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Working Papers Series

UMR 6031 TREE

Transitions Energétiques et Environnementales

TREE WP No. 4
October 2021

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Abstract

This paper develops a theoretical framework to study the deployment of free-of-emissions green hydrogen in the transport sector. We consider a vertically related market with hydrogen producers upstream and fuel stations downstream. Production technologies differ in cost efficiency and carbon emissions. We show that when consumers have limited information about the hydrogen origin, no new green producers are able to enter the market. A label for green hydrogen allows multiple production technologies to co-exist, but society is better off when producers use vertical restraints to increase consumers' information.

Keywords: Label, Vertical Restraints, Innovation, Hydrogen
JEL: L13, L15, L42, Q42

1. Introduction

Meeting the European Green Deal and the Paris Agreement implies achieving carbon neutrality by 2050. The European Commission (2020) states that

⋆We are thankful for the suggestions made by Anna Creti and Romain Gaté to improve the paper. We have also benefited from discussions with conference participants of the FAEE Student Workshop (November 26th 2021, Online) and Journées de Microéconomie Appliquée (June 4th 2021, Online). This research has been supported by the Chair "The Economics of Natural Gas". Any remaining errors are ours. The views expressed herein are strictly those of the authors and should not be construed to reflect the opinions of the Université de Pau et des Pays de l'Adour.

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reaching such goal requires to reduce the transport sector emissions by 90%. Renewable energy and bio-fuels are expected to decarbonise a large share of this sector, but there are still hard to abate parts of the transport system. Fuel-Cell Electric Vehicles (FCEV) could help reduce carbon emissions (CO2), but this is only true if the hydrogen used to power FCEV comes from a low-carbon source. Otherwise, the level of emissions will not be any lower than with current fuels (oil and gas).

Different production pathways are possible for hydrogen, which differ in costs and carbon emissions. Traditionally, production has relied on carbon-intensive fossil-fuels-based technologies with an unit cost of 1.5€/kg. The latter can be upgraded with Carbon Capture and Storage techniques (CCS) to reduce emissions but at a higher unit production cost of 2€/kg. Production from renewable energy sources is also possible but more costly (about 2.5-5.5€/kg). The International Energy Agency (2019) considers that some countries might try to exploit near-term opportunities based on fossil fuels and later on shift to more environmentally friendly processes. In the current EU legislation, there is not a distinction between these different production pathways: could this lack of legislation limit the deployment of decarbonised hydrogen?

The European Commission (2020) is working to develop a policy framework to support the transition to a decarbonised hydrogen market while informing consumers. It has stated its intention to provide a definition of decarbonised hydrogen building on the certification system *Certifhy* proposed by HyLaw (2019). This certification, developed as an industry initiative, proposes to build on green energy's guarantees of origin (GoO)[1]. This type of certification scheme is relevant in the hydrogen market since transportation and distribution optimisation requires unbundling production and consumption. This project differentiates between three types of hydrogen: Grey hydrogen produced using fossil-fuels-based technologies, Green and Blue hydrogen with 60% less emissions compared to grey hydrogen, respectively produced with renewable, and non-renewable energy. The second part of this paper aims to study whether this policy framework performs better than a *laissez faire* approach where producers take actions to inform consumers, in terms of conveying information and social welfare. For simplicity, we consider only

[1]A GoO certifies that for each demanded kg of decarbonised hydrogen, the equivalent will be produced using the relevant technology.

two types of hydrogen, low (grey) and high-quality (blue or green) hydrogen.

To answer the question of the deployment of decarbonised hydrogen, we develop a model of a hydrogen-based road transport sector, where consumers have no direct information about the production pathway. Traditionally, infrastructure-intensive markets (such as telecoms, energy, water, transportation, etc ...) have first relied on a state-owned monopoly but in the case of hydrogen, this is unlikely. Indeed, hydrogen is already widely used in industrial processes (e.g. refining), with well-established players along the supply chain. We consider a vertically related market with hydrogen producers upstream and fuel stations downstream (retailers). We consider an incumbent producer with fossil-fuel-based technology and a potential renewable entrant producer. When fuel stations, that sell hydrogen to FCEV owners, can not communicate on the hydrogen origin, we show that decarbonised hydrogen deployment can only be done by the incumbent. We then explore alternative solutions to solve the information problem: vertical restrictions and labels.

This paper contributes to two strands of economic literature. First, it contributes to the literature of vertical mergers with differentiated products (Bacchiega et al. (2018); Nocke and Rey (2018)). In particular, we consider a merger between a fuel station and a high-quality producer. Our main assumption is that integrated retailers do not support other producers' quality. In a similar setup, Nocke and Rey (2018) find that a merger between the low-quality producer and retailer increases their joint profits. This paper departs from their model introducing an information problem downstream and considering price competition. Nocke and Rey (2018) results hold when the cost difference between qualities is small. Otherwise, the merger does not increase their joint profits. Second, the paper contributes to the literature of labels in vertically related markets (Fulton and Giannakas (2004); Lapan and Moschini (2007); Bonroy and Lemarié (2012)). In a similar setup, Bonroy and Lemarié (2012) show that the introduction of a label in a vertically related market increases the high-quality quantity in the market. Retailer's heterogeneity compared to consumer's determines who bears the burden of the label. We depart from their paper considering retailers with identical distribution costs, as a result the high-quality producer always bears the cost of the label.

We first characterise the equilibrium outcome under the *laissez faire* approach. We find that depending on the cost difference between qualities we observe either pairwise vertical integration (when the cost difference is small) or single vertical integration with exclusive dealing (when the cost difference is large). We show that the merger between the incumbent and the independent station is profitable earlier than when it becomes socially desirable. We next consider a label policy and we show that producers and stations prefer to specialise which is always detrimental to society. As a consequence society will be better off without government intervention.

