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Human Evaluation of "Colored" Hydrogen Transactions Towards Carbon Neutrality

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ABSTRACT

An incorporated analysis of selling green hydrogen and gray hydrogen, as opposed to selling their mixed hydrogen, is investigated. Specifically, we analyze how the social surplus is characterized for the mixed hydrogen. We perform supply/demand analysis of the mixed hydrogen in terms of the ratio of the green hydrogen. Furthermore, we derive the equilibrium price and social surplus, and clarify the optimal sales of green hydrogen. In addition, for the case where green hydrogen and gray hydrogen are traded in separate markets, we discuss what measures can be taken to increase the demand for green hydrogen.

INTRODUCTION

Energy conversion has become a major issue for the next 30 years toward the goal of the Paris Accord, "2050 carbon neutral". Hydrogen is widely attracting attention as a bearer of green energy because it can be efficiently converted into energy for transportation and industry without emitting carbon dioxide (CO_2). However, most of the hydrogen currently in circulation is from fossil fuels, and CO_2 is generated at the manufacturing stage. Therefore, it is desired to build a hydrogen supply chain using renewable energy (McDowall, 2014; Momirlan and Veziroglu, 2005; Kothari et al., 2008). Hydrogen produced using fossil fuels is called gray hydrogen, and hydrogen produced using renewable energy is called green hydrogen (Ishaq and Dincer, 2021; Dincer, 2012). The green hydrogen strategy is an expensive strategy because it uses costly manufacturing technology, and its high cost hinders the spread of the market (Yu et al., 2021; Andrews and Shabani, 2014). Currently, the main method of selling green hydrogen and gray hydrogen to general consumers is to use a mixture of these types of "colored" hydrogen.

Various studies have been conducted on the spread of hydrogen, and proposals for a hydrogen credit system (Dong et al., 2021), i.e., for an efficient hydrogen operation strategy using wind power generation (Grüger et al., 2019), and a hydrogen supply chain in Pakistan (Gondal et al., 2018). Research on optimal setting of hydrogen supply chain (Nunes et al., 2015), necessity of CO_2 recovery and storage technology by verifying the carbon dioxide reduction effect of hydrogen energy has also been conducted. Furthermore, other lines of research include dynamic pricing mechanism for hydrogen stations using blockchain (Wang et al., 2022), decarbonization in the field of industry, transportation, construction, and electric power by utilizing hydrogen (Oliveira et al., 2021), economic development and expansion of hydrogen demand in China (Ma et al., 2010), hydrogen demand and optimal hydrogen supply network in Malaysian Peninsula (Kamarudin et al., 2009).

The issue of green energy related to hydrogen has also been discussed in various works, such as analysis of the feed-in tariff (FIT) and green power certificate system (TGC) in the UK by the manufacturing industry (Tańas et al., 2010). In addition, analysis of dynamic evolution of low carbon strategy choice (Chen et al., 2021), analysis of credit period in a two-tiered green supply chain consisting of manufacturers and retailers (Panja et al., 2020), and carbon emissions taxation issues have also been investigated. Presenting a two-step optimization model that strikes a good balance between reduction targets and emissions sector interests (Wei et al., 2014) and analysis of government subsidies for carbon tax and decarbonization to promote the introduction of green technology (Pan et al., 2021) are being studied. In this way, research is being carried out using various approaches to popularize green hydrogen, but there are few studies that discuss hydrogen sales methods.

In this paper, the supply and demand for mixed hydrogen of green hydrogen and gray hydrogen is analyzed by taking the ratio of green hydrogen as a parameter, and the social surplus is derived. We analyze how this is characterized and compare the method of selling green hydrogen and gray hydrogen without mixing them and the method of selling mixed hydrogen. This leads to the equilibrium price, equilibrium quantity, and optimal hydrogen distribution that maximizes the social surplus, and clarifies which economic factors should be focused on for the spread of green hydrogen. In addition, we consider what measures should be taken to increase the demand for green hydrogen when green hydrogen and gray hydrogen are traded in different markets.

