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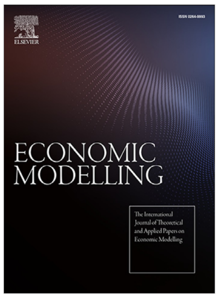

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Title Page (with Author Details)

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Abstract

This paper explores the coopetitive relationship between a private firm and a utility when the utility simultaneously competes with the firm in the output (EV charging-station) market and potentially co-operates in the input (electricity) market through its choice of a mark-up rate on the price of electricity supplied to the firm's charging stations. In the absence of regulation, we find the utility chooses to self-regulate itself (i.e., cooperate with the firm) in the input market in order to continue earning revenue from the sale of electricity to the firm's charging stations. We uncover the condition under which the utility chooses not to decrease its mark-up rate in response to an increase in market demand for EV charging. We similarly uncover the condition under which a regulator chooses a lower mark-up rate than the utility. Numerical analysis illustrates these findings.

JEL: D43, L5, L9

Keywords: coopetition; duopoly; regulation; electric vehicle charging stations

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September 5, 2022

Abstract

This paper explores the coopetitive relationship between a private firm and a utility when the utility simultaneously competes with the firm in the output (EV charging-station) market and potentially cooperates in the input (electricity) market through its choice of a mark-up rate on the price of electricity supplied to the firm's charging stations. In the absence of regulation, we find the utility chooses to self-regulate itself (i.e., cooperate with the firm) in the input market in order to continue earning revenue from the sale of electricity to the firm's charging stations. We uncover the condition under which the utility chooses not to decrease its mark-up rate in response to an increase in market demand for EV charging. We similarly uncover the condition under which a regulator chooses a lower mark-up rate than the utility. Numerical analysis illustrates these findings.

1 Introduction

Growth in the US electric vehicle (EV) market is confronting stakeholders with a host of challenges, such as how to improve EV battery storage efficiency, how to interconnect residential and commercial charging stations with the electricity grid to support demand response, and how to power the charging stations with cleaner sources of energy. This paper addresses an equally compelling regulative question concerning provision of commercial charging stations to meet growing demand from EV owners for electricity to charge their vehicles' batteries. How should the relationship between utility companies and private EV charging firms be regulated? In particular, how should this relationship be regulated when a utility plays the dual role of (1) natural monopolist in the supply of electricity to privately owned charging stations (via the input market), and (2) competitor with the very same private firms via operation of its own charging stations (in the output market), as is currently occurring with Duke Energy, San Diego Gas and Electric, Los Angeles

Department of Water and Power, Dominion Energy, Portland General Electric, New Jersey's Public Service Electric and Gas Company, and Duquesne Light Company, to name but a few utilities that either already operate their own stations or are considering doing so in the near future (Trabish, 2019; Walton, 2018, 2019, and 2020a-e; Bruggers, 2019)?[1,2] Markets where utility companies play this dual role typify what has come to be known as "coopetition", a neologism describing inter-organizational cooperative competition.

The term coopetition was coined in 1913 to describe the Sealshipt Oyster association's admonition to its 35,000 dealers not to compete against each other per se, rather to cooperate in order to better compete collectively against the association's diffuse competitor – oysters sold from wooden tubs (Cherington, 1913). Another early example of coopetition was Novell, Inc. founder and CEO Ray Noorda's well-documented strategy of sharing the market for network operating systems with its competitors, mainly Microsoft, with the aim of concomitantly expanding retail markets for Novell's newly conceived software products (Fisher, 1992). More recently, Samsung Electronics and Sony Corporation have formed a coopetitive relationship in the development and manufacture of flat-screen LCD TV panels (Gnyawali and Park, 2011).[3] To our knowledge, the unique features of potential coopetition in the EV charging market, where one of the "coopetitors" plays a role in both the input and output sides of the market, has yet to be studied. Questions of when and how best to regulate this form of coopetition – particularly in the context of emerging markets like commercial EV charging – therefore remain unanswered.[4]

That EV charging markets are emerging nationwide – and in fact must continue doing so in order to keep pace with projected consumer demand for EVs – is indisputable. The Edison Electrical Institute (EEI) projects that 18 million EVs will ply US roads by 2030, a 1,700 percent increase in number within roughly 10 years (EEI, 2018). By then EEI (2018) estimates EVs will represent seven percent of all vehicles on the

[1]Consolidated Edison's recent roll out of a demonstration charging-station network across New York City's five boroughs is an example of how utility companies located in more densely populated cities, where most residents do not have private charging capabilities, are piloting ownership of their own charging stations. Similar pilot programs are also being undertaken by utility companies located in large Canadian cities such as Montreal and Toronto, and efforts by a consortium of US utility companies to create a multi-regional charging network are also underway (Walton, 2020b and 2021).

[2]See Fitzgerald et al. (2017) for a report on the full slate of opportunities and constraints facing US utility companies regarding the promotion and commercialization of distributed energy resources.

[3]Brandenberger and Nalebuff (1996) instruct companies and organizations on how to identify and exploit coopetitive opportunities both intra- and inter-organizationally.

[4]We admittedly distinguish this unique relationship between a utility company and private firm as coopetition in a loose sense of the word. As will become clear in Sections 3 and 4, this is because cooperation between the two arises implicitly in our model, in the form of the utility choosing whether to self-regulate itself in the setting of its wholesale electricity mark-up rate, rather than explicitly, say where two competitors choose to solve a decision problem collectively in a multi-stage game, as in the case of Samsung and Sony. We can therefore think of the type of coopetition explored in this paper as being "one-sided" or "within-firm", as opposed to the more common type of coopetition arising between two private firms (or as depicted in De Ngo and Okura (2008) between a semi-public and private firm), which, by comparison, we can think of as "two-sided" or "between-firm" coopetition.

road and 20 percent of annual vehicle sales. Bandyk (2020) estimates that by 2040 EVs will account for 11 percent of US electricity consumption.[5] This expected growth in the US EV market will require roughly 10–15 million charging ports within the next 10 years (up from only 70,000 currently in operation), which in turn will require significant investment in EV charging infrastructure (EEI, 2018; USDE, 2017 and 2019; ICCT, 2019).[6] Private EV charging companies, such as ChargePoint, JuiceBox, Electrify America, Tesla, and EV Connect, along with some major oil companies, have emerged as major players in regional markets throughout the US. In regional markets where utility companies also own and operate charging stations, coopetitive relationships naturally arise between the utilities and private companies.[7]

In this paper we adopt a mixed duopoly framework within which to model the potential coopetitive relationship that arises between a private firm and a utility company when the latter simultaneously competes with the firm in the output market and cooperates in the input market through its choice of a lower mark-up rate on the price of electricity supplied to the firm's charging stations than would otherwise be the case under standard, price-setting monopoly conditions.[8] We first solve the conceptual model for a benchmark unregulated equilibrium, where the regulator (e.g., a public service commission or municipal government) is precluded from predetermining the utility's mark-up rate. Traditionally, utility pricing decisions are regulated through rate-case proceedings. Regulators are tasked with setting the utility's rate such that the utility recovers operating, energy-efficiency-program, and fixed-infrastructure costs without overcharging customers (ACEEE, 2019).[9] The unregulated equilibrium therefore serves as a polar benchmark against which to compare an equilibrium where the regulator rather than the utility determines the mark-up rate.

[5]Recent legislation in California (Senate Bill 100 passed in 2018) has set that state on the path of achieving 100 percent EV sales by 2045, which will ensure that three-quarters of light-duty, two-thirds of medium-duty, and one-third of heavy-duty vehicles are electric by 2045 (SCE, 2019).

[6]A charging station typically contains two separate charging ports. BNEF (2019) predicts that 30 million EVs will be on roads globally by 2030.

[7]Evidence of structural changes occurring at regional levels throughout the US suggests that opportunities for both utility and private companies to expand their presence in charging-station markets is encouraging. For instance, Walton (2020a) reports that city of Chicago, IL recently approved an ordinance requiring new construction of residential and commercial buildings of certain sizes to ensure that at least 20% of any supplied parking spaces be made-ready for EV charging stations. For a comprehensive assessment of opportunities available for US utilities to capitalize on the expected growth in EV charging markets over the next 10 – 20 years see Black & Veatch (2020).

[8]Mixed duopoly is distinguished in the literature from standard duopoly when one of the two firms is what De Ngo and Okura (2008) call "semi-public". In our case, the semi-public firm is a regulated utility company. See De Fraja and Delbono (1989) and Vickers and Yarrow (1988) for early work characterizing mixed duopoly markets.

[9]We thank an anonymous reviewer for pointing out that in more deregulated markets the legacy utilities might only be load-serving entities who do not own any generation assets and thus are purely buyers of electricity on the wholesale market themselves. Regulation also encompasses siting and required transmission and technology standards as well; aspects of regulation that this paper abstracts from.

For the unregulated case, we find that despite having what is essentially a monopoly position in the input market the utility instead chooses to self-regulate itself in order to continue earning revenue from the sale of electricity to the firm's charging stations, i.e., the utility effectively chooses to cooperate with firm by choosing a lower mark-up rate than would otherwise be the case, thus enabling the firm to remain in the charging-station market and compete with the utility. Further, we uncover the condition under which the utility chooses not to decrease its mark-up rate (i.e., to cooperate less) in response to an increase in market demand for EV charging. Simply stated, in an unregulated equilibrium with increasing market demand the utility chooses not to lower its mark-up rate in response to the exogenous increase in demand when it is relatively less valuable for the utility to do so; less valuable relative to the potential gains associated with increasing the number of charging stations it owns and operates. Choosing not to lower its mark-up rate in response to increased market demand would suggest that the utility is effectively choosing to compete more than cooperate in its coopetitive relationship with the private firm.

We similarly uncover the condition under which the regulator chooses a lower mark-up rate on behalf of the utility (i.e., induces more cooperation between the utility and firm) when the regulator is given the authority to set the rate, resulting in what we call a regulated equilibrium. We find that the regulator chooses a lower rate in the regulated equilibrium than an otherwise unregulated utility would select on its own when the marginal cost of the mark-up incurred by the private firm is greater than the corresponding marginal gain obtained by the utility. In other words, we identify the condition under which the regulator restores more cooperation in the coopetitive relationship between the utility and private firm. Numerical analysis illustrates these findings, and evinces additional properties of the model for two classes of market demand (constant and monotonically decreasing elasticities) exhibited by EV owners for electricity supplied by the utility's and firm's respective charging stations.

The numerical model allows us to compare two additional types of equilibria: partial- vs. full-information equilibria. Partial-information equilibria occur when the utility and regulator, respectively, condition their choices of the mark-up rate on the firm's anticipated demand responses in the unregulated and regulated regimes. In other words, partial information reflects a setting in which both the utility's and regulator's ranges of possible mark-up rates are restricted due to, among other things, technical or political constraints on the amount and type of consumer-demand information they have been able or allowed to obtain. In this way, their choices of mark-up rates are essentially governed by how well the utility and regulator are able to anticipate consumer demand responses. By contrast, full-information equilibria result when the utility and regulator perform grid searches over the entire universe of potential mark-up rates that maximize their respective objective functions; searches unconstrained by the firm's anticipated demand responses. As expected, we find that full-information equilibria are coincident with higher values of the utility's and regulator's objectives – utility profit and total surplus, respectively. Hence, there is value to having additional information. Nevertheless, these increases are coincident with some pronounced changes in some of the utility's and firm's choice variables.

In particular, when faced with an increase in linear market demand (i.e., demand with monotonically decreasing elasticity) the fully informed utility chooses to reduce its mark-up rate in an unregulated equilibrium. When faced with increasing isoelastic market demand (i.e., demand with constant elasticity) the utility instead dramatically increases the rate. Irrespective of market demand's form, the fully informed regulator 'zeros out' the utility's mark-up rate when market demand increases, effectively imposing a strict duopoly structure on the charging-station market. This result suggests that, when a regulator has authority to set the utility's mark-up rate, increasing market demand can help usher in a more competitive market structure itself.

However, we find that a partially informed utility does not increase its mark-up rate in an unregulated equilibrium as either linear or isoelastic market demand increases exogenously. Nevertheless, the private firm's charging-station output and profitability increase on the strength of the increases in demand. In the presence of increasing linear market demand, a partially informed regulator imposes a progressively lower mark-up rate, thus dramatically increasing the private firm's profitability. However, this is not the case in the presence of increasing isoelastic market demand, where the regulator chooses to hold the utility's mark-up rate constant.

The next section briefly reviews the relevant literature. Section 3 presents the conceptual model, and Section 4 characterizes the solutions for partial-information versions of the unregulated and regulated equilibria. Here we derive a series of analytical propositions describing key comparative statics effects. Section 5 presents results from the numerical analysis of the partial-information equilibria derived in Section 4, as well as for corresponding full-information equilibria. Section 6 concludes.