The remainder of this paper is organised as follows. Section 2 describes the hydrogen market value chain. Section 3 presents the equilibrium outcome when quality information is not passed to consumers. Section 4 presents the equilibrium outcome when producers use vertical restraints and when a label is introduced. Section 5 concludes.

2. Theoretical Framework

In this section, we describe the organisation of the road transport sector value chain based on FCEV.

2.1. Supply-side

We consider a vertically related market with hydrogen producers upstream and hydrogen fuel stations downstream. It is possible to produce hydrogen using several technologies that differ in terms of costs and negative externalities (carbon emissions). We consider two types of hydrogen $j = f, g$. A low quality one f with positive CO2 emissions, and a high quality one g with zero-emissions.

Producers sell hydrogen to fuel stations at a wholesale linear price w. Fuel stations distribute hydrogen to FCEV owners at retail price p.

Upstream market (Hydrogen Producers). We consider that there is an incumbent (i) monopoly producer offering a low environmental quality f produced at marginal cost c_f. The incumbent can upgrade its technology to a high environmental quality g at fixed investment fee $E_\gamma > 0$, increasing its unit cost to $\gamma + c_f > c_f$, where $\gamma \in [0; 1]$; the unit cost of capturing carbon emissions.

There is a potential entrant (e) with a high environmental quality g. The latter must incur a fixed investment fee E_g to enter the market and produces hydrogen at a cost c_g.

The incumbent has an absolute cost advantage with its low quality hydrogen ($c_g > c_f$).

Downstream market (Fuel Stations). For matters of simplicity, we consider that there are only two fuel stations 1 and 2 distributing hydrogen to consumers at a unit cost $d + w$. With d the distribution cost, and w the hydrogen wholesale price. We assume that distribution costs do not differ between the incumbent and new firms. This might be the case with an hydrogen pipeline network operated by a third party that does not differentiate by production technologies nor market structure. In Bonroy and Lemarié (2012) retailer's heterogeneity compared to consumer's determines who bears the burden of the label.
We assume that stations perfectly observe quality, but this information can not be conveyed to consumers.

2.2. Demand-side

The demand side of the market consists of a continuum of consumers with hydrogen valuation v, large enough to have a covered market. This is coherent with our framework since consumers here are FCEV owners, such that there is no outside option. We also assume that consumers have a willingness to pay for high environmental quality (θ), where the taste parameter for high environmental quality θ is uniformly distributed on the unit interval. Consumers may have limited information about quality at the level of fuel stations. We assume that they perfectly anticipate the market share $\alpha \in [0; 1]$ of high-quality producers and thus expect an average quality weighted by the market share of each quality. For instance, according to the International Renewable Energy Agency (2018) about 95% of today's hydrogen production relies on fossil fuel based technologies. The utility of a non informed θ-type consumer buying hydrogen at price p is then:

$$U = v + \theta\alpha - p$$

Otherwise, when consumers can perfectly observe the product quality at the level of fuel stations, then, denoting respectively p_f and p_g the price of the low and high quality, the indirect utility of a θ-type consumer is:

$$\text{U} = \begin{cases} v + \theta - p_g & \text{if} \quad \text{j=g} \\ v - p_f & \text{if} \quad \text{j=f} \end{cases}$$

2.3. Timing

Firms interactions are non-cooperative and take place in two stages. The timing of the game is as follows. In stage 1, producers make investment/entry decisions and compete in prices to sell to fuel stations. In stage 2, fuel stations compete in prices to supply consumers.

Hydrogen has many applications across sectors (e.g. transports, energy, industrial...) such that producers always have an outside option. We consider that producers only enter the transport market when they make positive profits. An hydrogen pipeline network allows fuel stations to have a constant flow of hydrogen, then, we consider a short-run price competition game. Our equilibrium concept is sub-game perfect equilibrium.

3. No information about quality

This section characterises our benchmark case where no information about hydrogen quality is provided to consumers at the level of fuel stations. Then, if both firms operate, only hydrogen of expected average quality $v + \theta\alpha$ is available in the market. Demand for the product with average quality α writes:

$$D_\alpha(p) = 1 + \theta\alpha - p$$

In stage 2, fuel stations compete à la Bertrand and buy from the lowest price producer at retail price w_α. At the equilibrium, the stations' retail price equals marginal cost:

$$p_\alpha = p_1 = p_2 = d + w_\alpha$$

each fuel station serves half of the market and makes null profits.

In stage 1, the incumbent might or not face an entry threat. We have four different sub-games, where the incumbent decides whether to invest or not, while facing or not an entry threat.

3.1. No entry threat

When the incumbent does not face an entry threat, it might upgrade its technology at an investment fee $E_\gamma > 0$ unknown to consumers. Its product quality improves and increases consumers demand from D_0 to D_1, but it results on larger production costs $c_f + \gamma > c_f$. The incumbent invests if and only if:

$$D_1(w_i^1)(w_i^1 - c_f - \gamma) - E_\gamma \geq D_0(w_i^0)(w_i^0 - c_f)$$

where $w_i^k = \text{argmax} \quad D_k(w_i)(w_i - c_f - \gamma \mathbb{1}_1) - E_\gamma \mathbb{1}_1$ and $k \in [0, 1]$

Lemma 1. *When there is not an entry threat, the incumbent invests in high-quality technology if and only if $E_\gamma \leq \hat{E}_\gamma$.*

Proof. See Appendix A.1. □

The threshold value $\hat{E}_\gamma$ is defined in Appendix A.1. Incentives to invest decrease with the cost of capturing CO_2 emissions $\left(\frac{\partial \hat{E}_\gamma}{\partial \gamma} = -\frac{1+\theta-\gamma-c_g-d}{2} < 0\right)$.