SUPPLY/DEMAND ANALYSIS OF MIXED HYDROGEN

In this section, we begin with characterizing the mixed hydrogen of green hydrogen and gray hydrogen. We denote by x the ratio of green hydrogen so that the ratio of gray hydrogen is given by $(1-x)$ with $0 \leq x \leq 1$. Specifically, if the (mixed) hydrogen contains only green hydrogen, then $x = 1$, whereas it consists of only gray hydrogen, then $x = 0$. Let q^{s} and q^{d} denote the supply and the demand quantities of the mixed hydrogen, respectively.

Supply

Here we assume that there is a person who obtains green hydrogen and gray hydrogen from independent markets and mixes the 2 types of "colored" hydrogen with the rate x of green hydrogen. The supply curves of the green and the gray hydrogens are respectively given by

Table 1. Values of the parameters used.

Parameters	Values
a_1^S	1.5
a_0^S	0.6
b_1^S	1000
b_0^S	400
a_1^d	0.6
a_0^d	0.8
b_1^d	1600
b_0^d	1000
c	4

$$P_1(q^{\mathrm{s}}) = b_1^{\mathrm{s}} + a_1{}^{\mathrm{s}}q^{\mathrm{s}}, \tag{1}$$

$$P_0(q^{\mathrm{s}}) = b_0^{\mathrm{s}} + a_0{}^{\mathrm{s}}q^{\mathrm{s}}, \tag{2}$$

where P_1 (q^{s}) and P_0 (q^{s}) denote the marginal costs along with $b_0^{\mathrm{S}}, b_1^{\mathrm{S}}, a_0^{\mathrm{S}}, a_1^{\mathrm{S}}$ being positive constants. Since the fixed production cost is more expensive and the price elasticity of supply is larger for green hydrogen than the ones for gray hydrogen, we assume that $b_1^{\mathrm{S}} > b_1^{\mathrm{S}}$and $a_1^{\mathrm{S}} > a_0^{\mathrm{S}}$ hold.

From the supply curves (1), (2), we then calculate the marginal cost P^{s} (x, q^{s}) of the mixed hydrogen where the ratio of green hydrogen is x. Specifically, when the total supply of the mixed hydrogen is q^{s}, the supply of green and gray hydrogen is given by xq^{s} and $(1 - x)q^{\mathrm{s}}$, respectively.

Since the total amount P^{s} $(x, q^{\mathrm{s}})q^{\mathrm{s}}$ of the transaction is equal to the sum of the amounts of the transactions of green and gray hydrogen, the marginal cost P^{s} (x, q^{s}) of the mixed hydrogen for the supply q^{s} must satisfy

$$P^{\mathrm{s}}(x, q^{\mathrm{s}})q^{\mathrm{s}} = P^{\mathrm{s}}(1, xq^{\mathrm{s}})(xq^{\mathrm{s}}) + P^{\mathrm{s}}(0, (1-x)q^{\mathrm{s}})[(1-x)q^{\mathrm{s}}]. \tag{3}$$

As a result, the marginal cost of the mixed hydrogen is expressed as

$$\begin{aligned} P^{\mathrm{s}}(x, q^{\mathrm{s}}) &= P_1(xq^{\mathrm{s}})x + P_0((1-x)q^{\mathrm{s}})(1-x) \\ &= xb_1^{\mathrm{s}} + (1-x)b_0^{\mathrm{s}} + [x^2 a_1^{\mathrm{s}} + (1-x)^2 a_0^{\mathrm{s}}]q^{\mathrm{s}}, \end{aligned} \tag{4}$$

which satisfies $P^{\mathrm{s}}(0, q^{\mathrm{s}}) = P_0(q^{\mathrm{s}})$ and $P^{\mathrm{s}}(1,q^{\mathrm{s}}) = P_1(q^{\mathrm{s}})$ given by (1), (2).

