country. Therefore, a fleet manager operating in France could approach a single electricity supplier to realize the outcomes described in Section 4. However, within many markets, including the United States and Germany, the electricity supply sector involves multiple providers. It is unclear who a commercial fleet manager like the United States Postal Service would approach as an electricity supply partner. Under either of these circumstances – not recognizing the opportunity, or lack of a single electricity supply partner – the fleet manager and auto manufacturer would engage in two-party bargaining and the electricity supplier(s) would act independently, free to invest in V2G services, but not participating directly in the EV-adoption decision. Such is the setting that we explore here.

In evaluating the 2-party partnership setting, the fleet manager and auto manufacturer decide on fleet composition, EVs versus ICEs, while the electricity supplier chooses how many EVs to connect to the grid for V2G services. Notation resembles that of Section 4 except that we use $\hat{\cdot}$ notation for objectives, $\hat{\pi}_n$, and decisions, \hat{x} and \hat{y} . We treat prices for electricity and batteries ($P_{E,t}^e$

and P_t^b , respectively) as exogenous to the EV decision (assuming both are provided in markets that are either competitive or regulated). We consider the electricity supplier's decision first.

5.1. The electricity supplier as an independent player

As an independent player in this game, the electricity supplier can only invest in, and benefit from, V2G services if the fleet manager and auto-manufacturer shift from ICEs to EVs – i.e., if $\hat{x} > 0$.

Given that the fleet manager and auto manufacturer choose to adopt EVs, the electricity supplier will benefit from the incremental demand generated by supplying power for these EVs without taking any action themselves – i.e., the electricity supplier realizes a value of $\sum_{t=1}^L \delta^t [d_t (P_{E,t}^e - \gamma_{E,t}^e)] \hat{x}$ regardless of their own V2G decision. As a consequence, the electricity supplier is less likely to pursue V2G services under this setting than they are when they participate as a cooperative partner in the game, with the following objective in the 2-party partnership setting:

$$\begin{aligned} \max_{\hat{y}} \hat{\pi}_S(\hat{x}, \hat{y}) &= \max_{\hat{y}} \sum_{t=1}^L \delta^t [A_{E,t} - P_t^b] \hat{y} - \beta_E(\hat{y}) + \sum_{t=1}^L \delta^t [d_t (P_{E,t}^e - \gamma_{E,t}^e)] \hat{x} \\ \text{s.t. } \hat{x}, \hat{y}, P_t^b &\geq 0 \\ 0 &\leq \hat{y} \leq \hat{x}. \end{aligned} \quad (13)$$

As stated above, we assume that the battery reserve price P_t^b and price and electricity $P_{E,t}^e$ are exogenous, e.g., as set by the regulator or market. As is intuitive, and as we will see below, these prices could have a determining effect on both the V2G and EV adoption outcomes.

Note that (13) is linear in \hat{y} based on the assumptions on $\beta_E(\hat{y})$. Therefore, $\hat{y}^* = K$ if $\frac{\partial \hat{\pi}_S(\hat{x}, \hat{y})}{\partial \hat{y}} > 0$ and $\hat{y}^* = 0$ if $\frac{\partial \hat{\pi}_S(\hat{x}, \hat{y})}{\partial \hat{y}} \leq 0$, where

$$\frac{\partial \hat{\pi}_S(\hat{x}, \hat{y})}{\partial \hat{y}} = \sum_{t=1}^L \delta^t [A_{E,t} - P_t^b] - \frac{d}{d\hat{y}} \beta_E(\hat{y}). \quad (14)$$

5.2. 2-party cooperative Nash equilibrium

Without the electricity supplier involved as an active player, the fleet manager and auto manufacturer cooperate in the 2-party game described by the following objective:

$$\begin{aligned} \max_{\hat{x}, \hat{y}} \hat{\pi}_{FA}(\hat{x}, \hat{y}, \mathbf{P}) &= \max_{\hat{x}, \hat{y}} \sum_{n \in \mathcal{N} \setminus S} R_n(\hat{x}, \hat{y}, \mathbf{P}) - C_n(\hat{x}, \hat{y}, \mathbf{P}) \\ \text{s.t. } R_n(\hat{x}, \hat{y}, \mathbf{P}) - C_n(\hat{x}, \hat{y}, \mathbf{P}) &\geq B_{n,0} \quad \forall n \in \mathcal{N} \setminus S \\ \hat{x}, \hat{y}, \mathbf{P} &\geq 0 \\ \hat{y} &\leq \hat{x} \leq K, \end{aligned} \quad (15)$$