3.2. Entry threat

When the incumbent faces an entry threat, it might or not upgrade its technology. First, we study the equilibrium outcome when the incumbent does not invest, in such case, both qualities might co-exist in the market $0 \leq \alpha \leq 1$. Second, we determine the conditions under which the incumbent invests such that $\alpha = 1$.

Lemma 2. *When there is an entry threat, there exist a unique equilibrium where entry is always deterred.*

- *When $E_\gamma \geq E_g$ the incumbent does not upgrade quality.*
- *When $E_\gamma \leq E_g$ the incumbent upgrades quality if $E_\gamma \leq \bar{E}_\gamma < E_g$.*

Proof. See Appendix A.2. □

When two producers compete with asymmetric fixed costs and there is only one product variety, only the cost-efficient firm serves the market. These results are in line with the literature on price competition with asymmetric costs (Chaudhuri (1996); Marquez (1997); Chowdhury (2002); Sheldon and Roe (2007); Coloma and Saporiti (2009)). In our model, only the incumbent can introduce high-quality hydrogen in the market. The information problem limits the transition to a low-carbon road transport sector since the incumbent only invests in high quality when it is profitable. This is the case for low-values of the fixed investment cost: when $E_\gamma(< \bar{E}_\gamma)$ the incumbent will invest in high-quality when it faces an entry threat. Otherwise when alone in the market, it is more likely to invest in high-quality technology *i.e.* for larger values of $E_\gamma(< \hat{E}_\gamma)$. It follows that here $\bar{E}_\gamma < \hat{E}_\gamma$.

4. Solutions to the information problem

We have an information problem at the level of fuel stations that limits the deployment of high-quality hydrogen in the market. This section proposes two solutions to this information problem. First, we study what may happen under a *laissez faire* approach. Second, we consider government intervention in the form of a label at the level of fuel stations.

4.1. No government intervention: Vertical restraints

Without government intervention, the entrant may consider entering directly the downstream market. We consider that there is a vertical merger between the entrant and fuel station 1. We also assume that when part of a vertical structure, stations deliver only one quality (single-fuel stations). An independent station may or may not buy from a vertical structure.

The entrant is a high-quality producer, then, consumers are aware that its station sells high-quality hydrogen, whereas the hydrogen quality is uncertain when buying from the independent station. Producers' market shares are anticipated but consumers do not observe how the former interact with the independent station. This context creates two different qualities on the market: a high quality from the entrant's fuel station, and a lower "uncertain" quality from the independent station. If we denote p_1 (resp. p_2) the price at the entrant's (independent) station, the demand for each station is:

$$D^1_\alpha(p_1, p_2) = \frac{1-\alpha-p_1+p_2}{1-\alpha} \quad \text{and} \quad D^2_\alpha(p_1, p_2) = \frac{p_1-p_2}{1-\alpha}$$

We first consider the case of single vertical integration between the entrant and fuel station 1 and analyse the integrated structure's incentives to supply the independent fuel station. Then, we study the incumbent's incentives to merge with the independent station, such that we only have integrated stations in the market. Finally, we compare these different regimes in terms of private incentives and welfare implications.

4.1.1. Single Vertical Integration with Exclusive Dealing (ED)

First, we consider the case in which the entrant sells exclusively through its own station. The independent station can only buy from the incumbent ($0 < \alpha < 1$) but this is not observed by consumers. In stage 2, the independent station competes with the entrant's. The latter chooses a retail price p_1, while facing unit cost $d + c_g$, and an investment fee E_g. The independent station chooses a retail price p_2, and has unit cost $d + w_i$, where w_i is the incumbent's wholesale price. The stations' programs are:

$$\max_{p_1} \quad \pi_1(p_1, p_2) = D^1_\alpha(p_1, p_2)(p_1 - c_g - d) - E_g$$
$$\max_{p_2} \quad \pi_2(p_1, p_2) = D^2_\alpha(p_1, p_2)(p_2 - w_i - d)$$

which gives the following retail prices:

$$p_1(w_i) = \frac{2(1 - \alpha + c_g) + 3d + w_i}{3}$$
$$p_2(w_i) = \frac{1 - \alpha + c_g + 3d + 2w_i}{3}$$

Retail prices are increasing in the incumbent's wholesale price. In terms of quantities, the high-quality is increasing in the wholesale price $\frac{\partial D^1_\alpha(p_1(w_i), p_2(w_i))}{\partial w_i} = \frac{1}{3} > 0$, while the low-quality is decreasing $\frac{\partial D^2_\alpha(p_1(w_i), p_2(w_i))}{\partial w_i} = -\frac{1}{3} < 0$. In stage 1, the incumbent chooses its wholesale price w_i:

$$w_i = \text{argmax} \quad \pi_i(w_i) = D^2_\alpha(p_1(w_i), p_2(w_i))(w_i - c_f)$$

which gives the equilibrium wholesale price:

$$w_i^* = \frac{1 - \alpha + c_g + c_f}{2}$$

We plug w_i^* into the equilibrium retail prices, and determine the equilibrium demanded quantities of the entrant's and incumbent's respective qualities:

$$D_e(p_1^*, p_2^*) = \frac{5(1 - \alpha) + c_f - c_g}{6(1 - \alpha)}$$
$$D_i(p_1^*, p_2^*) = \frac{1 - \alpha + c_g - c_f}{6(1 - \alpha)}$$

Finally, we determine the equilibrium market share of the high-quality producer:

$$\alpha^* = \frac{11 - \sqrt{1 + 24(c_g - c_f)}}{12}$$

The market share of the high-quality producer is decreasing on the cost difference between qualities, *i.e.* when the cost difference between high and low-quality hydrogen decreases, we have more high-quality in the market.

