THE POTENTIAL OF HYDROGEN IN GREEN STEEL PRODUCTION

BY

KEAN LONG LIM*, KEE SHYUAN LOH**, SOFIAH MD AUZAIR***, ABU BAKAR SULONG****

SYNOPSIS:

The iron and steel (I&S) sector is among the largest industrial consumer of coal. Today, about 70% of the steel produced uses coal as metallurgical coke for iron ore reduction and fuel for heating. It is estimated that every tonne of steel produced emits approximately 1.85 t of carbon dioxide, which contributes approximately 7% (~2.6 Gt) of global carbon dioxide emission annually.

There is an urgent need to reduce the carbon emissions of I&S sector or the industry will have to pay for a hefty carbon tax not just domestically, but internationally, and a possible risk of products export restriction, if continue with business as usual. In addition, financial institutions are expected to factor in the climate-related financial risks and charged a higher lending rate to the high-emitting sector with poor environmental-social-governance (ESG) ratings. Green and affordable hydrogen could be a sustainable potential solution to substitute coal as burning fuel and reducing agent.

This paper presents an overview on the hydrogen technologies, how hydrogen can decarbonize steel production, preliminary feasibility study for hydrogen as substitution to coal, the relationship of hydrogen with the ESG of a company, and concludes with how hydrogen helps to maintain the sustainability of business operations.

Keywords: Hydrogen, Climate change, Decarbonization, Clean Technology, Sustainability, Carbon Pricing, Direct Reduction Iron, Green Steel

*Senior Lecturer/Research Fellow, Ph.D., Fuel Cell Institute, Universiti Kebangsaan Malaysia UKM Bangi, Selangor, Malaysia
**Associate Professor/Senior Research Fellow, Ph.D., Fuel Cell Institute, Universiti Kebangsaan Malaysia UKM Bangi, Selangor, Malaysia
***Associate Professor, Ph.D., Faculty of Economics and Management, Universiti Kebangsaan Malaysia UKM Bangi, Selangor, Malaysia
****Professor, Ph.D., Department of Mechanical and Manufacturing Engineering, Universiti Kebangsaan Malaysia UKM Bangi, Selangor, Malaysia

1.0 Carbon Emissions of Iron and Steel Sector

Globally, the iron and steel (I&S) sector is among the largest industrial consumer of coal and is responsible for about 7% (~2.6 Gt) of global CO_2 emissions annually. It is not surprising that the recent UN Climate Change Conference (COP26) has identified that the high-emission steel sector was among the four Glasgow breakthroughs agenda that required acceleration in developing and deploying clean technologies in the hope of limiting global warming to 1.5 °C by 2030. The aim for the steel sector is to make near-zero-emission steel the preferred choice in global markets, with efficient use and near-zero emission steel production established and growing in every region by 2030 [1]. Another breakthrough agenda was to make affordable renewable and low carbon hydrogen globally available by 2030. Coincidentally, both breakthrough agendas are a great complement to each other. Green and affordable hydrogen could be a sustainable source to substitute coal and coke as burning fuel and reducing agent. In fact, I&S sector could be the key enablers to bring down the cost of green hydrogen further because of its large consumption of hydrogen in producing green steel.

According to National Energy Balance 2018 [2], Malaysia's coal and coke consumption was 35 million tonne SKE, which could be translated into 88 million tonne of carbon dioxide emission (CO_2e) equivalent [3]. Coal is consumed extensively for power generation and industry, especially in the cement, and iron and steel industry. While renewable energy can reduce coal addiction in power generation sector and replace heating fuel, coal is still consumed as a raw material in I&S industry. Coal is used as metallurgical coke for iron ore reduction and fuel for furnace heating in the I&S industry, where both processes emit a significant amount of carbon dioxide (CO_2). Approximately 70% of steel produced uses coal in the production process. Malaysia steel production ranks 4th in ASEAN region and 23rd in the world, respectively [4]. Hence, there is an urgent need to facilitate the I&S industry towards zero-carbon steel production because the industry will possibly have to pay for a hefty carbon tax not just domestically, but internationally, and a possible risk of products export restriction, if continue with business as usual. In addition, financial institutions are expected to factor in the climate-related financial risks and charged a higher lending rate to the high-emitting sector with poor environmental, social and governance (ESG) ratings (i.e. I&S industry) [5]. With only 10 major I&S production plants with furnace facilities in Malaysia, the I&S industry is accounted for approximately 2% of national CO_2 emissions, and the emission is expected to grow over time because I&S is the basic necessity for industrialization and national economic development.

