Certification of low-carbon hydrogen in the transport market

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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 reaching such a goal requires reducing the transport sector emissions by 90%.

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Renewable energy and biofuels 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 to 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).

A new technology's successful uptake depends rather on the purchasing behaviour of early adopters[1], than the general population's (Rogers (1962)). In the literature (O'Garra et al. (2005), Haraldsson et al. (2006), Al-Amin et al. (2016)), there is a consensus about consumers perceiving FCEV as a less polluting alternative to internal combustion engine vehicles (ICEV). However, whether this perception impacts a consumer's behaviour, depends on their level of information, and on the vehicle characteristics, such as the price or other specific performances. So far, FCEV's commercialisation strategy has followed an unsuccessful mass market strategy. Hardman et al. (2013) point out that given the similarities[2] between Tesla vehicles and FCEV, switching to a high-end niche market strategy would be more appropriate. Indeed, for the general population, their concern about the environment does not necessarily drive FCEV purchases (Al-Amin et al. (2016)). This is related to their high price compared to other zero-emissions vehicles such as Battery Electric Vehicles (BEV). Instead, for early adopters, performance and technological or environmental motivations might be far more important than cost savings (Hardman et al. (2017)). In particular, among all zero-emission vehicles, FCEV have the closest driving range, and refuelling time to ICEV (Hardman et al. (2016)). This is an advantage for consumers with an important average daily vehicle miles (Hardman et al. (2017)).

The main barrier for FCEV uptake identified by the literature is the lack of hydrogen refuelling infrastructure (Haraldsson et al. (2006), Al-Amin et al. (2016), Hardman et al. (2016), Hardman et al. (2017)). This was not the case for ICEV, nor BEV. In the former's case a distribution network for petrol was already present (Geels (2005), Melaina (2007), Hardman et al. (2017)); and in the latter's consumers could rely on the existing electric grid (Hardman et al. (2013), Hardman and Steinberger-Wilckens (2014)). Today,

[1]Consumers with a high level of education, income and a positive attitude towards science and technology.

[2]Both Tesla and FCEV are disruptive innovations, with high costs and a low level of emissions.

in the European Union (EU) the number of hydrogen refuelling stations is quite limited. Furthermore, they are dispersed across large geographical regions. As a result, market concentration with oligopolistic competition could be an important issue in the early years of this market. Like in the early days of the gasoline market, hydrogen stations are located in niche markets for manufacturing and industry (" Hydrogen Valleys"[3]). The EU long term strategy aims to deploy a network of pipelines to connect these clusters among each other (DGEC (2017)). This could potentially increase the level of competition between these clusters.

Another barrier identified in the literature, relates to the hydrogen source. In particular, sophisticated consumers might only purchase FCEV if the latter rely on low-carbon hydrogen (Hardman et al. (2017)). 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 a 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 fact, according to the International Renewable Energy Agency (2018) about 95% of today's hydrogen production relies on fossil fuel-based technologies. In EU legislation, there is no distinction between these different production pathways: could this lack of definition 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)[4]. This type of

[3] A "Hydrogen Valley" is a geographical area with a hydrogen ecosystem whose objective is to secure demand, while benefiting from synergies between actors in the supply chain. In the transport sector, we can give two examples the HyPort meta-project (Occitanie) and the Zero-Emissions Valley (Auvergne Rhône-Alpes).

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

certification scheme is relevant in the hydrogen market, since transportation and distribution optimisation requires unbundling production and consumption. *Certifhy* differentiates between three types of hydrogen: Grey hydrogen produced using fossil-fuel-based technologies, Green and Blue hydrogen with 60% fewer emissions compared to Grey hydrogen, respectively, produced with renewable, and non-renewable energy. This paper aims to study whether this policy framework performs better than a *laissez faire* approach by which producers take actions to inform consumers, in terms of conveying information and social welfare. For simplicity, we consider only two types of hydrogen, low (grey) and high-quality (blue or green) hydrogen.