It is interesting to note that for a given x, the marginal cost (4) is a linear function of the supply q^{s}. Fig. 1 shows the marginal cost as a function of x and q^{s} with the parameters $b_1^{\mathrm{s}}, b_0^{\mathrm{s}}, a_1^{\mathrm{s}}, a_0^{\mathrm{s}}$ that are given in Table I. We call this curved plane of the supply curves "curved supply plane." On the other hand, (4) is equivalently expressed as

$$\begin{aligned} P^{\mathrm{s}}\left(x, q^{\mathrm{s}}\right) &= \left(a_1^{\mathrm{s}} + a_0^{\mathrm{s}}\right) q^{\mathrm{s}} x^2 + \left(b_1^{\mathrm{s}} - b_0^{\mathrm{s}} - 2a_0^{\mathrm{s}} q^{\mathrm{s}}\right) x + b_0^{\mathrm{s}} + a_0^{\mathrm{s}} q^{\mathrm{s}} \\ &= \left(x + \frac{b_1^{\mathrm{s}} - b_0^{\mathrm{s}} - 2a_0^{\mathrm{s}} q^{\mathrm{s}}}{2\left(a_1^{\mathrm{s}} + a_0^{\mathrm{s}}\right) q^{\mathrm{s}}}\right)^2 \\ &\quad - \frac{\left(b_1^{\mathrm{s}} - b_0^{\mathrm{s}} - 2a_0^{\mathrm{s}} q^{\mathrm{s}}\right)^2}{4\left(a_1^{\mathrm{s}} + a_0^{\mathrm{s}}\right) q^{\mathrm{s}}} - \left(b_0^{\mathrm{s}} + a_0^{\mathrm{s}} q^{\mathrm{s}}\right), \end{aligned} \tag{5}$$

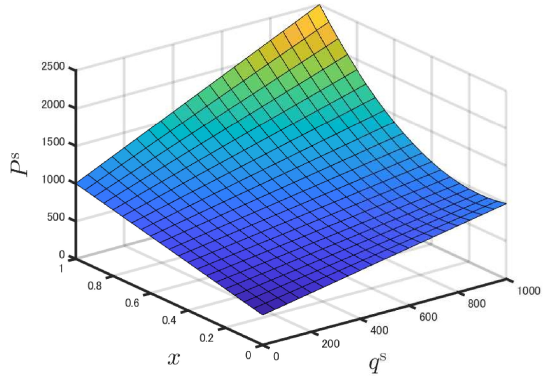

Figure 1: Curved supply plane $P^s\ (x, q^s\ )$.

so that $P^s\ (x, \cdot)$ is understood as a quadratic function of x. Furthermore, it can be seen that for a fixed amount of supply q^s, the optimal ratio $x = x^*(q^s)$ which makes the marginal cost minimum is given by

$$x * (q^s) \ = -\frac{b_1^s - b_0^s - 2a_0^s q^s}{2\left(a_1^s\ +\ a_0^s\right) q^s}, \tag{6}$$

and the resulting marginal cost is given by

$$P^s\left(x * (q^s), q^s\right) \ = -\frac{\left(b_1^s - b_0^s - 2a_0^s q^s\right)^2}{4\left(a_1^s\ +\ a_0^s\right) q^s} - \left(b_0^s\ +\ a_0^s q^s\right). \tag{7}$$

Consequently, it is observed that $x * (q^s) \to \frac{a_0^s}{a_1^s\ +\ a_0^s}$ and $P^s(x^*(q^s), q^s) \to \infty$ as $q^s \to \infty$.

Demand

Suppose that the demand curves for green hydrogen and gray hydrogen by the consumers are given by

$$P_1\left(q^d\right) \ = \ b_1^d - a_1^d q^d, \tag{8}$$

$$P_0\left(q^d\right) \ = \ b_0^d - a_0^d q^d, \tag{9}$$

where $P_1\ (q^d)$ and $P_0(q^d)$ denote the prices of willingness to pay with b_0^d, b_1^d, a_0^d, a_1^d being positive constants. Since green hydrogen with no carbon emission is perceived as more valuable and the price elasticity of demand is larger for green hydrogen than the ones for gray hydrogen, we assume that $b_1^d > b_0^d$ and $a_1^d < a_0^d$ hold.

Here the consumers are to buy the mixed hydrogen that is provided under certain mixture ratio of green hydrogen. Let $P^d\ (x, q^d)$ denote the demand curve of the mixed hydrogen. Like the curved supply plane, the collection of the demand curves $P^d(\cdot, q^d)$ forms the "curved demand plane" as given in Fig. 2. The parameters b_1^d, b_0^d, a_1^d, a_0^d that are given in Table I are used for this figure.