4.1.2. Single Vertical Integration with Non-Exclusive Dealing (NED)

Second, we consider that the entrant does not distribute exclusively through its own retailer. In stage 1, producers compete to serve the independent station.

Lemma 3. *There exists a unique Nash Equilibrium where the incumbent serves the independent station with* w_i^*.

Proof. See Appendix A.3. □

The entrant is never able to offer a wholesale price that guarantees positive profits to the independent station. At the equilibrium, the incumbent serves the independent station at its profit maximising wholesale price (w_i^*) regardless of the entrant's strategy. Consumers buying from the independent station get a lower quality than anticipated.

This is in line with Nocke and Rey (2018), which states that when there is a vertical merger between a producer and a retailer, an equilibrium where the vertically integrated firm "forecloses" the downstream rival exists. In our model, this equilibrium arises because of informational reasons.

4.1.3. Pairwise Vertical Integration (PVI)

Nocke and Rey (2018) show that when facing an integrated structure, an independent producer and a retailer can increase their joint profits by merging. We study whether this result holds when there is an information problem at the level of fuel stations. We consider that the incumbent merges with station 2, such that we have two competing vertically integrated supply chains. Consumers perfectly observe quality at the level of fuel stations, the entrant's and incumbent's station demands writes:

$$D^1(p_1, p_2) = 1 - p_1 + p_2 \quad \text{and} \quad D^2(p_1, p_2) = p_1 - p_2$$

The entrant's and incumbent's stations programs are:

$$\max_{p_1} \quad \pi_1 = D^1(p_1, p_2)(p_1 - c_g - d) - E_g$$

$$\max_{p_2} \quad \pi_2 = D^2(p_1, p_2)(p_2 - c_f - d)$$

which gives the following equilibrium retail prices:

$$p_1^* = \frac{2 + c_f + 2c_g + 3d}{3}$$

$$p_2^* = \frac{1 + 2c_f + c_g + 3d}{3}$$

In a vertically related market with differentiated products, at the equilibrium, whether the incumbent and the independent station have an incentive to merge depends on the cost difference between qualities.

Proposition 1. *The equilibrium outcome depends on the cost difference between qualities $\hat{c} = c_g - c_f$:*

- *If $\hat{c} \geq c^p$ the incumbent and independent station do not merge.*
- *If $\hat{c} < c^p$ the incumbent and independent station merge.*

Proof. See Appendix A.4. □

When the cost difference between qualities is large the incumbent prefers not to merge with the independent station and exploit the informational problem. There is a trade-off between the intensity of competition (driven by the perceived qualities) and cost-efficiency. When the cost difference between qualities is large, the incumbent prefers to exploit the double marginalisation. Otherwise, it prefers to differentiate from entrant's quality to reduce the intensity of competition.

Proposition 2. *Private incentives and society are aligned if the cost difference between qualities is either $\hat{c} \leq c^w$ or $\hat{c} \geq c^p$.*

Proof. See Appendix A.5. □

When $c^w < \hat{c} < c^p$ a merger between the incumbent and the independent station increases their joint profits but is detrimental to society.

4.2. Label

The European Commission (2020) is working on a certification scheme for low-carbon hydrogen based on green energy GoO. This is relevant in the case of the transport sector since it would help avoid duplication of infrastructure (a pipeline) while making possible quality differentiation. We have seen that without government intervention when the entrant decides to enter directly the downstream market, the equilibrium outcome is not always socially desirable.

We study the equilibrium outcome when a label [2] for high-quality hydrogen is introduced at the level of fuel stations.

We have shown that when consumers have no information about quality there is one equilibrium where entry is always deterred. Only for low values of the fixed investment fee on technology (E_γ) the incumbent upgrades its technology. A label policy might allow both low and high-quality hydrogen to co-exist in the upstream market.

$$D^e(p_e, p_i) = 1 - p_e + p_i \quad \text{and} \quad D^i(p_e, p_i) = p_e - p_i$$

We consider two types of stations, non-specialised and specialised, and compare their performance in terms of private incentives and social welfare.

4.2.1. Non specialised stations (NS)

Non-specialised stations simultaneously support both hydrogen qualities. This configuration has interlocking relationships (Rey and Vergé (2008)): the upstream competing firms deal with the same downstream competing retailers. The high-quality unit cost increases to $d + w_e + l$, where l is the unit certification cost. Costs for the low-quality remain unchanged. In stage 2, fuel stations compete à la Bertrand within each quality market. At the equilibrium, low and high-quality prices equal their respective marginal costs:

$$p_e(w_e) = p_1^e = p_2^e = w_e + d + l$$

$$p_i(w_i) = p_1^i = p_2^i = w_i + d$$

Stations serve half of each quality market, and make null profits. In stage 1, producers compete in prices:

$$w_i = \text{argmax} \quad \pi_i = D^i(p_i(w_i), p_e(w_e))(w_i - c_f)$$
$$w_e = \text{argmax} \quad \pi_e = D^e(p_i(w_i), p_e(w_e))(w_e - c_g) - E_g$$

which gives the following equilibrium wholesale prices:

$$w_i^* = \frac{1 + c_g + l + 2c_f}{3}$$

[2] A label is a policy instrument imposed by the government or a third-party regulating the presentation of a product's specific information to consumers Bonroy and Constantatos (2014)

$$w_e^* = \frac{2(1+c_g) - l + c_f}{3}$$

Proposition 3. *With non specialised stations we retrieve the same profits as with pairwise vertical integration if the certification cost is set to 0. As the certification cost increases, the entrant's profits and social welfare decrease.*