In the early days of the petrol market, a wide variety of delivery methods preceded conventional fuel stations (Melaina (2007)). The latter emerged in response to fluctuating prices and uncertain quality. Indeed, at the time, it was not an uncommon practice to use low-quality petroleum or dilute blends with cheaper kerosene (Melaina (2007)). Vertically integrated stations, i.e., company-owned stations embodied a sense of reliability; thus, buying from them allowed consumers to ensure access to a high quality fuel. This trend is is still present in developing countries such as Turkey, where illegal fuel trafficking is not an uncommon practice (OECD (2008)). Furthermore, to some extend, this image projected by company-owned stations today seems to prevail (Lewis (2008)). Although consumers' decision on where to buy has long been driven by prices (NACS (2020)), it seems that consumers preference for a certain store or chain highly influences their choice of station[5]. Although most of the empirical evidence is anecdotal, consumers do perceive certain station's brands to be superior. Moreover, brands are constantly being advertised in the media; if consumers perception was not affected by it, then this strategy would not be profitable for oil companies (Jaureguiberry (2010)). A stations' brand might signal higher quality, but the opposite effect is also possible. For instance, following the 2010 BP oil spill, BP-owned stations margins declined by 2.9 cents per gallon, and sales volume by 4.2% (Barrage et al. (2014)). Thus, to some degree, company-owned stations, compared to independent ones, do seem to provide some extra information about the

[5]The NACS (2020) survey finds that compared to 2015, consumers in 2020 are not as driven by price (58%) as they were five years ago (71%). In NACS (2020) study, almost two out of three consumers (62%) state a preference for a certain store or chain, while in 2002, only about 36% of consumers preferred one brand of gasoline (Blumberg, G. P. (2002)).

product's quality to consumers.

To answer the question of the deployment of decarbonised hydrogen, we developed a model of a hydrogen-based transport market, 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, which sell hydrogen to FCEV owners, are not able to communicate on the hydrogen origin, we show that the incumbent always deters entry. Furthermore, decarbonised hydrogen is never deployed on the market. We then explore alternative solutions to solve the information problem: a label and vertical restrictions.

This paper contributes to two strands of the economic literature. First, it contributes to the literature on 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. Second, the paper contributes to the literature on vertical mergers with differentiated products (Bacchiega et al. (2018); Nocke and Rey (2018)). In particular, we consider a merger between a fuel station and the 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. The Nocke and Rey (2018) result holds when the cost difference between qualities is small. Otherwise, the merger does not increase their joint profits.

We first characterise the equilibrium outcome with a label policy, and show that producers and stations prefer to specialise, which is detrimental to society. Then, we study the equilibrium under a *laissez faire* approach.

We find that depending on the cost difference between qualities, we either observe pairwise vertical integration (when the cost difference is small) or single vertical integration with exclusive dealing (when the cost difference is large). Furthermore, we show that the merger between the incumbent and the independent station is profitable earlier than it becomes socially desirable. As a consequence, society would 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 a label is introduced and when producers use vertical restraints. Section 5 concludes.

2. Theoretical Framework

In this section, we describe the organisation of the transport market 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 : 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 monopoly producer (i) 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 $\gamma \in [0; 1]$ is 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.

We assume that stations perfectly observe quality, but this information cannot 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. The environmental quality index of a product is denoted s_j, it follows that $s_g > s_f$. 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:

$$U = v + \theta(\alpha s_g + (1 - \alpha)s_f) - p$$

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:

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

To make the model tractable we assume that the true quality of low-carbon hydrogen is equal to $s_g = 1$, while the true quality of grey hydrogen is $s_f = 0$.

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. transportation, energy, industry, etc) 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. We have four different sub-games, where the incumbent decides whether to invest (or not), while facing (or not) an entry threat.

When the incumbent does not face an entry threat, it faces a demand $D(p) = 1 - p$, independent of hydrogen quality. As a result, the incumbent never invests in high-quality technology, since investing only increases costs.[6]

When the incumbent faces an entry threat, it might upgrade its technology (or not). First, we study the equilibrium outcome when the incumbent does not invest. In such a 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 1. *When there is an entry threat, there exists a unique equilibrium where entry is always deterred, and the incumbent never upgrades its quality.*

[6] With no entry threat, the issue of upgrading technology arises only when the market is not covered.

