The Impact of Cross-ownership on the Value of a Clean Technology in the Energy Market

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Abstract

This paper examines how corporate cross-ownership in a polluting fossil fuel oligopoly affects the value of a clean energy substitute with a given capacity in different environmental scenarios. When environmental damages are large enough, an increased cross-ownership among polluting firms reduces the gains from investment in the clean energy sector. However, if environmental damages are small enough, a non-marginal increase in cross-ownership may increase the value of a clean technology. The main intuition behind this result is that an increased cross-ownership results in a decrease of environmental damages due to an overall decrease of quantity of energy supplied by the polluting firms, and therefore, if environmental damages are large enough, there will be substantial gains from reduced pollution damages associated with it, thus decreasing the need for clean energy. However, if environmental damages are small enough, the welfare loss from a less intensified competition due to increased cross-ownership outweighs the possible benefits of reduced pollution, thereby increasing the value of a clean technology. Our qualitative conclusions hold true under different demand specifications.

Keywords: Cross-ownership; Clean Technology; Oligopoly; Energy; Environmental Damages

JEL Codes: L13, L41, Q4

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1 Introduction

The past few decades have witnessed a phenomenal growth of passive private equity investments between rival firms within the same industry, whereby they engage in cross-shareholdings and participate in various forms of co-operation.[1] These activities create the so-called cross-ownership structure that has characterized the complex economic ties and deep-rooted corporate relations among competing firms across nearly every sector. Notable examples include the global automobile industries (Alley, 1997; Ono et al., 2004), the Dutch financial sector (Dietzenbacher, Smid and Volkerink, 2000), the Nordic power market (Amundsen and Bergman, 2002), the Italian national banking sector (Trivieri, 2007), the pay-TV markets in Norway and Sweden (Foros, Kind and Shaffer, 2011) and the nonrenewable resource sector (Benchekroun, Dai and Long, 2021).

Viewing cross-ownership as "partial mergers", previous studies have focused mainly on the potential anticompetitive effects induced by cross-ownership (Reynolds and Snapp, 1986; Bresnahan and Salop, 1986; Malueg, 1992; Flath, 1992; Dietzenbacher, Smid and Volkerink, 2000; O'Brien and Salop, 2000; Gilo, Moshe and Spiegel, 2006; Brito, Ribeiro and Vasconcelos, 2014, 2018). From a competition perspective, firms' partial internalization of previous rivalry due to cross-ownership decreases competition and thus is highly unlikely to be considered as welfare-improving unless there are substantial cost-savings associated with this activity. However, this presumption may not hold true in the case of a polluting oligopolistic industry when there is a negative externality involved. The reason is that a higher level of cross-ownership among the polluting oligopolists results in an overall lower output and thereby reduces the amount of externality generated, so from an environmental perspective, the increased cross-ownership may not necessarily be undesirable! In light of these opposing effects of cross-ownership and given the extensive cross-ownership activity in the oil sector (Benchekroun, Dai and Long, 2021),[2] which contributes significantly to local and global deterioration of the environment, this paper examines how cross-ownership in a polluting oligopoly affects the value of a clean energy substitute with a given capacity in different environmental scenarios.

Renewable and clean energy investment is an important policy tool that can be leveraged to prevent catastrophic and irreversible damages to the climate and the environment. Major polluting countries

[1] For example, firms often form a joint venture, which is usually majority-owned and operated by one firm, and minority-held by the others. This translates into mutual shareholdings of one firm in another.

[2] According to a report by Water Street Partners based on the source from Rystad Energy, https://www.waterstreetpartners.net/blog/the-web-of-partnerships-between-bp-chevron-eni-exxonmobil-shell-and-total, intriguingly large amounts of joint-ventures exist among the top six multinational oil companies, i.e., ExxonMobile, British Petroleum (BP), Royal Dutch Shell, Chervon, Total and Eni in the production stage, let alone other stages such as exploration, refining, distributing and retailing. Other notable examples include: BP holds a 19.75% stake in the Russian oil giant Rosneft; the Mexican state-owned petroleum company Pemex holds a 9.3% stake in the Spanish oil giant Repsol; China's state-owned Sinopec holds a 30% stake in Petrogal Brasil, and 40% in Repsol YPF Brasil, respectively.

have been ramping up their clean energy efforts to meet the goals of the 2015 Paris climate agreement and have pledged to reaching a net-zero carbon emissions target by the middle of the century. These governments are providing strong regulatory support to reduce the global carbon footprint, forging a clear path for transition to a cleaner energy mix. However, despite the accelerating worldwide investments in renewable energy technologies and the falling costs of clean technology, a total independent supply from clean energy to satisfy the growing demand is nearly impossible, or at least unrealistic in the near future. Traditional polluting sources such as oil will continue to play a major role in energy supply. But given the cross-ownership links between rival fossil fuel producers, their incentive to compete tends to decrease with the heightened ownership stakes as one firm's gain may come at the loss of the other firms in which it has financial interests. As such, the industry output from the polluting source decreases, lowering the associated pollution and possibly decreasing the need for clean energy. We seek to understand how an increased cross-ownership among the polluting fossil fuel producers may impact the welfare gains from investment in a given source of renewable energy.

A substantial and still-growing body of literature is investigating the impact of clean energy sources and the transition to clean energy, but most researchers focus mainly on the impact of environmental policies in the presence of a clean technology. For instance, the availability of a backstop clean technology can play an important role in the outcome of the implementation of popular environmental policies and incentives (see e.g., Van der Ploeg and Withagen, 2015 or Jensen et al., 2015). Allowing for a backstop technology that at some point becomes available to replace conventional energy sources without assuming that the backstop capacity is unbounded, Gronwald, Long and Roepke (2017) examine the impact of two popular second-best policies: a subsidy for clean energy and an expansion of clean energy capacity. They show that both policy measures may result in an increase of emissions, but the former always enhances social welfare while the latter only does so if the cost of adding capacity remains small enough.

In this paper, we also assume that a clean technology is available but with a limited capacity, and energy is supplied by both a polluting source and a clean source. We do not examine the impact of different environmental policies, but rather we investigate the societal value of having a clean energy with a given capacity available and how it is impacted by changes in market structure. This paper is the first to determine how changes in current ownership structure among the polluting oligopolists impact the value, in terms of social welfare, of a clean energy source with a fixed given capacity. A companion paper by Benchekroun, Dai and Long (2021) examines the impact of cross-ownership in a resource oligopoly but does not include the possibility of a backstop technology – assumed readily available and demanded by the market – a key component of this analysis. This paper is also related to Bárcena-Ruiz and Campo (2012, 2017), who examine the interaction of cross-ownership and environmental policies such as a tax on pollution and emission standards.[3] Whereas they consider the case of an international duopoly and examine the strategic interactions at the environmental policy stage, we consider an oligopoly model and introduce a clean technology that can (partially) substitute for the polluting source. Our model and framework can be used as a stepping stone to then set up a meta-model in future research that will characterize the capacity of clean energy (as an equilibrium or an optimal choice) in a preliminary phase. We focus on how the complex interaction of changes in cross-ownership affects the market equilibrium as well as environmental damages in the presence of a backstop technology, and in a first analysis we opt to examine this question within a static framework.