To have a clearer view on the carbon emission impact of I&S, we have estimated the carbon emission intensity of I&S industry and compared it with that of palm oil industry based on the 2021 biennial report submitted to Nations Framework Convention on Climate Change (UNFCCC) by Malaysia government [6]. The results are summarized in Table 1. In 2016, Malaysia's national emission density was 0.302 kg CO_2e/RM, whereas both I&S industry and palm oil industry were 0.225 kg CO_2e/RM and 0.206 kg CO_2e/RM, respectively. In other words, every Ringgit Malaysia earned from I&S industry contributes to 0.225 kg CO_2e, but its carbon emission density is 10% higher than that of palm oil industry based on I&S industry's GDP of 2.9%. Taking account into approximately 454 palm oil mills operation in Malaysia, reducing carbon emission intensity of a single I&S production plant is equivalent to that of 50 palm oil mills in average.

The effect on social cost that affects the environment and society health need not be ignored. The social cost of carbon emission is an estimation of the total welfare lost across the global caused by an emission of one extra tonne of CO_2e. The social cost of carbon emission calculated based on recent study by Kikstra et al. [7] is USD$300 per tonne of CO_2e. Taking the baseline of I&S sector carbon emission in Malaysia calculated at 7.245 million tonne CO_2e, the total social cost would be USD$2.17 billion if the emissions double. That is of course, not considering the increase occurrence of disasters and extreme climate events over the years. Reversely, the shift to green steel could potentially reduce the total emission by 95%, which can be translated into benefits of USD$2.06 billion. Therefore, decarbonizing the I&S sector will make a significant impact on Malaysia's national determined contribution (NDC) commitment to reduce carbon emission intensity against gross domestic product (GDP) by 45% by 2030 compared to 2005 [6]. Such effort is also in line with the 12th Malaysia Plan's target [8] to advance green growth through accelerating technology adoption and innovation.

Table 1 Estimation of Carbon Dioxide Equivalent Emission Intensity By Sector Based on the 2021 Biennial UNFCCC Report [6]

Malaysia Carbon Dioxide Equivalent Emissions Data		
National CO_2e emission (million tonne)	334.586	
National GDP (RM million)	1,108,935	
National CO_2e/GDP (kg/RM) @ 2016	0.302	
National target CO_2e/GDP (kg/RM) @ 2030	**0.292**	
	Iron & Steel Sector	**Palm Oil Sector**
GDP by industry (%)	2.9	6.1
GDP by industry (RM million)	32,159	67,645
CO_2e emission (million tonne)	7.245	13.928*
CO_2e/GDP by industry (kg/RM)	0.255	0.206

** Based on Palm Oil Mill Effluent (POME)*

2.0 Hydrogen Production Technology

Hydrogen itself is a colourless gas. The colour-coded classification of hydrogen is related to its source of hydrogen and production technologies. In general, there are three main stream colour-coded classification of hydrogen, namely brown/black hydrogen, blue hydrogen and green hydrogen [9].

Brown/black hydrogen is produced from fossil fuel (ranging from coal to natural gas) through stream reforming, autothermal reforming, pyrolysis and gasification technologies with no carbon capture and storage (CCS) facilities installed. These type of hydrogen production processes are by far the cheapest route to produce hydrogen and is the most widely applied hydrogen production process in the industry, especially the fertiliser industry, which is the main consumer of hydrogen globally. Similarly, blue hydrogen is also produced from fossil fuel, mainly through steam reforming of natural gas, but its by-product of carbon dioxide is trapped and stored via CCS facilities. Therefore, it is very important that the production site of blue hydrogen should have access to the low-cost natural gas and suitable underground reservoir. Blue hydrogen is seemed as the low-carbon approach to produce cleaner hydrogen and as a bridging technology to green hydrogen [10]. On the other hand, green hydrogen is produced from renewable energy sources such as wind, solar, hydro, etc. Renewable energies generate electricity which is then used to split the water into hydrogen and oxygen gases via electrolysis.