Substituting (1)-(4) into (15) yields

$$\max_{\hat{x}, \hat{y}} \hat{\pi}_{FA}(\hat{x}, \hat{y}, P_E^e) = \max_{\hat{x}, \hat{y}} \hat{\gamma} \hat{x} + \hat{\lambda} \hat{y} - \hat{\psi} K - \gamma_E^p (D_E + \hat{x}) \hat{x}, \quad (16)$$

where

$$\begin{aligned}\hat{\eta} &= \varepsilon^c + \sum_{t=1}^L \delta^t \left[(M_{I,t} + d_t P_{I,t}^e) - (M_{E,t} + d_t P_{E,t}^e) \right] + \gamma_I^p > 0, \\ \hat{\lambda} &= \sum_{t=1}^L \delta^t P_t^b > 0, \text{ and} \\ \hat{\psi} &= \sum_{t=1}^L \delta^t \left[(M_{I,t} + d_t P_{I,t}^e) \right] + \gamma_I^p > 0,\end{aligned}$$

Note that $\hat{\pi}_{FA}(\hat{x}, \hat{y})$ in (16) differs from $\pi(x, y)$ in (8) through $\hat{\eta}$ where electricity price, $P_{E,t}^e$, replaces electricity production cost, $\gamma_{E,t}^e$; and through $\hat{\lambda}$, where the per vehicle present value of V2G service revenues, $\sum_{t=1}^L \delta^t P_t^b$, replaces the per vehicle present value of V2G cost avoidance realized by the electricity supplier, $\sum_{t=1}^L \delta^t A_{E,t}$.

Recalling the convexity of $-\gamma_E^p(D_E + x)x$, and given the otherwise linear nature of (16), the solution to (15) occurs at the boundary. As a result, there are three possible solutions: $\hat{y}^* = \hat{x}^* = 0$, $\hat{y}^* = 0 < \hat{x}^* = K$, and $\hat{y}^* = \hat{x}^* = K$, which are summarized by the following conditions:

$$\begin{aligned}\left[\sum_{t=1}^L \delta^t [A_{E,t} - P_t^b] \leq \frac{d}{d\hat{y}} \beta_E(\hat{y}) = F_E^b \right] &\Rightarrow [y^* = 0; x^* = K \chi(\hat{\pi}_{FA}(K, 0) - \hat{\pi}_{FA}(0, 0))] \\ \left[\sum_{t=1}^L \delta^t [A_{E,t} - P_t^b] > \frac{d}{d\hat{y}} \beta_E(\hat{y}) = F_E^b \right] &\Rightarrow [x^* = y^* = K \chi(\hat{\pi}_{FA}(K, K) - \hat{\pi}_{FA}(0, 0))].\end{aligned}\quad (17)$$

To illustrate this solution, we define the marginal profit earned by the fleet manager and auto manufacturer partnership for replacing an ICE with an EV as $\hat{\pi}_{FA}^x = \hat{\eta} - \frac{d}{dx} \left(\gamma_E^p(D_E + x)x \right)$, and the marginal value that the electricity supplier realizes for connecting a vehicle to V2G services as $\hat{\pi}_S^y = \frac{\partial \hat{\pi}_S(\hat{x}, \hat{y})}{\partial \hat{y}}$, which is defined in (14). Using these definitions, Figure 2 illustrates EV adoption choices at the optimal solution, (17).

The fleet manager does not invest in EVs within region $\hat{\Omega}_1$, and although they do adopt EV technology in region $\hat{\Omega}_2$, the electricity supplier does not invest in connecting these vehicles to the grid for V2G services. The fleet manager invests in EVs and the electricity supplier enables V2G services in regions $\hat{\Omega}_{3a}$ and $\hat{\Omega}_{3b}$, with the fleet manager choosing to adopt EVs in the former due to the present value of revenues from V2G services overcoming a negative value from the EV versus ICE comparison excluding V2G benefits.

6. Discussion

Factors beyond the scope of the models discussed in Sections 4 and 5 may influence the decisions of firms in both the two- and three-party cooperative game settings. For example, firms engaged in an EV adoption decision in the two-party setting can be influenced by the presence of potential intermediaries. Further, firms in either setting should account for a potential shift in the power generation sector from fossil fuels to renewable sources of energy and for the opportunity to share risk among parties. We focus on these issues here.