2 The Literature

As Dagnino (2007) explains, competitive models are predicated on agents' rent-appropriation strategies, while cooperative frameworks posit their agents' collective rent-generation strategies. Coopetition arises when agents simultaneously adopt both cooperation and competition strategies in order to advance their own private interests. In this sense, we can think of the cooperation component of coopetition as being "two-sided" (or "between-firm") since efforts are made by each firm in a given market to either expand the size of the existing market, enhance the quality of the good or service produced in the existing market, protect the existing market from foreign competition, or create a new market that in some way coexists with and complements the existing market. Competition then ensues between the firms in the newly enlarged or newly created market(s). By comparison, the type of coopetition explored in this paper is "one-sided" (or"within-firm"), in the sense that it is solely the utility company that balances its need for cooperation and competition with the private firm. The private firm competes with the utility given the latter's decision on how much to cooperate.[10]

Historical examples of between-firm coopetition abound. In addition to the cases of coopetition mentioned in Section 1, Okura (2007) analyzes the Japanese insurance market, where insurance firms invest cooperatively to lower underwriter risk while at the same time sell insurance policies competitively to max-

[10] This notion of one-sided coopetition is also distinguishable from two strands of the literature investigating what has come to be known as vertical foreclosure and channel dominance, respectively. Ordover et al. (1990) define vertical foreclosure as exclusion that results when unintegrated rivals in the output market (i.e., private retail firms) are potentially foreclosed from input supplies now controlled by the firm that vertically integrates across the input and output markets – a foreclosure that could cause the unintegrated rivals to exit the output market. This framework bears a relatively strong resemblance to ours, albeit in our case there is a single rival in the output market (the private firm) and a single integrated firm (the utility). Furthermore, in our set-up the utility is the monopoly supplier of the input to the private firm.

The vertical foreclosure literature considers the case where the vertically integrated firm coexists with multiple competitors in both the input and output markets (c.f., the earlier seminal works of Comanor, 1967; Fudenberg and Tirole, 1984; Comaner and Frech, 1985; Salinger, 1988; and more recently Ordover and Shaffer, 2007, and Kesavayuth and Zikos, 2012). In general, this literature finds that foreclosure is profitable for the vertically integrated firm when the gain in its profitability from integrating with an input supplier outweighs its potential losses incurred in the output market due to reduced competition in the input market (Ordover et al., 1990). As Kesavayuth and Zikos (2012) show, when vertically integrated firms can potentially join research and development (RD) networks in either the input or output markets that connect them with other integrated firms, the allure of foreclosing their rivals is naturally dispelled, especially in the case of strong network spillovers.

The channel-dominance literature is typified by Lu et al. (2011) and Ma et al. (2012). In this framework, a dominant manufacturer (i.e., input supplier) shares the input market with weaker competitors. Together the dominant and weaker manufacturers supply a retailer who interacts directly with consumers in the output market. Ma et al. (2012) show that it is not always optimal – in terms of its own profitability – for the dominant manufacturer to strictly follow the channel dominance strategy (where the dominant manufacturer cooperates with the retailer in jointly deciding the wholesale price and the allocation between them of surplus from this arrangement), even though dominant manufacturer, the retailer, and consumers benefit from this strategy at the weak manufacturer's expense. Not pursuing the channel dominance strategy in this framework corresponds to the utility deciding not to foreclose the private firm from competing in the EV charging market in our paper. In Lu et al.'s (2011) framework, the retailer has the ability to segment both the input market (between the dominant and weak manufacturer) and the corresponding output market (through the setting of differentiated prices, in particular, selling the low-cost/low-service good at a low price and the high-cost/high-service good at a higher price).

imize profits. Coopetition has similarly been analyzed in the Italian beverages industry (Bonel and Rocco, 2007), Italian opera houses (Mariani, 2007), and cross-functional software development teams (Ghobadi and D'Ambra, 2012a and 2012b).[11]

Gnyawali and Park (2009) identify the main factors driving coopetition at a microeconomic level, specifically among medium- and small-sized enterprises (SMEs). The authors describe six main factors: (1) risk and uncertainty associated with technological development, (2) costs of research and development, (3) prevalence of larger-sized competitors, (4) degree of technological convergence (toward the setting of industry-wide standards), (5) resources available to pursue large-scale innovation, and (6) product life-cycles. The larger/faster are (1)–(4), and the lower/shorter are (5) and (6), the more incentive exists for SMEs to collaborate in what are essentially input markets, in order to more effectively compete against each other and larger firms in common output markets, i.e., the more incentive for coopetition among the SMEs. Gnyawali and Park (2009) point to Mips Computer Systems as an example. Mips, a small firm employing less than 1,000 workers, was able to take on well-established players such as IBM and Hewlett-Packard by creating a constellation consisting of several small semiconductor firms in the reduced instruction-set computing industry.

By way of comparison, Gnyawali and Park (2011) consider between-firm coopetition among larger-scale firms, in particular the coopetitive relationship mentioned in Section 1 that developed between Samsung Electronics and Sony Corporation from 2003-2009 in the flat-screen LCD TV panel market – a classic case of two putative competitors pursuing an inter-firm alliance in order to create new knowledge and capabilities with the common goal of enhancing their innovation outcomes. In cultivating this relationship, Samsung contributed its technological acumen in LCD technology, while Sony contributed its technological strength and brand recognition in television. By Gnyawali and Park's (2011) account, Sony executives realized by 2003 that a stable supply of LCD panels was critical for its growth strategy in the flat-panel TV market. Samsung was one of the main LCD panel producers at that time. For Samsung, securing a partner like Sony was critical to its goal of achieving economies of scale. Yet, even while cooperating in the development of flat-screen technology, Sony and Samsung were competing fiercely in the flat-screen TV market, as well as in the development of new technologies and products.

At a more macroeconomic level, Carfi and Schiliro (2012) apply a game-theoretic framework to cli-

[11] Loebecke et al. (1999) couches knowledge transfer of the type explored in Ghobadi and D'Ambra (2012a and 2012b) in a conceptual game-theoretic framework.

mate change policy, where two countries engage in a non-cooperative Cournot market for their outputs, while simultaneously choosing whether to cooperate with each other through joint investment in low-carbon technologies. The authors identify payoff spaces where the countries cooperate not only in the low-carbon technology market ("pure coopetition"), but also in the output market ("double cooperation").

De Ngo and Okura (2008) characterize a mixed duopoly market in a modeling framework most closely related to ours. In their model, a private firm and semi-public firm (which is a partial welfare maximizer) each sequentially choose a cooperative level of effort to enlarge the market size (in the first stage) and a competitive level of effort to increase their respective market shares (in the second stage). In the market's subgame equilibrium, the competitive effort level of the semi-public firm is below that of the private firm, and the more the former is concerned about social welfare the less it competes. As a result, the semi-public firm's market share never exceeds that of the private firm. Further, the lower is the price elasticity of demand for the common good produced by the two firms, the more likely the private firm is to free ride on the cooperative effort of the semi-public firm. This leads to a general conclusion that – contrary to conventional wisdom, where competition and cooperation are considered as polar opposites, i.e., that a higher level of cooperation leads to a lower level of competition and vice versa – in a coopetitive game the relationship between competition and cooperation can be positive or negative depending upon the price elasticity level of the demand.

Despite the myriad differences between De Ngo and Okura's (2008) framework for between-firm coopetition and the one developed in this paper for within-firm coopetition – in particular, this paper's model characterizes a single-stage, simultaneous equilibrium where the semi-public firm is a regulated monopoly that is not concerned about social welfare per se – both models delineate rich sets of analytical propositions describing key aspects of their respective equilibriums. As mentioned in Section 1, this paper makes a unique contribution to the coopetition literature by assessing the role of regulation in an emerging market, where one of the participants otherwise sets the price of one of its competitor's inputs while at the same time competing in a common output market. Because this market – the EV charging market – is integral to the future of a lower-emissions transportation sector in the US, the analysis undertaken in this paper not only contributes to a relatively sparse extant literature, but also to an emergent issue of major social significance.[12] The paper also bridges the vertical foreclosure and channel dominance literatures with that

[12] We say "lower-emissions" rather than the commonly used "zero-emissions" because as Holland et al. (2016 and 2019) point out, electric vehicles are not necessarily emissions free. Since nearly 70% of electricity generated in the US is produced by burning coal and natural gas, the comparison between gas-powered and electric vehicles in most locations comes down to a comparison

pertaining to mixed-duopoly by investigating the extent to which a dominant firm is impelled to exert its dominance over its rivals (c.f., Ordover et al. (1990) and Ma et al. (2012), respectively, regarding vertical foreclosure and channel dominance).

3 The Conceptual Model

As described in Section 1, this paper develops a model of regulated coopetition in a given region's commercial EV charging market, where the market's rivals are, on the one hand, a private EV-charging firm (henceforth "firm"), and on the other a regulated electric utility company (henceforth "utility").[13] Because this paper investigates the effects of regulation on the coopetive relationship between a firm and utility, we assume at the outset that both agents have entered the market and neither choose to exit. Thus, we do not consider the broader implications associated with entry-exit decisions that would necessarily be accounted for in a general-equilibrium framework.

The firm and utility compete in the retail market (where electricity is sold to EV drivers at charging stations owned respectively by the firm and utility), but cooperate in the input market (where the firm purchases electricity from the utility to power its charging stations, similar to any purchase of electricity made by a utility customer). The regulator may choose to regulate the electricity price set by the utility in the input market (which in turn impacts the utility's profit margin in that market). In this case, the model depicts a competitive retail market and regulated monopoly in the input market. Without regulation, the model depicts competition in the retail market and unregulated monopoly in the input market.

As such, the standard duopoly model provides a convenient framework within which to assess the role of regulation in both nurturing coopetition between a firm and a utility and in safeguarding social welfare. To reiterate, the competition aspect of coopetition plays out in the retail EV charging market, where the firm and utility compete against each other for EV owners' use of the region's charging stations. The cooperation aspect simultaneously plays out in the wholesale electricity market, where the firm is a customer of the utility's.

between burning gasoline (to power the former type of vehicle) versus a regional mix of coal and natural gas (to power the later type). Holland et al. find considerable heterogeneity in the relative environmental benefits associated with electric vehicles; relative benefits that are either large and positive, large and negative, or negligible, depending upon geographical location. The heterogeneity is attributable almost entirely to differences in local air quality. Accounting solely for greenhouse gases, electric vehicles are associated with positive benefits in almost every location in the US.

[13] In contrast to a commercial charging market, a private charging market pertains to electric charging units that are installed by households in their garages, or charging units that are installed by businesses for use solely by their employees, e.g., located in the business's parking lot.

We begin by considering the firm's profit, π_f, expressed as,

$$\pi_f = p\left(Q;\alpha\right) q_f - c_f\left(w^f, q_f\right), \tag{1}$$

where function $p(Q;\alpha)$ represents inverse market demand for retail electricity demanded by EV owners from firm f's charging stations. We assume per-unit electricity price p is twice continuously differentiable ($\mathscr{C}^2$) and negatively related to aggregate electricity demand $Q = q_f + q_u$, where q_f and q_u represent consumers' total demand for electricity (to power their EVs) from the firm's and utility's respective charging stations located throughout the region. However, we impose no a priori assumption on the extent to which consumer demand for charging-station electricity is responsive to changes in price p, i.e., the slope and own-price elasticity of the market demand curve. While previous studies have generally reported inelastic demands for residential electricity in the US over both the short- and long-runs (c.f., Alberini and Filippini, 2011; Miller and Alberini, 2016; Sun and Yu, 2017; Burke and Abayasekara, 2018) as well as for gasoline (c.f., Espey's (1996) and Goodwin et al.'s (2004) meta-analyses), recent evidence from Norway suggests the price elasticity of demand specifically for EV charging may be higher (Fridstrøm and Østli, 2021).[14]

Parameter α is a shift parameter accounting for exogenous changes in market demand. To account for shifts in market demand conceptually, we assume that $\partial p(Q;\alpha)/\partial\alpha > 0$, i.e., that increases in α denotes an outward shift in inverse market demand. However, we impose no a priori assumption on any simultaneous changes in the slope of inverse demand as the curve shifts outward, i.e., we do not assume that the inverse market demand curve becomes flatter (i.e., $\partial^2 p(Q;\alpha)/\partial Q\partial\alpha > 0$), steeper (i.e., $\partial^2 p(Q;\alpha)/\partial Q\partial\alpha < 0$), or approaches constancy (i.e., $\partial^2 p(Q;\alpha)/\partial Q\partial\alpha \longrightarrow 0$). In Appendix E, we explore the implications of these different possibilities.

