The sunny side of green transport policies: the double dividend effect in a two-sided market

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Abstract

Decarbonizing the transport sector is a key measure to reduce carbon emissions at the global level. A crucial factor to achieve a sustainable transport system is the diffusion of electric vehicles. We study the network effects inducing a positive relationship between electric vehicles and charging stations. For that reason we develop a two-sided market model that captures such network externalities. A platform provides, on one side of the market, electric and gasoline vehicles to consumers; on the other side, it supplies retailers with charging stations. We use this framework to study policies tackling different sides of the market. In the presence of network effects and environmental damage from polluting cars, policies can lead to a double dividend: decreasing the quantity of gasoline vehicles can be economically improving, while reducing the negative impact of pollution.

Keywords: network effects, electric vehicles, pollution externality, optimal policies.

JEL codes: H2, L22, L91, R40.

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1 Introduction

In 2014, the transport sector accounted for 23% of the global carbon emissions, making it the second largest contributor after the electricity and heat generation sector. Moreover, road traffic alone accounted for three-quarters of transport emissions (IEA, 2015). Reducing carbon emissions from the transport sector is thus crucial for combating climate change. Electric vehicles (EVs) can play a major role to achieve efficient transportation while lowering emissions. However, economies are far from achieving the potential emission reduction offered by EVs. The reasons for their slow adoption are manifold:[1] among the others, the purchase costs of EVs are still high compared to gasoline vehicles (GVs) and the driving distances are limited. Moreover, the charging infrastructure is still inadequate due to the "chicken-egg" relationship existing between EVs and EV charging stations (EVCSs). The latter hinders a further expansion of the EV market: as the number of EVCSs is low, the value of EVs decreases, limiting EV sales and hence charging stations profitability (Caillaud and Jullien, 2003). To overcome this deadlock, governments use a wide array of policy measures to expand the usage of EVs.[2] Furthermore, cars manufacturers increase their brand specific EVCSs network to spur the adoption of their products. Recently, retailers assumed an important role in providing EVCSs. Shopping malls (such as IKEA, Rewe, Aldi) have started to install charging stations in their parking lots: the aim is to attract costumers who are offered the possibility to charge their EVs while shopping. This class of actors and their interaction with the diffusion of EVs will be the focus of the present work.

To the best of our knowledge, there exists to date little research that explores which policies are optimal to advance EV sales taking into account the network externality between EVs and charging stations. The aim of this paper is to progress in this area by explicitly modeling the relationships between EVs adoption and EVCSs availability. For this purpose, we develop a two-sided market framework with network externalities, which we then use for a study of policies that foster the diffusion of EVs. Moreover, we account for the possibility of substitution between EVs and GVs. In the model, a monopolistic platform sells EVs and GVs to one side of the

[1] See Hidrue et al. (2011); Koetse and Hoen (2014); Helveston et al. (2015); Zhou et al. (2016).

[2] For instance, income-tax credit or deduction for purchase of EVs, reduction of or exemption from purchase or registration tax, free battery charging, free parking, support for the deployment of charging infrastructure, grants for private installation of charging stations.

market (consumers) and EVCSs to the other side (retailers). Two-sided markets are particularly suited to capture the valuation of the existing charging station network by EV owners and of the circulating base of EVs by retailers. We introduce policies tackling the different sides of the market and we study how they affect quantities and prices. Finally, we analyze which policy mix maximizes welfare and how the latter is affected by the presence of a negative environmental externality and network effects.

The main contribution of the paper is to show that: (1) policies targeting one side of the market generate feedback effects on the other; network externalities affect outcomes through their absolute size and relative intensity; (2) in the presence of network effects and environmental damage from polluting cars, policies can lead to a double dividend: decreasing the quantity of gasoline vehicles can be economically beneficial, while reducing the negative impact of pollution. This result can represent a turning point in today's discussion about policies fostering EVs: even if EVs are technologically less advanced than GVs, the presence of network effects implies that such policies can generate a double dividend. Hence, our analysis provides novel insights about the effects operating in the EVs market and their implications for policy making.

Two-sided markets are characterized by three elements (Rochet and Tirole, 2004): first, the presence of a platform providing distinct services to two or more distinct groups of consumers, which rely on the platform to intermediate transaction between them; second, network externalities exist across groups of consumers: one side's utility from participation depends not only on the value of the good itself, but also on the number of users on the other side of the market. Network externalities generate feedback loops between the two sides that can exacerbate positive and negative shocks (arising, for instance, from policy implementations).[3] Only the platform internalizes the network effect as it recognizes that a larger network raises the users' willingness to pay and therefore its revenues; third, two-sided markets are characterized by a non-neutral price structure, designed so as to bring both sides on board. The pricing decision on each side depends on the demand faced on both sides of the market and on their interdependence through network externalities. Platforms can deviate from a competitive pricing in order to increase overall profits, e.g. by generating low revenues on one side and recouping the costs

[3]The notion of network externality is not to be confused with the one of complementary goods; in the latter case, consumers internalize the purchase decision of the complement good (e.g. razor and blades); when network effects operate, instead, the externality of the purchase decision is not internalized.

on the other side (Rochet and Tirole, 2004). Thus, in a two-sided market we can observe prices below marginal cost.[4] The advantage of using a two-sided market to study our problem follows from the characteristics identified above: first, car manufacturers produce both EVs and the charging stations, acting as a platform; second, the amount of EVCSs is a relevant element for consumers when purchasing an EV. Meanwhile, retailers only install charging stations if the number of EVs is sufficiently high, showing the existence of network externalities; third, the provision of free charging hints for a non-neutral price structure. Our methodology is close to Filistrucchi et al. (2017) who use a two-sided market structure to analyze the newspaper industry. We deviate thereof by allowing for the presence of two goods on the same market side. Moreover, we derive the system of demand functions instead of assuming it.

Seminal papers in the literature on two-sided markets are Rochet and Tirole (2003), Rochet and Tirole (2005) and Armstrong (2006). These papers laid the foundations for the theoretical structure including network externalities and a platform allowing the interaction of two different sides of a market. Subsequent papers, as for example Weyl (2010) and White and Weyl (2016), generalize the modeling framework by introducing new market structures and studying different types of platforms. Classical examples of two-sided markets are the newspaper market (Rysman, 2009; Filistrucchi et al., 2017), where a reader and an advertiser interact through a newspaper; system softwares, for which users buy applications created by developers, using the same system software (Dubé et al., 2010); credit or debit cards markets, where a card holder settles a transaction with a seller through the payment card provider platform (Armstrong and Wright, 2007); shopping malls, which represent a platform where shops and consumers interact; video-games, where a software can only be used in combination with the console provided by the same producer (Clements and Ohashi, 2005); the market for players and titles of compact discs (**?**).

There is a rich body of research analyzing the effect of environmental policies in the automobile market. Many studies focus on the effectiveness of fuel taxes and fuel standards as a response to environmental issues emerging from the transportation sector.[5] A policy approach analyzed in the literature is the establishment of eco-friendly rules like the Corporate Fuel Economy (CAFE) standard that led to a 50% reduction of fuel consumption per passenger

[4] E.g the selling for newspapers for free, covering the losses with the money from advertisement.

[5] See Jacobsen (2013); DeShazo et al. (2017); Alberini and Bareit (2017); Grigolon et al. (2018).

car mile (Greene et al., 2005). Other studies investigate policies targeting alternative fueled vehicles and the response of consumers to subsidies to EVs or installment of EVCSs.[6] Lin and Greene (2011) analyze the impact of promoting charging infrastructure on EVs usage, whereas Jin et al. (2014) study road tax exemptions, free use of bus line and parking areas, subsidized home chargers and license fee reduction.

There exists already a literature that uses two-sided models to study the network effects between charging stations and electric vehicles. For example, Yu et al. (2016), Springel (2016), Li et al. (2017) and Jang et al. (2018) apply such models to analyze the introduction of environmental policies. Yu et al. (2016) consider a sequential game and depict an EVCS investors' operational decision-making, such as pricing and station location. Springel (2016) uses Norwegian data to study the impact of network externalities and subsidy structure on the diffusion of EVs in a two-sided market, considering a simultaneous move game. Li et al. (2017) provide empirical evidence of existence of indirect network effects in the process of EVs diffusion. Jang et al. (2018) consider two different platforms, one producing EVs and one producing GVs, competing to attract two types of agents (car consumers and energy suppliers). We deviate from those papers by modeling one market side supplied with two goods (EVs and GVs) and the other with one good only (EVCSs). Compared to Springel (2016) and Li et al. (2017) we allow for substitution between EVs and GVs in the analysis and evaluate the outcomes in terms of welfare. In contrast to previous works, our results do not rely on Hotelling's type preferences, but on linear demand functions derived from quasi-linear utilities.

The paper is organized as follows: section 2 outlines the general model structure and compares the decentralized and first-best outcomes by analyzing the adoption of EVs relative to GVs. Section 3 analyzes second-best policy instruments favoring the diffusion of EVs, that is, a subsidy to EVs, a tax on GVs and a subsidy to EVCSs. Section 4 identifies the welfare-maximizing policies and shows the existence of a double dividend when the negative environmental externality from GVs and network effects are taken into account. In section 5, we provide an extension to the baseline model, which relaxes the assumptions of a monopolistic market structure. Section 6 concludes and proposes some lines for future research.

[6]See Sierzchula et al. (2014); Pöltz et al. (2014); Lieven (2015); Helveston et al. (2015); Langbroek et al. (2016); Zhou et al. (2016); Coffman et al. (2017).

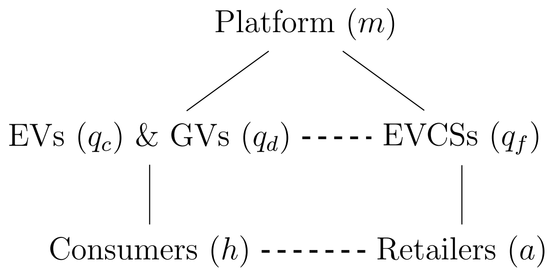
2 The model

2.1 Consumers and retailers

We consider a two-sided market with a continuum of potential users on each side, with mass normalized to one. Our economy is populated by two types of agents: consumers (h) and retailers (a). The former purchase vehicles and can choose between EVs (q_c) and GVs (q_d), while the latter demand EVCSs (q_f). We denote by p_c and p_d the purchase prices for EVs and GVs and by p_f the price of EVCSs. A monopolistic platform (m) produces EVs, GVs and EVCSs and sells the goods to the two sides of the market (consumers and retailers). For a graphical illustration of the economic structure see Figure 1. Consumers purchasing EVs and retailers purchasing EVCSs benefit from network effects due to positive externalities between the two goods. Following the empirical literature (Springel, 2016; Li et al., 2017), we assume that the network effects are asymmetric: the impact of an additional charging station on the purchase decision of consumers is different from the impact of an additional EV on the purchase decision of retailers. We acknowledge that similar network effects exist between gasoline vehicles and gasoline stations; however, we argue that they are of minor importance compared to the ones between EVs and EVCSs. This can be justified by two reasons: first, charging an EV requires more time than fueling a gasoline car; this can explain the strong incentive for retailers to install charging stations as consumers can charge their EVs while shopping; second, the marginal impact of a gasoline station is lower compared to the one of a charging station, as the number of gasoline stations is already sufficiently high. Moreover, it can be shown that, assuming lower network effects in the GVs market, their introduction does not affect our qualitative results. Based on this, we focus on the network effect for the new technology. In accordance, the number of gasoline stations does not enter the decision to buy a gasoline vehicle. Following Singh and Vives (1984), Häckner (2000) and Melitz and Ottaviano (2008), we assume that the aggregate utility function is quasi-linear. This specification implies no income effect; however, since the focus of our paper is on vehicles consumption, the assumption that higher income will not lead to the purchase of more cars by the same individual is plausible.[7]

[7] We acknowledge that there can be an argument for income effects as richer households are those who can switch first to EVs; however, in the present work we do not consider this effect in order to isolate the impact of network effects.

Figure 1: Market structure.