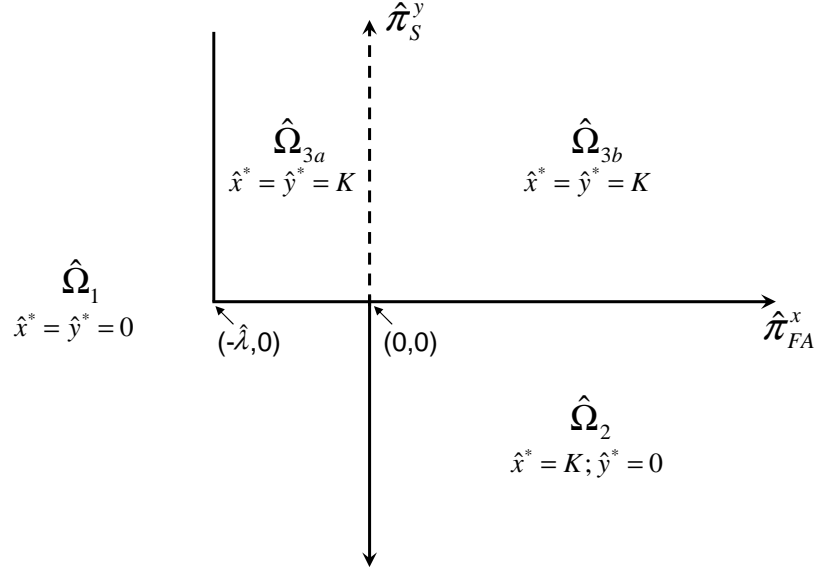


Figure 2 Regions of EV and V2G adoption when only the fleet manager and auto manufacturer cooperate.

6.1. The opportunity for and value of intermediation

The marginal value realized directly from the replacement of an ICE vehicle with an EV (excluding V2G benefits) and the marginal value of V2G services are both greater under the 3-party cooperative game than they when only the fleet manager and auto manufacturer partner. A direct comparison of these marginal values yields

$$\pi^x - \hat{\pi}_{FA}^x = \sum_{t=1}^L \delta^t d_t (P_{E,t}^e - \gamma_{E,t}^e) \geq 0, \quad (18)$$

and

$$\pi^y - \hat{\pi}_S^y = \sum_{t=1}^L \delta^t P_t^b = \hat{\lambda} \geq 0. \quad (19)$$

Due to this difference in marginal value, the regions where the two-party partnership would adopt EV technology (indicated by $\hat{\Omega}_2$, $\hat{\Omega}_{3a}$, and $\hat{\Omega}_{3b}$ in Figure 2) are contained within the regions of adoption under the three-party cooperative setting (indicated by Ω_2 , Ω_{3a} , and Ω_{3b} in Figure 1). This results in regions where an intermediary's actions can influence the outcome of the decision by the fleet manager and auto manufacturer partnership, as illustrated in Figure 3.

Within region Γ_1 , the fleet manager in the 3-party setting adopts EV technology while the fleet manager not partnering with the electricity supplier would not, with the width of Γ_1 determined by discounted electricity supply operating margins as described by the difference in (18). V2G services are not adopted within either the three-party or two-party cooperative settings within Γ_1 . The fleet manager in both cooperative game settings adopts EVs within Γ_2 ; however, V2G services would only be adopted by the three-party partnership within the region. The discounted price of V2G services – i.e., $\hat{\lambda}$, the difference in (19) – determines the width of Γ_2 . Within region

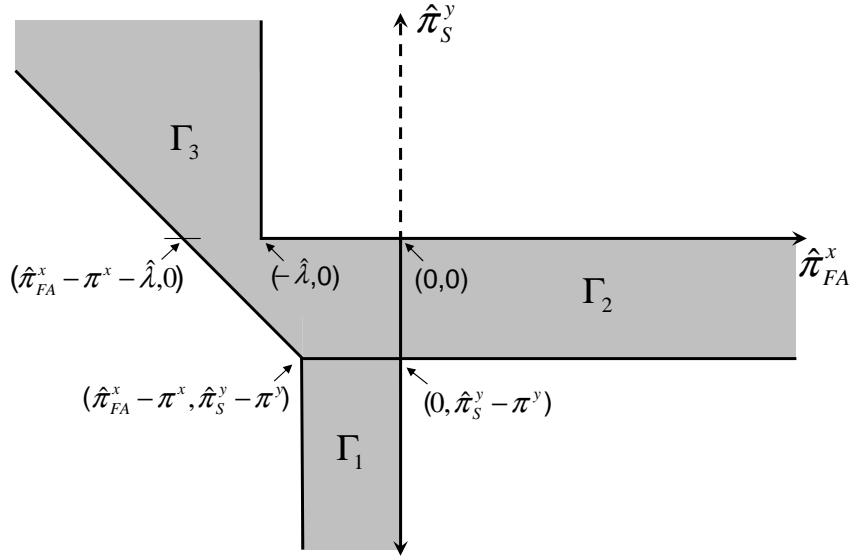


Figure 3 Regions within which intermediation can enable EV adoption and add value.