Specifically, we consider an energy market with two sources of supply: a polluting fossil fuel oligopoly and a renewable sector. The polluting oligopolists compete in quantity with a subgroup of the firms owning a share in each other's profits. We follow much of the literature on cross-ownership and consider a k-symmetric cross-ownership structure that has been adopted in Benchekroun, Dai and Long (2021). For simplicity, we assume that renewable energy can be competitively supplied with a given capacity R at a constant marginal cost assumed at nil but with a significant fixed cost. We evaluate the social welfare under the Cournot equilibrium with cross-ownership, taking into account both local and global environmental damages, and determine the change in welfare between the case where a quantity R of clean energy is available and a benchmark case where energy is solely supplied by the polluting oligopolists. This change in welfare can be interpreted as the value to society of investing a clean source of energy with capacity R. Our main findings show that an increased cross-ownership between rival firms reduces the gains from investing in such a clean source of energy if and only if environmental damages are large enough. However, as environmental damages become smaller, the value of a clean technology may actually go up. The main intuition behind this result is that an increased cross-ownership results in a decrease of environmental damages due to an overall decrease of quantity of energy supplied by the polluting firms, and therefore, if environmental damages are large enough, there will be substantial gains from reduced pollution damages associated with it, thus decreasing the need for clean energy. But if environmental damages are small, the welfare loss from a less intensified competition due to increased cross-ownership outweighs the possible benefits of reduced pollution, thereby increasing the value of a clean technology.

The remainder of the paper is structured as follows. Section 2 describes the model and characterizes the equilibrium under cross-ownership. Section 3 then investigates the welfare gains from a renewable energy as a function of the levels of cross-ownership. Finally, Section 4 concludes with a discussion of our findings and future recommendations.

[3]See Section 3.5 in Lambertini (2013) for an extension of Bárcena-Ruiz and Campo (2012, 2017) to the case of a differentiated polluting oligopoly.

2 The Model and Preliminaries

2.1 The model

Suppose energy is mainly generated from two sources. The first one is a fossil fuel, such as oil, supplied by an n-firm oligopoly where firms compete $\grave{a}$ la Cournot, while the other is a renewable energy, such as solar power or wind, supplied by a competitive fringe. Firms from the polluting source produce a homogeneous good and each firm j produces a quantity $q_j \geq 0$ with identical marginal cost $c > 0$. Renewable energy can be competitively supplied with a given capacity R at a constant marginal cost assumed nil.[4] Including a positive constant marginal cost of production from renewable energy, which is smaller than the marginal cost of production from the polluting source, does not change our qualitative results. To supply renewable energy, a fixed cost F – associated with installation, building storage and transmitting capacities, is incurred. We assume that the fixed cost F is small enough for the renewable energy source to be worth installing.[5]

Consumers enjoy surplus from energy consumption, denoted by the difference between a linear-quadratic utility and the expenses:

$$U(Q + R) = a(Q + R) - \frac{b}{2}(Q + R)^2 - p(Q + R), \tag{1}$$

where $Q \equiv \sum_{j=1}^{n} q_j$ is the total quantity produced from the polluting source, R is the supply from the clean energy, and p is the final market price of energy paid by consumers. Then, the demand for energy is linear and given by

$$p = a - b(Q + R), \tag{2}$$

where a is the reservation price with $a > c + bR$ to ensure a positive demand of energy from both sources.

Suppose polluting firms can engage in cross-ownership, we follow Benchekroun, Dai and Long (2021) and consider a k-symmetric cross-ownership structure in which a subset of k polluting firms ($2 \leq k \leq n$) engage in rival cross-shareholdings[6] and each firm has an equal ownership stake v in the other firms, while the remaining $n - k$ firms stay independent. We denote the set of firms as $J = \{1, 2, \cdots, n\}$, indexed by j, and use the subsets $I = \{1, 2, \cdots, k\}$, indexed by i and $O =$

[4]Once wind turbines or solar panels are installed, the marginal production cost of renewable energy is negligible.

[5]Clearly the value of the fixed cost F is important for the decision of whether or not to have the renewable source of energy installed.

[6]In an industry characterized by rival cross-shareholdings, the aggregate profits of a firm j include not only the stream of profits generated by the firm from its own operations, but also a share in its competitors' aggregate profits due to its direct and indirect ownership stakes in these firms (Flath, 1992; Gilo, Moshe and Spiegel, 2006).

$\{k+1, \cdots, n\}$, indexed by o, referring, respectively, to the insiders and the outsiders to the cross-ownership. Then, firm j's problem can be expressed as

$$\max_{q_j \geq 0} \Pi_j = \pi_j + v \sum_{i \neq j} \Pi_i = (p-c)q_j + v \sum_{i \neq j} \Pi_i, \tag{3}$$

where $\pi_j = (p-c)q_j$ denotes firm j's operating profit and $v \geq 0$ represents firm j's fractional shareholdings in firm i for any $i \neq j$. Let $\mathbf{\Pi}$ and $\boldsymbol{q}$ denote the $n \times 1$ vectors of aggregate profits and outputs, respectively, and $\boldsymbol{D}$ denote the $n \times n$ cross-shareholding matrix, then the aggregate profit functions can be expressed in matrix form as

$$\mathbf{\Pi} = (p-c)\boldsymbol{q} + \boldsymbol{D}\mathbf{\Pi}, \tag{4}$$

where $\boldsymbol{D} = \begin{bmatrix} \boldsymbol{A}_{kk} & \mathbf{0} \\ \mathbf{0} & \mathbf{0}_{n-k} \end{bmatrix}$, and $\boldsymbol{A}_{kk}$ is a $k \times k$ matrix with element 0 in the diagonal and v off-diagonal. This set of n equations implicitly defines the aggregate profit for each polluting firm. Then $\boldsymbol{I} - \boldsymbol{D} = \begin{bmatrix} \boldsymbol{B}_{kk} & \mathbf{0} \\ \mathbf{0} & \boldsymbol{I}_{n-k} \end{bmatrix}$, where $\boldsymbol{B}_{kk}$ is a $k \times k$ matrix with element 1 in the diagonal and $-v$ off-diagonal, and $\boldsymbol{I}_{n-k}$ denote the $(n-k) \times (n-k)$ identity matrix. We make the following assumption:

Assumption 1. *Each firm seeks to maximize the value of its aggregate profits, but controls only its own production q_j, with rival shareholdings $v < \frac{1}{k-1}$, i.e., firms only have a silent financial interest or non-controlling minority stake in the rivals.*

Assumption 1 guarantees that the aggregate stake of rivals in each cross-ownership participant, $(k-1)v$, is less than 1. [7] Under Assumption 1, matrix $(\boldsymbol{I} - \boldsymbol{D})$ is invertible, which implies that it is possible to solve for the aggregate profit functions:

$$\mathbf{\Pi} = (\boldsymbol{I} - \boldsymbol{D})^{-1}\Big[\big(a - b(Q+R) - c\big)\boldsymbol{q}\Big] = \begin{bmatrix} \boldsymbol{B}_{kk}^{-1} & \mathbf{0} \\ \mathbf{0} & \boldsymbol{I}_{n-k} \end{bmatrix} \Big[\big(a - b(Q+R) - c\big)\boldsymbol{q}\Big], \tag{5}$$

where $\boldsymbol{B}_{kk}^{-1}$ is given by the following matrix

$$\Omega \equiv \frac{1}{f(v)} \begin{bmatrix} 1-(k-2)v & v & \cdots & v \\ v & 1-(k-2)v & \cdots & v \\ \vdots & \vdots & \ddots & \vdots \\ v & v & \cdots & 1-(k-2)v \end{bmatrix}, \tag{6}$$