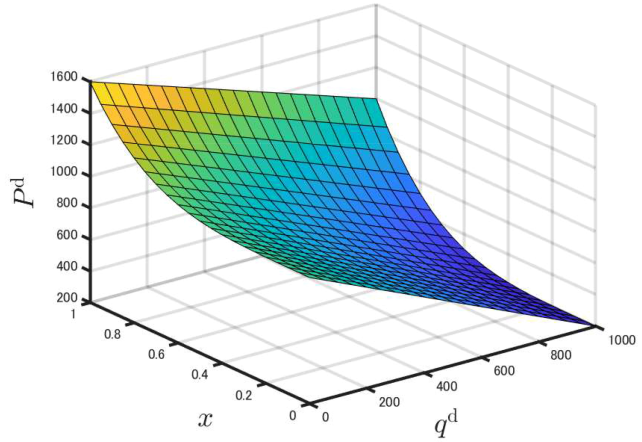

Figure 2: Curved demand plane $P^{\mathrm{d}}(x, q^{\mathrm{d}})$.

It is worth noting that the case where the mixed hydrogen instead of pure green or pure gray hydrogen is provided should be appropriately modeled according how the consumers value the mixed hydrogen. Specifically, when the demand q^{d} is fixed, we assume that $P^{\mathrm{d}}(x, q^{\mathrm{d}})$ is a function of x^c such that

$$P^{\mathrm{d}}\left(x, q^{\mathrm{d}}\right) = \alpha\left(q^{\mathrm{d}}\right) x^{\mathrm{c}} + \beta\left(q^{\mathrm{d}}\right) \tag{10}$$

where c is a positive constant and $\alpha(q^{\mathrm{d}})$ and $\alpha(q^{\mathrm{d}})$ are also positive such that $P^{\mathrm{s}}(0, q^{\mathrm{d}}) = P_0(q^{\mathrm{d}})$ and $P^{\mathrm{d}}(1, q^{\mathrm{d}}) = P_1(q^{\mathrm{d}})$. By this assumption, it follows that

$$\alpha(q^{\mathrm{d}}) = (b_1^{\mathrm{d}} - b_0^{\mathrm{d}}) - (a_1^{\mathrm{d}} - a_0^{\mathrm{d}})q^{\mathrm{d}}, \tag{11}$$

$$\beta(q^{\mathrm{d}}) = b_0^{\mathrm{d}} - a_0^{\mathrm{d}} q^{\mathrm{d}}, \tag{12}$$

so that (10) becomes

$$P^{\mathrm{d}}(x, q^{\mathrm{d}}) = \left(\left(b_1^{\mathrm{d}} - b_0^{\mathrm{d}}\right) x^{\mathrm{c}} + b_0^{\mathrm{d}}\right) - \left(\left(a_1^{\mathrm{d}} - a_0^{\mathrm{d}}\right) x^{\mathrm{c}} + a_0^{\mathrm{d}}\right) q^{\mathrm{d}}, \tag{13}$$

The power c in (13) indicates how the consumers affect their aggregate demand to the provided mixed hydrogen. As shown in Fig. 2, when c is large, the willingness to pay does not change much for the case where x is small (close to 0), whereas it does change rapidly for the case where x is large (close to 1), indicating that the price of the mixed hydrogen really matters and the use of green hydrogen is not really accepted by the consumers. On the other hand, when c is close to 1, the willingness to pay increases almost linearly as the ratio of green hydrogen increases in the mixed hydrogen. In this paper, we consider the case of $c \geq 1$ because the case where $0 \leq c \leq 1$ implies that the willingness to pay drastically increases when x becomes larger around $x = 0$ (very little ratio of green hydrogen), which is not very realistic.

It is also observed in Fig. 2 and (13) that the function $P^{\mathrm{d}}(\cdot, q^{\mathrm{d}})$ is a linear function of q^{d}. Figure 3 shows the contour plot of P^{d} (x, q^{d}) on the P^{d}-x plane. This indicates that smaller price and larger ratio of green hydrogen contribute to the increase of the demand.

Equilibrium State

From the microeconomic considerations, the equilibrium state is derived as the intersection of supply and demand curves. Based on this principle, in this section we characterize the set of equilibrium states for varying ratio of green hydrogen.