Γ_3 , the three-party partnership invests in both EV adoption and V2G services, while neither technology is adopted when only the fleet manager and auto manufacturer cooperate. Note that Γ_3 is contiguous, with its leftmost boundary intersecting the x-axis at $\hat{\pi}_{FA}^x - \pi^x - \hat{\lambda} \leq -\hat{\lambda}$, which follows from differences in the marginal value of EV and V2G adoption as indicated by (18) and (19), and from the geometry of the three-party solution given by (11). Within these regions, coordinating intermediation in the two-party cooperative setting would alter decisions and create value as indicated in Table 3.

Region	3-party solution	2-party solution	Value of intermediation*
Γ_1	$x^* = K, y^* = 0$	$\hat{x}^* = \hat{y}^* = 0$	$\pi(K, 0) - \hat{\pi}(0, 0) \geq 0$
Γ_2	$x^* = y^* = K$	$\hat{x}^* = K, \hat{y}^* = 0$	$\pi(K, K) - \hat{\pi}(K, 0) \geq 0$
Γ_3	$x^* = y^* = K$	$\hat{x}^* = \hat{y}^* = 0$	$\pi(K, K) - \hat{\pi}(0, 0) \geq 0$
$\pi(x, y)$ given in (8) = combined profits under the three party partnership			
$\hat{\pi}(x, y) = \hat{\pi}_{FA}(x, y) + \hat{\pi}_S(x, y)$ = combined profits under the two party partnership			
* Marginal “value of intermediation” is determined by (18) and (19)			

Table 3 EV and V2G decisions in both cooperative settings, and the value of intermediation.

All of this raises the natural question as to what organizations or entities would be motivated to act as an intermediary in the two-party cooperative setting, and how they would achieve a coordinated outcome among the three primary stakeholders. We consider two possible intermediaries – a national government motivated by social welfare and possibly financial benefits resulting from emissions mitigation, and a for-profit V2G service provider.

A national government as intermediary. From a public economics perspective, there are two operational concerns in the design of regulatory and tax/subsidy programs to implement CO2e

abatement. The first concern is meeting the requirements of the Kyoto Protocol in a cost-effective manner. The second is valuing the benefits of meeting other public policy objectives such as improved air quality related to reducing atmospheric ozone precursors, promoting better integration of renewables into the electricity grid, and providing a stimulus for achieving the necessary scale to allow economic manufacture of EVs for the broader commercial fleet and private vehicle markets. These issues are sufficiently interesting and complex to warrant separate studies, certainly beyond the ambitions of the present paper. On the matter of cost-effective implementation of Kyoto requirements, national governments of the EU-15 member states that were covered by the original Kyoto Protocol have committed themselves under the negotiated caps to achieve the EU-wide target through country specific targets. Failure to meet these means that the country involved has to purchase the necessary allowances through international offset markets (the CDM and JI markets). Thus, even if the fleet manager does not convert carbon savings into credits in the JI certificate market, there may be good reasons for the national government to provide incentives to them to shift toward an EV fleet as part of the country's accounting for its CO₂e emissions under its national Kyoto Plan.

A V2G service provider as intermediary. The emergence of V2G and battery service providers (e.g., Better Place) suggests the existence of a market space between energy providers and fleet operators. The deployment and management of a recharging grid, as proposed by such providers, entails not only the installment of EV recharging power points but, more importantly, the development of dedicated hardware and software for the control of the entire population of (client) electric vehicles. Aside from the development costs, such an EV “smartgrid” requires dedicated competencies and technology, which are specific to the EV “appliance”. Although electric suppliers can, in principle, dedicate resources and time to build such a system, this seems unlikely in settings where these suppliers operate within a significantly more limited geographic region than the major EV customers (i.e., fleet managers). Similarly, rather than the optimization of the energy supply network, the main concern of fleet operators is the cost associated with the purchase, operation and maintenance of their vehicles. On the other hand, a V2G service provider such as Better Place has straightforward incentives to optimally manage such smartgrid technology.