[7] Similar restriction can be found in Gilo, Moshe and Spiegel (2006) where the weight given to rivals' profits is bounded from above by $1/(n-1)$ when $k=n$.

with $f(v) = (1+v)\big(1-(k-1)v\big) > 0$. The aggregate profit function of firm $i \in I$ is

$$\Pi_i = \frac{1}{f(v)}\left[\big(1-(k-2)v\big)\pi_i + v \sum_{m \in I \backslash i} \pi_m\right], \tag{7}$$

while for firm $o \in O$, the aggregate profit function is

$$\Pi_o = \pi_o. \tag{8}$$

Production of firm j generates pollution, causing both local and global damages. For instance, extraction from oil sands as well as drilling and fracking from shale oil requires a large amount of water and uses potentially hazardous chemicals to release and process the oil, which generates large amounts of wastewater that may contain dissolved chemicals and other contaminants.[8] Significant water use for oil production, frequent pipeline spills and leaks, and the associated highly toxic waste pose an increasing threat to the already scarce water and land resources and inevitably affects the local ecosystem that relies on them.[9] For simplicity, we assume that each unit of output of a firm generates one unit of local pollution and that the local damage function is denoted by

$$D(q_j) = \frac{\beta}{2} q_j^2, \tag{9}$$

where β is a positive parameter capturing the degree of convexity of the local damage function. Meanwhile, the oil extraction and processing emit large amounts of carbon dioxide (CO_2) along with other pollutants such as NO_x, SO_2, PM and so on. These greenhouse gas emissions harm the environment and human health, and contribute to global warming. We denote the global damage function by

$$D(Q) = \frac{\lambda}{2} Q^2, \tag{10}$$

where λ is a positive parameter capturing the degree of convexity of the global damage function.[10]

Finally, we define the social welfare as the sum of consumer surplus and industry profits minus

[8] See https://www.eia.gov/energyexplained/oil-and-petroleum-products/oil-and-the-environment.php.

[9] For example, according to a report by Greenpeace Canada, ample evidence shows that over the past years oil sands mining in Alberta has destroyed thousands of acres of the boreal forest, which is home to large populations of wildlife (e.g., wolves, grizzly bear, lynx and moose) as well as to endangered species such as the woodland caribou and whooping cranes (Finkel, 2018).

[10] We acknowledge that the dynamic context is very important, as global warming depends primarily on stocks of greenhouse gases. But the cross-ownership literature focus mostly on a static framework, the only exception is Benchekroun, Dai and Long (2021) which examines profitability of cross-ownership in a resource game. In a first analysis, we abstain the consideration of a dynamic stock externality game and leave it for future work.

the total environmental damages:

$$W = a(Q+R) - \frac{b}{2}(Q+R)^2 - cQ - F - \sum_{j=1}^{n} \frac{\beta}{2} q_j^2 - \frac{\lambda}{2} Q^2. \tag{11}$$

2.2 The Equilibrium

We now characterize the Cournot equilibrium of this game. Given the symmetric ownership stake v, each firm j takes other firms' production Q_{-j} and the supply from clean energy R as given and chooses q_j to maximize its own aggregate profits Π_j. The first order condition for a typical firm $i \in I$ is given by

$$\big(1-(k-2)v\big)\frac{\partial \pi_i}{\partial q_i} + v \sum_{m \in I \setminus i} \frac{\partial \pi_m}{\partial q_i} = 0, \tag{12}$$

or

$$\big(1-(k-2)v\big)\big(a - b(q_i + Q_{-i} + R) - c - bq_i\big) - v \sum_{m \in I \setminus i} bq_m = 0, \tag{13}$$

while from the profit maximization for a typical firm $o \in O$, we have

$$a - b(q_o + Q_{-o} + R) - c - bq_o = 0. \tag{14}$$

Exploiting symmetry, we can then solve the Cournot cross-ownership equilibrium outputs as

$$q_i^v = \frac{1-(k-2)v}{(k+n+1-k^2)v+n+1}\frac{(a-c-bR)}{b}, \quad q_o^v = \frac{1+v}{(k+n+1-k^2)v+n+1}\frac{(a-c-bR)}{b}. \tag{15}$$

Thus, the equilibrium total output from the polluting source is

$$Q_v = kq_i^v + (n-k)q_o^v = \frac{((k+n-k^2)v+n)}{(k+n+1-k^2)v+n+1}\frac{(a-c-bR)}{b}. \tag{16}$$

Since the problem we examine features two sources of market failures – imperfect competition and negative externalities, the market outcome may result in under supply of the consumption good if market power effects outweigh the pollution effect. The premise of our work is that the negative externality outweighs the market power effect and resorting to a clean technology is considered. To this end, we make the following assumption on the damage parameters:

Assumption 2. The environmental damage parameters (λ, β) are such that

$$\lambda + \frac{\beta}{n} > \frac{b}{n}.$$

Assumption 2 guarantees that the Cournot equilibrium without cross-ownership results in more pollution than what is socially optimal.

3 The Value of a Clean Technology with Capacity R

In this section, we exploit the characterization of the Cournot equilibrium in the above-defined game to investigate how cross-ownership affects the value of a clean technology. We first define the value of a clean technology with capacity R as the difference in social welfare between the case where a quantity R of clean energy is available and a benchmark case where energy is solely supplied by the polluting oligopolists. We then justify Assumption 2 we made earlier on the environmental damage parameters. Next, we evaluate how the benefit of investing in a clean source of energy is affected by cross-ownership in the linear demand case. Finally, we check the robustness of the results with some other demand specifications.

The social welfare under cross-ownership is

$$W_v(k,n,v,R,\beta,\lambda) = a(Q_v+R)-\frac{b}{2}(Q_v+R)^2-cQ_v-F-\frac{\beta}{2}\left(k(q_i^v)^2+(n-k)(q_o^v)^2\right)-\frac{\lambda}{2}Q_v^2, \quad (17)$$

where Q_v, q_i^v and q_o^v are given by Equation (15) and (16). Then, the value of a clean technology can be defined as the change in social welfare in the presence of clean energy:

$$\Omega = W_v(k,n,v,R,\beta,\lambda) - W_v(k,n,v,0,\beta,\lambda) - F. \quad (18)$$

Equation (18) thus corresponds to the social benefit of investing in such a clean technology that generates R units of renewable energy for free. It represents society's maximum willingness to pay for such a clean technology. It will be useful to explicitly write down the value of a clean technology Ω as a function of (k,n,v,R,β,λ), but the expression is too cumbersome and thus we choose not to report it here.