Proof. See Appendix A.1. □

In line with the literature (Chaudhuri (1996); Marquez (1997); Chowdhury (2002); Sheldon and Roe (2007); Coloma and Saporiti (2009)), we find that when the incumbent and the entrant compete in prices with asymmetric marginal and fixed costs, and there is only one product variety, only the cost-efficient firm serves the market. As a result, only the incumbent can introduce high-quality hydrogen into the market, but this strategy is never profitable. Thus, the information problem limits the transition to a low-carbon transport market.

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 consider government intervention in the form of a label at the level of fuel stations. Second, we study what may happen under a *laissez faire* approach.

4.1. 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 to help avoid duplication of infrastructure (a pipeline) while making quality differentiation possible.

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

We have shown that when consumers have no information about quality, there is one equilibrium where entry is always deterred, and the incumbent never upgrades its technology. A label policy might allow both low and high-quality hydrogen to co-exist in the upstream market.

Denoting p_g (resp. p_f) the retail price of high (low) hydrogen quality, demand for each quality is:

$$D^g(p_g, p_f) = 1 - p_g + p_j \quad \text{and} \quad D^f(p_g, p_f) = p_g - p_f$$

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

4.1.1. 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. In stage 2, fuel stations compete à la Bertrand within each quality market. The high-quality unit cost is $d + w_e + l$, with l the unit certification cost, and w_e the high quality entrant wholesale price. The low-quality unit cost is $d + w_i$, with w_i the low-quality incumbent wholesale price. At the equilibrium, the retail low and high-quality prices are equal to their respective marginal costs:

$$p_g(w_e) = p_1^g = p_2^g = w_e + d + l$$

$$p_f(w_i) = p_1^f = p_2^f = w_i + d$$

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

$$\max_{w_e} \quad \pi_e = D^g(p_g(w_e), p_f(w_i))(w_e - c_g) - E_g$$

$$\max_{w_i} \quad \pi_i = D^f(p_g(w_e), p_f(w_i))(w_i - c_f)$$

which gives the following equilibrium wholesale prices:

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

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

4.1.2. 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:

$$\max_{p_1} \quad \pi_1(p_1, p_2) = D^g(p_1, p_2)(p_1 - w_e - d - l)$$

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

which gives the following retail prices:

$$p_1(w_e,w_i) = \frac{2 + w_i + 2w_e + 3d + 2l}{3}$$

$$p_2(w_e,w_i) = \frac{1 + 2w_i + w_e + 3d + l}{3}$$

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

$$\max_{w_e} \quad \pi_e(p_1(w_e,w_i),p_2(w_e,w_i)) = D^g(p_1(w_e,w_i),p_2(w_e,w_i))(w_e - c_g) - E_g$$

$$\max_{w_i} \quad \pi_i(p_1(w_e,w_i),p_2(w_e,w_i)) = D^f(p_1(w_e,w_i),p_2(w_e,w_i))(w_i - c_f)$$

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 2. *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.2. □

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

Proposition 1. *Private incentives are never aligned with society, producers and stations prefer to specialise which is detrimental to social welfare.*

Proof. See Appendix A.3. □

If the government wants to introduce a label at the level of fuel stations, then, it might want to label only non-specialised stations. Social welfare decreases with the certification cost regardless of the type of station.

4.2. No government intervention: Vertical restraints

We have seen that with a label at the equilibrium producers and stations prefer to specialise which is detrimental to society. Without government intervention, the entrant may consider directly entering 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 interacts 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.

4.2.1. 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:

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

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:

$$D^1(p_1^*, p_2^*) = \frac{5(1-\alpha)+c_f-c_g}{6(1-\alpha)}$$
$$D^2(p_1^*, p_2^*) = \frac{1-\alpha+c_g-c_f}{6(1-\alpha)}$$

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.

4.2.2. 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.4. □

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), who show 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.

4.2.3. 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 2. *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.5. □

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 the entrant's quality to reduce the intensity of competition.

Proposition 3. *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.6. □

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.