Cost function $c_f(\cdot)$ is assumed increasing and strictly convex in q_f and input price vector w^f, where for future reference w_1^f denotes the wholesale price paid by the firm to the utility for electricity delivered by the utility to the firm's charging stations, and w_2^f is the per-unit price paid by the firm to the utility for installation (by the utility) of the firm's charging infrastructure (i.e., the per-unit cost incurred by the firm for installation of its charging stations).[15] Hence, we assume the firm and, as will be shown below the utility,

[14] In Section 4, we identify where steeper market demand either strengthens or weakens the conceptual model's analytical propositions.

[15] We therefore assume the utility is responsible not only for the wholesale supply of electricity to the firm's charging stations, but also installation of the charging stations themselves, including installation of the make-ready and port components (c.f., Enelx, 2019). This assumption allows the quantity of installations to be determined endogenously within the model itself, rather than

each face a concave programming problem. Further, we assume the firm's associated marginal cost function, $\partial c_f(\cdot)/\partial q_f$, increases in input prices, i.e., $\partial^2 c_f(\cdot)/\partial q_f \partial w^f > 0$, and is non-decreasing in its output level, i.e., $\partial^2 c_f(\cdot)/\partial q_f^2 \geq 0$, both of which are standard convexity assumptions.

Lastly, we assume a fixed relationship between the aggregate amount of electricity supplied to EV owners via the firm's charging stations (i.e., q_f), and the quantity of the firm's charging stations, x_f,

$$x_f = \frac{q_f}{\beta_f}, \tag{2}$$

where parameter $\beta_f > 0$ represents the efficiency factor converting a firm's EV charging station into its electricity-output equivalent. We interpret β_f in the broadest sense possible. It represents not only a charging station's technical efficiency (e.g., time necessary for fully charging an EV and how well the station is maintained by the firm), but also non-technical efficiencies associated with how well the firm markets and locates its stations throughout the region.[16]

The utility's profit, π_u, is similarly expressed as,

$$\pi_u = p(Q;\alpha)\, q_u + w_1^f q_f - c_u(w^u, q_u, q_f), \tag{3}$$

where Q, $p(Q;\alpha)$, w_1^f, q_f, and q_u are as previously defined. Parameter w_u represents the utility's input price vector, where again for future reference w_1^u denotes the per-unit wholesale cost of electricity incurred by the utility, and w_2^u is the per-unit cost incurred by the utility for installation of charging infrastructure.[17] Including q_f separately in $c_u(\cdot)$ reflects the fact that the utility is the sole supplier of wholesale electricity to both the firm and itself.

Cost function $c_u(\cdot)$ is assumed increasing and convex in q_u, q_f, and input price vector w^u. Similar to the firm, the utility's associated marginal cost function, $\partial c_u(\cdot)/\partial q_u$, increases in input prices, i.e., $\partial^2 c_u(\cdot)/\partial q_u \partial w^u > 0$, and is non-decreasing in its own output level, i.e., $\partial^2 c_u(\cdot)/\partial q_u^2 \geq 0$. Further, we assume $\partial^2 c_u(\cdot)/\partial q_u \partial q_f = \partial^2 c_u(\cdot)/\partial q_f \partial q_u \geq 0$ and $\partial^2 c_u(\cdot)/\partial q_f^2 \geq 0$, reflecting the fact the utility's marginal cost responds no differently to the source of demand for wholesale electricity, whether the de-

exogenously pre-determined, say by prior regulation of the utility.

[16]The fixed relationship between x_f and q_f implies that once installed, the firm's charging stations run at full capacity. For the purposes of this study, which does not consider the role of excess capacity in the EV charging market, this abstraction helps maintain our focus on the role of regulation in promoting coopetition between the firm and utility.

[17]In the vertical foreclosure literature, w_1^u is identified as an internal transfer price (c.f., Ordover et al., 1990).

mand emanates from the firm or itself. As a result of these conditions, the utility also faces a concave programming problem.

Similar to the firm, we assume a fixed relationship between the aggregate amount of electricity supplied to EV owners via the utility's charging stations (i.e., q_u), and the quantity of the utility's charging stations, x_u, expressed as,

$$x_u = \frac{q_u}{\beta_u}, \tag{4}$$

where parameter $\beta_u > 0$ represents the efficiency factor converting a utility's EV charging station into its electricity-output equivalent. Similar to the firm, β_u represents the utility's production efficiency in the broadest sense possible.

To account for the utility's natural-monopoly advantage in the provision of wholesale electricity to the firm's charging stations, we now define w_1^f explicitly as,

$$w_1^f = [1 + \phi_u]\, w_1^u, \tag{5}$$

where $\phi_u \geq 0$ denotes the utility's mark-up rate on the electricity price charged to the firm.[18] Naturally, ϕ_u serves as the model's regulatory leverage point – in the presence of regulation, it is the regulator's choice variable. In the absence of regulation, ϕ_u serves as a measure of coopetition between the firm and utility, in particular the extent to which the utility chooses to cooperate with the firm in its role as the sole supplier of wholesale electricity to the firm's charging stations. In our setting, full cooperation between the utility and firm occurs when the utility sets $\phi_u = 0$ in an unregulated equilibrium. The setting of $\phi_u > 0$ indicates the existence of a coopetitive relationship between the utility and firm, with larger values of ϕ_u representing more competition and less cooperation in the relationship.

Without loss of generality, we henceforth assume,

$$w_2^f = w_2^u, \tag{6}$$

Equation (6) implies that, unlike the marked-up price of electricity charged by the utility to the firm, the utility does not charge an additional mark-up on the costs it incurs to build-out infrastructure for the

[18]Regulation of utilities typically takes the form of an allowable rate of return associated with any adjustment in utility rates that accompany major investments by the utility in its grid infrastructure. As such, regulation ultimately comes down to the choice of the utility's mark-up rate (c.f., Phillips, 1993; CPUC, 2019).

firm's charging stations.[19] Moreover, per-unit infrastructure build-out costs are assumed to be exogenously determined, which is reflective of the fact that base per-unit build-out costs are generally considered to be relatively common among utilities across the US (c.f., Future Energy, 2021). The important point for our modeling purposes is that the utility is precluded from charging the firm more per-unit for the build-out of the firm's infrastructure than it incurs for the build-out of its own infrastructure.

Thus, in sum, while per-unit cost w_1^f is assumed exogenous from the firm's perspective, it is endogenously determined within the model via the utility's choice of ϕ_u. In contrast, the utility's per-unit costs w_1^u and w_2^u are considered to be exogenously determined.

4 Equilibria

4.1 Unregulated Equilibrium

This section considers the case of an unregulated utility interacting simultaneously with the firm in both input and output markets, resulting in what we refer to as an unregulated equilibrium. This would occur, for example, when a utility is allowed to compete in the EV charging market through its "unregulated subsidiary", where the subsidiary is granted the authority to simultaneously compete freely in both the input and output markets, resulting in an admittedly idealized, benchmark version of an unregulated equilibrium (Phillips, 2014). We begin our analysis by solving equations (1) – (6) for a partial-information, Cournot equilibrium, where the firm and utility maximize their respective profits by simultaneously choosing the number of charging stations to install throughout the region, and, in addition, the utility conditions its optimal mark-up rate on the firm's demand response for wholesale electricity, i.e., the utility explicitly accounts for the firm's response function in its own decision problem.[20] In Section 5 we present results from a numer-

[19] We have been unable to find any evidence to suggest that US utilities actually charge mark-ups for infrastructure build-out.

[20] Explicitly accounting for the firm's response function in this manner is a convenient way to model the utility's partial-information advantage in its decision problem vis-a-vis the firm. Again, because the utility bases its choice of mark-up rate directly upon the firm's response function, rather than upon a universal grid search for the rate that maximizes its profit (as it would do with a full-information advantage), the utility's information is considered partial rather than full. The spatial problem of exactly where the firm and utility might optimally locate their respective charging stations is beyond the scope of this study. We assume the utility and firm respectively choose their optimal quantities of charging stations rather than quantities of electricity per se merely for expository convenience. Because of the assumed fixed relationships in equations (2) and (4), the two quantities are mutually determined for both the utility and firm. Lastly, a Cournot rather than Bertrand solution concept presumes that competition between the utility and firm occurs more on the production-capacity margin than the price margin, and that rivalry between the utility and firm in the output market will not necessarily lead to a perfectly competitive outcome in the long run (c.f., Kreps and Scheinkman, 1983; Boccard and Wauthy, 2000).

ical model that also solves for full-information version of the unregulated equilibrium, where the utility does not condition (and thus does not constrain) its choice of the mark-up rate on the firm's response function.[21]

In essence, the firm and utility each see themselves as competing for residual market demand, which results in a system of three optimality conditions,[22]

$$\Omega_{x_f} = p\left(Q;\alpha\right) + \frac{\partial p\left(Q;\alpha\right)}{\partial Q} q_f - \frac{\partial c_f(w^f,\phi_u,q_f)}{\partial q_f} \leq 0, \tag{7}$$

$$\Omega_{x_u} = p\left(Q;\alpha\right) + \frac{\partial p\left(Q;\alpha\right)}{\partial Q} q_u - \frac{\partial c_u\left(w^u,q_u,q_f\right)}{\partial q_u} \leq 0, \tag{8}$$

$$\Omega_{\phi_u} = w_1^u q_f + \left[\frac{\partial p\left(Q;\alpha\right)}{\partial Q} q_u - \frac{\partial c_u(w^u,q_u,q_f)}{\partial q_f} + w_1^u\left[1+\phi_u\right]\right]\frac{\partial q_f}{\partial \phi_u} \leq 0, \tag{9}$$

the simultaneous solution of which results in the set of functions $Q^* = Q\left(w_f^*, w^u, \beta_f, \beta_u, \alpha\right)$, $q_f^* = q_f\left(w_f^*, w^u, \beta_f, \beta_u, \alpha\right)$, $q_u^* = q_u\left(w_f^*, w^u, \beta_f, \beta_u, \alpha\right)$, $w_f^* = \left(\left(1+\phi_u^*\right)w_1^u, w_2^u\right)$, and $\phi_u^* = \phi_u\left(w_f^*, w^u, \beta_f, \beta_u, \alpha\right)$, which in turn characterizes the partial-information, unregulated equilibrium.

Equations (7) and (8) are familiar Kuhn-Tucker optimality conditions for the firm's and utility's respective quantity choices x_f and x_u, where marginal profit functions Ω_{x_f} and Ω_{x_u} are driven to zero(less than zero) at an interior(corner) solution via the choices of x_f and x_u, respectively. Equation (9) is the optimality condition for the utility's choice of mark-up rate ϕ_u, where marginal profit function Ω_{ϕ_u} is likewise driven to zero(less than zero) at an interior(corner) solution via the utility's choice of ϕ_u.

In deriving condition (9) we have invoked the assumption that the EV charging market converges to a partial-information equilibrium solution when equivalence is reached between the utility's conjecture of how the firm responds to its choice of ϕ_u (i.e., $\partial q_f/\partial\phi_u$), on the one hand, and the firm's actual choice of q_f on the other.[23] The rationale for investigating the partial-information formulation in this context is that utility companies generally have long histories of pricing the electricity delivered to their customers. It is

[21] We adopt the distinction between partial- and full-information equilibria for what is essentially a static game played between the firm and utility in a manner similar to the distinction made between closed- and open-loop equilibria in the context of dynamic game theory (Fudenberg and Levine, 1988; Wiszniewska-Matyszkiel, 2014). As we demonstrate in Section 5, the full-information equilibrium is the solution to a grid search over values of ϕ_u in a general neighborhood of the partial-information equilibrium resulting in higher profitability for the utility.

[22] Note that the steeper is market demand, the more likely are equations (7) and (8) to hold with strict inequality, and the less likely is equation (9).

[23] In specific, the utility's objective function for the partial-information problem may be written as,

$$\max_{x_u,\phi_u} p\left(q_f\left(\left[1+\phi_u\right]w_1^u, w_2^f, \beta_f, \alpha\right) + q_u; \alpha\right) q_u + \left[1+\phi_u\right] w_1^u q_f\left(\left(1+\phi_u\right)w_1^u, w_2^f, \beta_f, \alpha\right) - c_u\left(w^u, q_u, q_f\left(\left[1+\phi_u\right]w_1^u, w_2^f, \beta_f, \alpha\right)\right),$$

i.e., where the utility explicitly accounts for the firm's response function $q_f\left(\left[1+\phi_u\right]w_1^u, w_2^f, \beta_f, \alpha\right)$.

therefore conceivable that utility customers' demand responses are measurable with a relatively high degree of accuracy, which, in the case of our model, is reflected in the utility's incorporation of $\partial q_f/\partial\phi_u$ directly in its decision problem.[24] Also, as we will soon see, the partial-information formulation results in two key analytical propositions – Propositions 4 and 5 below.