Note that the first best quantity that maximizes social welfare is determined by

$$a - c - b\left(Q_{so} + R\right) = \left(\frac{\beta}{n} + \lambda\right) Q_{so}, \quad (19)$$

which yields

$$Q_{so} = \frac{a-c-bR}{\lambda + \frac{\beta}{n} + b}. \quad (20)$$

The standard Cournot equilibrium output without cross-ownership is given by

$$Q_c \equiv Q_v|_{v=0} = \frac{n}{n+1}\frac{(a-c-bR)}{b}. \tag{21}$$

Thus, Assumption 2 is equivalent to

$$\lambda + \frac{\beta}{n} > \frac{b}{n} \Longleftrightarrow Q_{so} = \frac{a-c-bR}{\lambda + \frac{\beta}{n} + b} < Q_c = \frac{n}{n+1}\frac{(a-c-bR)}{b}.$$

This says that when environmental damages are large enough, i.e., $\lambda + \frac{\beta}{n} > \frac{b}{n}$, the Cournot equilibrium without cross-ownership results in supply of energy from the polluting source larger than the socially optimal quantity (i.e., $Q_c > Q_{so}$). Therefore, Assumption 2 ensures that we are starting with a situation where the Cournot equilibrium under zero cross-ownership results in more pollution than what is socially optimal. Focusing on this region gives us more incentive to consider the energy supply from clean sources to reduce pollution, thereby increasing the importance of this study.

3.1 Linear Demand

We now turn to the main contribution of the paper: how does cross-ownership affect the value of a clean technology with capacity R? An increase in v results in a decrease of environmental damages due to an overall decrease of quantity of energy supplied by the polluting firms, and therefore, intuition suggests that increased cross-ownership should always reduce the gains from a clean source of energy.

We first examine how Ω is changing with respect to a marginal increase of v in the neighborhood of $v = 0$. Note that

$$\left.\frac{\partial \Omega}{\partial v}\right|_{v=0} = -\frac{kR(k-1)(2a-2c-bR)(\beta+\lambda n - b)}{b(n+1)^3}. \tag{22}$$

Since $a > c + bR$, we have $2a > 2c + 2bR > 2c + bR$. Also, under Assumption 2: $\lambda + \frac{\beta}{n} > \frac{b}{n} \Longleftrightarrow \beta + \lambda n - b > 0$. Then, for all $2 \leq k \leq n$,

$$\left.\frac{\partial \Omega}{\partial v}\right|_{v=0} < 0.$$

We can thus summarize in the following proposition:

Proposition 1. *Starting with a situation where the Cournot equilibrium under zero cross-ownership (i.e., $v = 0$) results in more pollution than what is socially optimal, a marginal increase of cross-ownership around $v = 0$ results in a decrease in the value of a clean technology.*

Note that it is when the damage parameters are large enough (i.e., $\beta + \lambda n > b$) that $\frac{\partial \Omega}{\partial v}\Big|_{v=0} < 0$, i.e., a marginal increase in v (from $v = 0$) results in a decrease in gains from a clean technology. This result a priori runs against intuition, since one would expect that an output cut due to cross-ownership would result in itself achieving larger decrease in pollution damages the larger the damage parameters, and therefore diminish the need for a clean energy.

Next, we extend the analysis to study the impact of v on Ω for all $v \in (0, \frac{1}{k-1})$. We have

$$\frac{\partial \Omega}{\partial v} = -\frac{kR(k-1)(2a-2c-bR)\Big(\beta - b(v+1) + \beta v\left(k^2-(n+2)\,k+n+2\right) + \lambda\big((k+n-k^2)v+n\big)\Big)}{b\Big((k+n+1-k^2)v+n+1\Big)^3}. \tag{23}$$

Given that $2 \leq k \leq n$ and $2a > 2c + bR$, $\frac{\partial \Omega}{\partial v}$ has the same sign as the function Γ, where

$$\Gamma\left(b,k,n,\beta,\lambda,v\right) = -\Big(\beta - b(v+1) + \beta v\left(k^2-(n+2)\,k+n+2\right) + \lambda\big((k+n-k^2)v+n\big)\Big). \tag{24}$$

After collecting v, Γ becomes

$$\Gamma\left(b,k,n,\beta,\lambda,v\right) = \Big(b - \beta\left(k^2-(n+2)\,k+n+2\right) - \lambda\left(k+n-k^2\right)\Big)v + \left(b - n\lambda - \beta\right). \tag{25}$$

Note that under Assumption 2: $\lambda + \frac{\beta}{n} > \frac{b}{n} \Longleftrightarrow \beta + \lambda n - b > 0$, therefore

$$\Gamma\left(b,k,n,\beta,\lambda,0\right) = b - n\lambda - \beta < 0. \tag{26}$$

Moreover, since Γ is linear in v, it can change the sign at most once over the interval $\left(0, \frac{1}{k-1}\right)$. Evaluating Γ at $v = \frac{1}{k-1}$ yields

$$\Gamma\left(b,k,n,\beta,\lambda,\frac{1}{k-1}\right) = -\frac{\beta}{k-1}\Big(\left(1-k\right)\left(n-k\right)+1\Big) - \frac{\lambda}{k-1}\Big(k(n-k+1)\Big) + \frac{bk}{k-1}. \tag{27}$$

First, note that $\Gamma\left(b,k,n,\beta,\lambda,\frac{1}{k-1}\right)$ is a decreasing function of λ. Therefore, for any b,β and $2 \leq k \leq n$, there exists a $\bar{\lambda}$ such that

$$\Gamma\left(b,k,n,\beta,\bar{\lambda},\frac{1}{k-1}\right) = 0 \Longleftrightarrow \bar{\lambda} = \frac{bk - \beta\big(\left(1-k\right)\left(n-k\right)+1\big)}{k(n-k+1)}. \tag{28}$$

Thus, we have

$$\Gamma\left(b,k,n,\beta,\lambda,\frac{1}{k-1}\right) < 0, \qquad \forall\, \lambda > \bar{\lambda}. \tag{29}$$

Combined with the linearity of the function Γ, Equation (26) and (29) suggest that for any $\lambda > \bar{\lambda}$,

$$\Gamma\left(b, k, n, \beta, \lambda, v\right) < 0 \Longleftrightarrow \frac{\partial \Omega}{\partial v} < 0, \quad \forall v \in \left(0, \frac{1}{k-1}\right).$$

Therefore, for any local damages and any number of firms that participate in cross-ownership, if the global damages are large enough, then an increase in cross-ownership decreases the need for a clean technology. We can thus establish the following lemma:

Lemma 1. *Suppose Assumption 2 holds, then an increased cross-ownership results in a decrease in the value of a clean technology if for any b, β and $2 \leq k \leq n$, $\lambda > \bar{\lambda} = \frac{bk-\beta\big((1-k)(n-k)+1\big)}{k(n-k+1)}$.*