Moreover, the quasi-linear utility function allows us to derive linear demand functions, which are the standard in the two-sided market literature. The choice variables for the consumers are the quantities of EVs and GVs. Still, the quantity of EVCSs enters the utility because the value of EVs to consumers depend on the availability of EVCSs

$$U_h(q_{0,h}, q_c, q_d; q_f) = q_{0,h} + \sum_{i\in\{c,d\}} \alpha_i q_i - \frac{1}{2}\left[\sum_{i\in\{c,d\}} \beta_i q_i^2 + 2(\gamma_1 q_c q_d - \gamma_2 q_c q_f)\right].$$

The parameter $q_{0,h} > 0$ represents the individual consumption level of the homogeneous numeraire good. We assume that the initial endowment of the homogeneous good is large enough for its consumption to be strictly positive at the market equilibrium. The positive demand parameters α_i and β_i measure the preference for the differentiated varieties with respect to the homogeneous good. The parameter $\alpha_i q_i$ captures the direct benefit of owning a car, whereas $\beta_i q_i^2$ represents cars' type-specific congestion costs (e.g. congestion at charging points). The parameter $\gamma_1 \in [0, \infty)$ captures the substitution effect between EVs and GVs.The parameter $\gamma_2 \in [0, \infty)$ denotes the network effect between EVs and EVCSs such that $\gamma_2 q_c q_f$ represents consumers' indirect benefit from EVCSs installment by retailers. Notice that consumers always derive utility from the purchase of EVs, even if q_f goes to zero. This assumption can be justified by the possibility to charge EVs at home. The term $\gamma_1 q_c q_d$ represents the congestion cost due to a higher number of EVs and GVs (e.g. traffic jams). We normalize the price of the numeraire good to one; hence, the aggregate budget constraint of consumers reads

$$q_{0,h} + p_c q_c + p_d q_d \leq m_c.$$

Given total income on the consumers' side, m_c, a share of it is allocated to the purchase of the numeraire good, a share to the purchase of EVs and a share to the purchase of GVs. The assumption of quasi-linear preferences makes it possible to measure gains and losses of utility in the same units as consumption. This implies that there is no revenue effect on cars' purchase decision and that the quantities of q_c and q_d chosen do not depend on income. Any change in the quantities purchased is only attributable to the substitution effect.

Retailers maximize a quasi-linear payoff function, which depends on the number of charging stations and electric vehicles. The latter is, however, a choice variable of households and not of retailers

$$F_a(q_{0,a}, q_f; q_c) = q_{0,a} + \alpha_f q_f - \frac{1}{2}\left[\beta_f q_f^2 - 2\gamma_4 q_c q_f\right].$$

The parameter $q_{0,a} > 0$ is the purchase level of the numeraire good, whereas q_f is the consumption level of EVCSs. As before, $\alpha_f q_f$ captures the direct benefit for retailers from owning a charging station, whereas $\beta_f q_f^2$ represents the congestion cost due to an excessive number of EVCSs owned by the same retailer (e.g. too many charging stations and too many EVs charging at the retailer's stations might reduce the parking spots available for GVs). The payoff function of retailers also includes the indirect benefit, $\gamma_4 q_c q_f$, due to the usage of EVs by consumers. However, the intensity of the network effect between EVs and EVCSs perceived by retailers, $\gamma_4 \in [0, \infty)$, might be different from the one perceived by consumers, γ_2 (Li et al., 2017). So far, we do not make assumptions on the relative intensity of the network effects for consumers or retailers; still, this will be relevant for our policy analysis. Given total income on the retailers' side, m_a, a share of it is allocated to the purchase of the numeraire good and a share to the purchase of EVCSs, that is,

$$q_{0,a} + p_f q_f \leq m_a.$$

The consumers' problem is given by

$$\max_{q_{0,h}, q_c, q_d} U_h \quad s.t. \quad q_{0,h} = m_h - p_c q_c - p_d q_d,$$

whereas retailers solve

$$\max_{q_{0,a},q_f} F_a \quad s.t. \quad q_{0,a} = m_a - p_f q_f.$$

Both constraints hold with equality because U_h (F_a) is strictly increasing in $q_{0,h}$ $(q_{0,a})$. Assuming for simplicity $\beta_i = 1$ with $i \in \{c, d, f\}$, the FOCs derived from the maximization problems of consumers and retailers are

$$\begin{aligned}
\frac{\partial U_h}{\partial q_{0,h}} &: \lambda_h - 1 = 0, \\
\frac{\partial U_h}{\partial q_c} &: \alpha_c - q_c - \gamma_1 q_d + \gamma_2 q_f - \lambda_h p_c = 0, \\
\frac{\partial U_h}{\partial q_d} &: \alpha_d - q_d - \gamma_1 q_c - \lambda_h p_d = 0, \\
\frac{\partial F_a}{\partial q_{0,a}} &: \lambda_a - 1 = 0, \\
\frac{\partial F_a}{\partial q_f} &: \alpha_f - q_f + \gamma_4 q_c - \lambda_a p_f = 0.
\end{aligned}$$

where λ_h (λ_a) is the Lagrange multiplier of the consumers' (retailers') budget constraint. The demand functions for EVs, GVs and EVCSs are then given by

$$\begin{aligned}
q_c &= \alpha_c - \gamma_1 q_d + \gamma_2 q_f - p_c, \\
q_d &= \alpha_d - \gamma_1 q_c - p_d, \\
q_f &= \alpha_f + \gamma_4 q_c - p_f.
\end{aligned} \tag{1}$$

The choice of quasi-linear utility functions implies that demands are linear in the quantities of goods and prices. From (1) we can see that the substitution between EVs and GVs leads to a negative impact on the quantities of both goods. On the contrary, the network effect between EVs and EVCSs implies a positive impact of the quantity of EVCSs (EVs) on the demand for

EVs (EVCSs), as captured by γ_2 (γ_4). From (1) we can derive inverse demands as

$$\begin{aligned} p_c &= \alpha_c - q_c - \gamma_1 q_d + \gamma_2 q_f, \\ p_d &= \alpha_d - q_d - \gamma_1 q_c, \\ p_f &= \alpha_f - q_f + \gamma_4 q_c. \end{aligned}$$

In what follows, we assume a profit-maximizing monopolistic platform with perfect information about the demand functions.

2.2 Platform

In our setup of a two-sided market, the monopolistic platform chooses the profit-maximizing quantities or prices given the interrelated demands of the two groups of customers. In what follows, we focus on a quantity-setting platform. Car production incurs constant marginal costs c_c and c_d, while the marginal cost of producing charging stations is c_f. Total profits generated by the platform are given by

$$\pi = (p_c - c_c)q_c + (p_d - c_d)q_d + (p_f - c_f)q_f,$$

where the first two terms represent profits extracted from consumers and the third term profits extracted from retailers. Given the demand function in (2), the FOCs of the maximization problem are

$$\begin{aligned} \frac{\partial \pi}{\partial q_c} &: \alpha_c - 2q_c - 2\gamma_1 q_d + (\gamma_2 + \gamma_4)q_f - c_c = 0, \\ \frac{\partial \pi}{\partial q_d} &: \alpha_d - 2q_d - 2\gamma_1 q_c - c_d = 0, \\ \frac{\partial \pi}{\partial q_f} &: \alpha_f - 2q_f + (\gamma_2 + \gamma_4)q_c - c_f = 0. \end{aligned}$$

For an interior solution, the profit-maximizing quantities are then given by

$$
\begin{aligned}
q_c^* &= \frac{1}{X}\left[2(\alpha_c - c_c) - 2\gamma_1(\alpha_d - c_d) + (\gamma_2+\gamma_4)(\alpha_f - c_f)\right], \\
q_d^* &= \frac{1}{X}\left[-2\gamma_1(\alpha_c - c_c) + \left[2 - \frac{1}{2}(\gamma_2+\gamma_4)^2\right](\alpha_d - c_d) - \gamma_1(\gamma_2+\gamma_4)(\alpha_f - c_f)\right], \\
q_f^* &= \frac{1}{X}\left[(\gamma_2+\gamma_4)(\alpha_c - c_c) - \gamma_1(\gamma_2+\gamma_4)(\alpha_d - c_d) + 2(1-\gamma_1^2)(\alpha_f - c_f)\right],
\end{aligned} \tag{2}
$$

where $X = 4(1-\gamma_1^2) - (\gamma_2+\gamma_4)^2$. Following the literature, we assume $X > 0$ (Economides and Tåg, 2012). We will refer to this condition as *monopoly condition*.[8] The latter implies $\gamma_1 \in [0,1]$, which allows us to derive an upper bound for the network effects, i.e. $\gamma_2, \gamma_4 \in [0,2)$. The network effects have a positive (negative) impact on the quantity of EVs (GVs). As the number of EVs (EVCSs) increase, it generates a positive externality on the retailers (consumers) purchasing EVCSs (EVs). If the number of GVs (EVs) increases, less EVs (GVs) are purchased, indirectly affecting the quantity of EVCSs as well. Given the optimal quantities in (2), we can find the profit-maximizing prices as

$$
\begin{aligned}
p_c^* &= \frac{1}{X}[(2(1-\gamma_1^2) - \gamma_2\gamma_4)(\alpha_c + c_c) - (\gamma_4^2\alpha_c + \gamma_2^2 c_c) - \frac{\gamma_1}{2}(\gamma_2^2 - \gamma_4^2)(\alpha_d - c_d) \\
&\quad + (1-\gamma_1^2)(\gamma_2 - \gamma_4)(\alpha_f - c_f)], \\
p_d^* &= \frac{1}{2}(\alpha_d + c_d), \\
p_f^* &= \frac{1}{X}[-(\gamma_2 - \gamma_4)(\alpha_c - c_c) + \gamma_1(\gamma_2 - \gamma_4)(\alpha_d - c_d) + (2(1-\gamma_1^2) - \gamma_2\gamma_4)(\alpha_f + c_f) \\
&\quad - (\gamma_2^2\alpha_f + \gamma_4^2 c_f)].
\end{aligned}
$$

Because of the network externalities, the prices of EVs and EVCSs depend on the demand parameters of both sides of the market. This means that when setting the profit-maximizing prices on one side, the producer also takes into account the impact of his decision on the other side. This is a standard result in the literature of two-sided markets,[9] where the price structure is non-neutral because externalities across groups affect the determination of the price. Furthermore, the prices of EVs and EVCSs also depend on the parameters of demand for GVs, due to the substitution between EVs and GVs; on the contrary, the price of GVs only depends

[8] Appendix A provides a study of the parameter space satisfying this condition.
[9] See Rochet and Tirole (2004); Armstrong (2006).

on the parameters of its own demand and does not equal marginal cost because of monopolistic power.[10] Notice that if we assume the intensity of the network effects to be the same on both sides, i.e. $\gamma_2 = \gamma_4$, prices for EVs and EVCSs would depend on the parameters of their own demand only.

2.3 First-best solution

In the first-best solution the social planner dictates the quantities that maximize welfare in the economy.[11] We assume that, in contrast to the atomistic agents, the social planner acknowledges the negative environmental externality and the presence of network effects. The social planner maximizes welfare (W^P), which given the quasi-linear specification, can be written as the sum of utility, payoff function and profits minus the damage due to pollution

$$W^P(q_{0,h}, q_{0,a}, q_c, q_d, q_f) = U_h(q_{0,h}, q_c, q_d; q_f) + F_a(q_{0,a}, q_f; q_c) + \pi(q_c, q_d, q_f) - \phi q_d,$$

where ϕ represents the intensity of damages due to pollution. The social planner maximizes welfare subject to the resource constraint of the economy

$$q_{0,h} + q_{0,a} + p_c q_c + p_d q_d, + p_f q_f \leq m_h + m_a.$$

Due to the quasi-linear specification, welfare is strictly increasing in the numeraire good and the constraint holds with equality. Solving the social planner's problem we find the optimal ratio of EVs to GVs (q_c^{fb}/q_d^{fb}) denoted by ζ_{fb} and we compare it to the ratio prevailing in the decentralized economy (ζ_m)

$$\zeta_{fb} = \frac{\alpha_c - c_c - \gamma_1(\alpha_d - c_d^P) + (\gamma_2 + \gamma_4)(\alpha_f - c_f)}{-\gamma_1(\alpha_c - c_c) + [1 - (\gamma_2 + \gamma_4)^2](\alpha_d - c_d^P) - \gamma_1(\gamma_2 + \gamma_4)(\alpha_f - c_f)}, \quad (3)$$

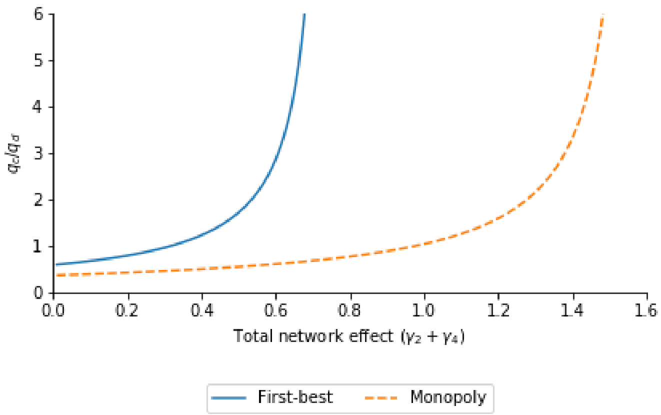
$$\zeta_m = \frac{2(\alpha_c - c_c) - 2\gamma_1(\alpha_d - c_d) + (\gamma_2 + \gamma_4)(\alpha_f - c_f)}{-2\gamma_1(\alpha_c - c_c) + \left[2 - \frac{1}{2}(\gamma_2 + \gamma_4)^2\right](\alpha_d - c_d) - \gamma_1(\gamma_2 + \gamma_4)(\alpha_f - c_f)}, \quad (4)$$

[10] The substitution effect does not affect the price of GVs because, when facing the demand for cars, the monopolist behaves as if the market was not two-sided; hence, the platform does not take into account the presence of externalities when setting the price for GVs.

