

An Analysis of Hydrogen Generation from Recyclable Aluminium Cans

การวิเคราะห์ประโยชน์ของการผลิตก๊าซไฮโดรเจนจากกระป๋องอะลูมิเนียมที่ใช้แล้ว

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Abstract

At present, many countries, including Thailand, rely on oil and natural gas for their energy needs. Since both are depletable sources of energy, over time, these resources are likely to become increasingly difficult to extract, causing the prices of these resources to rise significantly. Therefore, it becomes inevitable that, in the near future, we make a transition from these fossil fuels to clean and renewable sources of energy. At the same time, as the problems of geographic concentration of people become more pronounced, waste disposal becomes an important issue. Taken together, these two issues result in an increase in the attractiveness for scientists to explore the possibility of using recyclable resources to generate energy. Silva-Martínez, Sánchez, Gallegos & Sebastian (2007) took advantage of the corrosion reaction of aluminium from the aluminium cans with hydroxide ions from the sodium hydroxide to generate hydrogen. The hydrogen produced from such reaction can then be used in a commercial proton exchange membrane fuel cell to produce electricity, without further contribution to air pollution. In this paper, we develop an economic model and conduct the numerical simulations of this model based on some information obtained from our own reconstructed Silva-Martínez et al. (2007) experiment. Our results show that there exist sizable benefits associated with the hydrogen generation from aluminium cans.

Keywords: Aluminium; Energy Generation; Cost Saving; Recycle

บทคัดย่อ

ปัจจุบันหลายๆ ประเทศรวมทั้งประเทศไทยพึ่งพาการใช้ทรัพยากรน้ำมันและก๊าซธรรมชาติในการผลิตพลังงาน ซึ่งทรัพยากรเหล่านี้เป็นทรัพยากรที่มีอยู่อย่างจำกัด และไม่สามารถผลิตขึ้นมาทดแทนได้ภายในระยะเวลาอันสั้น ส่งผลให้ราคาของทรัพยากรเหล่านี้สูงขึ้น ดังนั้น การผลิตพลังงานจากทรัพยากรที่สะอาดและสามารถผลิตขึ้นใหม่ได้ในระยะเวลาอันสั้นจึงมีความจำเป็นอย่างยิ่ง ในขณะที่ปัญหามลพิษที่เพิ่มมากขึ้นเนื่องจากจำนวนประชากรที่เพิ่มขึ้น ทำให้การแปรรูปขยะบางประเภทเป็นพลังงานเป็นสิ่งที่น่าสนใจอย่างยิ่งในปัจจุบัน จากการศึกษาของ Silva-Martínez และคณะ (2007) พบว่าก๊าซไฮโดรเจนซึ่งสามารถนำไปใช้เป็นเชื้อเพลิงในเซลล์เชื้อเพลิงเพื่อผลิตกระแสไฟฟ้า สามารถผลิตได้จากการทำปฏิกิริยาระหว่างอะลูมิเนียมกับไฮดรอกไซด์ไอออน ซึ่งกระบวนการผลิตดังกล่าวเป็นกระบวนการที่สะอาดไร้มลพิษ ในบทความนี้ คณะผู้วิจัยสร้างแบบจำลองทางเศรษฐศาสตร์ พร้อมทั้งทำการวิเคราะห์เชิงปริมาณโดยใช้ข้อมูลที่ได้จากแหล่งต่างๆ รวมถึงผลการทดลองตามแนวคิดของ Silva-Martínez และคณะ (2007) การศึกษาชี้ให้เห็นถึงประโยชน์ที่ผู้ประกอบการจะได้รับจากการผลิตก๊าซไฮโดรเจนจากกระป๋องอะลูมิเนียมที่ใช้แล้ว

คำสำคัญ: อะลูมิเนียม; การผลิตพลังงาน; การประหยัดต้นทุน; การนำขยะกลับมาใช้ประโยชน์

Introduction

Fossil fuels, particularly oil and natural gas, have been the important sources of energy in many countries. Nevertheless, given that, in the long-run, these resources could be exhausted, a transition to alternative renewable sources of energy is increasingly vital and will eventually play a significant role in fulfilling the world's energy needs. At present, several alternative sources of renewable energy are available, including hydropower generated from water, solar energy, wind energy, geothermal energy and hydrogen. The extent to which these alternative types of energy will penetrate the market depends on many factors, including relative cost, impact on environment, quality and acceptance by end-users.

According to Yokthongwattana (2006), by comparing different types of fuels—wood, coal, crude oil, ethanol, natural gas, gasoline, hydrogen, methane, kerosene and methanol—in terms of their energy generation capacity, we find that hydrogen generates the highest energy per unit (MJ/Kg). Figure 1 illustrates. Moreover, the research by Jung, Kundu, Ku, Gil, Lee & Jang (2008) supplements that hydrogen is the best fuel for obtaining high performance from fuel cells. Thus, in this paper, we focus our attention on the generation or extraction of hydrogen.