Irrespective of a partial- or full-information formulation of the model's solution, comparative statics effects ensue at an interior equilibrium, which we coalesce into Propositions 1–3.

Proposition 1. *Equilibrium quantities q_f^* and q_u^* are negatively related, i.e., $\frac{\partial q_f^*}{\partial q_u} < 0$ and $\frac{\partial q_u^*}{\partial q_f} < 0$.*

Proof. See Appendix A.

From Proposition 1 we see that the standard substitutability result governing the output relationship between the two market participants continues to hold, even when one of the two (in our case the utility) exercises monopoly power over the supply of a critical input used by both participants in their production processes. This result is illustrated in Figure 1. For consistency with Proposition 1, the utility is depicted as the dominant producer of charging-station electricity and the firm is depicted as residual claimant, whose production level in concert with market demand ultimately determines the attendant equilibrium electricity price.

[INSERT FIGURE 1 HERE]

The figure includes an inverse market demand curve (D) for electricity and the utility's corresponding marginal revenue and cost curves (MR_u and MC_u, respectively). The utility's equilibrium output (q_u) is determined at the point where $MR_u = MC_u$, and the price the utility would obtain if it were a monopoly in the market is depicted as p_u. The firm's marginal revenue curve (MR_f) emanates from the intersection of p_u and D, and determines the market supply of electricity (Q) where it intersects with the firm's marginal cost curve (MC_f). For ease of illustration, we depict the firm's MC_f curve as equaling MC_u plus the utility's optimal mark-up rate ϕ_u, which, as described below in Proposition 4, is not necessarily set equal to p_u.[25] The firm's equilibrium electricity supply (q_f) is then equal to $Q - q_u$, and equilibrium market price (p^*) is determined at the intersection of MR_f and MC_f. As Figure 1 illustrates, because the equilibrium price and

[24] To the contrary, utilities generally do not have histories of competing with firms in the sale of retail products, such as EV charging stations and the electricity sold from them to the general public. Thus, in our partial-information formulation we retain the underlying feature of a Cournot equilibrium with respect to the utility's choice of x_u, i.e., unlike its choice of ϕ_u, the utility does not internalize the firm's response to its choice x_u.

[25] Our assumption of a linear MC_f curve represents a special case of the firm's cost function, $c_f\left(w^f, \phi_u, q_f\right)$, where ϕ_u enters the function linearly.

quantity are effectively set at p^* and Q, if the firm chooses to increase its output from q_u to q'_u the firm's output will reduce to $Q - q'_u$, which is consistent with the result in Proposition 1.[26]

Since the utility's mark-up rate ultimately determines the per-unit cost of one of the firm's inputs (w_1^f), and the firm's cost function is, by definition, positively related to this cost, Proposition 2 yields no surprise.

Proposition 2. *Equilibrium quantity q_f^* is negatively related to the utility's mark-up rate, i.e., $\frac{\partial q_f^*}{\partial \phi_u} < 0$.*

Proof. See Appendix B.

All else equal, the firm chooses to reduce its supply of charging stations (and thus the quantity of electricity supplied to EV owners) in the face of the utility's higher mark-up rate. This result is depicted in Figure 2, which zooms in on the firm's reaction to a rise in the mark-up rate.

[INSERT FIGURE 2 HERE]

An increase in the mark-up rate from ϕ_u to ϕ'_u effectively raises the firm's marginal cost curve from MC_f to MC'_f and, given the firm's marginal revenue curve, leads the firm to reduce its electricity supply from $Q - q_u$ to $Q - q'_u$.

Proposition 3 relates another standard comparative statics result for duopoly models where production is a linear function of inputs.

Proposition 3. *The relationship between x_f^* and β_f is negative, i.e., $\partial x_f^* / \partial \beta_f < 0$.*

Proof. See Appendix C.

As the marginal productivity of an input increases the firm responds by proportionally reducing its use of the input. As we will see in Section 5, the firm in our particular duopoly setting reduces its use of input x_f to the point at which it continues meeting its original residual demand.

Even though in a partial-information unregulated setting the utility has the option of driving the firm from the EV charging market – by setting its mark-up rate to a level at which the firm's production costs become prohibitive via a concomitant rise in w_1^f – and thus securing a monopoly position, Proposition 4 states that this is not necessarily the case in our particular setting.

Proposition 4. *The utility's optimal choice of ϕ_u^* in a partial-information equilibrium does not necessarily result in $q_f^* \longrightarrow 0$.*

[26] As Proposition 4 below demonstrates, the utility does not necessarily have incentive to increase its output to $q_u = Q$, i.e., to effectively eliminate the firm from the charging-station market.

Proof. See Appendix D.

This result occurs due to the utility's monopoly power in the wholesale electricity market, where it obtains revenue from sale of electricity to the firm equaling $w_1^u [1+\phi_u^*] q_f^*$. If this revenue stream is large enough to offset the concomitant effects of reduced market price, $p(Q^*;\alpha)$, and increased cost, $c_u(\cdot)$, then the utility will set the mark-up rate, ϕ_u^*, such that $q_f^* > 0$. Figure 3 illustrates this result.

[INSERT FIGURE 3 HERE]

In the figure, a relatively flat-sloped market demand curve, D, helps define six key areas beneath the curve. If it sets the mark-up rate, ϕ_u, such that the firm is driven from the market, then the utility's monopoly profit level is represented by area $A+B+C$. If instead the utility sets its mark-up rate such that the firm remains in the market, then the utility's profit is equal to area $B+C+E-\lambda F$, where λ represents the proportion of area F such that area λF corresponds to the (electricity-equivalent) build-out costs for the firm's charging stations that are incurred by the utility.[27] Hence, if area $E-\lambda F$ is larger than area A, the utility will choose it's mark-up rate such that the firm remains in the market.

As a preface to our final proposition for the partial-information, unregulated equilibrium in this section, we define the following terms (which are elaborated upon in the proposition's proof in Appendix E). Recalling that Ω_{x_u} and Ω_{ϕ_u} as defined in equations (8) and (9) represent the marginal profit functions for x_f and ϕ_u, respectively, we can similarly define $\Omega_{x_u x_u} < 0$ and $\Omega_{\phi_u x_u} > 0$, respectively, as the changes in marginal profitabilities of x_u and ϕ_u with respect to x_u. Further, we can define $\Omega_{x_u \alpha} > 0$ and $\Omega_{\phi_u \alpha} < 0$, respectively, as the changes in marginal profitabilities of x_u and ϕ_u with respect to α.

Proposition 5. *The utility's optimal choice of ϕ_u^* in a partial-information equilibrium does not decrease in response to an increase in market demand for EV charging when $\frac{|\Omega_{x_u x_u}|}{|\Omega_{\phi_u x_u}|} \leq \frac{|\Omega_{x_u \alpha}|}{|\Omega_{\phi_u \alpha}|}$, where functions $\Omega_{x_u x_u}$, $\Omega_{\phi_u x_u}$, $\Omega_{x_u \alpha}$, and $\Omega_{\phi_u \alpha}$ are each evaluated at the equilibrium values of x_u, x_f, and ϕ_u.*

Proof. See Appendix E.

In other words, the utility chooses not to decrease its mark-up rate in response to an increase in market demand for EV charging when the magnitude of the change in the marginal rate of substitution (MRS) between x_u and ϕ_u with respect to x_u is no greater than the change in MRS with respect to α.[28] Proposition

[27] Expressed in more general terms, this cost is equal to $\left(\partial c_u(\cdot)/\partial q_f\right) q_f$.

[28] MRS in this context equals the ratio of the firm's marginal profit levels, as opposed to how we typically think of MRS in the context of a consumer's problem, i.e., as the ratio of marginal utility levels.

5 is central to our investigation of coopetition. The extent to which ϕ_u^*, on the one hand, and α on the other are non-negatively related indicates the extent to which the balance between cooperation and competition in defining the nature of coopetition between the firm and utility in an unregulated equilibrium tilts away from cooperation toward competition as market demand for EV charging increases. In our model an increase in ϕ_u^* conveniently proxies for a decrease in cooperation between the two; cooperation emanating from the utility's side of the market.

Proposition 5 states a condition under which the utility chooses to reduce its level of cooperation with the firm as market demand for EV charging expands among EV owners. It informs us that an increase in market demand for electricity from EV charging stations (scale effect) enhances the relative value of an increment increase in q_u to the utility by more than the diminishment of q_u's relative value due to its increase (substitution effect). In other words, the utility chooses to raise its mark-up rate in reaction to an exogenous increase in market demand when it is relatively more valuable for it to do so.[29]

Figure 4 illustrates Proposition 5. The figure is simplified by the fact that it is not necessary to depict the actual shift in market demand in order to portray the result. This is because the proposition concerns the utility's mark-up decision after the shift in demand has occurred.

[INSERT FIGURE 4 HERE]

Here, the utility's profit level corresponding to the lower mark-up rate ϕ_u is equal to area $B+C+D+F+H-\lambda(G+I)$, while the utility's profit associated with higher mark-up rate ϕ_u' is equal to area $A+B+C+D+E+F-\lambda G$. Hence, the utility will choose to raise its mark-up rate when area $A+E$ exceeds area $H-\lambda I$.

We further explore Proposition 5 in Section 5, where a numerical version of the conceptual model developed in this section is used to simulate the coopetitive relationship between the firm and utility in both partial- and full-information equilibria. Before doing so though, we briefly characterize a partial-information version of the regulated equilibrium in the context of our conceptual model.

[29] Appendix E derives the implications for condition $\frac{|\Omega_{x_u x_u}|}{|\Omega_{\phi_u x_u}|} \leq \frac{|\Omega_{x_u \alpha}|}{|\Omega_{\phi_u \alpha}|}$ when the inverse market demand curve becomes steeper rather than flatter as it shifts outward (i.e., $\partial^2 p(Q;\alpha)/\partial Q \partial \alpha < 0$ rather than $\partial^2 p(Q;\alpha)/\partial Q \partial \alpha > 0$), and as the curve's slope approaches constancy (i.e., $\partial^2 p(Q;\alpha)/\partial Q \partial \alpha \longrightarrow 0$).

4.2 Regulated Equilibrium

A regulated equilibrium is characterized by equations (7) and (8) from Section 4.1. However, a new version of equation (9) results, not as a consequence of the utility's decision problem, but rather as the outcome of the regulator's problem. We assume the regulator is socially benevolent and thus chooses ϕ_u to maximize society's total surplus (TS),

$$\max_{\phi_u} \; TS = \pi_f^* + \pi_u^* + CS^*, \tag{10}$$

where $\pi_f^* = p\left(q_f^* + q_u\left(q_f^*\right); \alpha\right) q_f^* - c_f\left(w_f, q_f^*\right)$, $\pi_u^* = p\left(q_f^* + q_u\left(q_f^*\right); \alpha\right) q_u\left(q_f^*\right) + w_1^f q_f^* - c_u\left(w^u, q_f^*, q_u\left(q_f^*\right)\right)$, $CS^* = \int_{p(Q^*)}^{p^c} Q^{-1}(p;\alpha)\,dp$ (with p^c representing market demand's choke price), and $w_1^f = [1+\phi_u]\, w_1^u$. As in Section 4.1, superscript "*" indicates the optimality functions for q_f and q_u derived jointly as solutions to equations (7) and (8) from the unregulated equilibrium.

Two components of the regulator's objective function bear further mention. First, as part of its total surplus the region's consumer's surplus (CS) is explicitly accounted for by the regulator in its decision problem, defined conditionally as $CS^* = \int_{p(Q^*)}^{p^c} Q^{-1}(p;\alpha)\,dp$. As interpreted here, consumer's surplus represents the value of preferences attributable to market-oriented benefits derived from private transportation for work and leisure, potentially lower maintenance and repair costs over the life of an electric vehicle, driving a quieter vehicle with state-of-the-art technology, and the potential ability to integrate intermittent renewable energy sources and provide demand response – benefits reflected in the market inverse demand curve, $p(Q;\alpha)$. Excluded are potential non-market benefits associated with the warm glow that comes from the knowledge that air pollutants are not emitted while driving an EV, which benefits the local and global environment, and with load shifting, which reduces the costly ramp-up of natural gas powered generation during daily peak-demand periods.[30] These non-market benefits are potentially reduced by what has come to be known as "range anxiety", or the fear that the car's battery will die mid-trip before reaching a charging station, leaving the driver stranded.[31] Below, in footnote 33, we discuss the extent to which internalization of these non-market benefits and costs affects the regulated equilibrium.