While the production cost of green hydrogen is still high, accessibility to competitive and affordable renewable energies could reduce the full cost of green hydrogen drastically. The second largest cost for green hydrogen production is the technology to split the water, namely the electrolysers. During the electrolysis process, hydrogen and oxygen are produced. There are three types of low temperature (operating temperature below 100 °C) electrolysers: alkaline electrolyser (AWE), proton exchange membrane water electrolyser (PEMWE) and anion exchange membrane water electrolyser (AEMWE) [11]. The main characteristics of these water electrolysers are presented in Table 2.

Table 2 Characteristics of Water Electrolysers

Electrolyser	**AWE**	**PEMWE**	**AEMWE**
Operating temperature (°C)	70-90	50-80 °C	40-60 °C
Operating pressure (bar)	1-30	<70	<35
Electrolyte	High concentration of potassium hydroxide solution (KOH, 5-7 mol/L)	Solid membrane	Solid membrane support with low concentration of KOH (1 mol/L)
Electrode (anode): O_2	Nickel	Platinum alloy	Nickel alloy
Electrode (cathode): H_2	Nickel	Platinum alloy	Nickel alloy
Volume footprint	Bulky	Compact	Compact
Efficiency	~70%	~80%	~75%
H_2 gas purity	2N	5N	4N

AWE is one of the reliable and mature water splitting technologies and it has been deployed for large-scale hydrogen production from renewable energies. In alkaline environment, water is reduced by electrons to produce H_2 and hydroxyl ions (OH^-), then the OH^- transfers through the alkali electrolyte and a porous separator to the anode and is oxidized to produce water and O_2. The AWE is a relatively affordable technology because non-precious metal electrocatalysts that show favourable electrolysis performance in alkaline environment, can be used in the water splitting. However, AWE is inherently difficult to shut down/start up, contains corrosive concentrated alkaline aqueous electrolyte and requires consistent and stable power supply during operation [12].

Contrary to the AWE technology, PEMWE replaces the liquid electrolyte with a solid electrolyte membrane. In addition, proton (H^+) is responsible for charge transfer in PEMWE instead of OH^-. Water is split into oxygen and protons by platinum-based catalyst at the anode side. Next, the H^+ transfers through the solid electrolyte proton conducting membrane and recombine with electrons to form hydrogen at the cathode side. Typically, PEMWE is more costly than AWE due to the use of noble metal catalysts, titanium- based components and expensive coating materials [13-14]. Both AWE and PEMWE technologies are commercially available.

Meanwhile, AEMWE has a high potential to be the next generation water electrolyser but is much less mature technology compare to the former two. AEMWE consists of an anion exchange membrane sandwiched between the anode and cathode electrodes. Two half-cell reactions: the hydrogen evolution reaction (HER) and the oxygen evolution reaction (OER) are taking place at the cathode and anode, respectively, in the membrane electrode assembly. AEMWE leverages on the low-cost characteristics of AWE and the efficient and compact design of PEMWE, which make it a great option to reduce both capital expenses (CAPEX) and operation expenses (OPEX) in producing hydrogen via water electrolysis [15-17]. It is estimated that the investment cost of AEMWE could be 20% or more lower than that of PEMWE [18]. The trade off point is its inherently sluggish kinetics because the charge transfer through OH^- ions is slower than that of H^+ ions in PEMWE. The electrolysis mechanism is similar to that of AWE, except that the liquid electrolyte and separator are replaced with a solid anion conducting membrane. Hence, a thinner and higher change density membrane with good chemical and mechanical stability is the key challenge to be addressed. Figure 1 summarises the reaction mechanisms and electrolyser configurations of AWE, PEMWE and AEMWE.

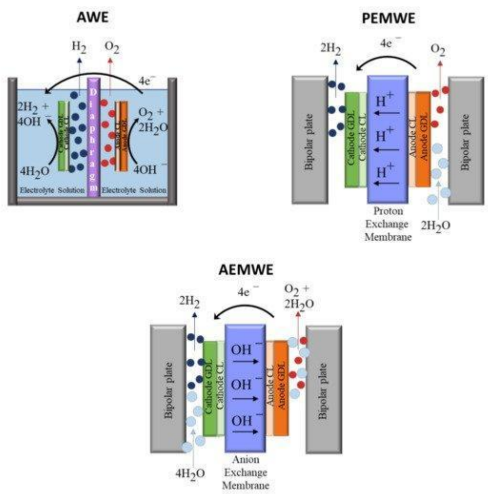

Figure 1 A Schematic Illustration of Operating Mechanisms of AWE, PEMWE and AEMWE [11]