[11] See Appendix B for the derivation of the first-best solution.

where $c_d^P = c_d + \phi$ represents the cost of producing GVs once the negative pollution externality is taken into account. From (3) and (4) we see that the ratio of EVs to GVs is always higher in the first-best compared to the monopolistic cases.[12] As illustrated in Figure 2, even when network effects are zero, the ratio in the first-best (solid line) is larger than in the monopoly because of the pollution externality.[13] However, the wedge increases for larger values of the network externalities as two effects sum up: the pollution externality and the stronger network effects. In the decentralized solution the platform completely ignores the environmental damage; moreover, it only partly internalizes the network effects as we assume perfect information about the demand functions. However, the network effects have an additional impact on the utility and payoff functions of consumers and retailers respectively, which is not internalized by the platform. Since these effects, which would increase the number of EVs, are not taken into account, there is a lower share of EVs in the decentralized economy compared to the first-best solution. This paves the way for policy intervention in the form of support measures favoring the diffusion of EVs and EVCSs.

Figure 2: Ratio of EVs to GVs in first-best and monopoly case as a function of total network effects.



[12]This holds generally true, independent of the actual values for the demand parameters and the network effects under the assumption of an interior solution. See Appendix B for a proof of this result.

[13]Our model specification allows us to focus on the impact of network effects on welfare; since welfare depends only on the sum of network effects, there is no need to disentangle the relative intensities on the two sides of the market.

3 Policy analysis

Several measures are available to policy makers in order to foster the development of the EV market. In our theoretical model, we focus on three such policy instruments: (1) subsidies to consumers for EV purchase (s_c): a price subsidy directly affects the buyers decision to purchase a vehicle by making the price of an EV comparable to (or even lower than) the price of a GV; (2) taxes on the purchase of GVs (t_d); (3) subsidies to EVCSs purchase (s_f): the government can subsidize the provision of charging stations by retailers in order to generate a positive externality on EVs consumption (through the network effect). In our analysis, we consider both the case in which the network effect is stronger for retailers ($\gamma_4 > \gamma_2$) and when it is stronger for consumers ($\gamma_2 > \gamma_4$). The first case implies that retailers care more about the number of EVs than what consumers do about the availability of EVCSs. This assumption relies on an asymmetric information argument: retailers are able to foresee future developments of the market and they can only provide electricity if consumers buy EVs; hence, the number of EVs is of major importance for them. On the other hand, consumers might have the option to charge their EVs at home such that the actual availability of charging stations is less relevant to them. The second case can be justified based on the findings by Li et al. (2017). They find that a 10% growth in the number of public charging stations increases EV sales by about 8%, while a 10% growth in EV stock leads to a 6% increase in charging station deployment, meaning that the network effect is stronger on the consumers' side.

3.1 Policy impacts for $\gamma_4 > \gamma_2$

In the following we analyze the effect of policy intervention on quantities and prices when the network effect is stronger for retailers. The results summarized in Table 1 are based on analytical derivations provided in Appendix C. All quantities depend only on the total size of the network effects such that the impacts of subsidies and taxes are independent of the relative intensity of the network effects ($\gamma_4 > \gamma_2$ vs. $\gamma_2 > \gamma_4$).[14] Subsidizing EVs (s_c) and taxing GVs (t_d) increases the number of EVs. Moreover, q_c increases with a subsidy to EVCSs (s_f) because of the network effect operating between the two goods. The quantity of GVs declines ($\Delta q_d = -$)

[14]This result is due to the assumption of a monopolistic platform and does hold when considering different market structures.

Table 1: Policy impacts for $\gamma_4 > \gamma_2$.

	EVs		GVs		EVCSs	
	Δq_c	Δp_c	Δq_d	Δp_d	Δq_f	Δp_f
s_c	$+$	$\pm$	$-$	0	$+$	$+$
t_d	$+$	$-$	$-$	$-$	$+$	$+$
s_f	$+$	$-$	$-$	0	$+$	$+$

with all the policies considered because of the substitution with EVs. The quantity of EVCSs increases ($\Delta q_f = +$) with subsidies (s_c and s_f) and taxes (t_d). Our results are in line with the previous literature (Springel, 2016; Li et al., 2017) showing that the positive feedback loops between EVCSs and EVs sales amplify the impact of subsidies on both sides of the market. Moreover, our model allows us to take into account the effect of policies in the GV sector.

The effect of policies on prices is more complex than for quantities; in particular, we observe different outcomes depending on the relative intensity of the network effects. When subsidizing EVs, the effect on their price is ambiguous ($\Delta p_c = \pm$) and depends on the substitution effect as well as on the network effects.[15] If the substitution between EVs and GVs is strong or if the network effects are large enough, s_c reduces the price of EVs. The effect on p_c when taxing GVs follows from the assumption on the relative intensity of network effects; only when retailers attach higher importance to the network than consumers it will be reduced ($\Delta p_c = -$). The same outcome occurs when subsidizing EVCSs ($\Delta p_c = -$). Hence, it appears that the monopolist has an incentive to reduce the price of the good which enjoys the stronger network effect and whose quantity is more sensitive to quantity changes on the other side. When $\gamma_4 > \gamma_2$, an increase in q_f will strongly lift up q_c; hence the monopolist can reduce p_c and still earn profits from the EV market. Such a result depends on the two-sided market structure of the model, allowing the platform to set prices in order to extract the largest possible profits from both groups of buyers (Rochet and Tirole, 2004). The price of GVs only depends on the parameters

[15] In particular the effect will be positive (negative) if $2(1-\gamma_1^2) - \gamma_4(\gamma_2 + \gamma_4) > (<)0$ and $X > 0$. Figure 12 in Appendix C provides a graphical representation of parameter values leading to a positive price effect.

of its own demand and it is not affected by s_c or s_f ($\Delta p_d = 0$). A tax on GVs (t_d) decreases the price of GVs, i.e. the monopolist decides to lower the price of the taxed good in order to create a positive demand despite the policy adopted. The price of EVCSs increases with the subsidy to EVs and by a tax on GVs ($\Delta p_f = +$); a result that is similar to the one obtained for the price of EVs and which crucially relies on the assumption that the network effect is stronger on the retailers' side. The platform increases the price on the side of the market which enjoy the stronger network effect. A policy targeting the EVCSs sector directly generates an increase in the price of EVCSs as demand is now higher and the monopolist can charge a higher price. In general, the effect of any subsidy or tax depends on which side of the market is targeted. Quantities and the price of GVs are, however, independent on the relative intensity of network effects.

3.2 Policy impacts for $\gamma_2 > \gamma_4$

The results obtained when the network effect is stronger on the consumers' side are summarized in Table 2. As outlined before, the effects on the quantities are independent of the relative

Table 2: Policy impacts for $\gamma_2 > \gamma_4$.

	EVs		GVs		EVCSs	
	Δq_c	Δp_c	Δq_d	Δp_d	Δq_f	Δp_f
s_c	$+$	$+$	$-$	0	$+$	$-$
t_d	$+$	$+$	$-$	$-$	$+$	$-$
s_f	$+$	$+$	$-$	0	$+$	$\pm$

intensity network effects. Considering prices, a subsidy to EVs (s_c) increases the respective price ($\Delta p_c = +$); this happens because the subsidy increases demand for EVs and hence the monopolist can charge a higher price. This result differs from the one we obtained for $\gamma_4 > \gamma_2$, where the impact of s_c on the price of EVs was ambiguous. A tax on GVs (t_d) or a subsidy to charging stations (s_f) increase the price of EVs, an opposite outcome compared to the case in which the network effect is stronger on the retailers' side. Since EVs have stronger network effect on charging stations, the platform's profit-maximizing behavior entails a price increase on the consumers' side and a price reduction on the retailers' side. The price of GVs behaves in the same way regardless of the relative intensity of the network effects, so it decreases when taxing GVs as before. The price of EVCSs now decreases with both a subsidy to EVs and a tax on GVs ($\Delta p_f = -$). The reversed impact of these policies compared to the previous case follows from the fact that the network effect on consumers is stronger than on retailers; hence, p_f can be reduced without incurring in losses. Notice that the decrease in p_f is counteracted by an increase in p_c. Targeting the EVCS sector itself, the subsidy has an ambiguous impact on the price of EVCSs ($\Delta p_f = \pm$), depending on the substitution and network effects.[16] We also find that the effects of s_c on p_c and of s_f on p_f cannot be jointly negative.[17] The economic interpretation of this result follows from the two-sided market structure: as consumers and retailers represent two different sides of the market, the platform will never reduce the price on both sides; on the contrary, as explained in the literature (Rochet and Tirole, 2003), the platform chooses a price structure, which allows to reduce the price on one side and cover the losses by increasing the price on the other side. From our analysis, we can conclude that the relative intensity of the network effects influences the outcomes of the model in terms of prices[18]. In particular, due to the non-neutral price structure, the effects of some policies reverse depending on the relative intensity. Appendix C provides a deeper discussion of the policy impacts, including the results obtained for relevant values of the parameters.

4 Welfare

In this section, we introduce the possibility for a policy-maker to choose the welfare-maximizing combination of subsidies and taxes, under the constraint of a balance budget and taking into account the negative externality from GVs. Moreover, we investigate how the presence of network effects impact optimal welfare, that is, welfare once the optimal combination of policies applies. In our simulations we focus on the effect of the sum of positive network externalities

[16]The condition for a positive (negative) impact on the price is given by $2(1-\gamma_1^2)-\gamma_2(\gamma_2+\gamma_4) > (<)0$ and $X > 0$. Figure 15 in Appendix C provides a graphical representation of parameter values leading to a positive price effect on EVCSs.

[17] Figure 19 in Appendix C provides a reasoning for this result.

[18]See Figures 16, 17 and 18 in Appendix C. The graphs show how the effect vary depending on the relative intensities of the network effects.

enjoyed by consumers and retailers rather than on the individual values assumed by γ_2 and γ_4. Our choice is justified by the fact that optimal welfare can be characterized through quantities alone, which only depend on the total network effect $(\gamma_2 + \gamma_4)$.[19]

We find that the optimal combination of policies includes subsidies to EVs and EVCSs (s_c and s_f) and taxes on GVs (t_d).[20] In order to show how the optimal policies influence the outcomes of the model, Figure 3 builds on Figure 2 and represents the ratio of EVs to GVs in the first-best (solid line), in the monopoly (dashed line) and when the optimal combination of policies applies (dashed-dotted line). The optimal policies partially correct for the environmental externality from pollution and for the network effects: the ratio of EVs to GVs is higher compared to the monopoly case and the solution gets closer to the first-best outcome. However, the assumption of a balanced budget does not allow the policy maker to achieve the first-best solution.

Figure 3: Ratios of EVs to GVs in the first-best, optimal and monopoly solutions.