Second, with its choice of ϕ_u the regulator is assumed to account not only for the firm's response

[30] See Andreoni (1990) for more background on the notion and implications of the warm glow effect, what the author also calls "impure altruism".

[31] The causes and effects of range anxiety have garnered attention recently in the social sciences literature, including in economics, where range anxiety has been found to be a barrier among prospective EV consumers (c.f., Hidrue et al., 2011; Egbue, 2012). As Noel et al. (2019) point out, range anxiety is increasingly psychological in nature, rather than technical, and this psychology is perpetuated through reactionary rhetoric.

function, q_f^*, but also for the effect of q_f^* on q_u in a partial-information equilibrium. Thus, in the partial-information version of the regulated equilibrium the regulator effectively conditions on two dimensions, as opposed to the single dimension to which the utility conditions on the unregulated equilibrium.

As shown in Appendix F, differentiating (10) with respect to ϕ_u results in,[32]

$$\Omega_{\phi_u} = w_1^u \left[q_f^* - \frac{\partial c_f(w^f, q_f^*)}{\partial w_1^f} \right] + \left[w_1^u [1+\phi_u] - \frac{\partial p(Q;\alpha)}{\partial Q} q_u - \frac{\partial c_u(w^u, q_u, q_f^*)}{\partial q_f^*} - \frac{\partial c_f(w^f, q_f^*)}{\partial q_f} \right] \frac{\partial q_f^*}{\partial \phi_u} \leq 0, \quad (11)$$

which solves implicitly for $\phi_u^{**} = \phi_u(w^u, \beta_f, \beta_u, \alpha)$, i.e., the regulator's optimal choice of the utility's mark-up rate.

When compared with (9), optimality condition (11) leads to our final proposition.

Proposition 6. *$\phi_u^{**} < \phi_u^*$ when $\left[w_1^u \frac{\partial c_f(\cdot)}{\partial w_1^f} + \frac{\partial c_f(\cdot)}{\partial q_f} \frac{\partial q_f^*}{\partial \phi_u} \right] > \frac{\partial p(\cdot)}{\partial Q} \frac{\partial q_f^*}{\partial \phi_u} q_u^*$, where all functions are evaluated at the regulated-equilibrium values of x_f and x_u.*

Proof. See Appendix G.

Proposition 6 states that the regulator chooses a lower mark-up rate than the utility would otherwise choose on its own when the marginal cost of the mark-up incurred by the firm is greater than the corresponding marginal gain obtained by the utility. The firm's marginal cost from the mark-up is represented by the left-hand side of the inequality, $\left[w_1^u \frac{\partial c_f(\cdot)}{\partial w_1^f} + \frac{\partial c_f(\cdot)}{\partial q_f} \frac{\partial q_f^*}{\partial \phi_u} \right]$. The first term in this expression is the "direct" marginal cost associated with the change in the firm's input price, w_1^f, that comes about via the change in mark-up rate ϕ_u (via equation (5)). The second term is the "indirect" marginal cost associated with the corresponding change in the firm's output level, q_f^*. In contrast, the utility's marginal benefit from the mark-up is represented by the right-hand side of the inequality, $\frac{\partial p(\cdot)}{\partial Q} \frac{\partial q_f^*}{\partial \phi_u} q_u^*$. This expression reflects the change in the utility's revenue that comes about via the change in its residual demand when the firm adjusts q_f^* in response to the change in ϕ_u. Hence, the regulator chooses a lower mark-up rate when to do otherwise would cost the firm more than the utility gains in revenue. Proposition 6 therefore states the condition under which the regulator will tilt the degree of cooperation between the firm and utility more in the direction of the former when the two are engaged in a coopetitive relationship.[33]

[32]Note that this equation is less likely to hold with strict inequality as market demand becomes less responsive to price.

[33]The extent to which a regulator can actually internalize the aforementioned non-market benefits and costs associated with access to EV charging stations has obvious implications for the difference between ϕ_u^{**} and ϕ_u^* in Proposition 6. To see this, note that directly accounting for non-market benefits and costs in the regulator's decision problem entails the adding of a separate function in equation (10), e.g., $E(Q^*)$, where, assuming the non-market marginal benefits outweigh the non-market marginal costs, $E_{Q^*} > 0$, i.e., the non-market marginal net benefit of additional charging-station output, $Q^* = q_f^* + q_u(q_f^*)$, is positive. With this addition,

In sum, this section's analytical results suggest that an unregulated utility (our benchmark case) – which could conceivably foreclose the private firm from competing in the charging-station market – nevertheless self-constrains itself by setting a mark-up rate that does not necessarily drive the firm from the market (Proposition 4). The condition governing an unregulated utility's response to an increase in market demand for EV charging stations – in particular, its decision of whether to increase its mark-up rate on electricity sold to the firm – is also derived (Proposition 5). We similarly derive the condition governing a regulator's choice of the mark-up rate when it has authority to regulate the utility – in particular, its decision to set a lower rate than that chosen by the utility itself when it is unregulated (Proposition 6).

5 Numerical Analysis

In this section, we specify a numerical version of the conceptual model developed in Section 3 in order to elucidate Section 4's main Propositions 4-6, and to explore the extent to which the partial- and full-information versions of the unregulated and regulated equilibria diverge from one another in a numerical context. Because no known empirical data exists or is readily available for any given region of the country – data of sufficient quantity, quality, and relevance – that would enable econometric estimation of the parameters chosen for our numerical analysis, we acknowledge that the ensuing exercise is purely demonstrative, suggestive of how our conceptual model might best be tested empirically once the necessary data becomes available.

With these caveats in mind, we assume the utility company and private firm are each constrained by constant-returns-to-scale, Cobb-Douglas production technologies, resulting in respective cost functions for the firm and utility, $c_f = K_f \left(w_1^f\right)^{\gamma_f} \left(w_2^f\right)^{(1-\gamma_f)} q_f$ and $c_u = K_u \left(w_1^u\right)^{\gamma_u} \left(w_2^u\right)^{(1-\gamma_u)} (q_f + q_u)$, where $K_i = \gamma_i^{-\gamma_i} (1-\gamma_i)^{(\gamma_i - 1)}, 0 < \gamma_i < 1, i = f, u$ (Varian, 1992). Two different specifications of market demand are considered: linear ($p(Q) = a - bQ$, $a > 0, b > 0$) and isoelastic ($p(Q) = A/Q$, $A > 0$). All other variables, parameters, and functions are as defined in equations (1) – (6) from Section 3. The specific set of initial parameter values chosen for the ensuing analysis are contained in Table 1.

[INSERT TABLE 1 HERE]

the term $-E_{Q^*} \frac{\partial q_f^*}{\partial \phi_u} > 0$, appears on the left-hand side of equation (11), which then appears on the left-hand side of Proposition 6's necessary and sufficient condition. As a result, the condition is, all else equal, more likely to hold. Or, if the condition would have held in the absence of the new term, it would now imply that $\phi_u^* - \phi_u^{**} > 0$ is larger, i.e., that the regulator chooses a lower mark-up rate than would otherwise have been the case. Also note that Proposition 6's necessary and sufficient condition is less likely to hold as market demand becomes less responsive to price.

Although the initial parameter values in Table 1 are arbitrarily chosen for the purpose of our analysis, our numerical results are stable (i.e., convergence is reached after minimal iterations of the model) for a wide range of values. Further, corresponding equilibrium values of the model's choice variables maintain their relative differences as parameter values are altered.[34]

5.1 Unregulated Equilibrium

We begin by presenting results in Table 2 for the partial- and full-information versions of the unregulated equilibrium given linear market demand for charging-station electricity among EV owners (see Appendix H for the specific forms of optimality conditions (7) – (9) used to generate the results).[35] The upper(lower) half of the table contains results for the partial-(full-) information equilibria. Increases in parameter a represent exogenous increases in inverse market demand.[36]

[INSERT TABLE 2 HERE]

As shown in Table 2, the condition presented in Proposition 5 (delineating a non-decreasing mark-up rate as market demand increases) is met for the partial-information version of the unregulated equilibrium, i.e., ϕ_u^* increases monotonically with parameter a. The utility's choice of ϕ_u^* also increases monotonically with parameter a in the full-information equilibrium. Interestingly, when endowed with full information the utility sets a lower mark-up rate than when endowed with partial information, irrespective of the level of market demand. Remaining variables show similar patterns across the two equilibria as market demand increases. Both the firm's and utility's output levels – q_f^* and q_u^* – increase with parameter a, but the rate of increase for $q_f^*(q_u^*)$ is larger in the full-(partial-) information equilibrium. Interestingly, while the firm's equilibrium output levels increase when the utility is endowed with full as opposed to partial information, the utility's own output level slightly decreases. As expected, the utility's respective profit levels, π_u^*, are larger under full information than partial information for each level of market demand. So are the firm's profit levels, π_f^*, and by larger percentages (relative to their respective partial-information equilibrium levels). Interestingly, both consumers and total surpluses – CS^* and TS^* – increase in the full-information equilibria (relative to their respective partial-information equilibrium levels).

[34] Matlab v. R2016b (9.1.0.441655) 64-bit is used for this section's analysis.

[35] Recall that the full set of conditions (7) – (9) are used to generate results for the partial-information equilibrium values of $q_i, i = u, f$, and ϕ_u, while only conditions (7) and (8) are used to generate results for the full-information equilibrium values of $q_i, i = u, f$. The full-information equilibrium value of ϕ_u is identified from a grid search that chooses maximum utility profit, π_u.

[36] Similar results are obtained for decreases in parameter b, which represent exogenous reductions in the magnitude of the inverse demand's slope.

By way of comparison, Table 3 presents results for the unregulated equilibria given increases in isoelastic market demand (represented by increases in parameter A). In several respects, the differences between these results for isoelastic market demand and those presented in Table 2 for linear market demand are stark – differences driven by the (rectangular) hyperbolic nature of the former. First, although Proposition 5's condition for a non-decreasing mark-up rate is again met for the partial-information equilibrium, it is met at the 'boundary' – ϕ_u^* remains constant as parameter A increases (as does the equilibrium price of charging-station electricity).

[INSERT TABLE 3 HERE]

Second, Table 3's results demonstrate that, unlike the case of linear market demand, both firm and utility output levels decrease significantly when the utility is endowed with full information in the presence of isoelastic market demand. Again the utility's mark-up rate increases monotonically with increases in demand. As a result, equilibrium price, p^*, sharply increases and the firm's profit falls, while the utility's increases. Both consumer's and total surpluses exhibit steep declines. To the contrary, as with linear market demand partial-information values of q_f^*, q_u^*, π_f^*, π_u^*, CS^*, and TS^* all increase with parameter A.

5.2 Regulated Equilibrium

Table 4 presents results for the regulated equilibrium in the presence of linear market demand (henceforth the "**" superscript denotes a regulated-equilibrium value). The pattern of changes in the variables' partial-information equilibrium values as parameter a increases is generally the same as the pattern that emerged for the unregulated partial-information equilibrium, except in one important case (we compare these two partial-information equilibria in detail below (in Table 6)). Rather than increasing with parameter a, the utility's mark-up rate ϕ_u^* under partial-information regulation decreases. Comparing these results with those in Table 2 we see that the condition presented in Proposition 6 (delineating when the regulator's choice of the utility's mark-up rate will be less than the utility's choice in an unregulated equilibrium) is met for the partial-information version of the unregulated equilibrium, i.e., $\phi_u^{**} < \phi_u^*$.

[INSERT TABLE 4 HERE]

As with the unregulated equilibria, the firm's(utility's) charging-station output levels increase(decrease) in the full-information equilibria (relative to the partial-information equilibria) in the presence of linear market demand. Interestingly, when endowed with full information, the regulator eliminates (i.e., zeros out) the utility's mark-up rate at each level of market demand, which in turn creates a pure duopoly structure in the charging market. Given the underlying parameter values chosen for this analysis – in particular, $\gamma_f = \gamma_u = 0.6$ and $\beta_f = \beta_u = 2$ from Table 1 – we are not surprised that the firm's and utility's equilibrium output levels equate, i.e., $q_f^{**} = q_u^{**}$. Relative to the partial-information equilibrium, the concomitant increases(decreases) in $q_f^*(q_u^*)$ results in increases(decreases) in firm(utility) profit levels.[37] Finally, as expected, both consumers and total surpluses increase when the regulator is endowed with full information.

Table 5 presents results for the regulated equilibrium in the presence of isoelastic market demand. The partial-information results mirror those for regulation in the presence of linear market demand, except in one key respect. Rather than decreasing as linear demand increases, the utility's mark-up rate remains constant when facing isoelastic demand, in concert with a constant equilibrium market price. The full-information results similarly mirror those in the presence of linear market demand, except that as a consequence of the regulator zeroing out the utility's mark-up rate, both the firm's and utility's charging-station output levels increase relative to their partial-information equilibrium levels across all levels of demand.