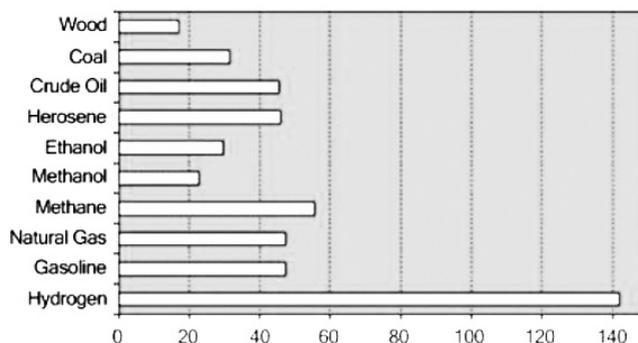


Figure 1 Energy Generation Capacities of Different Types of Fuels

Source: Yokthongwattana (2006)

There are different methods of producing hydrogen, for instances, water electrolysis, biological process, and chemical methods (Wu & Zhang, 2005). To be successful in the hydrogen economy, it is essential that the technology used to produce hydrogen be well developed with strong consideration of sustainable and renewable demands. According to the study conducted by Wang, Leung, Leung & Ni (2008), the biological processes and water electrolysis suffer from the following drawbacks. While the reforming of biomass under the biological process suffers from the low conversion efficiencies, high transportation cost and emission of carbon dioxide, the electrochemical water electrolysis is considered to be a very costly method as electricity is required¹. Attention has, therefore, been

¹ New approaches are under development in order to reduce cost associated with the electrolysis of water.

diverted to the chemical methods. At present, the chemical methods have been the dominant approaches in the market for commercial production of hydrogen. However, this approach has been largely dominated by steam reforming of natural gas; around 96 percent of hydrogen is produced by reforming of natural gas (48 percent), oil (18 percent) and coal gasification (30 percent). Though steam reforming of natural gas is relatively inexpensive and allows firms to produce commercial bulk of hydrogen, this method has been criticized because of its by-product, namely carbon monoxide, which is a highly toxic gas.

Consequently, a vast amount of scientific research on the generation of hydrogen based on the chemical methods have been undertaken, aiming at producing hydrogen in a less costly way, in the most efficient manner as well as imposing less adverse effect on the environment. Recently, increasing attention has been devoted to the research in chemical reactions of reactive metals. Among the different types of metals, aluminium has been considered to be the most promising candidate in the generation of hydrogen (Kravchenko, Semenenko & Bulychev, 2005; Soler, Macanás, Muñoz & Casado, 2007). According to Alenejad & Mahmoodi (2009) and Czech & Troczynski (2010), aluminium is considered to be an appropriate reactive metal because it is abundantly available in the earth's crust, it can be fully recycled and it is light. Jung et al. (2008) add that aluminium offers a promising hydrogen source with high power density as the hydrogen produced per 1 gram of aluminium is quite high (i.e. 95 percent of the theoretical maximum). They also argue that the hydrogen production from aluminium is also a suitable mode of hydrogen supply in oil refineries as this will help replace the conventional method of hydrocarbon reforming.

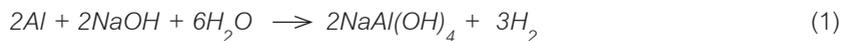
Aluminium possesses a number of valuable mechanical, electrical and thermal properties (Wang et al., 2008, p. 2). They have, for a long time, been related to energy production and storage, particularly in batteries because of their "high theoretical ampere-hour capacity, voltage and specific energy" (Silva-Martínez, Sánchez, Gallegos & Sebastian, 2007, p. 3159). Under this approach, hydrogen can be produced from the corrosion reaction of aluminium with hydroxide ions. Typically, aluminium in the forms of powder, strip, pellets, flakes, foil and wire needs to be purchased, from the chemical companies; thus, this process of hydrogen production is still not entirely economical.

The research conducted by Silva-Martínez et al. (2007) could help a great deal in saving the costs of hydrogen production and, at the same time, dealing with the waste disposal problem because they showed that aluminium obtained from the aluminium waste cans could be used in the hydrogen generation process. Specifically, Silva-Martínez et al. reacted the aluminium from the waste aluminium cans² with sodium hydroxide with no temperature control and discovered that quite large amounts of hydrogen can be generated.

² According to Silva-Martínez et al. (2007, p. 3159), the empty soft drink cans are, first, dipped into a concentrated sulphuric acid to eliminate the paint and plastic film of the aluminium cans. The ends of the cans were then cut off and the rest of the aluminum cans were cut into small pieces.

The Aluminium-Water Reaction Approach

The chemical reaction that governs the production of hydrogen by reacting aluminium with sodium hydroxide is given by the following equation:



According to equation (1), two moles of aluminium (i.e. 2Al), two moles of sodium hydroxide (i.e. 2NaOH) and six moles of water (i.e. 6H₂O) would produce three moles of hydrogen (i.e. 3H₂)³ and two moles of sodium tetrahydroxoaluminate (i.e. 2NaAl(OH)₄), where the latter is a by-product. As discussed in Wang et al. (2008), the sodium hydroxide depleted for the hydrogen evolution in step 1 according to equation (1) will be regenerated through the NaAl(OH)₄ decomposition in second step according to the following equation:



From equation (2), we can see that sodium hydroxide, which is used here as the catalyst, can be fully recovered, while some aluminium can be recovered from Al(OH)₃ through another chemical reaction. Aluminium and sodium hydroxide can then be reused in the future rounds of hydrogen production process.