Proof. See Appendix A.6. □

4.2.2. Specialised Stations (S)

Specialised stations only support one quality, *i.e.*, only buy from one producer, we consider station 1 only buys from the entrant and station 2 from the incumbent. Consumers choose which station to visit based on their preferences for high-quality hydrogen. In stage 2, stations compete in prices with differentiated products. The programs of the specialised stations are:

$$p_1 = \text{argmax} \quad \pi_1(p_1, p_2) = D^e(p_1, p_2)(p_1 - w_e - d)$$

$$p_2 = \text{argmax} \quad \pi_2(p_1, p_2) = D^i(p_1, p_2)(p_2 - w_i - d)$$

which gives the following retail prices:

$$p_1^* = \frac{2 + w_i + 2w_e + 3d + 2l}{3}$$

$$p_2^* = \frac{1 + 2w_i + w_e + 3d + l}{3}$$

In stage 1, producers choose the wholesale price for their respective qualities:

$$w_e = \text{argmax} \quad \pi_e(p_1^*, p_2^*) = D^e(p_1^*, p_2^*)(w_e - c_g) - E_g$$

$$w_i = \text{argmax} \quad \pi_i(p_1^*, p_2^*) = D^i(p_1^*, p_2^*)(w_i - c_f)$$

which yields the following equilibrium wholesale prices:

$$w_e^* = \frac{5 + c_f + 2c_g - l}{3}$$

$$w_i^* = \frac{4 + 2c_f + c_g + l}{3}$$

The following lemma describes the difference between having non-specialised or specialised stations:

Lemma 4. *When stations do not specialise, the label puts an economic burden on the entrant. Otherwise, if they specialise both the entrant and its specialised station share the economic burden of the label.*

Proof. See Appendix A.7. □

In terms of welfare, society is always better off with non-specialised stations, but producers and stations prefer specialised ones.

Moreover, producers retrieve the same joint profits with non-specialised stations as with two vertically integrated chains. Then, a vertical merger is never profitable for producers when the government introduces a label. Social welfare decreases with the certification cost regardless of the type of station.

Proposition 4. *Private incentives are never aligned with society, producers and stations prefer to specialise which is detrimental to social welfare.*

Proof. See Appendix A.8. □

If the government wants to introduce a label at the level of fuel stations, then, it might want to label only non specialised stations. In the next section, we compare how the *laissez faire* equilibrium performs in terms of welfare versus the label.

4.3. Should we use a label for high-quality hydrogen?

As shown in the previous section, government intervention in the form of a label reveals information about quality but at the equilibrium private incentives are never aligned with society. Indeed, producers and stations specialise but society will be betteroff if they did not. In the *laissez faire* scenario, vertical integration acts as an information mechanism such that both hydrogen qualities co-exist in the downstream market. In particular, under pairwise vertical integration consumers have perfect information about quality.

Proposition 5. *Social welfare is always higher with the laissez faire approach.*

Proof. See Appendix A.9. □

Proposition 2 shows that a socially desirable outcome is achieved when $\hat{c} \geq c^p$ or $\hat{c} \leq c^w$. When $c^w < \hat{c} < c^p$ the first best is not achieve at the equilibrium but the *laissez faire* approach leads to a higher social welfare than a label.

5. Conclusion

This paper studies the conditions that favour the decarbonisation of an hydrogen-based road transport sector. The results can be also extended to other low-carbon technologies such as electricity or bio-fuels. Building on the certification scheme *Certifhy* proposed by HyLaw (2019) we studied why industrial players might propose a labelling initiative, and whether without government intervention firms could achieve on their own an outcome that maximises social welfare.

We have seen that the lack of a proper definition of low-carbon hydrogen results in a quite strong information problem: new low-carbon hydrogen producers are excluded from the market.

A label like Certifhy's allows high-quality producers to enter the market. Nevertheless, society will be better off without government intervention.

Currently, low-carbon hydrogen is not cost-competitive but in the future, we expect it to decrease, such that the cost difference between qualities becomes small. During such transition without government intervention, we would experience a mismatch between private incentives and society. Instruments such as a high carbon price or subsidies to environmentally friendly technologies could help low-carbon hydrogen to become cost-competitive.

Appendix A. Proofs

Appendix A.1. Proof of Lemma 1

The analysis of the equilibrium builds on Chowdhury (2002). There is one producer with an absolute cost advantage: marginal and fixed cost advantage. Costs functions have increasing returns to scale. Let $W = \{w_0, ..., w_n\}$, with $n \in N$, denote the set of permissible wholesale prices with $w_0 = 0$ and $w_n = 1 - d$. Let $\pi_j(w) = (1 - w - d)(w - c_j)$ be the variable profit of a firm of quality j, with $c_j > c_-j$. Let's assume that firm j has undercut its rival with wholesale price w. Let $\bar{w}(E_j)$ be the minimum wholesale price such that $\pi_j(w) = E_j$, and $w_j(\epsilon) \in W$ the minimum wholesale price such that

$\pi_j(w) - E_j \geq 0$, with ϵ very small.

There are two Nash Equilibrium with grid price variation (Chaudhuri (1996); Chowdhury (2002)). In the first one, firm $-j$ charges $w_j(\epsilon) - \epsilon$ and firm j charges $w_j(\epsilon)$; and in the second one firm $-j$ charges $w_j(\epsilon)$ while firm j charges $w_j(\epsilon) + \epsilon$. As ϵ tends to zero there is only one Nash equilibrium: the limit-pricing outcome $\bar{w}_j(E_j)$. Thus, there is only one Nash equilibrium where the firm with the cost advantage $(-j)$ deters entry by setting its wholesale price equal to the other firm's limit price $w_{-j} = \bar{w}_j(E_j)$. □

Before investing the incumbent always has an absolute cost advantage $c_g > c_f$ (and $E_f = 0$), then, entry is deterred with:

$$w_i^0 = \bar{w}_e(E_g)^0 = \frac{1 - d + c_g - \sqrt{(1 - d - c_g)^2 - 4E_g}}{2}$$