Proposition 4. *With pairwise vertical integration we retrieve the same profits as with non specialised stations 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.7. □

Producers retrieve the same joint profits with two vertically integrated chains as with non-specialised stations. As producers and stations prefer to specialise, then, a vertical merger is never profitable for producers when the government introduces a label. 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 better-off 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.8. □

Proposition 3. 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 achieved 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 a hydrogen-based transport market. The results can be also extended to other low-carbon technologies, such as electricity or biofuels. 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 an outcome on their own that maximises social welfare.

We have seen that the lack of a proper definition of low-carbon hydrogen results in quite a 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 its cost 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 carbon tax 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 us assume that firm j has undercut its rival with wholesale price w. Let $\bar{w}(E_j)$ be the minimum wholesale price such that $\pi_j(\bar{w}(E_j)) = E_j$, and $w_j(\epsilon) \in W$ the minimum wholesale price such that $\pi_j(w_j(\epsilon)) - E_j \geq 0$, 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 $w_{-j} = \bar{w}_j(E_j)$. □

If the incumbent does not upgrades its quality, it always has an absolute cost advantage $c_g > c_f$ (and $E_f = 0$), then, entry is deterred with:

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

If the incumbent upgrades its quality, since demand remains unchanged, entry is also deterred with $\bar{w}_e(E_g)$. However, the incumbent now needs to cover an investment fee $E_\gamma > 0$; losing its absolute cost advantage. In such a case, a strictly dominant strategy for the incumbent is to never upgrade its technology. □

Appendix A.2. Proof of Lemma 2

When a costly label is introduced at the level of non-specialised stations, producers profits are:

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

Stations make zero profits $\pi_1 = \pi_2 = 0$. Social welfare is:

$$SW^{NS} = v + \int_{1-D^g(p_g^*,p_f^*)}^{1} \theta d\theta - D^g(p_g^*, p_f^*)(c_g + d + l) - D^f(p_g^*, p_f^*)(c_f + d) - E_g$$

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

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:

$$\frac{\partial SW^{NS}}{\partial l} = -\frac{\partial D^f(p_g^*, p_f^*)}{\partial l}[1 + D^f(p_g^*, p_f^*)] - l\frac{\partial D^g(p_g^*, p_f^*)}{\partial l} - D^g(p_g^*, p_f^*)$$

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

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

When stations specialise, producers profits are:

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

and stations profits are:

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

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

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

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

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

$$\frac{\partial \pi_2^S}{\partial l} = \frac{2}{81}(4 - c_f + c_g + l) > 0$$

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 is:

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

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

The effect of the label on social welfare is:

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

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

Thus, social welfare decreases with the label. □

Appendix A.3. Proof of Proposition 1

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-specialised stations but this outcome is never played at the equilibrium. □

Appendix A.4. Proof of Lemma 4

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 is:

$$D(p) = 1 - p$$

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 $\pi_e = \frac{D(p)}{2}(c_g - c_g) + \frac{D(p)}{2}(c_g + d - c_g - d) - E_g < 0$.
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 $\pi_e = (w_e - c_g - d)D(p) - E_g \geq 0$.

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 the 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 $0 < \alpha < 1$ the demand addressed to the independent station is:

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

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

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

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

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

Given that $0 < \alpha < 1$ 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^*. □

Appendix A.5. Proof of Proposition 2

We determine the strategy played by producers at the equilibrium. In Appendix A.5 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 strategy 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.6. Proof of Proposition 3

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 against the alternative:

$$SW^{ED} - SW^{PVI}$$

$$= \frac{1}{144}[7-40(c_g-c_f)^2-\sqrt{1+24(c_g-c_f)}+4(c_g-c_f)(3\sqrt{1+24(c_g-c_f)}-8)]$$

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

Appendix A.7. Proof of Proposition 4

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:

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

Stations make zero profits $\pi_1 = \pi_2 = 0$. Social welfare is:

$$SW^{NS} = v + \int_{1-D^g(p_g^*,p_f^*)}^{1} \theta d\theta - D^g(p_g^*,p_f^*)(c_g+d+l) - D^f(p_g^*,p_f^*)(c_f+d) - E_g$$

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

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.8. 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. □

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