In this paper, we reconstruct the experiment of Silva-Martinez et al. (2007) to obtain information on the amount of aluminium that can be obtained from the aluminium waste can and to get a clearer picture of this type of hydrogen generation process. This information will be useful for our numerical simulations based on the simple economic model developed in this paper.

Figure 2 shows our own reconstructed Silva-Martinez et al. (2007) experiment. It illustrates a step-by-step procedure of how aluminium can be prepared from the aluminium waste can; the hydrogen production from the corrosion of reaction of aluminium pieces and sodium hydroxide as well as the coupling of the hydrogen production with the proton exchange membrane (PEM) fuel cell.

³ In theory, one gram of aluminium would generate 0.0556 moles of hydrogen, while 0.049 moles of hydrogen were obtained from the real experiment (Silva-Martinez et al., 2007, p.3160).

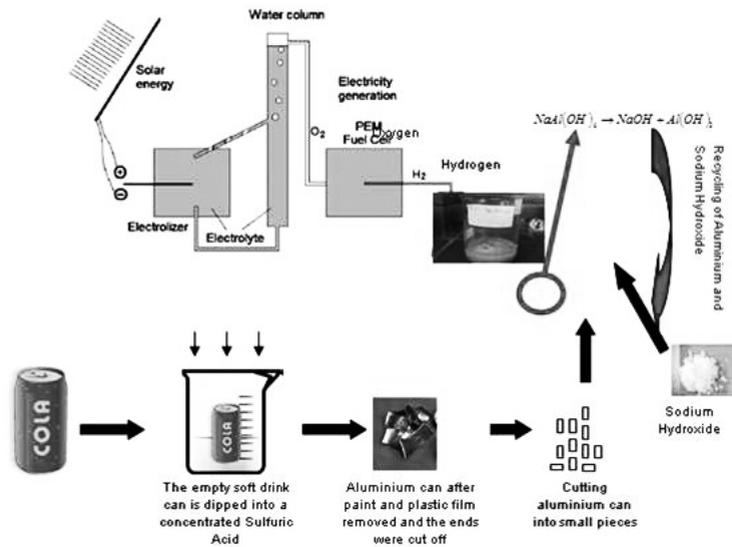


Figure 2 A step-by-step procedure of hydrogen production based on the aluminium-water reaction approach

Source: Adaption from Silva-Martinez et al. (2007) experiment

This approach has several interesting features. First, it is quite cost efficient in the sense that waste aluminium cans are usually very cheap and are abundantly available. Second, since aluminium and sodium hydroxide can be recovered and reused to produce even more hydrogen in the future rounds of production, this should help the hydrogen-producing firms in saving their costs. Third, the hydrogen purity is sufficiently high so it can be used in PEM fuel cell to generate electricity. Since the corrosion processes of aluminium is totally carbon dioxide free (Wang et al, 2008), it has a minimal adverse impact on the environment.

The Current Situation in Thailand

In Thailand, hydrogen is generated as a by-product in the petroleum and petrochemical industries. Domestic firms then use hydrogen as one type of fuels in the steam production. However, the scale of hydrogen production and utilization as fuel in the production process is still considered to be relatively small. This calls for greater public interests in the hydrogen generation technology, especially based on the aluminium-water reaction approach⁴. In this paper, we argue that, instead of using the new aluminium as the input in the hydrogen production process, firms would benefit in terms of cost saving by using aluminium obtained from aluminium waste cans.

In what follows, we provide a brief discussion on the importance of this particular method (i.e. hydrogen generation from aluminium waste cans) over some conventional ways (i.e. recycling

⁴ Sangla, Thepchan & Suppadit (2007) also call for an improved development of hydrogen technology in Thailand. They recommend that we should perhaps look into the possibility of using our agricultural products, such as rice, corn and tapioca, in the hydrogen generation process based on the biological process. Nevertheless, as pointed out earlier, the biological method has some limitations owing to its low efficiency, high cost of transportation of biomass and emission of carbon dioxide.

of aluminium waste cans). It is widely known that aluminium waste cans are, conventionally, recycled. The recycling process of aluminium beverage cans can be described as follows. The waste cans are first cut into small pieces, cleaned chemically/mechanically and blocked to minimize oxidation losses when melted. The blocks are then loaded into furnace and heated to produce molten aluminium (Wikipedia, 2011). It is argued that this recycling process is far less expensive and less energy intensive than creating new aluminium. Thus, the key advantage associated with the recycling of aluminium largely hinges upon cost saving and energy saving, with the production of new aluminium being used as the benchmark for comparison.

In this paper, we do not argue that the aluminium recycling should be replaced by the use of aluminium waste in the generation of hydrogen. We just want to highlight an alternative way of making the most out of aluminium waste cans. The key value-added prospects of this way of utilizing the aluminium waste cans are twofold. First, it can help firms in reducing cost associated with the production of hydrogen. Instead of using newly purchased aluminium in the production process, the firms can enjoy a lower cost of production by using aluminium waste cans. In this sense, this process implies cost saving in energy generation, which is different from cost saving in the generation of new aluminium cans used as packaging for consumption goods. Second, as explained in the previous subsection and in greater details in the following section, the aluminium obtained from the aluminium waste cans can also be recycled and reused in future rounds of hydrogen production, if the firms know how to make the most out of the sodium tetrahydroxoaluminate, which is the by-product from the hydrogen production process based on the aluminium-water reaction approach.