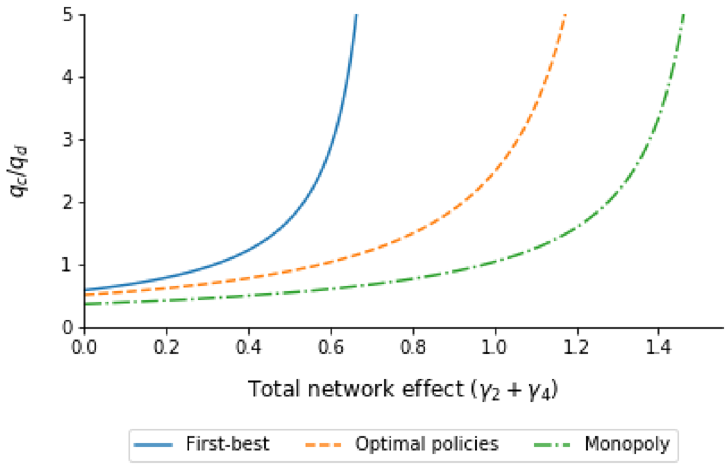


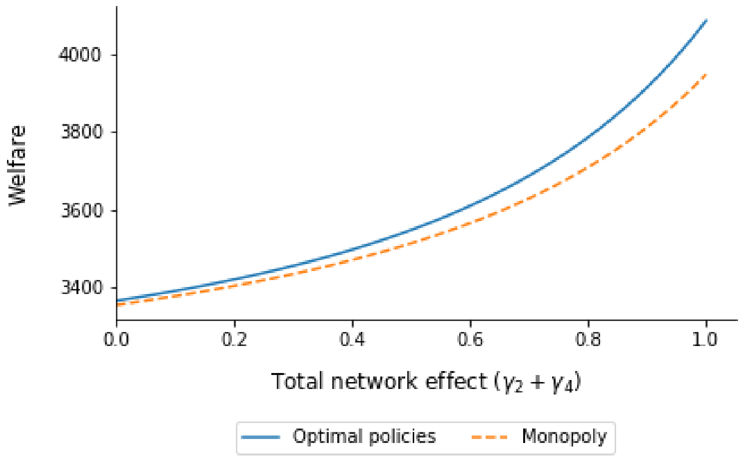
Figure 4 allows for a comparison between welfare in the optimal (solid line) and in the monopolistic case (dashed line). When the optimal policies apply, welfare is higher than in the decentralized equilibrium; this holds true even when the network effects are zero because of the pollution externality, which is not taken into account by private agents. Moreover, in the presence of network effects the gap between the welfare widens because the externality due to

[19]The simulation is based on a total network effect up to a maximum value of one, knowing that each individual network effect is subject to an upper bound of two.

[20]Notice that we will use the term *optimal policies* to denote policies correcting for the externality due to the network effects and environmental externality. We do not consider policies tackling the monopoly externality as this is not the focus of our paper.

network effects kicks in on top of the environmental externality. This means that policies are used to account for the two externalities; the implications of this mechanism become apparent in the next section.

Figure 4: Optimal and monopolistic welfare as a function of total network effect.



4.1 Double dividend

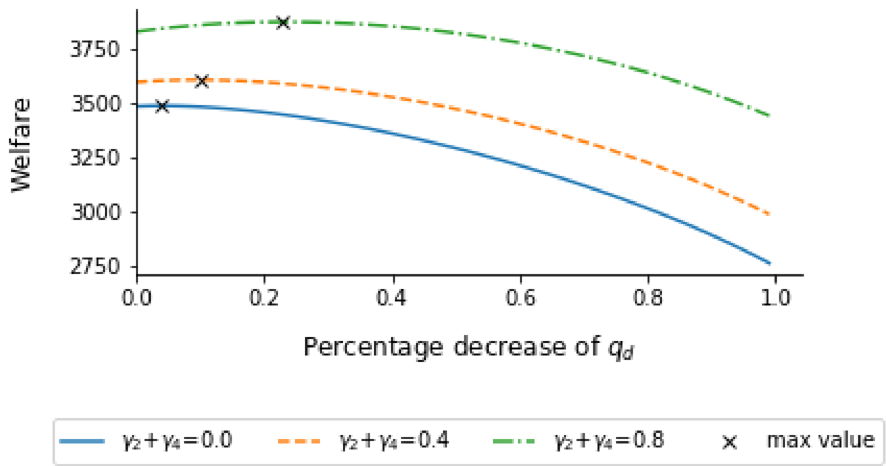
Countries have started to set targets in terms of reducing the amount of polluting cars circulating; in order to achieve such targets, policy-makers adopted subsidies to EVs and EVCSs and taxes on GVs. However, such measures - in particular taxes on GVs - have led to political pressure due to discontent in the general public.[21] Indeed, the environmental benefit derived from reducing the number of GVs is not sufficient to generate widespread support for such measures. For policies reducing the amount of GVs to be well received, attention should be drawn on the economic benefit embedded in a lower number of GVs: in this section we show that the presence of network effects can lead to the emergence of a double dividend, meaning that economic welfare can be improved while reducing the negative impact of pollution. Hence, awareness of the double dividend effect could play a crucial role in the political debate.

We assume that the policy-maker maximizes welfare as before with the additional constraint of achieving a given target in terms of the number of GVs circulating. In particular, we consider a given target percentage reduction of GVs compared to the decentralized level (q_d^*) and we

[21] See for example the "yellow vests" protests in 2018 in France.

simulate the impact on optimal welfare of different values of such target.[22] Figure 5 shows how optimal welfare changes with the percentage reduction of GVs. We see that using an optimal policy mix to reduce q_d can be welfare improving. In the case of no network effects (solid line), the policy-maker can maximize welfare by decreasing q_d to account for the negative environmental externality. Adding network effects, the policy-maker faces a second externality and the q_d that maximizes welfare is therefore lower. This effect becomes stronger for higher values of the network effects.

Figure 5: Optimal welfare as a function of a percentage decrease of GVs, for different values of the total network effect.

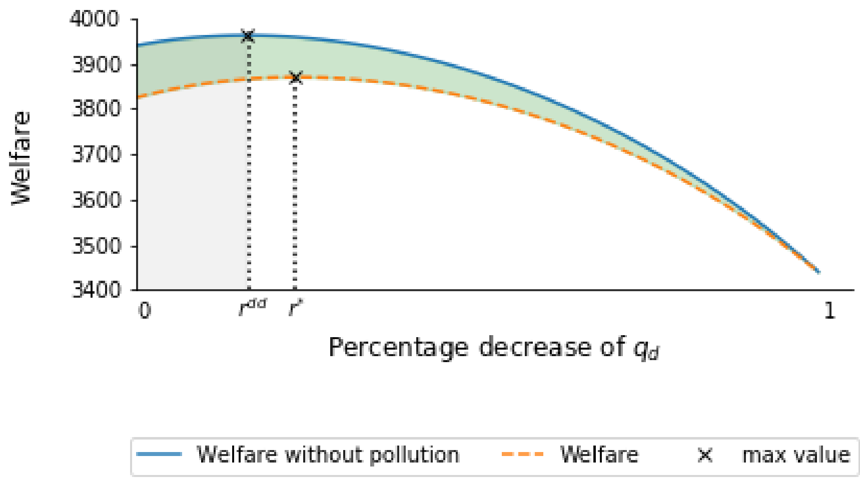


In what follows, we disentangle the environmental and network externalities in order to show the existence of a double dividend. Figure 6 represents the evolution of economic welfare (W^E), which does not take the environment into account, and total welfare (W^P), as a function of the percentage reduction of GVs. The wedge between the two curves represents the environmental damage and it reduces as the number of GVs shrinks. Both for economic and total welfare, there is scope for improvement when policies aim at decreasing q_d. This scope is bigger when considering total welfare as it takes into account the environmental externality next to the network externality. For a decrease in the range from 0 to r^{dd}, the economic and total welfare increase because EVs enjoy network effects; moreover, increasing EVs compared to GVs reduces the negative externality due to pollution produced from GVs. Reducing q_d up to the threshold

[22] We assume $q_d = q_d^*(1-r)$, with $r \in [0, 1]$; hence, $r = 1$ means that no GVs exist in the economy.

r^* increases total welfare, but from r^{dd} to r^* this comes at a cost in terms of economic welfare. Therefore, the policy-maker is facing a strong double dividend for a reduction of q_d in the shaded gray area. Such a double dividend is attributable to the presence of pollution and network effects. This implies that optimal policies can increase economic welfare and at the same time enhance environmental quality. Notice that, combining the findings in Figure 5 and Figure 6 implies that the scope for a strong double dividend increases with the total network effects.

Figure 6: Double dividend.

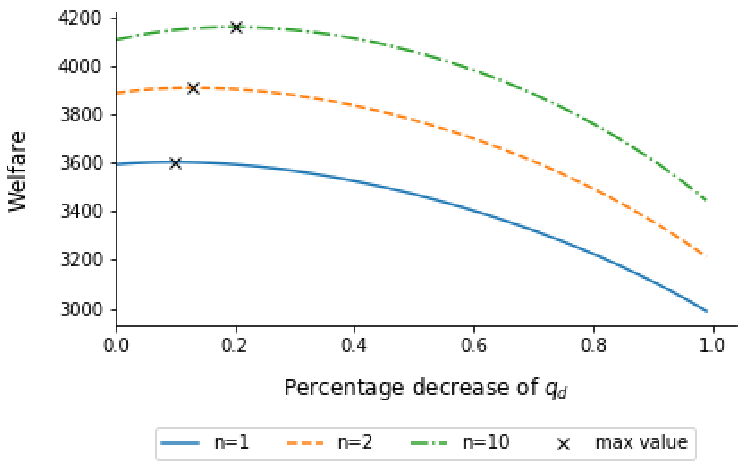


5 Extension: oligopoly

In this section we relax the assumption of a monopolistic market structure in favor of an oligopoly. We assume that n identical firms compete *à la Cournot*; each firm i with $i = 1, ..., N$ chooses the quantities of EVs, GVs and EVCSs taking into account the decisions of the other firms.[23] As in Figure 4 in the monopoly case, it can be shown that for fixed n welfare is increasing with the network effects. Figure 7 shows how welfare evolves with the percentage decrease of the quantity of GVs, for different numbers of firms. Compared to the monopoly case ($n = 1$), welfare is larger for higher number of firms for any value of the percentage reduction of GVs. Figure 8 shows that assuming an oligopolistic market structure the double dividend effect is

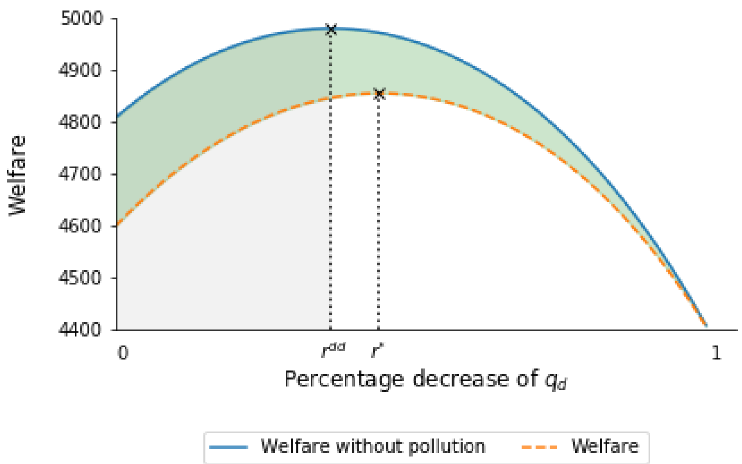
[23] Appendix D provides the solution to the model when an oligopolistic market structure is assumed.

Figure 7: Welfare as a function of a percentage decrease in the quantity of GVs, for different n, with $\gamma_2 + \gamma_4 = 0.4$.



still present: in the gray shaded area welfare can be improved with no negative impact on the environment. Moreover, we find that increasing the number of firms, the double dividend effect becomes stronger and welfare is maximized for a lower number of GVs.

Figure 8: Double dividend assuming $n = 10$.



6 Conclusion

Following the increasing potential attributed to EVs to decarbonize the transport sector, which is at odd with their still limited diffusion, the debate about the design of policies supporting EVs adoption has gained importance. One of the main obstacles identified is the lack of an appropriate charging infrastructure. This generates the so-called range anxiety, which reduces the possibility for consumers to perceive EVs and GVs as substitute. Besides government intervention, the retail sector plays a role in expanding the charging network. However, the number of charging stations purchased by retailers will not increase as long as the number of EVs is low. Hence, the market for EVs exhibits a "chicken-egg" problem due to the presence of network externalities operating between the two goods. With this paper, we contribute to this debate by providing a theoretical framework that takes into account the two-sidedness of the EV market and the indirect network effects operating between EVs and EVCSs. Additionally, we account for the degree of substitutability between EVs and GVs, and for the pollution externality generated by GVs.