6.2. Impact of a shift to renewable power on EV adoption

We have treated the costs and pricing of electricity, including related V2G operations, as well as carbon emissions intensity as static in this analysis. In reality, there are complex interactions both in technology planning and in public and regulatory policy that influence these factors over time. For example, motivated by portfolio standards and feed-in tariffs, there are strong incentives in many jurisdictions for expanding renewable energy sources. As renewables such as wind and solar

power are intermittent supply sources, their increased adoption over time will give rise to increased demand for frequency regulation and backup power to support their integration into the existing grid. As a consequence, V2G arising from a significant diffusion of EVs could play a significant role (and V2G service pricing, P_t^b , would likely be impacted), but only if interconnection and local smart-grid control devices are present to enable the integration. Further, a shift over time toward renewable sources of energy would have implications for the carbon intensity of electricity used in recharging EV batteries, potentially altering the per vehicle value of emissions improvements, ε^c , obtained by replacing an ICE with an EV, which would alter the EV-adoption decision. Similarly, this interdependence would affect the technology mix for electricity supply itself – the presence of widely deployed EVs could facilitate increased penetration of renewable energy sources. This suggests that the prices, costs and carbon intensity of electricity supply relating to EV operations arise from a complex and interdependent system impacting the EV-adoption decision given by (11) in the three-party cooperative setting, and by (17) in the two-party cooperative setting, as well as the value of intermediation. These points are central features of the current discussion of the promises of smart-grid initiatives (Kempton et al., 2009).

6.3. Risk sharing in EV adoption

While not captured within the stylized models presented in Sections 4 and 5, the actual EV decision faced by the fleet manager and other stakeholders will be affected by stochastic processes describing developments in the electricity and fuel markets and in the price of batteries. As discussed in Neboian et al. (2010), the appropriate framework for the stochastic problem is a real options approach. Such an approach implies that the vehicle replacement decision at each time period will depend on the state variables describing the current and expected evolution of key pricing and cost variables. The central uncertainties from the fleet manager and auto manufacturer perspectives are focused on two issues. First, the auto manufacturer faces risk from tooling and initial investment costs for EVs related to whether and when they reach minimum optimum scale for annual production and sales. Second, the partnership faces technology risks with respect to developments in battery performance which could directly impact EV demand (and pricing) and indirectly impact the resale value of EVs at the end of their lease period (i.e., older models may lose considerable value if they are not compatible with newer battery technologies). As a result, a variety of risk sharing issues arise for the partnership. These are similar to the multi-party risk-sharing problem originally analyzed by Karl Borch (1967) in the context of insurance markets⁷.

⁷ Since Borch's original exposition in the context of insurance markets, the theory of risk sharing has become central to several fields, including decision analysis (Raiffa, 1970), capital asset pricing theory (Aase, 2002) and principal-agent theory (Laffont and Martimort, 2002).

Several approaches are available to unbundle and price these risks. Concerning the first risk, leaving aside the cost of the EV battery, initial investment costs for new vehicle models are well understood in the automobile industry, as are minimum scale requirements for annual production. The key issue for the auto manufacturer in setting EV prices in the early years will be the expected sales of EVs for the model(s) in question. Total sales to all participants, $D_E + x$, are a key determinant of efficiency in the analysis in Section 4 and 5, and can be expected to be a central determinant of price in meeting the auto manufacturer's threshold return levels. Fleet operators can be expected to cooperate amongst themselves in buying consortia to provide both increases in bargaining power as well as to provide the auto manufacturer additional assurance that it will reach minimum scale.

Concerning batteries, there are non-pricing issues related to risk sharing that are evident in practice. One of the principle non-pricing concerns relates to the unbundling of battery prices from the price of the chassis. This unbundling makes the better understood costs of tooling and assembly line investments for EVs more transparent and leaves room for private companies (such as Better Place and others) to provide battery exchange service and infrastructure for both fleets and individual private owners⁸. Synergies between this unbundling and attaining threshold economies of scale are a matter of great interest to companies in the auto sector currently bringing EVs to market. However the details and value of such unbundled arrangements are yet to be made clear in the market place. Further, the auto manufacturer could transfer some of the risk associated with technology change in battery design to the reinsurance capital market through securitized instruments defined on an index of battery price or performance. What emerges from this discussion is the importance of rigorous study of the risk sharing issues embedded within the EV decision, for which the analysis of Sections 4 and 5 forms the foundation.