The Structure of the paper

In this paper, we develop a simple economic model and conduct the numerical simulations based on our model predictions, the results from our own reconstructed Silva-Martinez et al. (2007) experiment and other data sources to show how the energy-producing firms would benefit from switching to this approach of hydrogen generation. Moreover, this could help us in raising the interests of the general public about the benefits their countries would receive from the recycling of aluminium waste cans: addressing the waste disposal problems and minimizing the use of virgin materials. Based on the result of our simple analysis, we will then make policy recommendations to the Thai government to call for greater supports and cooperation by the firms in Thailand to adopt this Waste-to-Energy scheme.

The remainder of the paper is structured as follows. The following section presents our model: discussing the environment, the analysis and the results. In the final section, we discuss some policy implications and give the concluding remarks.

The Model

The Environment

In this paper, we consider one developing country consisting of one representative hydrogen-producing firm⁵. The production of hydrogen requires aluminium (Al), sodium hydroxide ($NaOH$) and water (H_2O) as key inputs. In this paper, we consider a situation in which aluminium (Al) is obtained from aluminium cans. Before being used in the hydrogen production process based on the aluminium-water reaction approach, empty aluminium cans need to be, first, dipped into a concentrated sulphuric acid (H_2SO_4) to eliminate the paint and plastic film of the aluminium cans. Even though the sulphuric acid is not an input in the hydrogen production per se, it is essential since, without it, the aluminium cans cannot be used to generate hydrogen.

Let Ω denotes the key inputs used in the generation of hydrogen based on the aluminium-water reaction approach, where $\Omega = 2Al + 2NaOH$ is interpreted as two moles of aluminium and two moles of sodium hydroxide. Let $W = 6H_2O$ denotes 6 moles of water and let $SA = H_2SO_4$ represents the amount of sulphuric acid used to prepare the aluminium from the aluminium can. Let C_Ω be the cost of Ω (i.e. the cost the firm incurred from purchases of two moles of aluminium and two moles of sodium hydroxide), let C_W denotes the cost of six moles of water used in the production of hydrogen and C_{SA} denotes the cost associated with SA amount of sulphuric acid.

Let H denotes a mole of hydrogen generated from this process. The unit price of hydrogen is denoted by P_H , where $P_H > 0$. The hydrogen production technology follows equation (1). Note that H is linear in Ω , W and SA . Consider the following equation:

$$3H = \Omega + W + SA \text{ or } H = \frac{1}{3}(\Omega + W + SA) \quad (3)$$

In each period t , the profit of this representative firm, π_t , is defined as total revenue minus total cost:

$$\pi_t = 3P_H H - C_\Omega \Omega - C_W W - C_{SA} SA \quad (4)$$

where $t = [1, \infty)$. Our assumption is that, in each period t , the representative firm's target is to generate 3 moles of hydrogen; thus, this firm's revenue and cost associated with a generation of 3 moles of hydrogen are given by $3P_H H$ and $C_\Omega \Omega + C_W W + C_{SA} SA$, respectively. It is necessary that we fix the amount of firm's output (i.e. hydrogen), revenue and resources used in the production as this would allow us to focus on finding answers to the following questions:

Question 1 How does the ability of firm in recovering and reusing the aluminium and sodium hydroxide (captured by Ω) in the future rounds of hydrogen production help it to save cost?

Question 2 How does the use of the aluminium waste cans instead of other types of aluminium wastes enhance the cost-saving for the firm?

⁵ This analysis can be extended to include many firms, but only one representative firm is enough for us to make our points.

Analysis and Discussion of Results

To find an answer to Question 1, we now consider two scenarios. In the first scenario, the firm exploits the benefits from decomposition of the by-product, which is sodium tetrahydroaluminate or $NaAl(OH)_4$, as described in equation (2). This allows the firm to fully recover $NaOH$ (sodium hydroxide) and partially recover Al (aluminium) from further process of chemical reaction of $Al(OH)_3$ (aluminium hydroxide). In the second scenario, the firm does not exploit the benefits from decomposition of sodium tetrahydroaluminate, $NaAl(OH)_4$, in the future rounds of hydrogen production process.

Under the first scenario, let $\omega \in (0,1)$ denotes the recovery rate, i.e. the fraction of Ω , which could be recovered and reused in the future rounds of hydrogen production due to the decomposition of sodium tetrahydroaluminate as described above. Since the target amount of hydrogen to be produced at each period is fixed at three moles of hydrogen and the amount of inputs used in the production is fixed at $\Omega + W + SA$, it follows that the amount of inputs that the firm needs to purchase at each period can be calculated as follows.

At $t = 1$, the firm needs to purchase $\Omega + W + SA$.

At $t = 2$, the firm can recover and reuse $\omega\Omega$ from what it purchased in the previous period; thus, in order to obtain Ω required in this round of hydrogen production, the firm needs to purchase an additional amount of $(1 - \omega)\Omega$ and $(W + \mu SA)$, where $\omega \in (0,1)$. Since some of the aluminium is recovered from the decomposition of sodium tetrahydroaluminate obtained from the previous round of hydrogen production, it follows that only a fraction (μ) of the sulphuric acid needs to be purchased for the newly acquired aluminium can at $t = 2$.