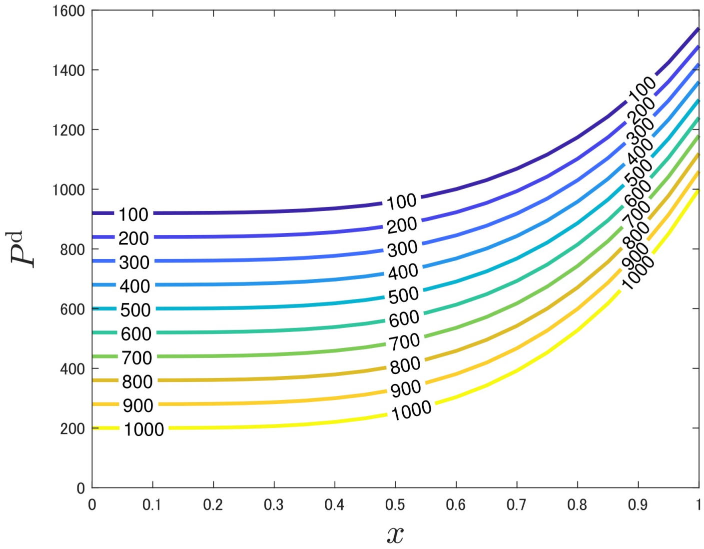

Figure 3: Contour plot of the curved demand plane (the values in the plot indicate the demand).

Let $P*(x)$ and $q*(x)$ be the equilibrium price and the equilibrium quantity, respectively, of the mixed hydrogen with the green hydrogen ratio x. In this case, by equating the right-hand sides of (4) and (13) and by solving for q^{d}, it follows that

$$q*(x) = \frac{\left(b_1^{\mathrm{d}} - -b_0^{\mathrm{d}}\right) x^{\mathrm{c}} - \left(b_1^{\mathrm{s}} - b_0^{\mathrm{s}}\right) x + b_0^{\mathrm{d}} - -b_0^{\mathrm{s}}}{\left(a_1^{\mathrm{d}} - a_0^{\mathrm{d}}\right) x^{\mathrm{c}} + \left(a_1^{\mathrm{s}} - a_0^{\mathrm{s}}\right) x^2 - 2a_0^{\mathrm{s}} x + a_0^{\mathrm{s}} + a_0^{\mathrm{d}}}, \tag{14}$$

so that the equilibrium price $P^*(x)$ is obtained as

$$P*(x) = (b_1^{\mathrm{s}} - b_0^{\mathrm{s}})x + b_0^{\mathrm{s}}[(a_1^{\mathrm{s}} + a_0^{\mathrm{s}})x^2 - 2a_0^{\mathrm{s}}x + a_0^{\mathrm{s}}] \cdot \frac{(b_1^{\mathrm{d}} - b_0^{\mathrm{d}})x^{\mathrm{c}} - (b_1^{\mathrm{s}} - b_0^{\mathrm{s}})x + b_0^{\mathrm{d}} - b_0^{\mathrm{s}}}{(a_1^{\mathrm{d}} - a_0^{\mathrm{d}})x^{\mathrm{c}} + (a_1^{\mathrm{s}} - a_0^{\mathrm{s}})x^2 - 2a_0^{\mathrm{s}}x + a_0^{\mathrm{s}} + a_0^{\mathrm{d}}}. \tag{15}$$

The red curve in Fig. 4 indicates the set of equilibrium states $(q^*(x), P^*(x))$ under varying x for the case of parameters given in Table I.

Surplus

We can discuss suppliers' surplus, consumers' surplus, and the social surplus by the curved supply and demand planes.