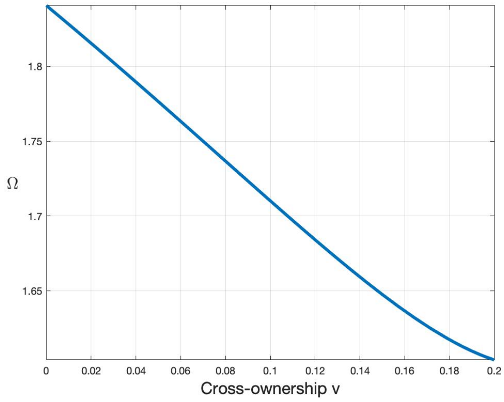
It should be noted that when $\lambda < \bar{\lambda}$, the sign of $\frac{\partial \Omega}{\partial v}$ is ambiguous and depends on v. To illustrate these findings, we provide several numerical simulations in the following. Figure 1a shows the value of a clean technology Ω as a function of the level of cross-ownership v when Lemma 1 holds, e.g., when we fix $a = 2$, $b = 1$, $c = 0.2$, $R = 0.2$, $n = 9$, $k = 6$, $\beta = 8$, $F = 0.1$, and choose $\lambda = 6$ such that

$$a > c + bR, \quad \beta + \lambda n > b,$$
$$\lambda > \bar{\lambda} = \frac{bk - \beta\big(\left(1-k\right)\left(n-k\right)+1\big)}{k(n-k+1)} = \frac{6 - 8(-5 \times 3 + 1)}{6(9-6+1)} = 4.92.$$

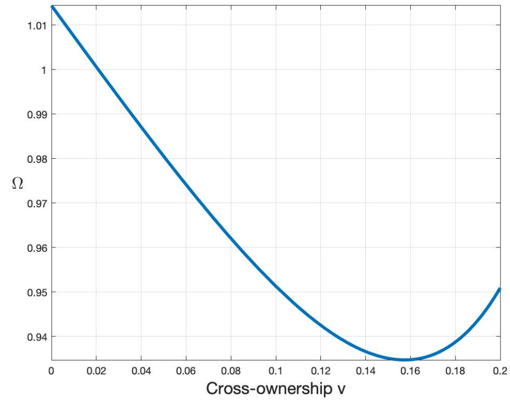
As we can see, Ω is decreasing in v for all $v \in \left(0, \frac{1}{k-1}\right)$. However, if we decrease the value of λ to $3, 1, 0.1$ (i.e., $\lambda < \bar{\lambda} = 4.92$), we can have cases where Ω is a U-shaped function of v for $v \in \left(0, \frac{1}{k-1}\right)$, as shown in Figure 1b, 1c and 1d, respectively. More specifically, when $\lambda < \bar{\lambda}$, we have $\frac{\partial \Omega}{\partial v} < 0$ for all $v \in (0, \hat{v})$ but $\frac{\partial \Omega}{\partial v} > 0$ for all $v \in (\hat{v}, \frac{1}{k-1})$, where $\hat{v}$ is the shareholding that minimizes Ω. Thus, if the global environmental damages are not large enough, an increased cross-ownership may actually increase the need for a clean technology when the cross-shareholdings are high enough. The intuition behind this result is that larger shareholdings between rival firms will induce them to compete less aggressively and thus reduce their production by more, hence leading to a lower pollution. But if the environmental damages are not large enough, the benefits of a reduced pollution may not recoup the loss of a less intensified competition. As a result, there is a strong case for investing in clean energy.

Also note that $\Gamma\left(b, k, n, \beta, \lambda, \frac{1}{k-1}\right)$ is a decreasing function of β if $(1-k)(n-k)+1 > 0$, that is, when $n - k < \frac{1}{k-1}$. But for $k \geq 2$, we have $\frac{1}{k-1} \leq 1$, so the number of outsiders $(n-k)$ can only be 0. If $n - k = 0$, then $(1-k)(n-k)+1 = 1 > 0$ for all $2 \leq k \leq n$. Therefore, $\Gamma\left(b, k, n, \beta, \lambda, \frac{1}{k-1}\right)$ is a decreasing function of β if and only if $k = n$ for all $2 \leq k \leq n$, i.e., all the firms are involved in cross-ownership. This implies that there exists a $\bar{\beta}$ such that

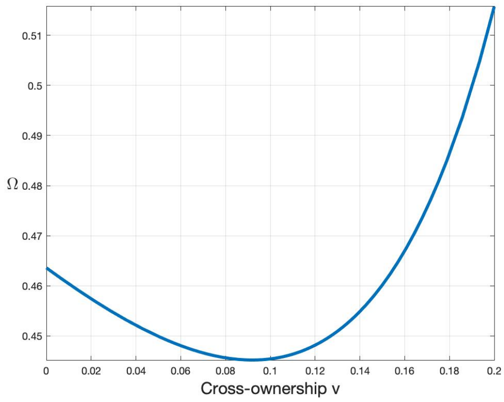
$$\Gamma\left(b, k, n, , \bar{\beta}, \lambda, \frac{1}{k-1}\right) = 0 \Longleftrightarrow \bar{\beta} = (b-\lambda)k, \text{ if } \lambda < b. \tag{30}$$



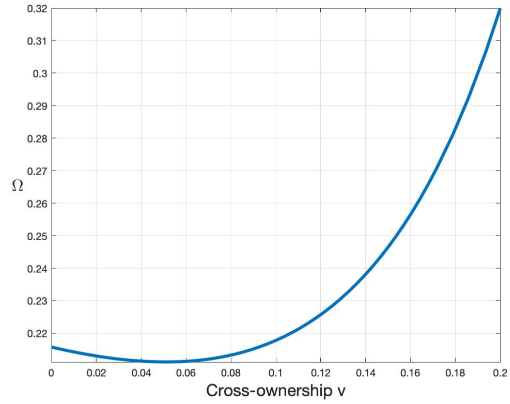
(a) $\lambda = 6$



(b) $\lambda = 3$



(c) $\lambda = 1$



(d) $\lambda = 0.1$

Figure 1: Linear demand when λ varies

Thus, we have

$$\Gamma\left(b, k, n, \beta, \lambda, \frac{1}{k-1}\right) < 0, \ \forall\, \beta > \bar{\beta}. \tag{31}$$

This combined with the linearity of Γ and Equation (26) indicates that for any $\beta > \bar{\beta}$,

$$\Gamma\left(b, k, n, \beta, \lambda, v\right) < 0 \Longleftrightarrow \frac{\partial \Omega}{\partial v} < 0, \quad \forall v \in \left(0, \frac{1}{k-1}\right).$$