[INSERT TABLE 5 HERE]

Comparing the partial-information results from Table 5 with those from Table 3 we see that again the condition presented in Proposition 6 for $\phi_u^{**} < \phi_u^*$ is met. Interestingly, the utility's mark-up rates remain constant as isoelastic market demand increases in both the unregulated and regulated equilibria.

Lastly, to look closer at the differences between the unregulated and regulated equilibria, Table 6 presents the partial-information results for both equilibria in the presence of linear market demand.

[INSERT TABLE 6 HERE]

Irrespective of the level of market demand, we see that moving from an unregulated to a regulated equilibrium results in an increase(decrease) in firm(utility) charging-station output, and an overall increase in total output, $Q^{**} > Q^*$. Consequently, firm(utility) profit levels increase(decrease). As expected, consumers surplus increases as well at each level of market demand. However, the results for total surplus are puzzling. Although at the lowest demand level (represented by $a = 50$) we see that, as expected, $TS^{**} > TS^*$, this

[37] Firm and utility levels differ as a consequence of the utility's cost function, $c_u(\cdot)$, depending upon both q_u and q_f rather than solely the former.

inequality is flipped for the higher demand levels of $a = 75$ and $a = 100$. The only explanation we have for this result is that as linear market demand increases, the second constraint imposed on the regulator – that it account not only for the effect of its choice of the mark-up rate on the firm's output level, $\partial q_f^*/\partial \phi_u$, but also for the feedback effect of firm output on utility output, $\partial q_u/\partial q_f^*$ – constrains the regulator enough to lower its highest obtainable level of total surplus, even when maximizing this surplus is its underlying objective. In comparing the partial-information results in Tables 3 and 5 we see that this is not the case for isoelastic market demand, i.e., $TS^{**} > TS^*$ at all levels of demand. Thus, this surprising result may in fact be specific to linear demand.

In sum, our numerical analysis suggests that the regulator's and utility's respective choices of the mark-up rate, and, in response, the private firm's output levels, are quite sensitive to the form of market demand. In an unregulated equilibrium, regardless of whether the utility has partial or full information about the firm's demand response, the utility chooses to decrease its mark-up rate in response to an exogenous increase in linear market demand, and to not decrease the mark-up rate when faced with an increase in isoelastic market demand. As expected, in a regulated equilibrium the regulator (whether partially or fully informed) chooses not to increase the utility's mark-up rate in response to increases in either linear or isoelastic market demand.

6 Conclusion and Policy Implications

This paper has developed a theoretical framework within which to explore the inherent coopetitive relationship arising between a private firm and a utility company when the latter simultaneously competes with the firm in the output (i.e., EV charging-station) market and cooperates in the input market through its choice of a mark-up rate on the price of electricity supplied to the firm's charging stations. In the absence of regulation, we find that despite having a monopoly position in the input market the utility chooses to self-regulate itself in order to continue earning revenue from the sale of electricity to the firm's charging stations. This result suggests that utilities considering whether to operate EV charging stations themselves should be careful not to foreclose competition from private firms by setting overly burdensome mark-up rates on the electricity sold to them. We also uncover the condition under which the utility chooses not to decrease its mark-up rate in response to an increase in market demand for EV charging. Choosing not to lower its mark-up rate suggests that the utility is effectively choosing to compete more than cooperate in its coopetitive relationship with the private firm; a result that would not bode well for consumers in the EV charging market. We similarly uncover the condition under which the regulator chooses a lower mark-up rate than the utility (in what we call a regulated equilibrium) when the regulator is given the authority to set the rate. Choosing a lower mark-up rate restores more cooperation in the coopetitive relationship between the utility and private firm.

Numerical analysis illustrates these findings and evinces additional properties of the model for both linear and isoelastic specifications of market demand exhibited by EV owners. For example, when endowed with full information and facing linear market demand an unregulated utility sets a lower mark-up rate than when it is endowed with partial information. When faced with isoelastic market demand the fully informed utility instead sets a dramatically higher rate. Irrespective of market demand specification, the fully informed utility increases its mark-up rate as demand increases. The partially informed utility likewise increases its markup rate as linear demand increases, but holds the rate constant in the face of increasing isoelastic market demand. Thus, the structure of market demand for EV charging potentially has a profound impact on the mark-up rate a utility would choose to set when left unregulated; an impact that is modulated by the extent to which the utility is informed about the private firm's response to changes in that rate. However, as market demand increases, the utility – whether it is partially or fully informed and facing linear or isoelastic market demand – chooses not to decrease its mark-up rate. Together, these results strike a cautionary note about the responses of a utility to increases in market demand for EV charging.

In a regulated equilibrium, the partially informed regulator also holds the mark-up rate constant in the face of increasing isoelastic demand, but decreases the rate in the face of increasing linear demand. This decreasing rate unexpectedly coincides with lower total surplus at higher demand levels vis-a-vis the partial-information unregulated equilibrium, suggesting that the partially informed regulator is better served by deferring to the unregulated equilibrium in the presence of linear market demand, since its overall objective is to maximize this surplus. The fully informed regulator zeros out the mark-up rate irrespective of market demand specification, thus inducing a pure duopoly market structure. This strategy on the part of the fully informed regulator leads to the highest possible total surplus in both demand specifications.

As mentioned in Section 1, the need for more charging stations to service expected future growth in EV ownership in several regions of the US is inescapable, if not urgent. Utility companies, such as Duke Energy, San Diego Gas and Electric, Los Angeles Department of Water and Power, and Dominion Energy, have begun to recognize potentially abundant market opportunities, not only in attendant input markets (e.g., infrastructure build-out and delivery of electricity to the stations), but also in the supply of electricity directly to EV owners via utility-owned charging stations. As a result, questions resound concerning how best to regulate emergent coopetitive relationships between utilities and private firms in regional EV charging-station markets. Predicated upon a succinct yet commensurable theoretical framework, our numerical results suggest where we might look for answers.

In particular, the structure of market demand and the extent to which the regulator is informed about private firm demand responses to changes in the mark-up rate have potentially large impacts on the equilibrium outcome when the utility is regulated in its coopetitive relationship with private firms. Our numerical results suggest that to the extent market demand is linear and the regulator is less well-informed, the charging market should be less-regulated as demand increases over time – less-regulated when the regulator's goal is to maximize a region's total surplus. Yet, irrespective of whether the regulator maximizes total surplus relative to an unregulated equilibrium, and regardless of the structure of market demand and the extent to which the regulator is informed, total electricity supplied from charging stations is larger (and corresponding per-unit is price lower) under regulation. Hence, if society's primary goal in the face of increased use of EVs is to provide the most charging-station electricity as possible, particularly in markets where a coopetitive relationship exists between the utility and private firms, then regulation should be undertaken.

As empirical data becomes available from regional markets where utility companies are engaged in coopetitive relationships with private firms, our numerical results can be tested empirically. In concert with data from regional markets where coopetition is not occurring, i.e., where solely private firms own and operate a given region's charging stations, the question of whether coopetition itself (and which of its specific features) facilitates or impedes the supply of charging-station electricity can likewise be addressed. Both of these questions – concerning the effectiveness of coopetition and the extent to which it is regulated – are likely to become ripe for empirical investigation.

Appendices

A Proof of Proposition 1

Assume initially an interior unregulated equilibrium. Thus, from equation (7) $\Omega_{x_f} = 0$. Next, recall that (1) inverse market demand function $p(Q^*;\alpha)$ is assumed decreasing in Q^*, (2) by definition of Q, q_f and q_u are perfect substitutes, and (3) in the context of the duopoly model the firm and utility each treat EV-owner demand for their electricity as residual.

Point 1 implies that the first term in Ω_{x_f} decreases in response to an increase in q_u. Similarly, points 2 and 3 imply the second term, $\partial p(Q^*;\alpha)/\partial Q$, is non-increasing in response to an increase in q_u, i.e., the (negative) slope of residual market demand for q_f effectively becomes steeper. Thus, at initial q_f^*, $\Omega_{x_f} < 0$ in the face of an increase in q_u. Given concavity of the firm's programming problem, q_f^* must therefore decrease in order to restore $\Omega_{x_f} = 0$.

A similar argument applies for an increase in q_f. Given an interior unregulated equilibrium, $\Omega_{x_u} = 0$ from equation (8). Points 1 – 3 again imply that the first and second terms in Ω_{x_u} are deceasing and non-increasing, respectively, in response to an increase in q_f. Further, given the curvature assumption $\partial^2 c_u(\cdot)/\partial q_u \partial q_f \geq 0$, the third term in Ω_{x_u} is non-increasing in q_f. Thus, at initial q_u^*, $\Omega_{x_u} < 0$ in the face of an increase in q_f. Given concavity of the utility's programming problem, q_u^* must therefore decrease in order to restore $\Omega_{x_u} = 0$. □

B Proof of Proposition 2

Assume initially an interior unregulated equilibrium. Thus, from equation (7) $\Omega_{x_f} = 0$. Next, recall that the firm's cost function, $c_f(\cdot)$ is by definition increasing in w_f. By equation (5), $\partial w_1^f/\partial \phi_u > 0$. Thus, $c_f(\cdot)$ also increases in ϕ_u, implying that at initial q_f^*, $\Omega_{x_f} < 0$ in the face of an increase in ϕ_u. Given concavity of the firm's programming problem, q_f^* must therefore decrease in order to restore $\Omega_{x_f} = 0$. □

C Proof of Proposition 3

Begin by noting that satisfaction of the firm's second-order conditions (SOCs) for profit maximization at an interior equilibrium requires $\Omega_{x_f x_f} < 0$ from condition (7). Given equation (2), and via a simple application of the chain rule of differentiation, $\Omega_{x_f\beta_f} = \Omega_{x_f x_f}[x_f/\beta_f] < 0$. This means that at an initial equilibrium, where from equation (7) $\Omega_{x_f} = 0$, an increase in β_f causes $\Omega_{x_f} < 0$. Given concavity of the firm's programming problem, x_f^* must therefore decrease in order to restore $\Omega_{x_f} = 0$. □

D Proof of Proposition 4

Assume initially an interior unregulated equilibrium. Thus, from equation (9), $\Omega_{\phi_u} = 0$ and $q_f^* > 0$. Clearly this is a possibility for a set of parameter values $\{w^u, \beta_f, \beta_u, \alpha\}$ and optimal choice variables $\{x_f^*, x_u^*, \phi_u^*\}$ such that the marginal benefits associated with $q_f^* > 0$, i.e., $w_1^u \left[q_f^* + w_1^u(1+\phi_u^*)\left(\partial q_f^*/\partial \phi_u\right)\right]$, equals the corresponding marginal costs, i.e., $[[\partial p(Q^*;\alpha)/\partial Q]\, q_u^* - \partial c_u(\cdot)/\partial q_f]\left(\partial q_f^*/\partial \phi_u\right)$. It is therefore not necessarily the case that $q_f^* \longrightarrow 0$. □

E Proof of Proposition 5

Totally differentiating equations (8) and (9) with respect to the utility's choice variables x_f and ϕ_u and parameter α results in a matrix representation of the system of equations,

$$\begin{bmatrix} \Omega_{x_u x_u} & \Omega_{x_u \phi_u} \\ \Omega_{\phi_u x_u} & \Omega_{\phi_u \phi_u} \end{bmatrix} \cdot \begin{bmatrix} \frac{dx_u}{d\alpha} \\ \frac{d\phi_u}{d\alpha} \end{bmatrix} = \begin{bmatrix} -\Omega_{x_u \alpha} \\ -\Omega_{\phi_u \alpha} \end{bmatrix} \tag{E.1}$$

where,

$$\Omega_{x_u x_u} = 2\frac{\partial p(\cdot)}{\partial Q} + \frac{\partial^2 p(\cdot)}{\partial Q^2} q_u - \frac{\partial^2 c_u(\cdot)}{\partial q_u^2} \leq 0 \tag{E.2}$$

$$\Omega_{x_u \phi_u} = \Omega_{\phi_u x_u} = \left[\frac{\partial p(\cdot)}{\partial Q} + \frac{\partial^2 p(\cdot)}{\partial Q^2} q_u - \frac{\partial^2 c_u(\cdot)}{\partial q_u q_f}\right]\left(\frac{\partial q_f}{\partial \phi_u}\right) \tag{E.3}$$

$$\Omega_{\phi_u \phi_u} = \left[2w_1^u + \frac{\partial^2 p(\cdot)}{\partial Q^2} q_u - \frac{\partial^2 c_u(\cdot)}{\partial^2 q_f}\right]\left(\frac{\partial q_f}{\partial \phi_u}\right) + \left[\frac{\partial p(\cdot)}{\partial Q} q_u - \frac{\partial c_u(\cdot)}{\partial q_f} + w_1^u(1+\phi_u)\right]\left(\frac{\partial q_f^2}{\partial \phi_u^2}\right) \leq 0 \tag{E.4}$$

$$\Omega_{x_u \alpha} = \frac{\partial p(\cdot)}{\partial \alpha} + \frac{\partial^2 p(\cdot)}{\partial Q \partial \alpha} q_u \tag{E.5}$$

$$\Omega_{\phi_u \alpha} = \frac{\partial^2 p(\cdot)}{\partial Q \partial \alpha}\frac{\partial q_f}{\partial \phi_u} q_u. \tag{E.6}$$