In our model, a platform sells EVs and GVs to consumers on one side of the market and EVCSs to retailers on the other side. Within this framework, consumers make their car purchasing decisions by maximizing utility, which is affected by the number of EVCSs, and retailers choose charging stations based on the maximization of their payoff function, which in turn, depends on the number of EVs. We introduce policies targeting prices of EVs, GVs and EVCSs and study how they affect the adoption of EVs in the presence of network externalities. We then introduce a negative externality from GVs and compute the welfare-maximizing combination of policies. Finally, we show how a reduction in the number of GVs affects optimal welfare.

The main results of the paper are: (1) the presence of network effects has an impact on the profit-maximizing quantities and prices. We find that policies tackling one side of the market also affect the other side and thus generate feedback loops; the choice of subsidizing EVs does not only have a positive effect on the number of EVs *per se*, but also on the quantity of EVCSs. More charging stations, in turn, generate a positive feedback effect on the number of EVs. Since the network effects work both on the EVs and EVCSs' sides, the same positive outcome in terms of EVs adoption occurs when subsidizing EVCSs; (2) policies are non-neutral, that is, subsidies to consumers (EVs) or retailers (EVCSs) are not equivalent; this is due to the dependence of prices on the relative intensity of network effects; (3) the set of welfare-maximizing policies implies subsidies to EVs and EVCSs as well as taxes on GVs; (4) in the presence of network effects and of a negative environmental externality from GVs, there is scope for a strong double dividend: decreasing the quantity of gasoline vehicles can be economically improving, while reducing the negative impact of pollution. The findings of our model imply that it is important to account for network externalities between EVs and EVCSs when designing EVs promoting policies. The resulting feedback loops might exacerbate shocks to either side of the market and thus generate effects which are greater than any single market study suggests. Ignoring the interdependence of electric vehicles and charging stations could therefore lead to underestimation of the impact of policy measures. Finally, the presence of a strong double dividend implies that a lower number of GVs can be economically-improving while reducing the negative impact of pollution.

Future research should focus on introducing non-linearities in the demand functions and on a more in depth study of the impact of relaxing the assumption of a monopolistic platform. Moreover, our economic setting might be studied in a dynamic framework such that the adoption of new technology (EVs and EVCSs) follows from non-simultaneous decisions of consumers and retailers. In addition, the pricing decision by the platform might be affected by the production costs of suppliers (e.g. batteries production). A more realistic model might therefore also allow for vertical integration of production.

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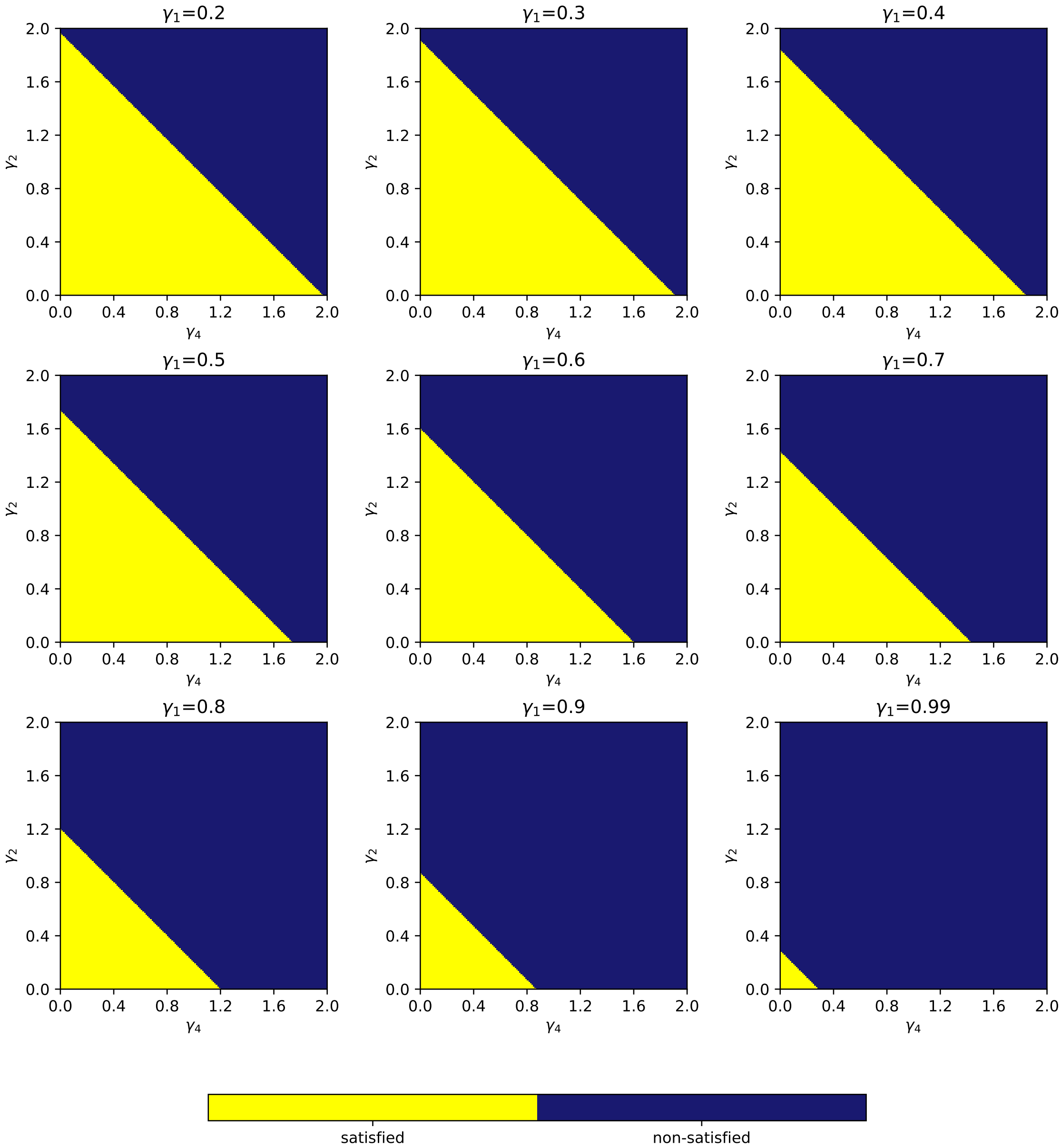
A The *monopoly condition*

In Figure 9 we show the combination of parameters such that the condition $X = 4(1-\gamma_1^2) - (\gamma_2+\gamma_4)^2 > 0$ is satisfied. Note that the degree of substitutability ($\gamma_1 \in [0,1]$) imposes an upper bound for the network effects, i.e. $\gamma_2, \gamma_4 \in [0,2)$. The set of network effects (γ_2, γ_4) such that the *monopoly condition* is satisfied decreases with a higher substitution between EVs and GVs. We also observe that the effect of the substitution parameter is non-linear.

Figure 9: Values of the parameters γ_1, γ_2 and γ_4 such that the *monopoly condition* is satisfied ($X > 0$).



B First-best solution

The social planner takes into account the negative externality due to pollution and solves:

$$\max_{q_{0,h},q_{0,a},q_c,q_d,q_f} W^P \quad s.t. \quad q_{0,h}+q_{0,a}=m_h+m_a-p_cq_c-p_dq_d-p_fq_f,$$

where $W^P=U_h+F_a+\pi-\phi q_d$. The FOCs of the social planner problem are

$$\begin{aligned}
\frac{\partial W}{\partial q_c} &: \alpha_c-q_c-\gamma_1q_d+(\gamma_2+\gamma_4)q_f-c_c=0,\\
\frac{\partial W}{\partial q_d} &: \alpha_d-q_d-\gamma_1q_c-c_d^P=0,\\
\frac{\partial W}{\partial q_f} &: \alpha_f-q_f+(\gamma_2+\gamma_4)q_c-c_f=0.
\end{aligned}$$

where $c_d^P=c_d+\phi$ is the cost of producing GVs when pollution is taken into account. For an interior solution, the welfare-maximizing quantities are

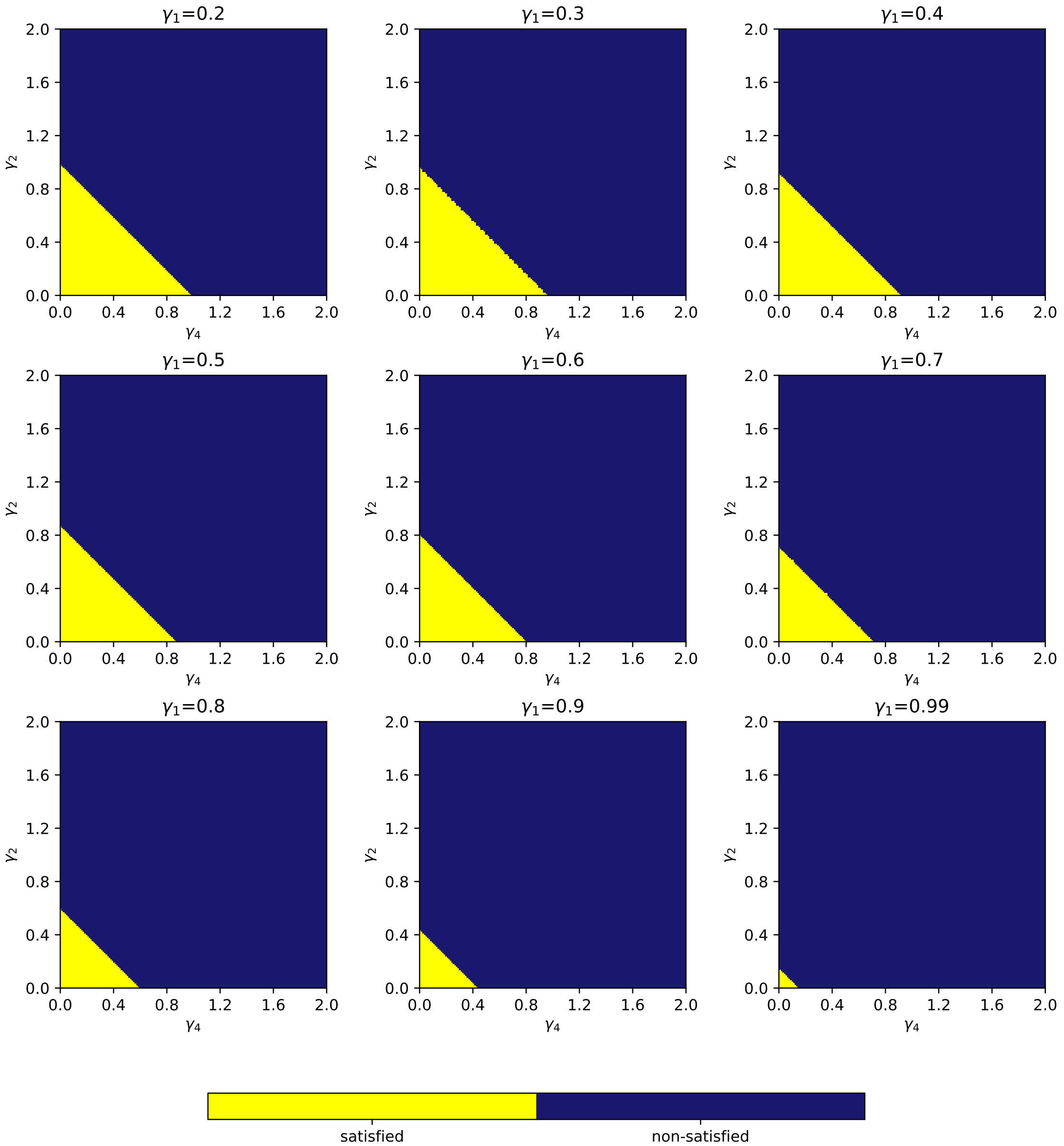
$$\begin{aligned}
q_c^{fb} &= \frac{1}{\tilde{X}}\left[\alpha_c-c_c-\gamma_1(\alpha_d-c_d^P)+(\gamma_2+\gamma_4)(\alpha_f-c_f)\right],\\
q_d^{fb} &= \frac{1}{\tilde{X}}\left[-\gamma_1(\alpha_c-c_c)+\left[1-(\gamma_2+\gamma_4)^2\right](\alpha_d-c_d^P)-\gamma_1(\gamma_2+\gamma_4)(\alpha_f-c_f)\right],\\
q_f^{fb} &= \frac{1}{\tilde{X}}\left[(\gamma_2+\gamma_4)(\alpha_c-c_c)-\gamma_1(\gamma_2+\gamma_4)(\alpha_d-c_d^P)+(1-\gamma_1^2)(\alpha_f-c_f)\right],
\end{aligned}$$

where $\tilde{X}=1-\gamma_1^2-(\gamma_2+\gamma_4)^2$. The condition $\tilde{X}>0$ is stricter than $X>0$ in the monopoly case and will be referred to as the *first-best condition*. The set of parameters satisfying the *monopoly condition* includes the one satisfying the *first-best condition* as

$$X=\tilde{X}+3(1-\gamma_1^2),$$

where the second term can only be non-negative due to $\gamma_1\in[0,1]$. In Figure 10, we plot all the combinations of parameters satisfying the *first-best condition*. The set of γ_2 and γ_4 such that the condition holds shrinks with the substitution parameter γ_1. The economic intuition is that if two goods are good substitutes it is more likely that one of the two disappears.