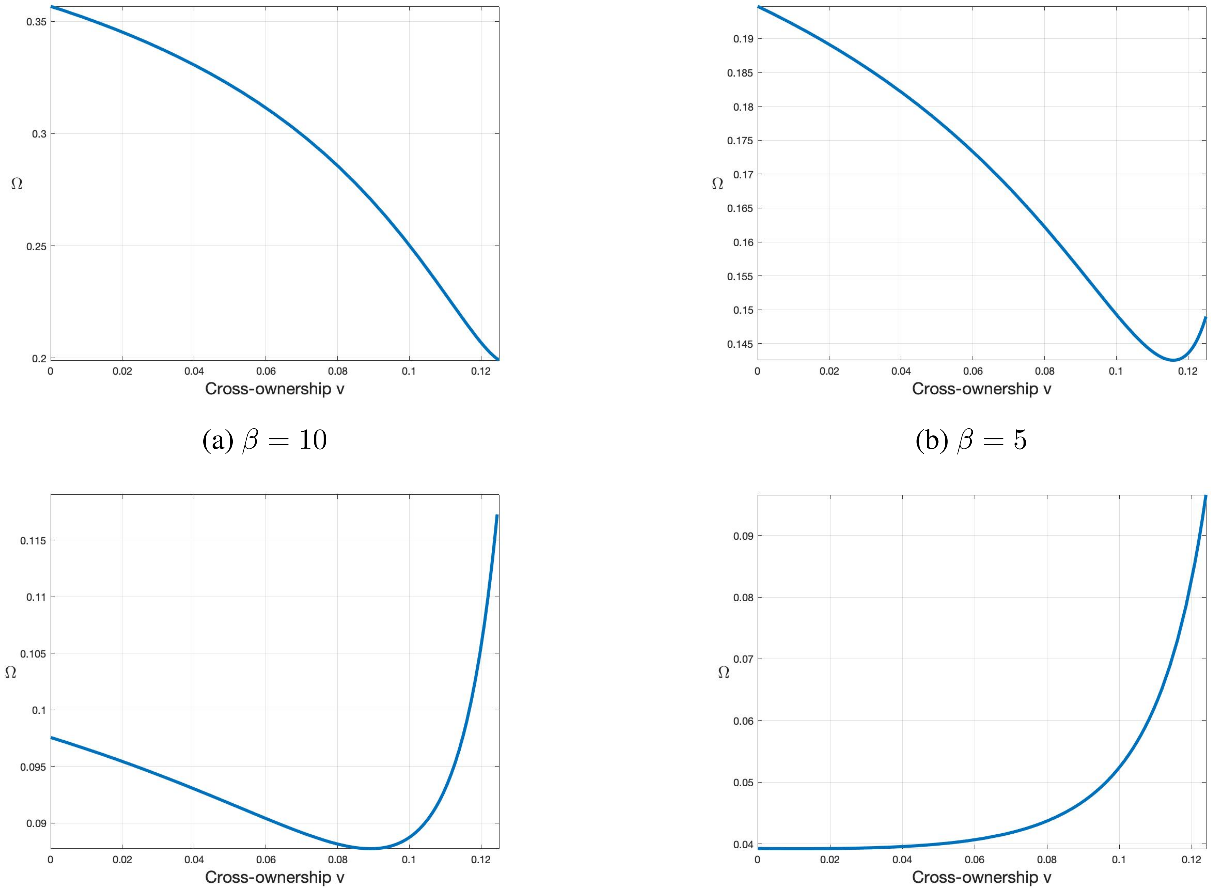
Therefore, provided that global damages are small enough and all firms participate in cross-ownership, then an increased cross-ownership decreases the value of a clean technology if the local damages are large enough. We can summarize this result in the following lemma:

Lemma 2. *Suppose Assumption 2 holds, then an increased cross-ownership results in a decrease in the value of a clean technology if for any $\lambda < b$ and $n = k$, $\beta > \bar{\beta} = (b - \lambda)k$.*

It should be noted that when conditions in Lemma 2 do not hold, the sign of $\frac{\partial \Omega}{\partial v}$ is ambiguous and depends on v. We use several numerical examples to illustrate these results. Figure 2a shows the value of a clean technology Ω as a function of the level of cross-ownership v when Lemma 2 holds, e.g., when we fix $a = 2$, $b = 1$, $c = 0.1$, $R = 0.2$, $k = n = 9$, $\lambda = 0.1$, $F = 0.02$ and choose $\beta = 10$ such that

$$a > c + bR, \quad \beta + \lambda n > b, \quad \beta > \bar{\beta} = (b - \lambda)k = (1 - 0.1) \times 9 = 8.1$$

As illustrated in Figure 2a, Ω is decreasing in v for all $v \in \left(0, \frac{1}{k-1}\right)$. However, if we change the value of β to $\beta = 5, 2, 0.2$, respectively, we can have cases where Ω is a U-shaped function of v, or an increasing function of v, for $v \in \left(0, \frac{1}{k-1}\right)$, as shown in Figure 2b, 2c and 2d, respectively. Clearly, an increased cross-ownership may actually increase the need for a clean technology that



(a) $\beta = 10$ (b) $\beta = 5$

(c) $\beta = 2$ (d) $\beta = 0.2$

Figure 2: Linear demand when β varies

generates R units of renewable energy. This is especially true when both local and global damages are small enough as those in Figure 2d, where the benefit of investing in a clean technology is always increasing in the level of cross-ownership. In this case, the welfare loss due to reduced competition always outweighs the small environmental gains from reduced pollution.

Based on the results from Lemma 1 and Lemma 2 as well as the numerical simulations, we can thus establish the following result:

Result 1. *Suppose Assumption 2 holds and the number of firms that participate in cross-ownership* *is significant enough, then an increase in cross-ownership decreases the value of a clean technology if and only if environmental damages are large enough. However, as environmental damages become smaller, the value of a clean technology may actually go up as the welfare loss from a less intensified competition due to increased cross-ownership outweighs the environmental gains from reduced pollution.*

3.2 Robustness Check

While we have considered linear demand so far, we would also like to know whether our results obtained in the linear model are robust to other demand formulations. Specifically, we consider the following two demand specifications:

(a) a semi-loglinear demand function:

$$p = -\frac{1}{\psi} \ln \left(\frac{Q+R}{\psi} \right), \quad \psi > 0, \tag{32}$$

which can be obtained by maximizing the consumer surplus:

$$U(Q+R) = \frac{(Q+R)}{\psi} \left[1 - \ln \left(\frac{Q+R}{\psi} \right) \right] - p(Q+R). \tag{33}$$

(b) a loglinear/iso-elastic demand function:

$$p = \frac{1-\varphi}{\psi} \left(\frac{Q+R}{\psi} \right)^{\frac{1}{\varphi-1}}, \quad 0 \le \varphi < 1, \tag{34}$$

with the corresponding consumer surplus function:

$$U(Q+R) = -\frac{(1-\varphi)^2}{\varphi} \left(\frac{Q+R}{\psi} \right)^{\frac{\varphi}{\varphi-1}} - p(Q+R). \tag{35}$$

First, we examine how the value of a clean technology Ω is changing as the level of cross-ownership goes up when we fix the same set of parameters values: $R = 0.2$, $c = 0.2$, $n = 9$, $k = 6$, $\beta = 8$, $F = 0.1$ as in Figure 1 and vary λ from 6 to 3, 1 and 0.1, respectively. Figure 3a-3d shows the cases with a semi-loglinear demand function when $\psi = 2$, while Figure 3e-3h shows the cases with an iso-elastic demand function when $\psi = 1$ and $\varphi = 0.5$. In both cases as shown in Figure 3, the value of a clean technology is always decreasing in the level of cross-ownership when the global damages are large enough(e.g., $\lambda = 6$), but as λ becomes smaller (e.g., $\lambda = 0.1$), there will be a strong need for investment in a clean technology when the shareholding is larger enough, as a substantial lessening of competition causes more harm than the benefits of reducing pollution.

Second, we plot Ω as a function of v when we fix the same set of parameters values: $R = 0.2, c = 0.1$, $n = k = 9$, $\lambda = 0.1$, $F = 0.02$ as in Figure 2 and vary β from 10 to 5, 2 and 0.2, respectively. Figure 4a-4d shows the cases with a semi-loglinear demand function when and $\psi = 2$, while Figure 4e-4h shows the cases with an iso-elastic demand function when $\psi = 1$ and $\varphi = 0.5$. As shown in Figure 4, when the local damages are large enough (e.g., $\beta = 10$), the value of a clean technology Ω is always decreasing in the level of cross-ownership v. However, as β becomes smaller (e.g., $\beta = 0.2$), we will have cases where Ω increases with v and thus there is need to invest in the clean sector as the loss from reduced competition outweighs the potential gains from less pollution.