Expressions $\Omega_{x_u x_u}$ and $\Omega_{\phi_u \phi_u}$ in equations (E.2) and (E.4), respectively, are both non-positive via the problem's second-order conditions, and expressions $\Omega_{x_u \alpha}$ and $\Omega_{\phi_u \alpha}$ in equations (E.5) and (E.6) are both indeterminate in sign. Irrespective of these expressions signs, a simple application of Cramer's Rule leads to Proposition 5. □

It is straightforward to see from equations (E.5) and (E.6) and the condition presented in Proposition 5 that if $\partial^2 p(Q;\alpha)/\partial Q \partial \alpha < 0$, then compared with the case of an equal-in-magnitude $\partial^2 p(Q;\alpha)/\partial Q \partial \alpha > 0$, Proposition 5's condition is less likely to hold when the term $\partial^2 p(Q;\alpha)/\partial Q \partial \alpha q_u$ is small enough in magnitude. This is because, all else equal, the numerator on the righthand side of the condition $\frac{|\Omega_{x_u x_u}|}{|\Omega_{\phi_u x_u}|} \leq \frac{|\Omega_{x_u \alpha}|}{|\Omega_{\phi_u \alpha}|}$ is smaller. Further, in the case of $\partial^2 p(Q;\alpha)/\partial Q \partial \alpha \longrightarrow 0$, note that denominator of the condition's righthand side goes to infinity, thus ensuring the condition holds with certainty.

F Derivation of Equation (11)

Differentiating (10) with respect to ϕ_u results in the following optimality condition,

$$\Omega_{\phi_u} = w_1^u \left[q_f^* - \frac{\partial c_f(w^f, q_f^*)}{\partial w_1^f} \right] + \left[p(Q;\alpha) + \frac{\partial p(Q;\alpha)}{\partial Q} \left[1 + \frac{\partial q_u}{\partial q_f^*} \right] \left[q_f^* + q_u \right] \right.$$
$$\left. - \frac{\partial c_u(w^u, q_u, q_f^*)}{\partial q_f^*} - \frac{\partial c_u(w^u, q_u, q_f^*)}{\partial q_u} - \frac{\partial c_f(w^f, q_f^*)}{\partial q_f} + w_1^u [1 + \phi_u] \right] \frac{\partial q_f^*}{\partial \phi_u} - \frac{\partial p(Q;\alpha)}{\partial Q} \left[\frac{\partial q_f^*}{\partial \phi_u} + \frac{\partial q_u}{\partial q_f^*} \frac{\partial q_f^*}{\partial \phi_u} \right] \left[q_f^* + q_u \right] \leq 0. \tag{F.1}$$

Canceling the terms $\frac{\partial p(Q;\alpha)}{\partial Q} \left[\frac{\partial q_f^*}{\partial \phi_u} + \frac{\partial q_u}{\partial q_f^*} \frac{\partial q_f^*}{\partial \phi_u} \right] \left[q_f^* + q_u \right]$ in (F.1), and substituting optimality condition (8) holding with equality, we obtain equation (11). □

G Proof of Proposition 6

Recall that equation (9) holding with equality, i.e., $\Omega_{\phi_u} = 0$ in that equation, solves for $\phi_u^* > 0$. When the condition of Proposition 6 holds, i.e., $\left[w_1^u \frac{\partial c_f(\cdot)}{\partial w_1^f} + \frac{\partial c_f(\cdot)}{\partial q_f} \frac{\partial q_f^*}{\partial \phi_u} \right] > \frac{\partial p(\cdot)}{\partial Q} \frac{\partial q_f^*}{\partial \phi_u} q_u^*$, this means that equation (11) holds with inequality, i.e., $\Omega_{\phi_u} < 0$ in that equation, when evaluated at ϕ_u^*. Thus, to restore equality, i.e., $\Omega_{\phi_u} = 0$ in equation (11), ϕ_u must decrease from ϕ_u^*, implying our result, $\phi_u^{**} < \phi_u^*$. □

H Specifications of Conditions (7) – (9) and (11) for Numerical Analysis

H.1 Linear Market Demand

Given the functional forms adopted in Section 5, equations (7)-(9) in the text become, respectively,

$$x_f = \frac{a - bq_u - K_f\left(w_1^u\left[1+\phi_u\right]\right)^{\alpha_f}\left(w_2^f\right)^{1-\alpha_f}}{2b\beta_f}$$

$$x_u = \frac{a - bq_f - K_u\left(w_1^u\right)^{\alpha_u}\left(w_2^u\right)^{1-\alpha_u}}{2b\beta_u}$$

$$q_f = \frac{\left[bq_u + K_u\left(w_1^u\right)^{\alpha_u}\left(w_2^u\right)^{1-\alpha_u} - w_1^u\left[1+\phi_u\right]\right]\alpha_f\beta_f K_f\left(w_1^u\left[1+\phi_u\right]\right)^{\alpha_f-1}\left(w_2^f\right)^{1-\alpha_f} w_1^u}{2b\beta_f w_1^u}$$

and equation (11) becomes,

$$\begin{aligned}&\left[a - b\left[q_f^* + q_u^*\right]\right]\left[\frac{\partial q_f^*}{\partial\phi_u} + \frac{\partial q_u^*}{\partial q_f^*}\frac{\partial q_f^*}{\partial\phi_u}\right] - K_f\alpha_f\left(w_2^f\right)^{1-\alpha_f}\left[\left(w_1^u\left[1+\phi_u\right]\right)^{\alpha_f-1} w_1^u q_f^* - \left(w_1^u\left[1+\phi_u\right]\right)^{\alpha_f}\frac{\partial q_f^*}{\partial\phi_u}\right]\\ &= K_u\left(w_1^u\right)^{\alpha_u}\left(w_2^u\right)^{1-\alpha_u}\left[\frac{\partial q_f^*}{\partial\phi_u} + \frac{\partial q_u^*}{\partial q_f^*}\frac{\partial q_f^*}{\partial\phi_u}\right] - w_1^u\left[q_u^* + \left[1+\phi_u\right]\frac{\partial q_u^*}{\partial q_f^*}\frac{\partial q_f^*}{\partial\phi_u}\right],\end{aligned}$$

where

$$\frac{\partial q_f^*}{\partial\phi_u} = -\frac{\alpha_f K_f\left(w_1^u\left[1+\phi_u\right]\right)^{\alpha_f-1}\left(w_2^f\right)^{1-\alpha_f} w_1^u}{2b}$$

and

$$\frac{\partial q_u^*}{\partial q_f^*}\frac{\partial q_f^*}{\partial\phi_u} = -0.5\frac{\partial q_f^*}{\partial\phi_u}.$$

H.2 Isoelastic Market Demand

Equations (7)-(9) in the text become, respectively,

$$q_u = \frac{K_f\left(w_1^f\right)^{\alpha_f}\left(w_2^f\right)^{1-\alpha_f} Q^2}{A}$$

$$q_f = \frac{K_u\left(w_1^u\right)^{\alpha_u}\left(w_2^u\right)^{1-\alpha_u} Q^2}{A}$$

$$\left(w_1^u\right)^2\left(1+\phi_u\right)\alpha_f Q^2 = 2w_1^f w_1^u q_f Q + A\alpha_f w_1^u q_u + \alpha_f w_1^u Q^2 K_u\left(w_1^u\right)^{\alpha_u}\left(w_2^u\right)^{1-\alpha_u}$$

and equation (11) becomes,

$$w_1^u\left(1+\phi_u\right)\frac{\partial q_f^*}{\partial \phi_u}+w_1^u q_f^*=$$
$$\frac{A\left[q_f^*+q_u^*\right]\left[\frac{\partial q_f^*}{\partial \phi_u}+\frac{\partial q_u^*}{\partial q_f^*}\frac{\partial q_f^*}{\partial \phi_u}\right]}{\left(q_f^*+q_u^*\right)^2}+K_f\left[\alpha_f\left(w_1^f\right)^{\alpha_f-1}\left(w_2^f\right)^{1-\alpha_f}q_f^* w_1^u+\left(w_1^f\right)^{\alpha_f}\left(w_2^f\right)^{1-\alpha_f}\frac{\partial q_f^*}{\partial \phi_u}\right]$$
$$+K_u\left(w_1^u\right)^{\alpha_u}\left(w_2^u\right)^{1-\alpha_u}\left[\frac{\partial q_f^*}{\partial \phi_u}+\frac{\partial q_u^*}{\partial q_f^*}\frac{\partial q_f^*}{\partial \phi_u}\right]$$

where

$$\frac{\partial q_f^*}{\partial \phi_u}=-\frac{\alpha_f w_1^u\left[q_f^*+q_u^*\right]}{2w_1^f}$$

and

$$\frac{\partial q_u^*}{\partial q_f^*}\frac{\partial q_f^*}{\partial \phi_u}=-\left[\frac{A-2K_u\left(w_1^u\right)^{\alpha_u}\left(w_2^u\right)^{1-\alpha_u}Q}{K_u\left(w_1^u\right)^{\alpha_u}\left(w_2^u\right)^{1-\alpha_u}Q}\right]\frac{\partial q_f^*}{\partial \phi_u}.$$

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Table 1: Initial Parameter Values

Parameter	Description	Initial Value
a	Vertical intercept (choke price) of linear inverse market demand curve ($).	50
b	Slope of linear inverse market demand curve ($).	0.25
A	Isoelastic market demand curve's constant term ($).	750
β_f	Private firm's charging-station efficiency parameter (units per station).	2
β_u	Utility's charging-station efficiency parameter (units per station).	2
γ_f	Private firm's cost-function substitutability parameter.	0.6
γ_u	Utility's cost-function substitutability parameter.	0.6
w_u^1	Per-unit wholesale cost of electricity incurred by the utility ($).	0.25
w_u^2	Per-unit cost incurred by the utility company for installation of charging infrastructure ($).	1

Table 2: Unregulated Equilibria in the Presence of Increasing Linear Market Demand

Variables	Values of a		
	50	75	100
1. Partial-Information Equilibrium			
q_f^*	13	22	31
q_u^*	92	137	183
Q^*	105	159	214
p^*	24	35	47
ϕ_u^*	200	369	575
π_f^*	42	122	246
π_u^*	2,748	6,733	12,828
CS^*	1,373	3,173	5,724
TS^*	4,163	10,028	18,798
2. Full-Information Equilibrium			
q_f^*	15	26	38
q_u^*	91	135	179
Q^*	106	161	217
p^*	23	35	46
ϕ_u^*	185	336	518
π_f^*	60	174	354
π_u^*	2,757	6,764	12,902
CS^*	1,405	3,260	5,892
TS^*	4,222	10,198	19,148

Table 3: Unregulated Equilibria in the Presence of Increasing Isoelastic Market Demand

Variables	Values of A		
	750	800	850
1. Partial-Information Equilibrium			
q_f^*	5.69	6.07	6.45
q_u^*	65	69	74
Q^*	71	75	80
p^*	11	11	11
ϕ_u^*	57	57	57
π_f^*	4.86	5.18	5.51
π_u^*	712	759	807
CS^*	1,163	1,241	1,318
TS^*	1,880	2,005	2,131
2. Full-Information Equilibrium			
q_f^*	0.26	0.23	0.20
q_u^*	14.75	14.33	13.97
Q^*	15.01	14.56	14.17
p^*	50	55	60
ϕ_u^*	858	1,008	1,168
π_f^*	0.22	0.08	0.17
π_u^*	779	832	885
CS^*	0.07	0.08	0.08
TS^*	780	832	885

Table 4: Regulated Equilibria in the Presence of Increasing Linear Market Demand

Variables	Values of a		
	50	75	100
1. Partial-Information Equilibrium			
q_f^{**}	48	91	125
q_u^{**}	76	105	138
Q^{**}	124	196	263
p^{**}	20	27	35
ϕ_u^{**}	41	15	13
π_f^{**}	568	2,048	3,893
π_u^{**}	1,260	3,041	5,080
CS^{**}	1,923	4,780	8,625
TS^{**}	4,417	9,869	17,599
2. Full-Information Equilibrium			
q_f^{**}	67	100	134
q_u^{**}	67	100	134
Q^{**}	134	200	268
p^{**}	18	26	34
ϕ_u^{**}	0	0	0
π_f^{**}	1,118	2,510	4,457
π_u^{**}	1,077	2,449	4,376
CS^{**}	2,235	5,020	8,915
TS^{**}	4,430	9,979	17,749