1) Suppliers' Surplus: Suppliers' surplus is characterized as the area below the equilibrium price and above the supply curve. Let $S^{s}(x)$ denote the suppliers' surplus when the green hydrogen ratio is x. It follows from (4), (14), and (15) that

$$\begin{aligned} S^{s}(x) &= \int_{0}^{q*(x)} \left(P*(x) - P^{s}(x,q)\right) dq \\ &= \frac{1}{2}\left[\left(a_1^{s} + a_0^{s}\right)x^2 - 2a_0^{s}x + a_0^{s}\right] \\ &\cdot \left[\frac{\left(b_1^{d} - -b_0^{d}\right)x^{c} - \left(b_1^{s} - b_0^{s}\right)x + b_0^{d} - b_0^{s}}{\left(a_1^{d} - a_0^{d}\right)x^{c} + \left(a_1^{s} + a_0^{s}\right)x^2 - 2a_0^{s}x + a_0^{s} + a_0^{d}}\right]. \end{aligned} \tag{16}$$

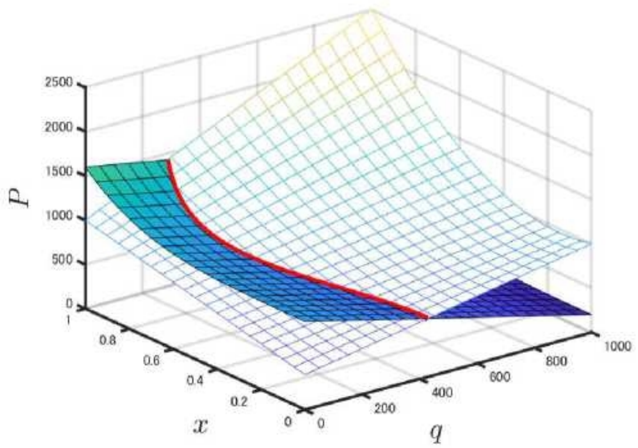

Figure 4: Set of equilibrium states ($q*(x)$,$P*(x)$) under varying x (red curve).

Note that the values of $S^{s}(0)$ and $S^{s}(1)$ do not depend on c and they are given by

$$S^{s}(0) = \frac{a_0^{s}\left(b_0^{d} - b_0^{s}\right)^2}{2\left(a_0^{d} + a_0^{s}\right)}, \tag{17}$$

$$S^{s}(1) = \frac{a_1^{s}\left(b_1^{d} - b_1^{s}\right)^2}{2\left(a_1^{d} + a_1^{s}\right)^2}. \tag{18}$$

Fig. 5 shows the suppliers' surplus as a function of x and c with the parameters given in Table I. The red curve indicates the set of points such that $S^{s}(x)$

is maximized over x for each of c. It is observed that when c is close to 1, the function $S^{\mathrm{s}}\,(x)$ is concave with respect to x and there is a maximum point in the the interval $0 < x < 1$. On the other hand, when c increases, $S^{\mathrm{s}}(x)$ becomes convex with respect to x so that it takes a maximum value at $x = 1$. In other words, when the demand for green hydrogen is high, the producer surplus is maximized in the state of mixed hydrogen containing green hydrogen, but when the demand for green hydrogen is low, the producer surplus is maximized in the state of 100% of green hydrogen. When a hydrogen procuring company procures hydrogen to maximize the producer surplus, the mixed hydrogen is traded at the ratio of green hydrogen shown by the red line in Fig. 5.

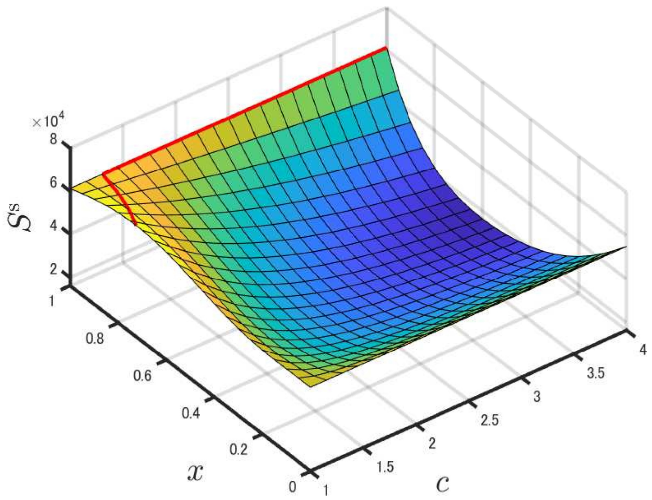

Figure 5: Suppliers' surplus as a function of x and c.