□

Appendix A.2. Proof of Lemma 2

After investment, the incumbent needs to cover an investment fee $E_\gamma > 0$, thus loosing its absolute cost advantage when $E_\gamma \geq E_g$. In such case, a strictly dominant strategy for the incumbent is not to upgrade its technology. Otherwise, if it keeps an absolute cost advantage after investment *i.e.* $E_g > E_\gamma$, entry can be deterred using limit-pricing:

$$w_i^1 = \bar{w}_e(E_g)^1 = \frac{1 + \theta - d + c_g - \sqrt{(1 + \theta - d + c_g)^2 - 4(E_g + c_g(1 + \theta - d))}}{2}$$

and the incumbent invests if and only if:

$$D_1(\bar{w}_e(E_g)^1)(\bar{w}_e(E_g)^1 - c_f - \gamma) - E_\gamma \geq D_0(\bar{w}_e(E_g)^0)(\bar{w}_e(E_g)^0 - c_f)$$

We have:

$$\frac{1}{4}((1 + \theta - c_g - d + \sqrt{(1 + \theta - d + c_g)^2 - 4(E_g + c_g(1 + \theta - d))})$$

$$(1 + \theta + c_g - d - 2(c_f + \gamma) - \sqrt{(1 + \theta - d + c_g)^2 - 4(E_g + c_g(1 + \theta - d))})$$

$$-(1-c_g-d+\sqrt{(1-d-c_g)^2-4E_g})(1+c_g-d-2c_f-\sqrt{(1-d-c_g)^2-4E_g})) = \hat{E}_\gamma$$

When $E_g > E_\gamma$, if $\hat{E}_\gamma \geq E_\gamma$ the incumbent invests in high-quality technology ($\alpha = 1$). Otherwise if $\hat{E}_\gamma < E_\gamma$, it remains a low-quality one ($\alpha = 0$). □

Appendix A.3. Proof of Lemma 3

We study equilibrium candidates for the low-quality wholesale price when the entrant does not deal exclusively.

First, we assume that the two stations buy from the entrant such that $\alpha = 1$. There is only high-quality hydrogen in the market and demand writes:

$$D_1(p) = 1 + \theta - p$$

In stage 2, the entrant's and the independent station compete to serve consumers. Station 1 (resp. 2) has marginal cost $c_g + d$ ($w_e + d$), since we have price competition there are three possibilities:

1. If $w_e < c_g$, then, station 2 serves all market with $p = c_g + d - \epsilon$, and makes $\pi_2 > 0$. However, this implies that the entrant makes negative profits since $w_e - c_g < 0$.
2. If $w_e = c_g$, then, each station serves half the market with $p = c_g + d$, and makes $\pi_1 = \pi_2 = 0$. However, this implies that the entrant makes negative profits since $\pi_e = \frac{D_1(p)}{2}(c_g - c_g) + \frac{D_1(p)}{2}(c_g + d - c_g - d) - E_g < 0$.
3. If $w_e > c_g$, then, station 1 serves all market with $p = w_e + d - \epsilon$, and makes $\pi_1 > 0$. In such case the entrant makes positive profits since $\pi_e = (w_e - c_g - d)D_1(p) - E_g \geq 0$.

If the entrant is the only upstream producer, then, station 2 never makes positive profits. Indeed, the only strategy that guarantees the entrant a non-negative profit is $w_e > c_g$ implying that station 1 serves all market.

Second, we consider the strategy of the incumbent. If it wants to sell to the independent station, it must guarantee the latter a profit such that:

$$\pi_2(w_i) \geq \pi_2(w_e)$$

If the incumbent serves the independent station, then, we have both qualities in the market $\alpha \in]0;1[$ the demand addressed to the independent station writes:

$$D^2_\alpha(p_1,p_2) = \frac{p_1 - p_2}{1-\alpha}$$

If the incumbent serves the independent station, stations programs are:

$$\max_{p_1} \quad \pi_1(p_1,p_2) = D^1_\alpha(p_1,p_2)(p_1 - c_g - d) - E_g$$
$$\max_{p_2} \quad \pi_2(p_1,p_2) = D^2_\alpha(p_1,p_2)(p_2 - w_i - d)$$

which gives the following retail prices:

$$p_1(w_i) = \frac{2(1-\alpha+c_g)+3d+w_i}{3}$$
$$p_2(w_i) = \frac{1-\alpha+c_g+3d+2w_i}{3}$$

The independent station profit is thus:

$$\pi_2(w_i) = \frac{(1-\alpha+c_g-w_i)^2}{9(1-\alpha)}$$

As mentioned above the entrant sets it wholesale price equal to $w_e > c_g$, which implies non positive profits for the independent station. If it is the incumbent who serves the independent station, a wholesale price $w_i \in]1-\alpha+c_g; c_f[$ guarantees positive profits $\pi_i = (w_i - c_f)(\frac{1-\alpha+c_g-w_i}{1-\alpha}) \geq 0$.

If $\pi_2(w_i) \geq 0$ the independent station will buy from the incumbent, this is the case for any $1-\alpha+c_g \geq w_i$.

Let's now study the incumbent's equilibrium strategy, the wholesale price that maximises its profits is such that:

$$w_i = \text{argmax} \quad \pi_i(w_i) = (w_i - c_f)(\frac{1-\alpha+c_g-w_i}{1-\alpha})$$
$$\iff \quad w_i^* = \frac{1-\alpha+c_g+c_f}{2}$$

Given that $\alpha \in]1;0[$ and $c_g > c_f$, it follows that $1-\alpha+c_g > w_i^*$. Then, at the equilibrium the incumbent serves the independent station at w_i^*. $\square$

Appendix A.4. Proof of Proposition 1

We determine the strategy played by producers at the equilibrium. In Appendix A.3 we have shown that regardless of the entrant's strategy, *i.e.* whether it deals exclusively or not, the incumbent always serves the independent station with its profit-maximising wholesale fee from when the entrant deals exclusively w_i^*.