Figure 10: Values of the parameters γ_1, γ_2 and γ_4 such that the *first-best condition* is satisfied ($\tilde{X} > 0$).



In what follows, we show that in the presence of network effects and pollution externality, the ratio of EVs to GVs in the first-best is always higher compared to the monopoly outcome; this result does not depend on the actual values of the demand parameters and network externalities. We define $\zeta_{fb} = \zeta_{fb}^N/\zeta_{fb}^D$, and $\zeta_m = \zeta_m^N/\zeta_m^D$. Using Equations (3) and (4), we can write

$$\begin{aligned}\zeta_m &= \frac{2\zeta_{fb}^N - (\gamma_2+\gamma_4)(\alpha_f - c_f)}{2\zeta_{fb}^D + \gamma_1(\gamma_2+\gamma_4)(\alpha_f-c_f) + \frac{3}{2}(\gamma_2+\gamma_4)^2(\alpha_d-c_d)},\\ &= \frac{\zeta_{fb}^N - \frac{1}{2}(\gamma_2+\gamma_4)(\alpha_f-c_f)}{\zeta_{fb}^D + \frac{1}{2}\gamma_1(\gamma_2+\gamma_4)(\alpha_f-c_f) + \frac{3}{4}(\gamma_2+\gamma_4)^2(\alpha_d-c_d^D)},\end{aligned}$$

which implies $\zeta_m^N \leq \zeta_{fb}^N$ and $\zeta_m^D \geq \zeta_{fb}^D$. Hence, for any parameter values $\zeta_m \leq \zeta_{fb}$.

C Policies

We analytically derive the impacts of policies in the form of subsidies and taxes on quantities and prices, and provide simulations of those effects for different policy choices. The policies take the form of subsidies to EVs and EVCSs (s_c and s_f) as well as a tax on GVs (t_d). The policy parameters are chosen such that they take values between zero (no policy intervention) and a maximum value eliminating the demand for GVs ($q_d = 0$). The latter are given by

$$\begin{aligned}s_c^{max} &= \frac{q_d^* X}{2\gamma_1},\\ t_d^{max} &= \frac{q_d^* X}{2 - \frac{1}{2}(\gamma_2+\gamma_4)^2},\\ s_f^{max} &= \frac{q_d^* X}{\gamma_1(\gamma_2+\gamma_4)},\end{aligned}$$

where q_d^* represents the demand for GVs in the monopoly case without policy intervention.

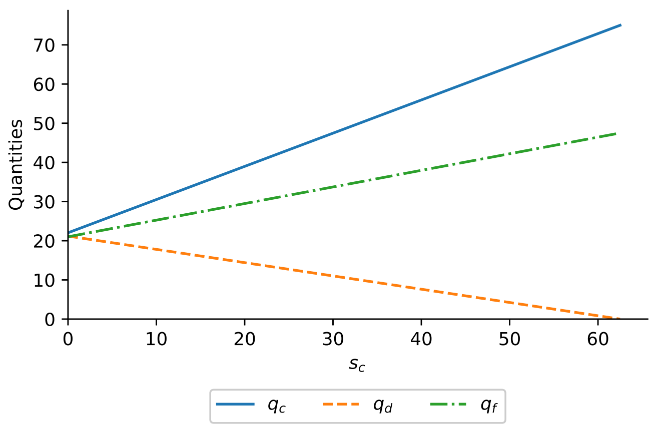
Subsidy to EVs (s_c)

When a subsidy is provided to the purchase of EVs, the optimal quantities are

$$
\begin{aligned}
q_c^{s_c} &= q_c^* + \frac{2}{X} s_c, \\
q_d^{s_c} &= q_d^* - \frac{2\gamma_1}{X} s_c, \\
q_f^{s_c} &= q_f^* + \frac{\gamma_2 + \gamma_4}{X} s_c.
\end{aligned}
$$

Recalling that $X = 4(1 - \gamma_1^2) - (\gamma_2 + \gamma_4)^2$, larger substitution and network effects increase the magnitude of the change in all the quantities. In the absence of substitution possibilities between EVs and GVs ($\gamma_1 = 0$), the subsidy to EVs does not affect the quantity of GVs; similarly, q_f is not affected if there are no network effects ($\gamma_2 + \gamma_4 = 0$). Figure 11 illustrates the behavior of quantities for different values of the subsidy to EVs. The optimal prices when

Figure 11: Effect on the quantities when a subsidy to EVs applies, with the model parameters $\gamma_1 = 0.4, \gamma_2 + \gamma_4 = 1, \alpha_c = 40, \alpha_d = 60, \alpha_f = 20, c_c = 0, c_d = 0$ and $c_f = 0$. In general, the impacts are independent of network effects.

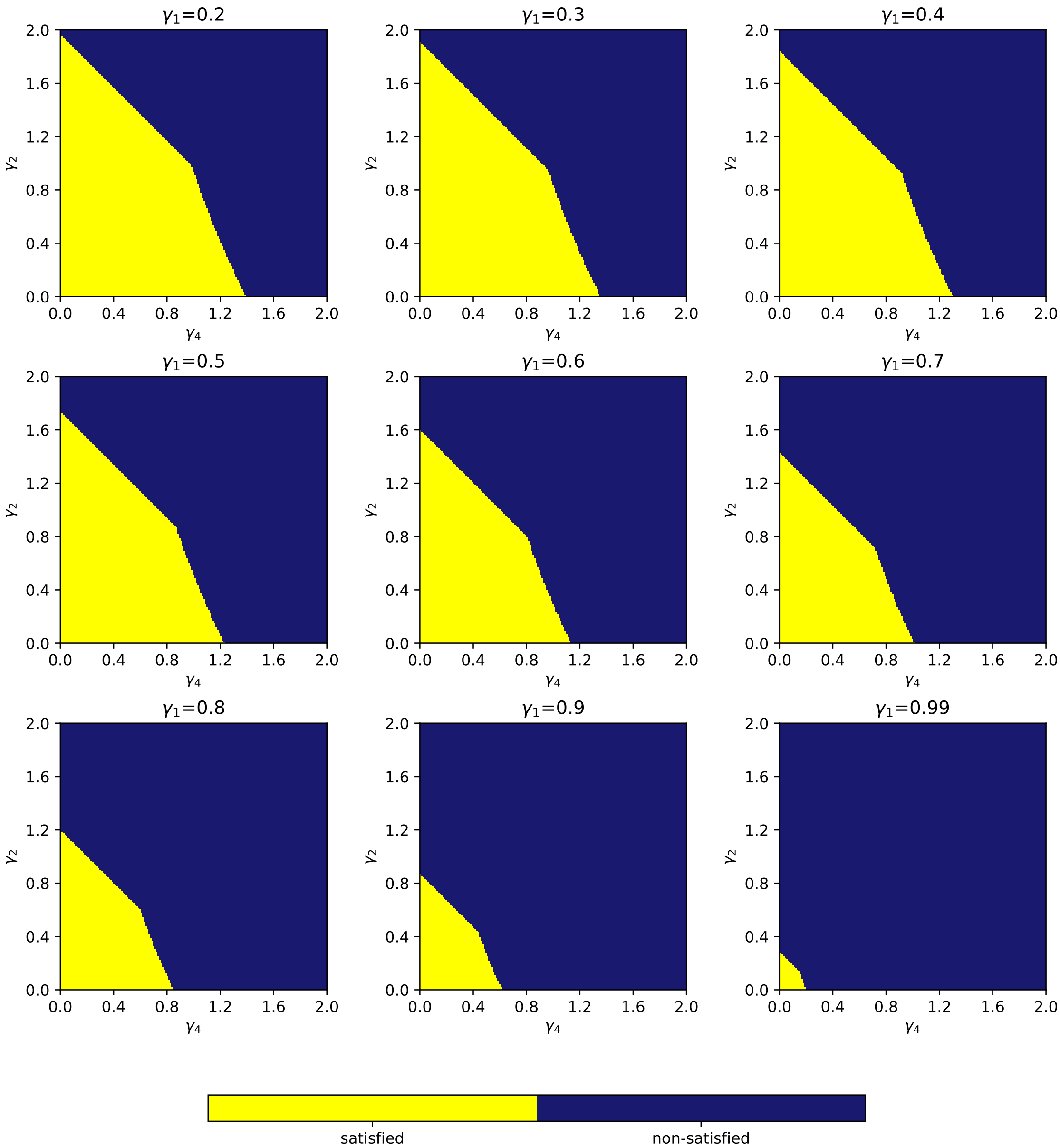


the subsidy is in place are

$$
\begin{aligned}
p_c^{s_c} &= p_c^* + \frac{2(1 - \gamma_1^2) - \gamma_4(\gamma_2 + \gamma_4)}{X} s_c, \\
p_d^{s_c} &= p_d^*, \\
p_f^{s_c} &= p_f^* - \frac{(\gamma_2 - \gamma_4)}{X} s_c,
\end{aligned}
$$

showing that if substitution is perfect ($\gamma_1 = 1$) and the network effect is not existing for retailers ($\gamma_4 = 0$), the price of EVs is not affected by the presence of the subsidy to EVs. Moreover, there is no effect on p_f if the network intensities are the same on the two sides of the market ($\gamma_2 = \gamma_4$). Figure 12 shows the conditions on the network effects γ_2 and γ_4 for a positive impact of s_c on p_c using different values of the substitution parameter γ_1, focusing on the set of parameters satisfying the *monopoly condition*. High substitutability reduces the parameter space such that s_c has a positive impact on p_c.

Figure 12: Graphical representation of the parameter space $(\gamma_1, \gamma_2, \gamma_4)$ satisfying the *monopoly condition* and leading to a positive impact of an EV subsidy on the price of EVs, i.e. $X > 0$ and $2(1-\gamma_1^2)-\gamma_4(\gamma_2+\gamma_4) > 0$.



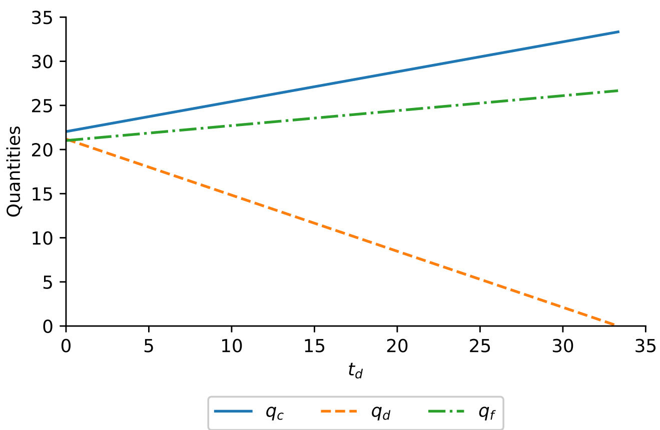
Taxes on GVs (t_d)

If a tax is imposed on the demand for polluting cars only, the optimal quantities are

$$\begin{aligned} q_c^{t_d} &= q_c^* + \frac{2\gamma_1}{X} t_d, \\ q_d^{t_d} &= q_d^* - \frac{2 - \frac{1}{2}(\gamma_2 + \gamma_4)^2}{X} t_d, \\ q_f^{t_d} &= q_f^* + \frac{\gamma_1(\gamma_2 + \gamma_4)}{X} t_d. \end{aligned}$$

The tax on GVs affects quantities of EVs and EVCSs, and GVs. The impact on the quantity of EVs is higher the stronger the substitution effect. Notice that if there is no substitutability between EVs and GVs ($\gamma_1 = 0$), nor q_c neither q_f are affected by the tax. Moreover, the quantity of EVCSs is not affected if the network effects are zero ($\gamma_2 + \gamma_4 = 0$). Figure 13 illustrates the behavior of quantities for different values of the tax on GVs.