At $t = 3$, an amount, $\omega^2\Omega$, purchased at $t = 1$ can be recovered and reused, while an amount $\omega(1 - \omega)\Omega$ purchased at $t = 2$ can be recovered and reused in this round of production. It follows that the extra amount which needs to be purchased this period is given by $\Omega - \omega^2\Omega - \omega(1 - \omega)\Omega$, which equals to $(1 - \omega)\Omega$. The firm also needs to acquire $(W + \mu SA)$ units of water and sulphuric acid.

Similar calculation is then repeated at time $t \in [4, \infty)$. The results from our calculations show that, at each $t \in [4, \infty)$, the firm needs to purchase $(1 - \omega)\Omega + W + \mu SA$. Given that the costs of Ω , W and SA are given by C_Ω , C_W and C_{SA} , respectively, the costs incurred by the firm at each period t are shown in Figure 3.

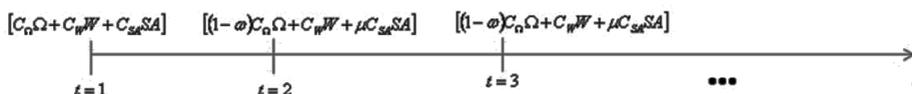


Figure 3 Costs incurred by the firm which reuses recovered inputs in the future rounds of hydrogen production

It follows from Figure 3 that, if the firm reuses recovered resources in hydrogen production in each period, the present discounted value of cost stream, $PDC_{re\ cover}$, is given by equation (5).

$$PDC_{re\ cover} = [C_{\Omega}\Omega + C_W W + C_{SA} SA] + \delta[(1-\omega)C_{\Omega}\Omega + C_W W + \mu C_{SA} SA] + \delta^2[(1-\omega)C_{\Omega}\Omega + C_W W + \mu C_{SA} SA] + \delta^3[(1-\omega)C_{\Omega}\Omega + C_W W + \mu C_{SA} SA] + \dots \quad (5)$$

where $\delta = \left(\frac{1}{1+r}\right)$ is the discount factor and $r \in (0,1)$ is the discount rate.

The expression in equation (5) can be simplified as follows:

$$PDC_{re\ cover} = [C_{\Omega}\Omega + C_W W + C_{SA} SA] + [(1-\omega)C_{\Omega}\Omega + C_W W + \mu C_{SA} SA](\delta + \delta^2 + \delta^3 + \dots) \\ = [C_{\Omega}\Omega + C_W W + C_{SA} SA] + [(1-\omega)C_{\Omega}\Omega + C_W W + \mu C_{SA} SA] \left(\frac{\delta}{1-\delta}\right) \quad (6)$$

Under the second scenario, the firm does not exploit the possibility of reusing the recovered resources in the future rounds of hydrogen production process. Thus, at each period t , the firm needs to purchase $\Omega + W + SA$ units of inputs. Given that the costs of Ω , W and SA are given by C_{Ω} , C_W and C_{SA} , respectively, the costs incurred by firm at each period t under this second scenario are shown in Figure 4.

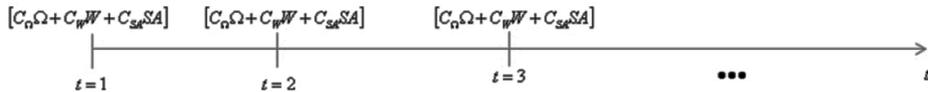


Figure 4 Costs incurred by the firm which does not reuse the inputs that can actually be recovered in the future rounds of hydrogen production

Under this scenario, the present discounted value of cost stream $PDC_{not\ re\ cover}$, is given by equation (7)

$$PDC_{not\ re\ cover} = [C_{\Omega}\Omega + C_W W + C_{SA} SA] + \delta[C_{\Omega}\Omega + C_W W + C_{SA} SA] + \delta^2[C_{\Omega}\Omega + C_W W + C_{SA} SA] + \delta^3[C_{\Omega}\Omega + C_W W + C_{SA} SA] + \dots \quad (7)$$

The expression in equation (7) can be simplified as follows:

$$PDC_{not\ re\ cover} = [C_{\Omega}\Omega + C_W W + C_{SA} SA](1 + \delta + \delta^2 + \delta^3 + \dots) \\ = [C_{\Omega}\Omega + C_W W + C_{SA} SA] \left(\frac{1}{1-\delta}\right) \quad (8)$$

It follows that, by reusing the recovered resources, the cost-saving obtained by the firm, CS , is given by equation (9):

$$CS = PDC_{not\ re\ cover} - PDC_{re\ cover} = [C_{\Omega}\Omega + C_W W + C_{SA} SA] \left(\frac{1}{1-\delta}\right) - [C_{\Omega}\Omega + C_W W + C_{SA} SA] \\ - [(1-\omega)C_{\Omega}\Omega + C_W W + \mu C_{SA} SA] \left(\frac{\delta}{1-\delta}\right) \\ = \left(\frac{\delta}{1-\delta}\right) [\omega C_{\Omega}\Omega + (1-\mu)C_{SA} SA] \quad (9)$$