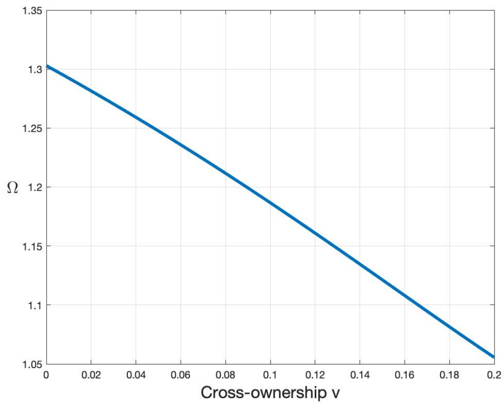
As evident from these numerical results with the semi-loglinear and iso-elastic demand functions, our conclusion from Result 1 is quite robust. It should be noted that the above results also hold with some other demand specifications and parameter values.

4 Conclusion

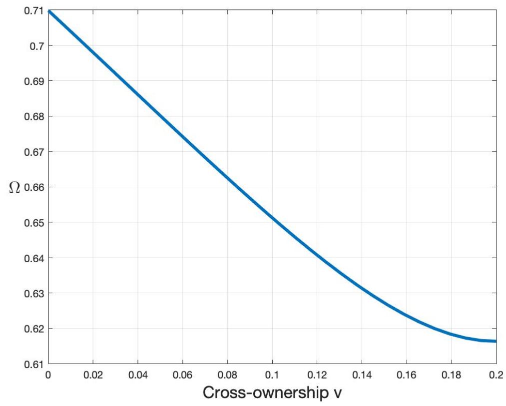
In this paper, we investigate the impact of cross-ownership in a polluting fossil fuel oligopoly on the value of a clean energy substitute with a given capacity in different environmental scenarios. We show that an increased cross-ownership among polluting firms decreases the value of a clean technology if environmental damages are large enough. However, in the case of a non-marginal increase in cross-ownership, this result may be reversed when environmental damages are small enough. The main intuition behind these findings is that an increased cross-ownership results in a decrease of environmental damages due to an overall decrease in energy supply by the polluting firms, and therefore, if environmental damages are large enough, there will be substantial gains from reduced pollution damages associated with it, thus decreasing the need for clean energy. But if environmental damages are small, the welfare loss from a less intensified competition due to increased cross-ownership outweighs the possible benefits of reduced pollution, thereby increasing the value of a clean technology.

We have assumed that the backstop technology is readily available and can generate R units of clean energy demanded by the market. Our analysis and framework can be used as a starting point of a meta-model where the capacity of the clean energy is determined endogenously in a preliminary phase, see e.g., Goyal and Joshi (2003), Goyal and Moraga-Gonzalez (2001) for R&D network collaboration games and Benchekroun and Claude (2007) for the case of polluting oligopolists. Our analysis also reveals that the interaction of cross-ownership and environmental policies targeting a transition to clean sources of energy should be carefully examined. When such ownership changes raise concerns and come under scrutiny by antitrust authorities, a specific analysis is necessary and represents a promising line for future research, see e.g., Benchekroun and Chaudhuri (2011), Dragone, Lambertini and Palestini (2013), Yong, Friesen and McDonald (2018) in the case of collusive behavior and environmental policy; and Choi, Espínola-Arredondo and Muñoz-García (2020), Fikru and Gautier (2016, 2017, 2020) in the case of mergers of polluting oligopolists.

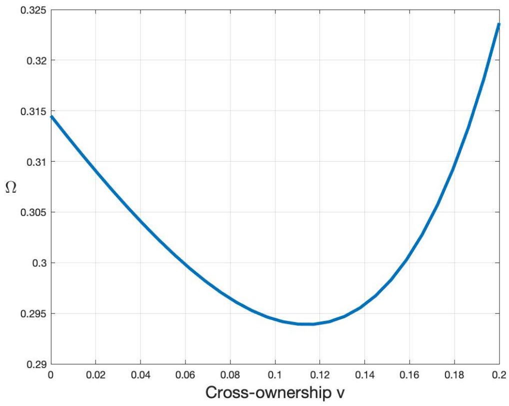
Figure 3: Semi-loglinear(a-d) and iso-elastic(e-h) demand when λ varies