2) Consumers' Surplus: Consumers' surplus is characterized as the area below the demand curve and above the equilibrium price. Let $S^{\mathrm{d}}\,(x)$ denote the consumers' surplus when the green hydrogen ratio is x. It follows from (4), (14), (15) that

$$\begin{aligned} S^{\mathrm{d}}(x) &= \int_0^{\mathrm{q}*(\mathrm{x})} \left(P^{\mathrm{d}}\,(x,q) - P^{*}(\mathrm{x})\right) \mathrm{dq} \\ &= \frac{1}{2}\frac{\left(b_1^{\mathrm{d}} - b_0^{\mathrm{d}}\right)x^{\mathrm{c}} - \left(b_1^{\mathrm{s}} - b_0^{\mathrm{s}}\right)x + b_0^{\mathrm{d}} - b_0^{\mathrm{s}}}{\left(a_1^{\mathrm{d}} - a_0^{\mathrm{d}}\right)x^{\mathrm{c}} + \left(a_1^{\mathrm{s}} + a_0^{\mathrm{s}}\right)x^2 - 2a_0^{\mathrm{s}}x + a_0^{\mathrm{s}} + a_0^{\mathrm{d}}} \\ &\quad \cdot \left[1 - \frac{\left(a_1^{\mathrm{s}} + a_0^{\mathrm{s}}\right)x^2 - 2a_0^{\mathrm{s}}x + a_0^{\mathrm{s}}}{\left(a_1^{\mathrm{d}} - a_0^{\mathrm{d}}\right)x^{\mathrm{c}} + \left(a_1^{\mathrm{s}} + a_0^{\mathrm{s}}\right)x^2 - 2a_0^{\mathrm{s}}x + a_0^{\mathrm{s}} + a_0^{\mathrm{d}}}\right]. \end{aligned} \quad (19)$$

Note that the values of $S^{\mathrm{d}}(0)$ and $S^{\mathrm{d}}(1)$ do not depend on c and they are given by

$$S^{\mathrm{d}}(0) = \frac{a_0^d \left(b_0^{\mathrm{d}} - b_0^{\mathrm{s}}\right)^2}{2\left(a_0^{\mathrm{d}} + a_0^{\mathrm{s}}\right)^2}, \quad (20)$$

$$S^{\mathrm{d}}(1) = \frac{a_1^{\mathrm{d}} \left(b_1^{\mathrm{d}} - b_1^{\mathrm{s}}\right)^2}{2\left(a_1^{\mathrm{d}} + a_1^{\mathrm{s}}\right)^2}. \quad (21)$$

Fig. 6 shows the consumers' surplus as a function of x and c with the parameters given in Table I. The red curve indicates the set of points such that $S^{\mathrm{d}}(x)$ is maximized over x for each of c. It is observed that when c is close to 1, the function $S^{\mathrm{d}}(x)$ is concave with respect to x and there is a maximum point in the the interval $0 < x < 1$. On the other hand, when c increases, $S^{\mathrm{s}}(x)$ becomes convex with respect to x so that it takes a maximum value at $x = 0$. In other words, when the demand for green hydrogen is high, the consumers' surplus is maximized in the state of mixed hydrogen containing green hydrogen, but when the demand for green hydrogen is low, the producer surplus is maximized in the state of 100% of gray hydrogen. When a hydrogen procuring company procures hydrogen to maximize the consumers' surplus, the mixed hydrogen is traded at the ratio of green hydrogen shown by the red line in Fig. 6.

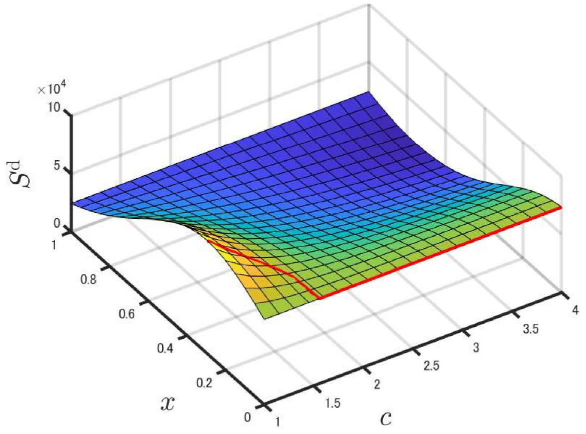

Figure 6: Consumers' surplus as a function of x and c.