Given that $\Omega > 0$, $SA > 0$, $C_\Omega > 0$, $C_{SA} > 0$, $\omega \in (0,1)$, $\mu \in (0,1)$ and $\delta \in \left(\frac{1}{2}, 1\right)$, it follows that $CS > 0$. Moreover, CS is strictly increasing in ω , C_Ω , Ω , C_{SA} and SA , which implies that the firm will benefit more in terms of cost saving by reusing recovered inputs from each round of production if the recovery rate is higher, aluminium and sodium hydroxide are relatively expensive; a large amount of aluminium and sodium hydroxide is required in the production; the cost of sulphuric acid is high; and a larger amount of sulphuric acid is required. Moreover, the cost saving is decreasing in μ . This means the higher is the additional sulphuric acid the firm needs to purchase at each period to meet the required amount, the lower would be the cost saving for the firm.

From the firm's perspective, if T denotes the number of periods when the firm decides whether to reuse the recovered resources in the future rounds of hydrogen generation, it follows that $PDC_{recovery}^T$ which represents the present discounted value of cost stream from period $t = 1$ to period $t = T$ under the first scenario, is given by equation (10).

$$PDC_{recovery}^T = [C_\Omega \Omega + C_W W + C_{SA} SA] + \delta [(1-\omega)C_\Omega \Omega + C_W W + \mu C_{SA} SA] + \delta^2 [(1-\omega)C_\Omega \Omega + C_W W + \mu C_{SA} SA] + \dots + \delta^{T-1} [(1-\omega)C_\Omega \Omega + C_W W + \mu C_{SA} SA] \quad (10)$$

which can be simplified as:

$$PDC_{recovery}^T = [C_\Omega \Omega + C_W W + C_{SA} SA] + [(1-\omega)C_\Omega \Omega + C_W W + \mu C_{SA} SA] \sum_{t=1}^{T-1} \delta^{t-1} \quad (11)$$

Similarly, $PDC_{not\ recovery}^T$ which represents the present discounted value of cost stream from period $t = 1$ to period $t = T$ under the second scenario, is given by the following expression:

$$PDC_{not\ recovery}^T = [C_\Omega \Omega + C_W W + C_{SA} SA] + \delta [C_\Omega \Omega + C_W W + C_{SA} SA] + \delta^2 [C_\Omega \Omega + C_W W + C_{SA} SA] + \dots + \delta^{T-1} [C_\Omega \Omega + C_W W + C_{SA} SA] \quad (12)$$

which can be rewritten as:

$$PDC_{not\ recovery}^T = [C_\Omega \Omega + C_W W + C_{SA} SA] + [C_\Omega \Omega + C_W W + C_{SA} SA] \sum_{t=2}^T \delta^{t-1}. \quad (13)$$

To illustrate, we show the results from our numerical simulations for $PDC_{recovery}^T$ (given by equation (11)) and $PDC_{not\ recovery}^T$ (given by equation (13)) in Figure 5. The parameters used in our numerical examples are given in Table 1.

Table 1 Parameter values for numerical simulation

Parameters	Definition	Values
ω	Recovery rate of aluminium and sodium hydroxide	0.5
C_{Ω}	Cost of aluminium and sodium hydroxide	125.56 ⁶
r	Discount rate	0.04
μ	Additional proportion of sulphuric acid that needs to be purchased	0.15
C_W	Cost of water	0.006804
C_{SA}	Cost of sulphuric acid	32.22

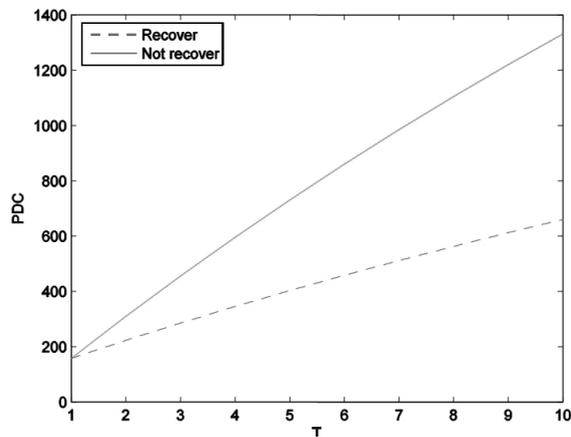


Figure 5 Results from numerical simulations for $PDC_{recover}^T$ and $PDC_{not\ recover}^T$

Based on the results shown in Figure 5, one can see that the cost saving, CS, which is the difference between the two lines, is increasing over time.

In what follows, we conduct a simple numerical analysis to find an answer to Question 2. We now want to find out whether the firm receives even more benefits by using the aluminium from the aluminium waste cans as an input in the production of hydrogen. To make the comparison interesting, we obtain the prices of some relevant types of aluminium wastes from Wongpanit Company (2011). This company is a well known buyer of recyclable wastes in Thailand. Among few types of aluminium wastes that Wongpanit Company typically buys from the public, two types are relevant for the purpose of comparison, namely the aluminium wire and the thin aluminium. To facilitate this analysis, we obtain the prices of sodium hydroxide and sulphuric acid used in the hydrogen production based on the aluminium-water reaction approach from Sigma-Aldrich (2008). Prices of these chemicals are in pound sterling. The water price is obtained from the Metropolitan

⁶ This is based on the costs calculated in Table 2 below.