Table 5: Regulated Equilibria in the Presence of Increasing Isoelastic Market Demand

Variables	Values of A		
	750	800	850
1. Partial-Information Equilibrium			
q_f^{**}	44	47	50
q_u^{**}	152	162	173
Q^{**}	196	209	223
p^{**}	4	4	4
ϕ_u^{**}	7	7	7
π_f^{**}	37	40	42
π_u^{**}	503	537	570
CS^{**}	1,928	2,056	2,185
TS^{**}	2,468	2,632	2,797
2. Full-Information Equilibrium			
q_f^{**}	220	234	249
q_u^{**}	220	234	249
Q^{**}	440	468	498
p^{**}	1.70	1.70	1.70
ϕ_u^{**}	0	0	0
π_f^{**}	188	200	213
π_u^{**}	55	59	62
CS^{**}	2,533	2,702	2,871
TS^{**}	2,776	2,961	3,146

Table 6: Unregulated Vs. Regulated Partial-Information Equilibria Given Increasing Linear Market Demand

Variables	Values of a		
	50	75	100
1. Unregulated Equilibrium			
q_f^*	13	22	31
q_u^*	92	137	183
Q^*	105	159	214
p^*	24	35	47
ϕ_u^*	200	369	575
π_f^*	42	122	246
π_u^*	2,748	6,733	12,828
CS^*	1,373	3,173	5,724
TS^*	4,163	10,028	18,798
2. Regulated Equilibrium			
q_f^{**}	48	91	125
q_u^{**}	76	105	138
Q^{**}	124	196	263
p^{**}	20	27	35
ϕ_u^{**}	41	15	13
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π_u^{**}	1,260	3,041	5,080
CS^{**}	1,923	4,780	8,625
TS^{**}	4,417	9,869	17,599

Figure 1: Proposition 1.

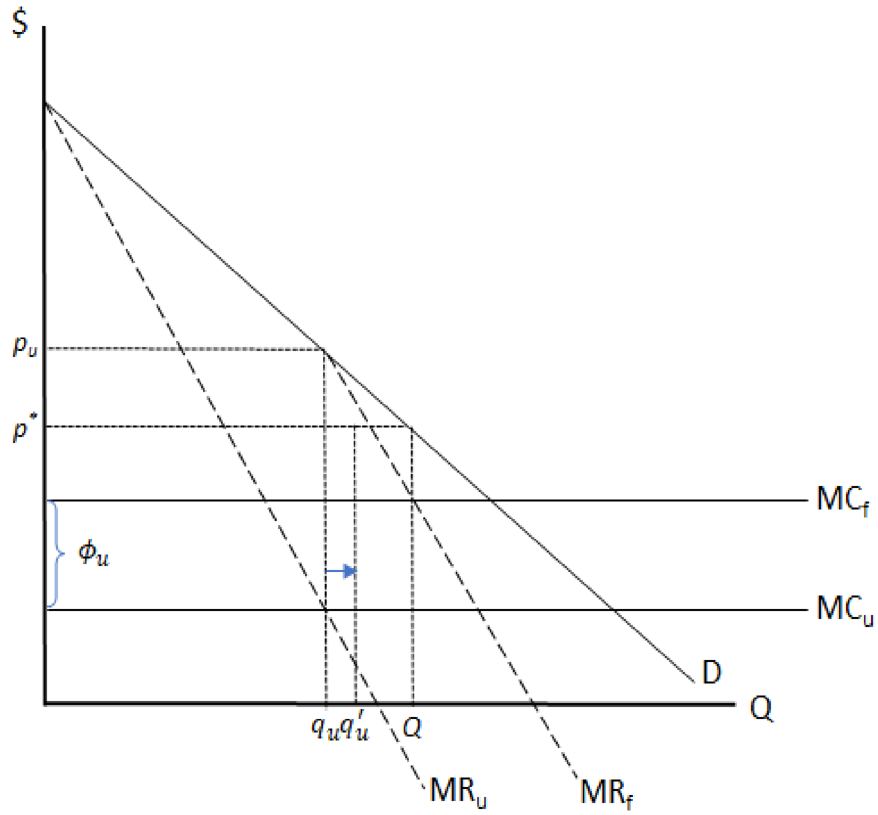


Figure 2: Proposition 2.

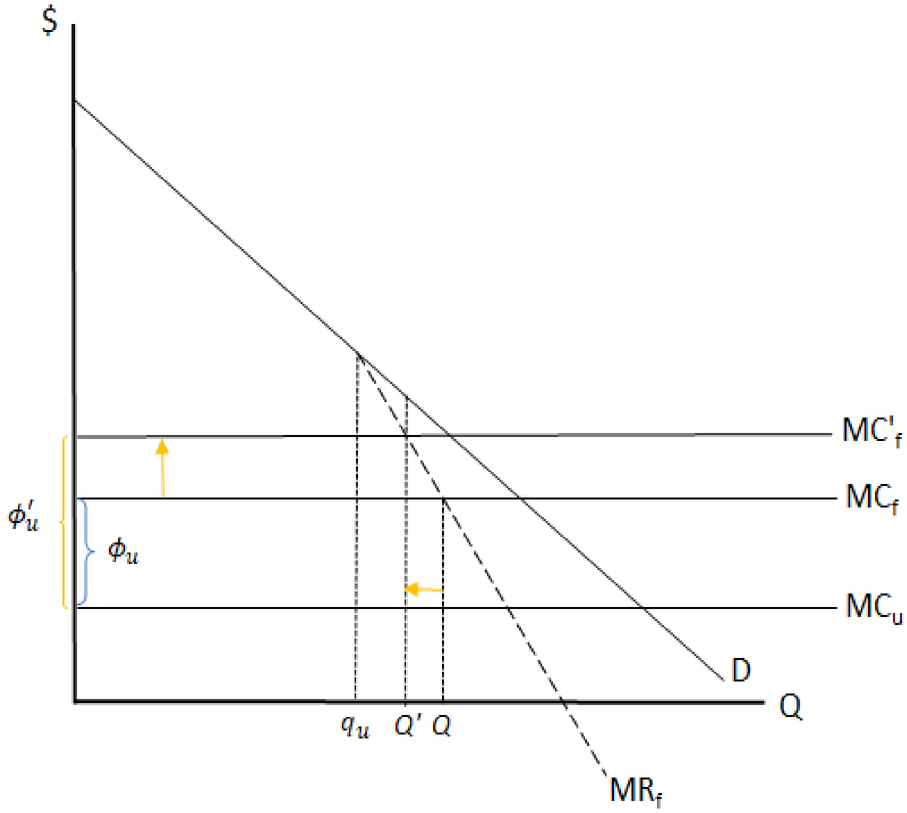


Figure 3: Proposition 4.

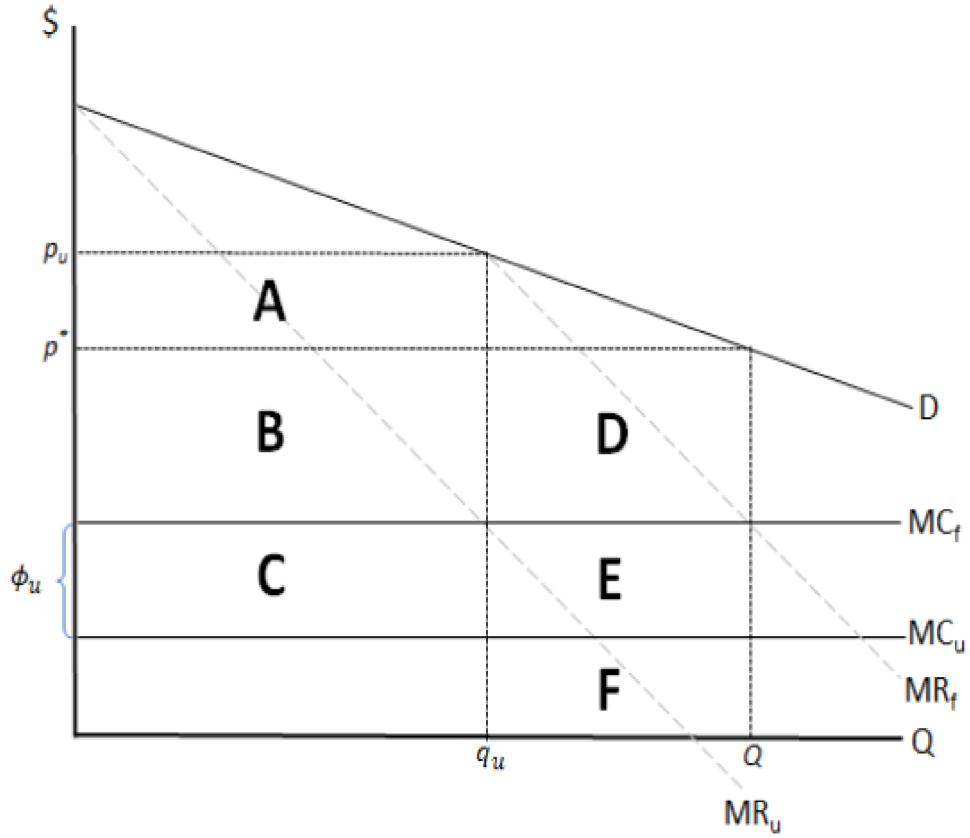
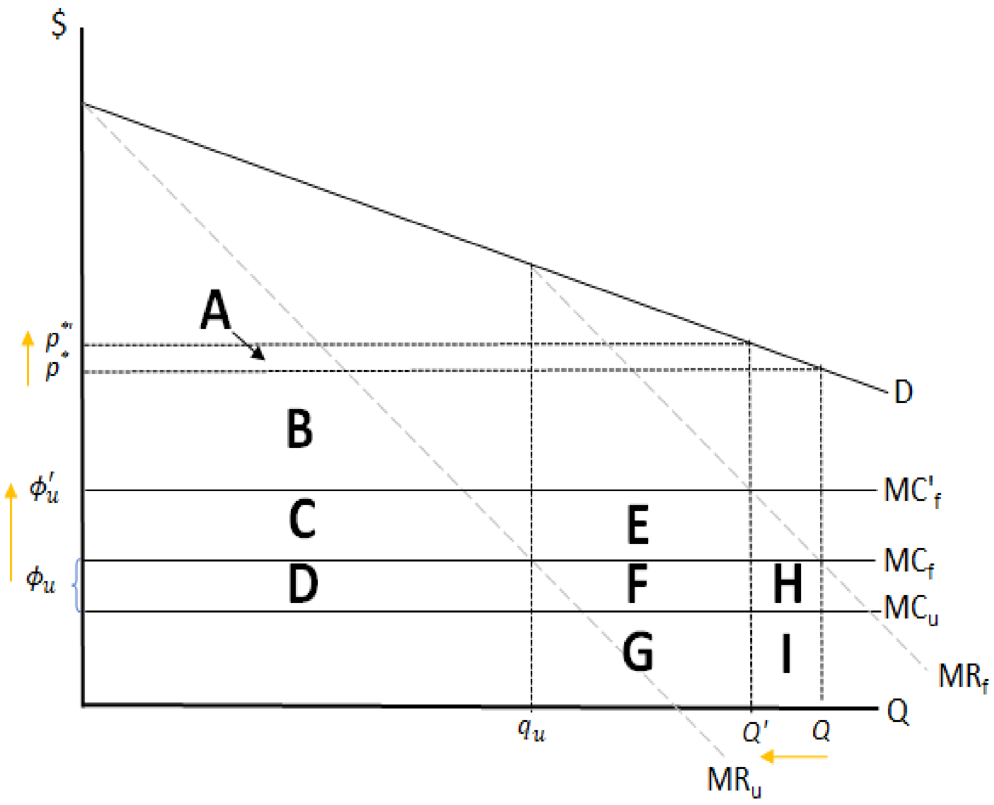


Figure 4: Proposition 5.



Research Highlights

- Theoretical framework explores coopetition in an EV charging market between a private firm and utility.
- In absence of regulation, utility self-regulates the wholesale mark-up rate it charges for electricity.
- Conditions are derived under which a regulator chooses to lower utility's mark-up rate.
- Numerical analysis illustrates these findings for different types of market demand.

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May 2, 2022

Dear Editors Chu and Mallick:

I acknowledge that I have no conflict of interests with the writing, researching, funding, and publication of submitted manuscript.

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