3) Social Surplus: Social surplus is characterized as the area below the demand curve and above the supply price, which corresponds to the sum of the suppliers' surplus and the consumers' surplus. Let $S(x)$ denote the consumers' surplus when the green hydrogen ratio is x. It follows from (4), (14), (15) that

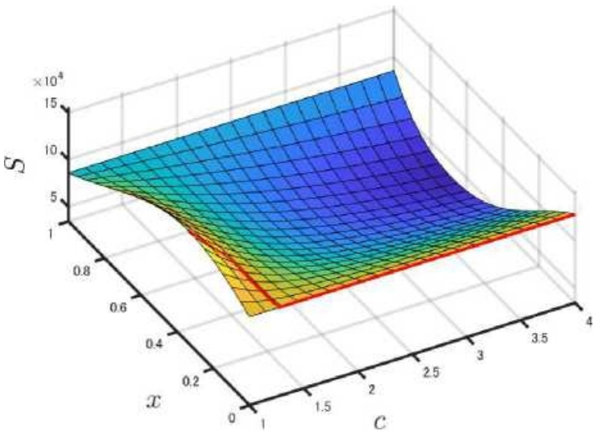

Figure 7: Social surplus as a function of x and c.

$$S(x) = \frac{\left[\left(b_1^d - b_0^d\right)x^c - \left(b_1^s - -b_0^s\right)x + b_0^d - b_0^s\right]^2}{2\left[\left(a_1^d - a_0^d\right)x^c + \left(a_1^s + a_0^s\right)x^2 - 2a_0^s x + a_0^s + a_0^d\right]}. \tag{22}$$

Note that the values of $S^d(0)$ and $S^d(1)$ do not depend on c and they are given by

$$S(0) = \frac{\left(b_0^d - b_0^s\right)^2}{2\left(a_0^d + a_0^s\right)}, \tag{23}$$

$$S(1) = \frac{\left(b_1^d - b_1^s\right)^2}{2\left(a_1^d + a_1^s\right)}. \tag{24}$$

Fig. 7 shows the social surplus as a function of x and c with the parameters given in Table I. The red curve indicates the set of points such that $S(x)$ is maximized over x for each of c. Similar to the consumers' surplus, it is observed that when c is close to 1, the function $S(x)$ is concave with respect to x and there is a maximum point in the the interval $0 < x < 1$. On the other hand, when c increases, $S(x)$ becomes convex with respect to x so that it takes a maximum value at $x = 0$. In other words, when the demand for green hydrogen is high, the consumers' surplus is maximized in the state of mixed hydrogen containing green hydrogen, but when the demand for green hydrogen is low, the producer surplus is maximized in the state of 100% of gray hydrogen. When a hydrogen procuring company procures hydrogen to maximize the social surplus, the mixed hydrogen is traded at the ratio of green hydrogen shown by the red line in Fig. 7.

CONCLUSION FOR COLORED HYDROGEN

When there are two separate markets dealing with green and gray hydrogen where the consumers have the same property as discussed in Section II-B. It is expected from the microeconomic theory that the resulting green hydrogen ratio x goes to the value which makes the social surplus maximum.

If the society becomes more sensitive to CO_2 emission, the power c tends to be closer to 1 so that the green hydrogen ratio x increases from 0 to a nonzero value that is shown in Section II-D.3 and the more green hydrogen is chosen by the consumers to reduce CO_2 emission.

It is important to note that when the parameters are taken as in Table I, it follows that $S(0) > S(1)$ holds and hence if c is large, then the social surplus is maximum at $x = 0$ (completely gray hydrogen) as shown in Fig. 7. However, it follows from (23), (24) that if a_1^{d}, a_1^{s}, b_1^{d} are small and b_1^{s} is large, then $S(1) > S(0)$ may hold so that for any $c > 1$, the social surplus may be maximized with respect to x that is closer to 1. In other words, if green hydrogen becomes a good whose demand and supply will increase significantly as prices rise, the willingness to pay for green hydrogen will increase, and fixed costs in the supply of green hydrogen will decrease, then green hydrogen will be produced. As a consequence, green hydrogen will become more widespread and our society will be closer to carbon neutral.

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