Figure 13: Effect on the quantities when a tax to GVs applies, with the model parameters $\gamma_1 = 0.4, \gamma_2 + \gamma_4 = 1, \alpha_c = 40, \alpha_d = 60, \alpha_f = 20, c_c = 0, c_d = 0$ and $c_f = 0$. In general, the impacts are independent of network effects.



The optimal prices are

$$\begin{aligned} p_c^{t_d} &= p_c^* + \frac{\gamma_1(\gamma_2^2 - \gamma_4^2)}{X} t_d, \\ p_d^{t_d} &= p_d^* - \frac{1}{2} t_d, \\ p_f^{t_d} &= p_f^* - \frac{\gamma_1(\gamma_2 - \gamma_4)}{X} t_d, \end{aligned}$$

showing that in case of no substitutability or identical network effects, p_c and p_f are not affected by the tax. As discussed in the paper, the effect of the tax on p_c and p_f depends on the relative intensity of network effects.

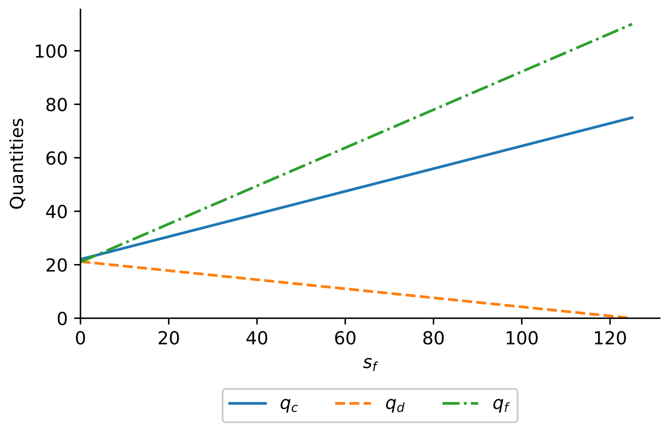
Subsidy to EVCSs (s_f)

When a subsidy is provided to EVCSs, the optimal quantities are

$$
\begin{aligned}
q_c^{s_f} &= q_c^* + \frac{\gamma_2 + \gamma_4}{X} s_f, \\
q_d^{s_f} &= q_d^* - \frac{\gamma_1(\gamma_2 + \gamma_4)}{X} s_f, \\
q_f^{s_f} &= q_f^* + \frac{2(1 - \gamma_1^2)}{X} s_f.
\end{aligned}
$$

When the subsidy applies, EVs, EVCSs and GVs purchases are affected. In the absence of network effects ($\gamma_2 + \gamma_4 = 0$) such subsidy has no effect on q_c and q_d. Also, no substitution ($\gamma_1 = 0$) implies that q_d is not affected, whereas perfect substitution ($\gamma_1 = 1$) rules out any effect of the subsidy on q_f. Figure 14 illustrates the behavior of quantities for different values of the subsidy to EVCSs.

Figure 14: Effect on the quantities when a subsidy to EVCSs applies, with the model parameters $\gamma_1 = 0.4, \gamma_2 + \gamma_4 = 1, \alpha_c = 40, \alpha_d = 60, \alpha_f = 20, c_c = 0, c_d = 0$ and $c_f = 0$. In general, the impacts are independent of network effects.



The optimal prices when a subsidy to EVCSs is in place are

$$\begin{aligned} p_c^* &= p_c^* + \frac{(1-\gamma_1^2)(\gamma_2-\gamma_4)}{X} s_f, \\ p_d^* &= p_d^*, \\ p_f^* &= p_f^* + \frac{2(1-\gamma_1^2)-\gamma_2(\gamma_2+\gamma_4)}{X} s_f, \end{aligned}$$

showing that p_c is not affected by the policy if there is perfect substitution or the network effects equal. Any effect on p_f is eliminated when EVs and GVs are perfect substitutes and if the network effect on the consumers' side is zero. Figure 15 shows the conditions on the network effects γ_2 and γ_4 for a positive impact of s_f on p_f using different values of the substitution parameter γ_1, focusing on the set of parameters satisfying the *monopoly condition*.

The dependence of prices on the relative intensity of network effects is illustrated in Figures 16, 17 and 18. The graphs show that the price of GVs represents an exemption thereof as it is solely affected by its own demand parameters (α_d and c_d) as well as the tax on GVs only. In contrast, the prices of EVs and EVCSs are generally influenced, both in terms of magnitude and sign by the relative intensity of network effects. Figure 16 shows that for the chosen parameters, the price of EVs is always increasing with the subsidy to EVs, whereas the price of EVCSs is increasing for $\gamma_2 > \gamma_4$ and decreasing otherwise. As expected, in Figure 17, where a tax is applied, the signs of the impacts are reversed depending on the relative intensities of network effects. For $\gamma_2 > \gamma_4$ the price of EVs is increasing and the price of EVCSs is decreasing. For $\gamma_4 > \gamma_2$, the outcome is reversed. Finally, Figure 18 shows that, for the chosen parameters, the price of EVs is increasing with a subsidy to EVCSs for $\gamma_4 > \gamma_2$ and decreasing otherwise, whereas the price of EVCSs is always increasing.

Figure 15: Graphical representation of the parameter space $(\gamma_1, \gamma_2, \gamma_4)$ satisfying the *monopoly condition* and leading to a positive impact of an EVCSs subsidy on the price of EVCSs, i.e. $X > 0$ and $2(1-\gamma_1^2)-\gamma_2(\gamma_2+\gamma_4) > 0$.

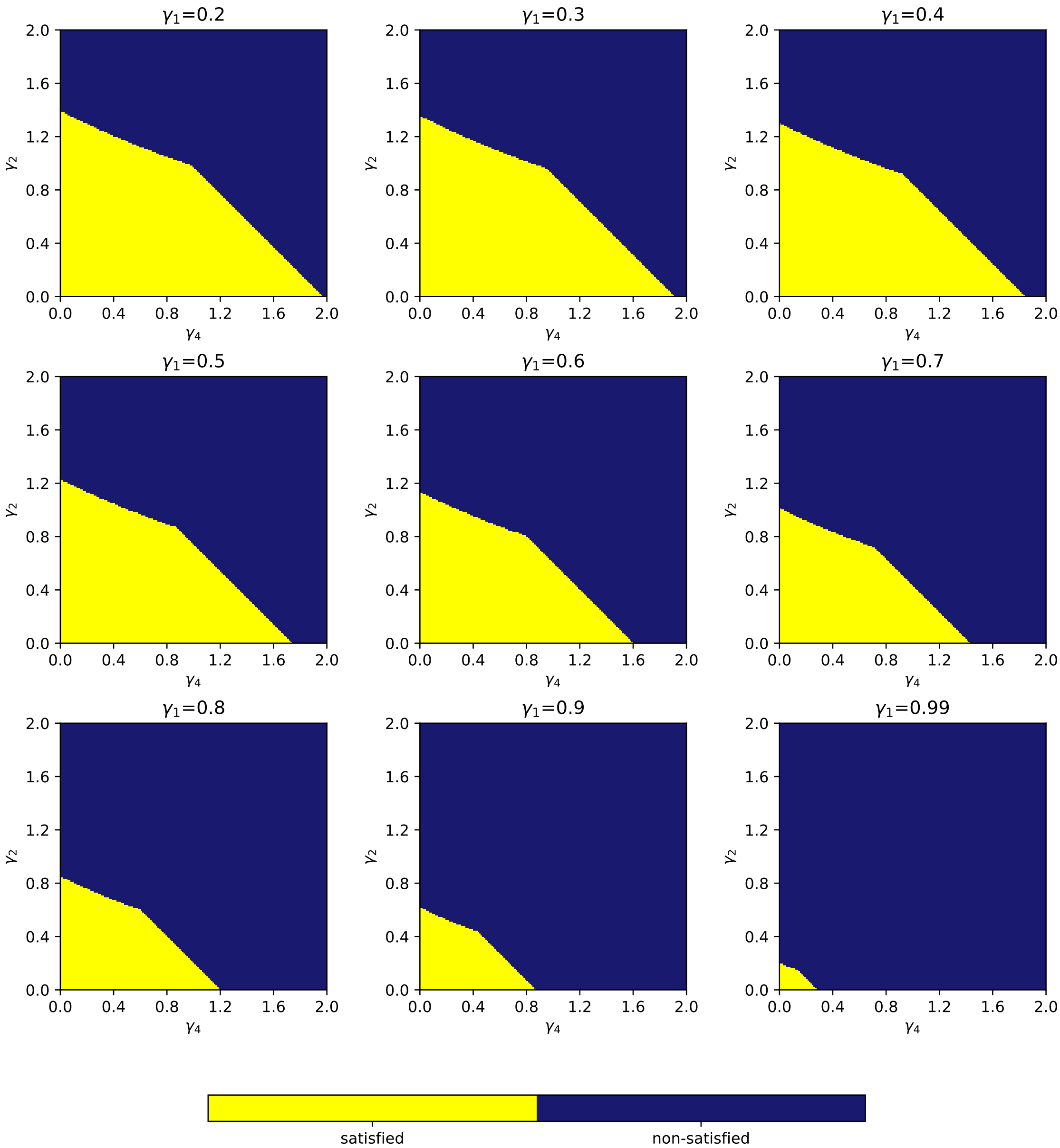


Figure 16: Effect on the prices of EVs, GVs and EVCSs when a subsidy to EVs applies, with the model parameters $\gamma_1 = 0.4, \gamma_2, \gamma_4 \in \{0.4, 0.6\}, \alpha_c = 40, \alpha_d = 60, \alpha_f = 20, c_c = 0, c_d = 0$ and $c_f = 0$.

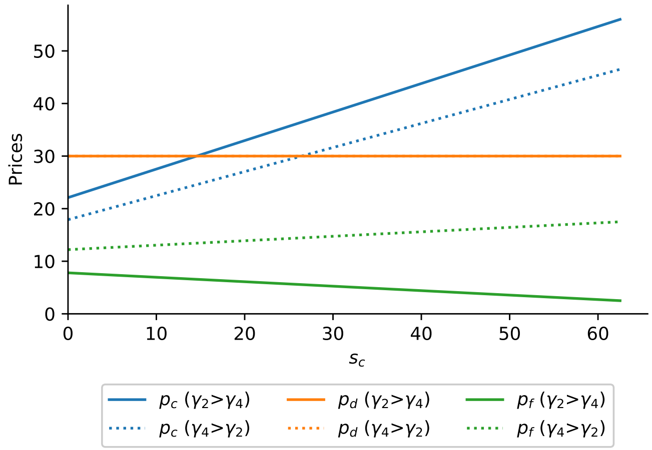


Figure 17: Effect on the prices of EVs, GVs and EVCSs when a tax on GVs applies, with the model parameters $\gamma_1 = 0.4, \gamma_2, \gamma_4 \in \{0.4, 0.6\}, \alpha_c = 40, \alpha_d = 60, \alpha_f = 20, c_c = 0, c_d = 0$ and $c_f = 0$.