Water Works Authority (2011). The amount shown in Table 2 is in domestic currency (Thai Baht, THB). The exchange rate used in the conversion is obtained from the Bank of Thailand (2011), and it is the weighted average selling rates of the Thai commercial banks. The exchange rate (THB/GBP) is 50.3430 THB/GBP (as of 30th May 2011). Please see Appendix 1 for more detailed explanation of the measurement units.

Table 2 Costs of inputs based on different types of aluminium wastes

Type of Aluminium Wastes	Price of Aluminium Wastes ⁷ (per kilo gram)	Price per Mole of Aluminium ⁸	Price per Mole of Sodium Hydroxide	Price per Mole of Water	Price of Sulphuric Acid	Total cost ⁹
Aluminium waste can	42 THB	1.16 THB	61.62 THB	0.001134 THB	32.22 THB	157.79 THB
Thin aluminium	45 THB	1.21 THB	61.62 THB	0.001134 THB	32.22 THB	157.89 THB
Aluminium wire	63 THB	1.70 THB	61.62 THB	0.001134 THB	32.22 THB	158.87 THB

With a slight modification applied to equation (6), we can calculate the present discounted value of cost associated with each type of aluminium, *i*, by using the following formula:

$$PDC_{re\ cover}^{can} = [C_{\Omega_{can}} \Omega_{can} + C_W W + C_{SA} SA] + [(1-\omega)C_{\Omega_{can}} \Omega_{can} + C_W W + \mu C_{SA} SA] \left(\frac{\delta}{1-\delta} \right) \quad (14)$$

$$PDC_{re\ cover}^i = [C_{\Omega_i} \Omega_i + C_W W + C_{SA} SA] + [(1-\omega)C_{\Omega_i} \Omega_i + C_W W + \mu C_{SA} SA] \left(\frac{\delta}{1-\delta} \right) \quad (15)$$

where *i* represents two other types of aluminium wastes that are used in the comparison.

To illustrate, we present some numerical results for the calibration of $PDC_{re\ cover}^{can}$ and $PDC_{re\ cover}^i$ in Table 3, based on $\omega = 0.5$, $\mu = 0.15$, $r = 0.04$, $C_{\Omega_{can}}$, C_{Ω_i} , C_W and C_{SA} , which are given in Table 2.

Table 3 Numerical results for the calibration of $PDC_{re\ cover}$ associated with each type of aluminium waste

Type of Aluminium Wastes	Aluminium waste can	Thin aluminium	Aluminium wire
$PDC_{re\ cover}$	1,848.28 THB	1,849.63 THB	1,862.86 THB

⁷ Prices as of 19th May 2011

⁸ According to an experiment conducted by Dr. Chamnan Random, following the approach used in Silva-Martinez et al. (2007), one empty aluminium waste can (Sprite) without ends give 8.173 grams of aluminium. After being dipped into a sulphuric acid (H₂SO₄) to remove paint and plastic films, 7.9686 grams of aluminium are obtained. The price quoted in Table 2 has been adjusted, taking into account this issue. It is important to note that using the can from other brand of soft drink can give very slightly different amount of aluminium.

⁹ This total cost is based on 3 moles of hydrogen production.

Instead of using other types of aluminium wastes –the thin aluminium and the aluminium wire– if the firm uses the aluminium waste cans, the firm’s cost savings are presented in Table 4 below.

Table 4 Cost savings for the firm based on the production of 3 moles of Hydrogen

Type of Aluminium Wastes	Thin aluminium	Aluminium wire
Cost Saving	1.35 THB	14.58 THB

From Table 4, it shows that the cost saving from using the aluminium waste can instead of other types of aluminium waste is not that huge; however, this calculation is based on the production of only 3 moles of hydrogen. In practice, firms that produce hydrogen for commercial purpose would definitely produce hydrogen at a much larger scale, thus the cost saving for the firms could be much higher.

Last but not least, let us consider $PDC_{recover,i}^T$ (a modified version of equation (11)), which represents the present discounted value of cost stream from period $t = 1$ to period $t = T$ associated with aluminium type i under the situation that the recovered resources are reused in the future rounds of hydrogen generation. The expression for $PDC_{recover,i}^T$ is given by equation (16):

$$PDC_{recover,i}^T = [C_{\Omega_i} \Omega_i + C_W W + C_{SA} S_A] + [(1 - \omega) C_{\Omega_i} \Omega_i + C_W W + \mu C_{SA} S_A] \sum_{t=2}^T \delta^{t-1}. \quad (16)$$

Figure 6 shows the results from our numerical simulations of $PDC_{recover,i}^T$ relative to $PDC_{recover,can}^T$ where $i =$ thin aluminium, aluminium wire.