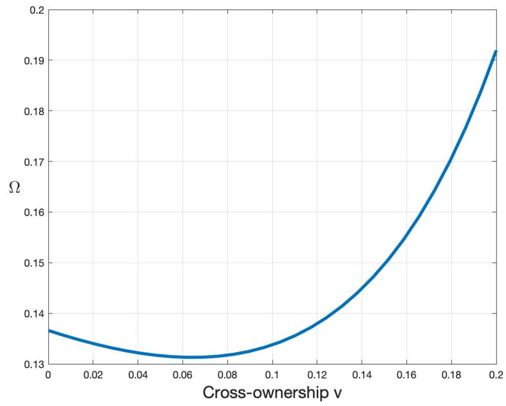
(a) $\lambda = 6$



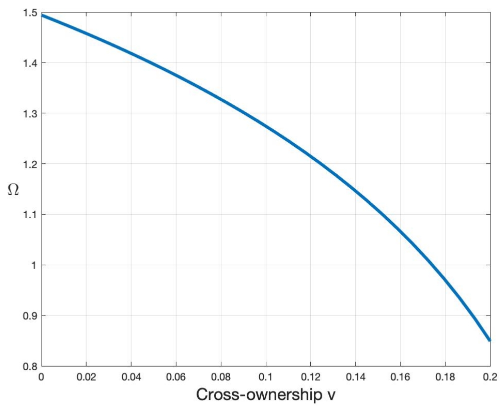
(b) $\lambda = 3$



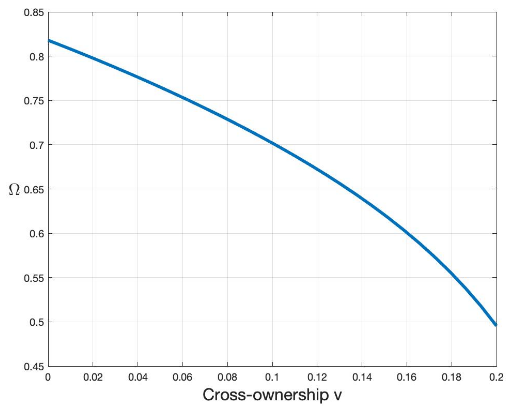
(c) $\lambda = 1$



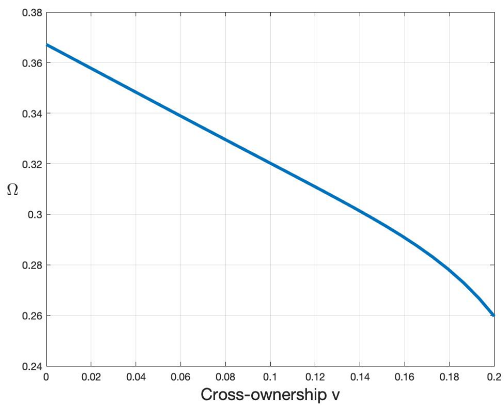
(d) $\lambda = 0.1$



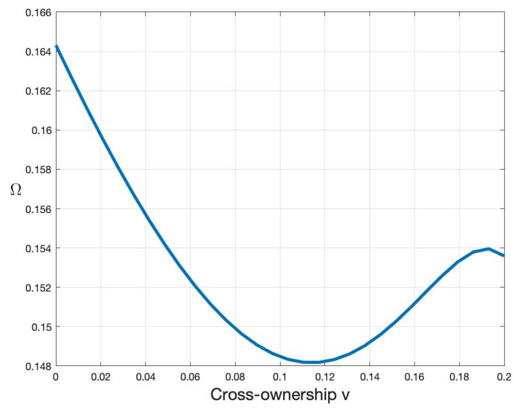
(e) $\lambda = 6$



(f) $\lambda = 3$

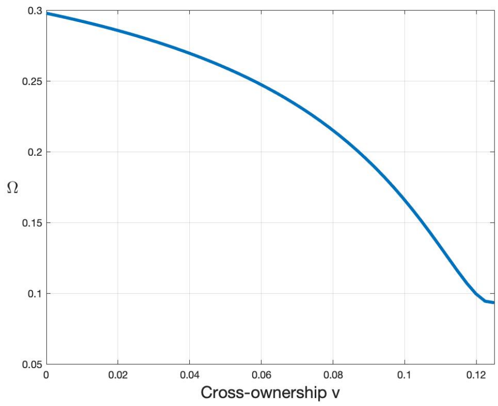


(g) $\lambda = 1$

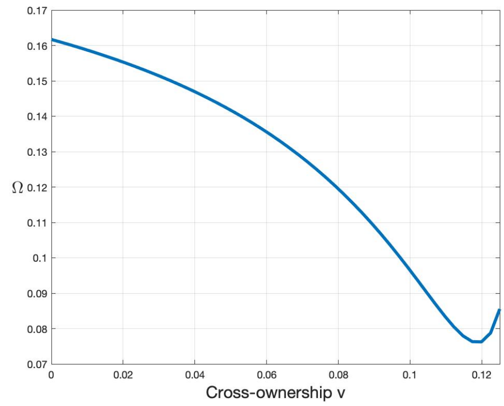


(h) $\lambda = 0.1$

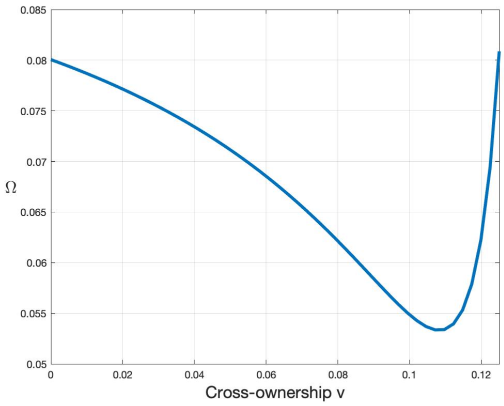
Figure 4: Semi-loglinear(a-d) and iso-elastic(e-h) demand when β varies



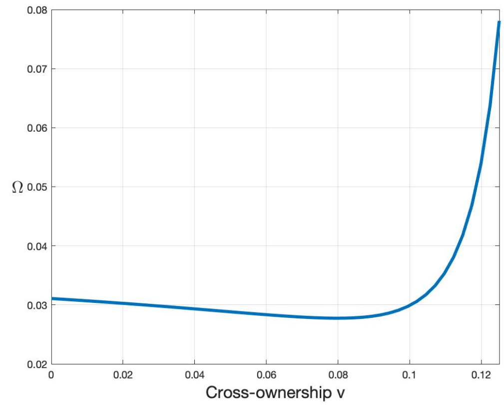
(a) $\beta = 10$



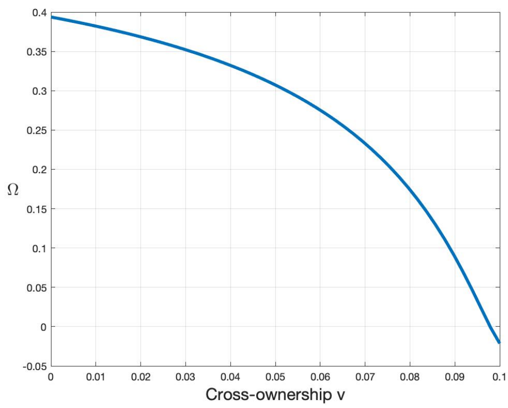
(b) $\beta = 5$



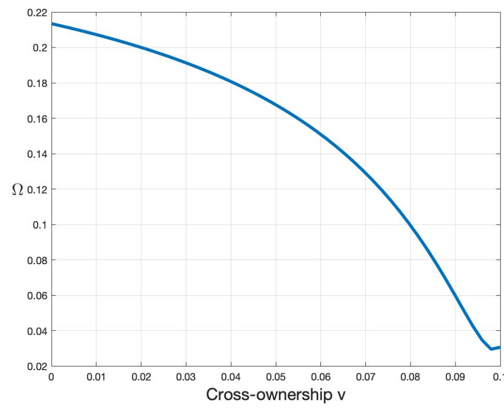
(c) $\beta = 2$



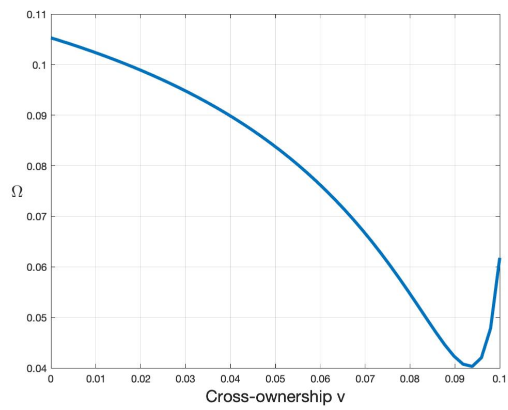
(d) $\beta = 0.2$



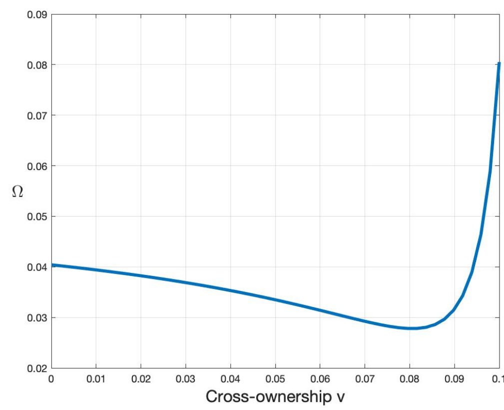
(e) $\beta = 10$



(f) $\beta = 5$



(g) $\beta = 2$



(h) $\beta = 0.2$

Author Declarations

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Conflicts of interest

The Authors declare that there is no conflict of interest.

Availability of data and material

Not applicable.

Code availability

Matlab codes used to generate the figures in the paper can be accessed through the following link: https://www.dropbox.com/sh/jr3z26pvoj3e8ll/AABt3TM3eW0lJVmbbmZjl4-Sa?dl=0

Authors' contributions

The authors contribute equally to the paper.

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