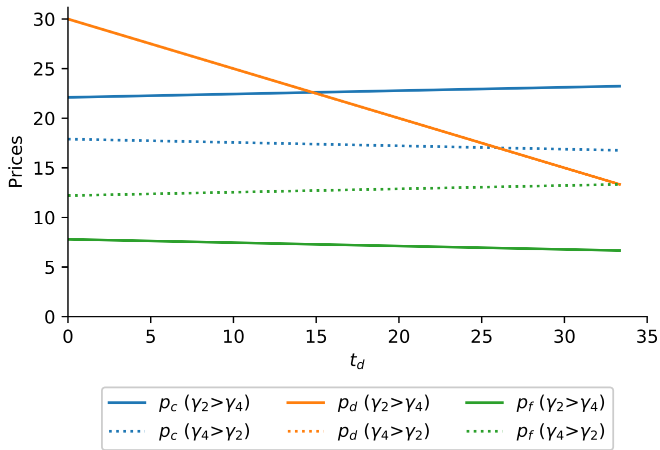
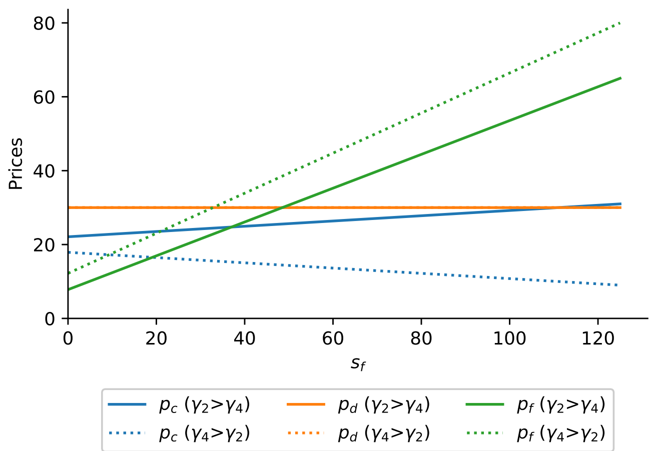


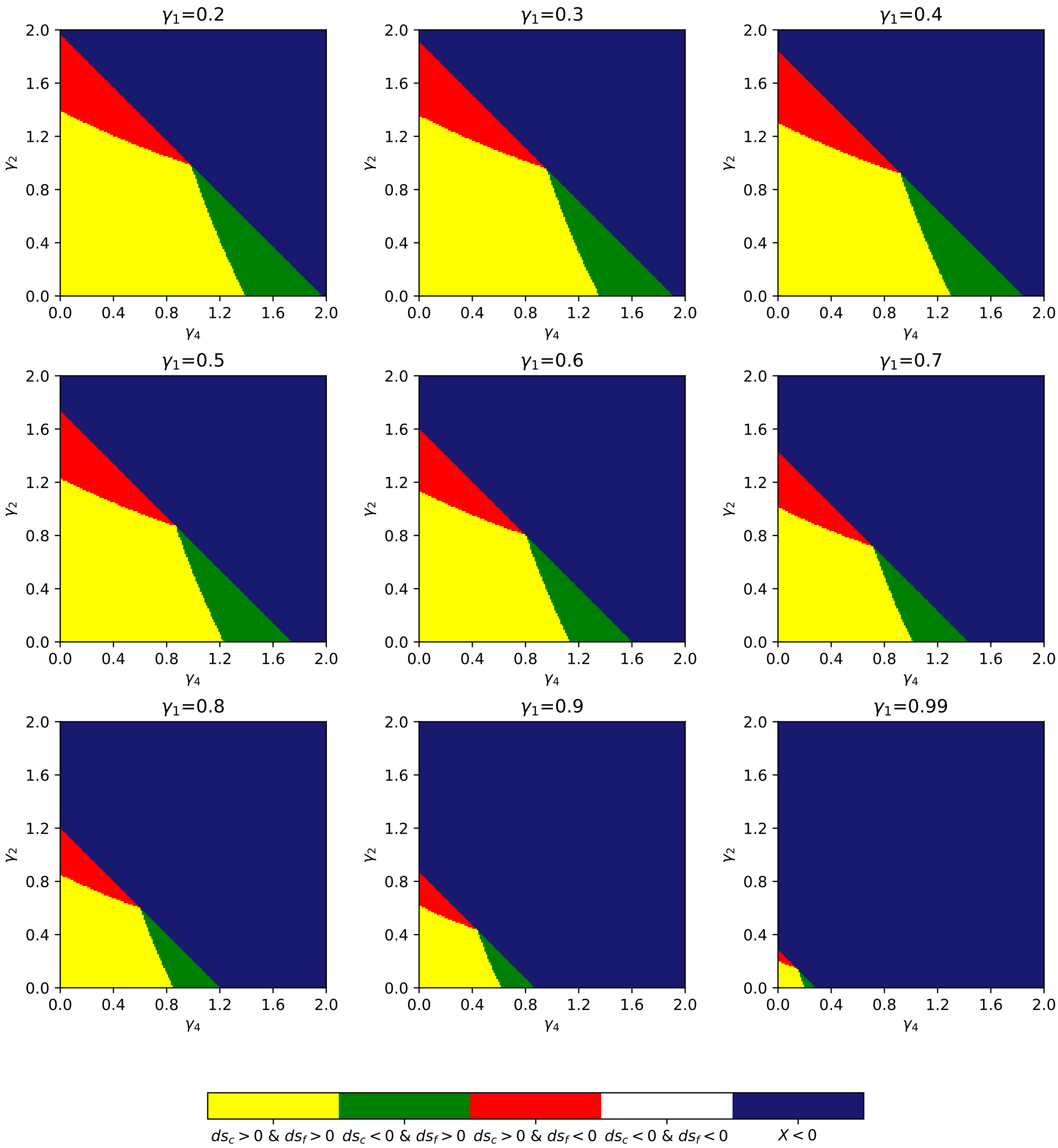
Figure 18: Effect on the prices of EVs, GVs and EVCSs when a subsidy to EVCSs applies, with the model parameters $\gamma_1 = 0.4, \gamma_2, \gamma_4 \in \{0.4, 0.6\}, \alpha_c = 40, \alpha_d = 60, \alpha_f = 20, c_c = 0, c_d = 0$ and $c_f = 0$.



Subsidies to EVs ($\mathbf{s_c}$) and EVCSs ($\mathbf{s_f}$)

In the following, we study the parameter space of substitution and network effects, $(\gamma_1, \gamma_2, \gamma_4)$, with respect to the price effect of both subsidies s_c and s_f. To simplify the notation we use $\partial p_c/\partial s_c = ds_c > 0$ to denote a positive impact of the subsidy to EVs on the price of EVs and $\partial p_f/\partial s_f = ds_f > 0$ to denote a positive impact of the subsidy to EVCSs on the price of EVCSs. Figure 19 provides a graphical illustration of this study separating the parameter space based on the different price effects, taking the *monopoly condition* into account. We can distinguish four different sets: (1) both subsidies have a positive effect on respective prices ($ds_c > 0$ and $ds_f > 0$); (2) negative effect of the subsidy to EVs on their price and positive effect of the subsidy to EVCSs on their price ($ds_c < 0$ and $ds_f > 0$); (3) positive effect of the subsidy to EVs on their price and negative effect of the subsidy to EVCSs on their price ($ds_c > 0$ and $ds_f < 0$); (4) both subsidies have a negative effect on respective prices ($ds_c < 0$ and $ds_f < 0$); (5) monopoly condition not satisfied ($X < 0$). Figure 19 shows that the set of parameters such that both subsidies have a negative effect on respective prices is empty, that is ds_c and ds_f can never be jointly negative. This follows from our assumption $X > 0$ and the fact that $ds_c + ds_f = X$. The economic interpretation of this finding follows from the two-sided market structure: as consumers and retailers represent two different sides of the market, the platform will never reduce the price on both sides.

Figure 19: Graphical representation of the parameter space $(\gamma_1, \gamma_2, \gamma_4)$ satisfying the *monopoly condition* and determining the sign of the impact of s_c on p_c and of s_f on p_f, provided that $X > 0$.



D Oligopoly

When an oligopolistic market structure is assumed the inverse demand functions faced by firms become

$$\begin{aligned} p_c &= \alpha_c - Q_c - \gamma_1 Q_d + \gamma_2 Q_f, \\ p_d &= \alpha_d - Q_d - \gamma_1 Q_c, \\ p_f &= \alpha_f - Q_f + \gamma_4 Q_c. \end{aligned}$$

where $Q_j = \sum_{i=1}^{N} q_{i,j}$ with $j = \{c, d, f\}$ is the total quantity of each good produced in the economy and $q_{i,j}$ denotes the quantity of each good produced by firm i. Each firm maximizes individual profits taking into account the quantities produced by the other firms

$$\begin{aligned} \pi_i &= (p_c - c_c)q_{i,c} + (p_d - c_d)q_{i,d} + (p_f - c_f)q_{i,f} \\ &= (\alpha_c - Q_c - \gamma_1 Q_d + \gamma_2 Q_f - c_c)q_{i,c} + (\alpha_d - Q_d - \gamma_1 Q_c - c_d)q_{i,d} \\ &\quad +(\alpha_f - Q_f + \gamma_4 Q_c - c_f)q_{i,f}. \end{aligned}$$

Profit maximization yields

$$\begin{aligned} \frac{\partial \pi_i}{\partial q_{i,c}} &: \alpha_c - (Q_c + q_{i,c}) - \gamma_1(Q_d + q_{i,d}) + \gamma_2 Q_f + \gamma_4 q_{i,f} - c_c = 0, \\ \frac{\partial \pi_i}{\partial q_{i,d}} &: \alpha_d - (Q_d + q_{i,d}) - \gamma_1(Q_c + q_{i,c}) - c_d = 0, \\ \frac{\partial \pi_i}{\partial q_{i,f}} &: \alpha_f - (Q_f + q_{i,f}) + \gamma_2 q_{i,c} + \gamma_4 Q_c - c_f = 0. \end{aligned}$$

From the FOCs we can derive the reaction functions of firm i, i.e. the optimal quantities of the EVs, GVs and EVCSs produced by each firm given production of the three goods by the other firms. The reaction functions are linear because of the assumption of linear demand and cost functions. Moreover, the quantity of each good produced by firm i depends on the quantity of the other two goods produced by the firm itself because of the presence of substitution and network effects. Firms are identical, hence they all produce the same quantities of EVs, GVs and EVCSs: $q_{i,j} = q_{-i,j} = q_j$, for all the goods in the economy. For an interior solution, optimal quantities produced by each firm i are

$$\begin{aligned}
q_c^* &= \frac{1}{X_{olig}}[(n+1)(\alpha_c - c_c) - \gamma_1(n+1)(\alpha_d - c_d) + (n\gamma_2+\gamma_4)(\alpha_f - c_f)], \\
q_d^* &= \frac{1}{X_{olig}}[-\gamma_1(n+1)(\alpha_c - c_c) + \left[n+1 - \frac{(n\gamma_2+\gamma_4)(\gamma_2+n\gamma_4)}{n+1}\right](\alpha_d - c_d) \\
&\quad -\gamma_1(n\gamma_2+\gamma_4)(\alpha_f - c_f)], \\
q_f^* &= \frac{1}{X_{olig}}[(\gamma_2+n\gamma_4)(\alpha_c - c_c) - \gamma_1(\gamma_2+n\gamma_4)(\alpha_d - c_d) + (n+1)(1-\gamma_1^2)(\alpha_f - c_f)].
\end{aligned}$$

where $X_{olig} = (n+1)^2(1-\gamma_1^2) - (n\gamma_2+\gamma_4)(\gamma_2+n\gamma_4) > 0$ is defined as the *oligopoly condition*. For $n = 1$, the *oligopoly condition* coincides with the *monopoly condition*; in general, for $n > 1$, we can write

$$X_{olig} = X + 2(n-1)(1-\gamma_1-\gamma_2\gamma_4),$$

meaning that for $1-\gamma_1-\gamma_2\gamma_4 > (<)0$, the set of parameter satisfying the *oligopoly condition* (*monopoly condition*) is larger than the one satisfying the *monopoly condition* (*oligopoly condition*). Since prices do not affect welfare as in the baseline model, we do not report them in the oligopolistic case. When the optimal policies apply, the optimal quantities become

$$\begin{aligned}
q_c^{pol} &= q_c^* + \frac{1+n}{X_{olig}}s_c + \frac{\gamma_1(1+n)}{X_{olig}}t_d + \frac{n\gamma_2+\gamma_4}{X_{olig}}s_f, \\
q_d^{pol} &= q_d^* - \frac{\gamma_1(1+n)}{X_{olig}}s_c - \frac{(n+1) - \frac{1}{n+1}(n\gamma_2+\gamma_4)(\gamma_2+n\gamma_4)}{X_{olig}}t_d - \frac{\gamma_1(n\gamma_2+\gamma_4)}{X_{olig}}s_f \\
q_f^{pol} &= q_f^* + \frac{\gamma_2+n\gamma_4}{X_{olig}}s_c + \frac{\gamma_1(\gamma_2+n\gamma_4)}{X_{olig}}t_d + \frac{(1+n)(1-\gamma_1^2)}{X_{olig}}s_f.
\end{aligned}$$

Notice that welfare now includes profits from all the n firms in the economy and damage is given by the total amount of GVs produced, that is

$$W = U_h + F_a + n\pi_i - \phi Q_d,$$

where $Q_d = nq_d$. As in the monopoly case, however, profits are simply redistributed within the economy and they do not matter in the welfare determination.