Then, to determine the equilibrium strategy when there is a vertical merger between the entrant and station 1, we study whether a vertical merger between the incumbent and the independent station 2 is a strictly dominant strategy. We have:

$$\pi_i^{PVI} - (\pi_i^{ED} + \pi_2^{ED}) = \frac{(1 + c_g - c_f)^2}{9} - \frac{(1 - \alpha + c_g - c_f)^2}{9(1 - \alpha)}$$

$$= \frac{11 + 12(c_g - c_f)^2 - \sqrt{1 + 24(c_g - c_f)} + 6(c_g - c_f)(1 - \sqrt{1 + 24(c_g - c_f)})}{108}$$

Merging with the independent station is a strictly dominant for the incumbent if and only if $\pi_i^{PVI} - (\pi_i^{ED} + \pi_2^{ED}) > 0$. If $\hat{c} = c_g - c_f \leq 0.65 = c^p$ a vertical merger increases joint profits. Otherwise, if $\hat{c} > c^p$ the merger does not guarantee larger profits. □

Appendix A.5. Proof of Proposition 2

We now determine the outcome that provides the largest social welfare which writes:

$$SW = v + \int_{1-D^1(p_1^*, p_2^*)}^{1} \theta d\theta - D^1(p_1^*, p_2^*)(c_g + d) - D^2(p_1^*, p_2^*)(c_f + d) - E_g$$

We compare the social welfare when the incumbent and the independent station merge versus when they do not:

$$SW^{ED} - SW^{PVI} = \frac{1}{144}[7 - 40(c_g - c_f)^2$$

$$-\sqrt{1 + 24(c_g - c_f)} + 4(c_g - c_f)(3\sqrt{1 + 24(c_g - c_f)} - 8)]$$

Whether a merger between the incumbent and the independent station is desirable for society depends on the cost differences between qualities. If

$\hat{c} \geq \frac{1}{50}[14+\sqrt{46}] = c^w$ a vertical merger is not desirable for society since $SW^{ED} \geq SW^{PVI}$. Otherwise, if $\hat{c} \leq c^w$ a vertical merger is welfare enhancing.

When $\hat{c} \in]c^w; c^p[$ at the equilibrium the incumbent and independent station merge which is detrimental to society; whereas when either $\hat{c} \leq c^w$ or $c^p \geq \hat{c}$ the equilibrium outcome is socially desirable. □

Appendix A.6. Proof of Proposition 3

First, recall that when we have two vertically integrated chains competing in the downstream market producers profits are:

$$\pi_i^{PVI} = \frac{(1+c_g-c_f)^2}{9} \quad \text{and} \quad \pi_e^{PVI} = \frac{(2+c_f-c_g)^2}{9} - E_g$$

and social welfare is $SW^{PVI} = \frac{18(v-d)+5(c_g-c_f)^2+2(4-7c_g-2c_f)}{18} - E_g$. When a costly label is introduced at the level of non-specialised stations, producers profits are:

$$\pi_i^{NS} = \frac{(1+c_g-c_f+l)^2}{9} \quad \text{and} \quad \pi_e^{NS} = \frac{(2+c_f-c_g-l)}{9} - E_g$$

Stations make null profits $\pi_1 = \pi_2 = 0$. Social welfare writes:

$$SW^{NS} = v + \int_{1-D^e(p_e^*,p_i^*)}^{1} \theta d\theta - D^e(p_e^*,p_i^*)(c_g+d+l) - D^i(p_e^*,p_i^*)(c_f+d) - E_g$$

$$= \frac{18(v-d)+5(c_g-c_f)^2+2(4-7c_g-2c_f)-2l[c_g-c_f+4l(1+l)]}{18} - E_g$$

If we set *l=0* we have $\pi_i^{NS} = \pi_i^{PVI}$, $\pi_e^{NS} = \pi_e^{PVI}$ and $SW^{NS} = SW^{PVI}$. □

Appendix A.7. Proof of Lemma 4

The effect of a costly label on producers profits when stations do not specialise is:

$$\frac{\partial \pi_i^{NS}}{\partial l} = \frac{2}{9}(1+c_g-c_f+l) > 0 \quad \text{and} \quad \frac{\partial \pi_e^{NS}}{\partial l} = -\frac{2}{9}(2+c_f-c_g-l), < 0$$

The effect on social welfare is:

$$\frac{\partial SW^{NS}}{\partial l} = -\frac{\partial D^i(p_e^*, p_i^*)}{\partial l}[1 + D^i(p_e^*, p_i^*)] - l\frac{\partial D^e(p_e^*, p_i^*)}{\partial l} - D^e(p_e^*, p_i^*)$$

$$\frac{\partial SW^{NS}}{\partial l} = -\frac{1}{9}(7 - 5(c_g - c_f + l)) < 0$$

A costly label puts a burden on the high-quality producer, and reduces social welfare.