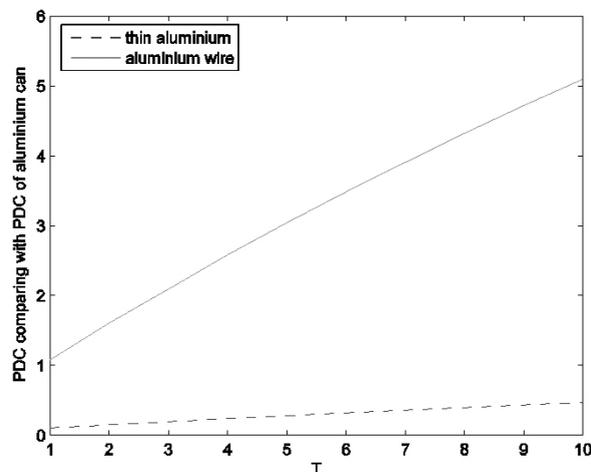


Figure 6 Results from numerical simulations of $PDC_{recover,i}^T$ relative to $PDC_{recover,can}^T$ where $i =$ thin aluminium, aluminium wire

Policy Implications and Concluding Remarks

In this section, we discuss some policy implications which follow from our analysis presented above. Thailand has encountered waste disposal problems for a long time. The amount of municipal solid waste (MSW) generated in Thailand in 2008 was 15.03 million tons (an increase of 0.25 million tons from 2007) or 41,064 tons per day (Pollution Control Department, 2008, p. 18). It was found that, in 2008, 3.405 million tons of MSW were used in various forms and had served different purposes: (1) 0.249 million tons (7%) were used to generate biogas; (2) 0.126 million tons (4%) were used to generate electricity and renewable energy; and (3) 3.03 million tons (89%) were recycled through different channels, such as community waste recycling centers, waste banks, etc. Since a sizable part of MSW can be recycled or reused for different purposes, cooperation among the general Thai public, private sectors, and NGOs should be enhanced so that the general public have greater interests to recycle the wastes and the private/public companies are encouraged to adopt an appropriate technology to make a beneficial utilization of waste such as energy generation. The Waste-to-Energy scheme should be promoted.

What do Thai people do with used aluminium beverage cans? Some Thai people sell used aluminium beverage cans to small or large buyers of recyclable wastes. Others recycle waste cans by inventing new art/craft products. As will be discussed in greater details in Appendix 2, some Thais donate aluminium cans to the Prostheses Foundation which produces prosthesis legs for poor amputees in Thailand, giving them an opportunity to walk again. It was recently discovered that aluminium waste cans could be used in the production of solar cell panel.

The key points put forward by this paper are consistent with the Waste-to-Energy campaign. By using aluminium waste cans as inputs in the production of hydrogen based on the aluminium-water reaction approach, this would help us tackle the waste disposal problems, reduce the air pollution (since the aluminium corrosion process which generates hydrogen is totally free of carbon dioxide, this method of energy production clearly dominates the steam reforming approach) and save the costs of energy production. Moreover, this process of hydrogen generation minimizes the use of virgin materials.

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Appendix 1

In this appendix, we provide greater information about the conversion from mole into grams and millilitres for those who are not familiar with this kind of measure. As an essential part of this conversion, one needs to find out the molar mass of the element or compound and this can be done by consulting the periodic table. The unit of the molar mass is in grams per moles (g/mole). Once one obtained the molar mass, this can be converted from grams to moles or moles to grams by using the following formulas:

$$\text{Number of moles} = \text{number of grams} \div \text{molar mass}$$

$$\text{Number of grams} = \text{number of moles} \times \text{molar mass}$$

To illustrate, let us convert 2 moles of aluminium into grams. We need to first find the molar mass of aluminium, which is 26.98. We then multiply the number of moles (i.e. 2 in this case) with 26.98, which is the molar mass for aluminium. We find that 2 moles of aluminium are equivalent to 53.96 grams.

Moreover, one can convert the volume into mass with the following formula:

$$\text{Mass} = \text{volume} \times \text{density}$$

Given that the density of pure water is 1, it follows that:

$$\text{Number of moles} = \text{volume} \div \text{molar mass}$$

Provided that the molar mass of water is 18.015, 6 moles of water is equivalent to 6×18.015 or 108.09 milliliters.

Appendix 2

During the past few years, the Prostheses Foundation under the Patronage of Her Royal Highness Somdej Phra Srinagarindra Boromarajajonani together with the Pollution Control Department have accepted donations of aluminium cans' lids from the Thai general public. The donated cans' lids have been brought to melt as the materials and components for the production of prosthesis legs to be given to the poor Thai amputees, giving them an opportunity to walk again and improving their quality of lives. The amount of aluminium cans' components donations in 2009 were 12.365 tons (Pollution Control Department, 2009), while the amount of donations for 2010 were 10.134 tons¹⁰.

Our policy recommendations based on the analysis in this paper are twofold. First, the general Thai public should be better informed about the usefulness from recycling the aluminium waste cans. To maximize the benefits from each aluminium waste can, each can should be separated into two parts: the ends of the can that are cut off can be donated to Thailand's Prostheses Foundation and the Pollution Control Department, and the rest can be deposited in the designated areas which will then be transported to the hydrogen-producing companies under the Waste-to-Energy scheme.

¹⁰ This information was obtained from the Pollution Control Department on 21st March 2011 as the Pollution Control Department Annual Report for 2010 is not yet available on public domain.