7. Implications, Conclusions, and Future Research

Within the preceding sections, we developed a cooperative, game-theoretic model of the EV-adoption decision accounting for the joint payoffs of the three primary stakeholders – the fleet manager, the auto manufacturer, and the electricity supplier. We considered a setting where all three of these stake-holders partner and a setting where only the fleet manager and auto manufacturer partner, reflecting regional differences in the feasibility of involving a national-scale electricity supplier within the EV-adoption decision. Comparison of the resulting EV-adoption regions generated insights into the conditions under which V2G infrastructure intermediation can facilitate broader use of EV technology in commercial fleets. As such, this research has implications for

⁸ This matter is currently being discussed in the context of the Nissan LEAF, one of the EVs for the general market. For details, see <http://earth2tech.com/2010/02/12/nissan-come-get-your-electric-car-in-april-batteries-included/>.

three audiences: the primary stakeholders in the EV-adoption decision; potential intermediaries; and academics conducting research within sustainable operations and fleet management.

For the principle stakeholders in the EV-adoption decision, this research illustrates the value embedded in extending the traditional vehicle replacement paradigm to include EVs as an alternative while incorporating the electricity supplier in the purchasing discussion. Within the stylized settings explored here, this value is indicated in Table 3 above, where the value of intermediation can also be thought of as the value of the electricity supplier's cooperation. Along with this direct implication for the principle stakeholders, this research suggests additional sources of value that can be achieved through partnerships. Auto manufacturer economies of scale are driven by not only the focal fleet manager's volume, but outside volume as well (represented by D_E within the models of Sections 4 and 5).

This suggests that it is in the interest of all stakeholders exploring EV-adoption to contribute to the development of fleet purchasing consortia while, under the traditional paradigm, this effort would fall primarily to the auto manufacturer or to smaller fleet managers attempting to improve their bargaining power. In this spirit, and building on the initiative reported in this paper, La Poste has taken the lead on collaborative innovation in this area in France, coordinating a purchasing alliance across major fleet operators. The objective of this alliance is to increase the leverage of members by aggregating volumes, while also providing the winning automotive and battery suppliers a head start in achieving minimum production volumes. In addition, La Poste has launched a new business venture "Greenovia" to explore and harvest opportunities to assist other fleet managers acquire and operate EV fleets. In the context of the present research, these initiatives address auto manufacturer scale and learning benefits as well as positioning for eventual intra-coalition transfer payments between the fleet manager and auto manufacturer. These collaborative initiatives are naturally expected to have positive profit consequences for La Poste in addition to promoting sustainable fleet operations.

This research also has implications for potential intermediaries within the EV-adoption decision, particularly those with interest in providing V2G infrastructure in regions where electricity supplier participation is less feasible. The regions where intermediation can enable EV adoption – i.e., Γ_1 , Γ_2 and Γ_3 in Figure 3 – illustrate the conditions under which an outside player can create value by influencing the EV adoption decision. For policy makers, these regions in conjunction with Table 3 indicate the social welfare that can be added through intermediation. For organizations interested in for-profit intermediation, Table 3 indicates the upper bound of the value that can be captured by participating in the market.

To our knowledge, this research is the first to model the cooperative game between stakeholders involved in the EV-adoption decision. As such, it provides a foundation for future work for those

studying related issues in sustainable operations and fleet management. Exploring the impact of the auto manufacturer's learning curve with respect to EV production offers a natural direction for extension. Characterizing this learning effect, and endogenizing outside EV demand, D_E , to (costly) efforts by the fleet manager to develop a consortia and to auto manufacturer pricing would be one direction of interest, while extending the model to multiple periods to understand the auto manufacturer's optimal pricing path for this outside demand. It would also be interesting to study the cooperative game described here in a dynamic setting that accounted for the disruptive potential of EVs relative to ICEs. If cumulative experience led to improvements in battery range, then sufficient learning would enable EVs to penetrate additional ICE markets as a "disruptive technology" (Christensen 1997), which would deliver additional value for all three stakeholders studied here. It is generally understood that such scale effects and associated learning by doing in technological progress functions will produce lower prices during product introduction to encourage cumulative learning. However, strategic effects from competitive learning can affect this monotonicity, per Fudenberg and Tirole (1983). Furthermore, monotonicity may also not hold when the stochastic elements affect the rate of learning itself, per Mazzola and McCardle (1997). Finally, the risk sharing issues and the interdependency between EV-adoption and a shift toward renewable sources of energy discussed in Section 6 also deserve further study.

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