When stations specialise, producers profits are:

$$\pi_i^S = \frac{(4 + c_g - c_f + l)^2}{27} \quad \text{and} \quad \pi_e^S = \frac{(5 + c_f - c_g - l)^2}{27} - E_g$$

stations profits writes:

$$\pi_2^S = \frac{(4 + c_g - c_f + l)^2}{81} \quad \text{and} \quad \pi_1^S = \frac{(5 + c_f - c_g - l)^2}{81}$$

The effect of a costly label on producers and stations profits, when stations specialise in one quality is:

$$\frac{\partial \pi_i^S}{\partial l} = \frac{2}{27}(4 - c_f + c_g + l) > 0$$

$$\frac{\partial \pi_e^S}{\partial l} = -\frac{2}{27}(5 + c_f - c_g - l) < 0$$

$$\frac{\partial \pi_1^S}{\partial l} = -\frac{2}{81}(5 + c_f - c_g - l) < 0$$

$$\frac{\partial \pi_e^S}{\partial l} = \frac{2}{81}(4 - c_f + c_g + l) > 0$$

The entrant's and its specialised station profits decrease with the label, whereas the incumbent's and its specialised station profits increase. Social Welfare when stations specialise writes:

$$SW^S = v + \int_{1-D^e(p_1^*, p_2^*)}^{1} \theta d\theta - D^e(p_1^*, p_2^*)(c_g + d + l) - D^i(p_1^*, p_2^*)(c_f + d) - E_g$$

$$= \frac{162(v-d)+17(c_g-c_f)^2+65-2(32c_f+49c_g)+l[17l-2(17(c_f+c_g)-49)]}{162} - E_g$$

The effect of the label on social welfare is:

$$\frac{\partial SW^S}{\partial l} = -\frac{\partial D^i(p_1^*, p_2^*)}{\partial l}[1+D^i(p_1^*, p_2^*)] - l\frac{\partial D^e(p_1^*, p_2^*)}{\partial l} - D^e(p_1^*, p_2^*)$$

$$\frac{\partial SW^S}{\partial l} = -\frac{1}{81}(49-17(c_g-c_f+l)) < 0$$

Thus, social welfare decreases with the label.□

Appendix A.8. Proof of Proposition 4

First, we determine the strategy played by producers when a label is introduced at the level of stations:

$$\Pi_e^S - \Pi_e^{NS} = \frac{1}{27}[13+2(c_g-c_f)(1-c_g+c_f-4l)+2l(1+l)] > 0$$

$$\Pi_i^S - \Pi_i^{NS} = \frac{1}{27}[13+2(c_g-c_f)(1-c_g+c_f-4l)+2l(1+l)] > 0$$

Regardless of the cost difference between qualities and the label cost producers always prefer specialised stations. Stations prefer also to specialise:

$$\Pi_1^S - \Pi_1^{NS} = \frac{(5+c_f-c_g-l)^2}{81} > 0$$

$$\Pi_2^S - \Pi_2^{NS} = \frac{(4+c_g-c_f+l)^2}{81} > 0$$

Second, we determine the socially desirable outcome:

$$SW^S - SW^{NS} = -\frac{7}{162}[1-2(c_g-c_f+l)]^2 < 0$$

Thus, society will be better off with non-specialise stations but this outcome is never played at the equilibrium. □

Appendix A.9. Proof of Proposition 5

We compare whether a label would be welfare enhancing when the cost difference between qualities is $c^w < \hat{c} < c^p$:

$$SW^{PVI} - SW^{S} = \frac{l}{162}[14 - 10(c_g - c_f) - 5l] > 0$$

Thus, society is always better-off without government intervention. What about if the government only allowed non-specialised stations to use the label:

$$SW^{PVI} - SW^{NS} = \frac{1}{162}[7 + (1 - 2(c_g - c_f))^2 + 2l(49 - 17(c_g - c_f)) - 17l^2] > 0$$

Thus, a label never performs better than vertical restraints in terms of social welfare. □

References

Bacchiega, E., O. Bonroy, and E. Petrakis (2018). Contract contingency in vertically related markets. *Journal of Economics & Management Strategy 27*(4), 772–791.

Bonroy, O. and C. Constantatos (2014). On the Economics of Labels: How Their Introduction Affects the Functioning of Markets and the Welfare of All Participants. *American Journal of Agricultural Economics 97*(1), 239–259.

Bonroy, O. and S. Lemarié (2012). Downstream labeling and upstream price competition. *European Economic Review 56*(3), 347–360.

Chaudhuri, P. R. (1996). The contestable outcome as a bertrand equilibrium. *Economics Letters 50*(2), 237 – 242.

Chowdhury, P. R. (2002). Limit-pricing as bertrand equilibrium. *Economic Theory 19*(4), 811–822.

Coloma, G. and A. Saporiti (2009). Bertrand's price competition in markets with fixed costs. RCER Working Papers 549, University of Rochester - Center for Economic Research (RCER).

European Commission (2020). A hydrogen strategy for a climate-neutral Europe.

Fulton, M. and K. Giannakas (2004). Inserting gm products into the food chain: The market and welfare effects of different labeling and regulatory regimes. *American Journal of Agricultural Economics 86*(1), 42–60.

HyLaw (2019). Deliverable 4.5 EU policy Paper.

International Energy Agency (2019). The Future of Hydrogen: Seizing today's opportunities.

International Renewable Energy Agency (2018). Hydrogen from renewable power technology outlook for the energy transition.

Lapan, H. and G. Moschini (2007). Grading, minimum quality standards, and the labeling of genetically modified products. *American Journal of Agricultural Economics 89*(3), 769–783.

Marquez, R. (1997). A note on bertrand competition with asymmetric fixed costs. *Economics Letters 57*(1), 87 – 96.

Nocke, V. and P. Rey (2018). Exclusive dealing and vertical integration in interlocking relationships. *Journal of Economic Theory 177*(C), 183–221.

Rey, P. and T. Vergé (2008). Economics of vertical restraints. In P. Buccirossi (Ed.), *Handbook of Antitrust Economics*, pp. 353–390. The MIT Press.

Sheldon, I. and B. Roe (2007). Credence good labeling: The efficiency and distributional implications of several policy approaches. *American Journal of Agricultural Economics 89*(4), 1020–1033.