3.0 Substitution of Coal with Hydrogen in Iron and Steel Production

The conventional route of iron making is to mix coking coal with iron ores, and the mixture is heated in a blast furnace with hot air to remove the oxygen from the iron ores. The main reaction equations are shown below. As can be seen from the equations, enormous amount of CO_2 is produced during the reduction process. On average, the production of 1 tonne of steel emits 1.85 tonne of CO_2.

$$C(s) + O_2(g) \rightarrow CO_2(g) \quad \text{Eq. (1)}$$

$$C(s) + CO_2(g) \rightarrow 2CO(g) \quad \text{Eq. (2)}$$

$$Fe_2O_3(s) + 3CO(g) \rightarrow 2Fe(l) + 3CO_2(g) \quad \text{Eq. (3)}$$

Eq. 3 also indicates that carbon monoxide (CO) is the main reducing agent and it is produced from the coking coal. The reducing agent can be replaced by carbon free sources, such as hydrogen as shown in Eq. 4, carbon emission during the reduction process can be avoided at large. If the process is coupled with a green hydrogen source, then the overall iron and steel production can be considered as zero carbon emission, and the product can be known as the green steel.

$$Fe_2O_3(s) + 3H_2(g) \rightarrow 2Fe(l) + 3H_2O(g) \quad \text{Eq. (4)}$$

Gas-based reduction process is not foreign to the I&S sector, where such reduction process is well-known as direct reduction iron. Reduction gas, usually methane or hydrogen, is fed into a shaft furnace to reduce the iron ore below the melting point of iron. The sponge iron product is in the form of direct reduced iron (DRI) or it can be further compressed to hot briquet iron (HBI), which can be processed into steel grade products in an electric arc furnace (EAF) [19]. Figure 2 shows a comparison between steel production through conventional (using coal) and green hydrogen routes.

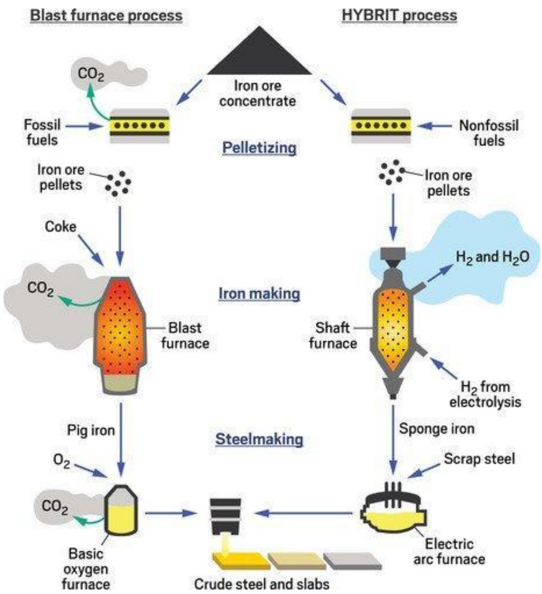

Figure 2 Conventional and Green Hydrogen Route to Produce Steel [20]

The world's first hydrogen DRI pilot plant, known as Hydrogen Breakthrough Ironmaking Technology (HYBRIT), was launched in 2016. This pilot plant is a joint initiative by three Swedish companies: SSAB, LKAB and Vattenfall, and it has successfully produced the first batch of green steel to AB Volvo to produce prototype vehicles and components. Apart from the HYBRIT process, the other two commonly used gas-based DRI processes – MIDREX and HYL III/ ENERGIRON – also have the capability to utilise 100% pure hydrogen in the shaft furnace. While the potential of hydrogen can be maximised with a shaft furnace, ThyssenKrupp Stahl AG in Germany has successfully demonstrated a direct injection of hydrogen into a blast furnace (BF) to partially offset the coal consumption [21]. According to the company, their target was to reduce CO_2 emission by 20% in BF. The hydrogen was supplied by a gas pipeline by Air Liquide that produced hydrogen from a PEMWE. Regardless of the type of furnace used, an efficient and affordable water electrolysis system is needed to produce green hydrogen from renewable sources and to minimize the carbon footprint.

4.0 Feasibility of Hydrogen in Iron and Steel Production in Malaysia

As a preliminary estimation, a comparison between the raw materials prices of coal and hydrogen is made in Figure 3. The comparison is made with the range of coal price for the past 10 years, by taking the minimum cost of RM 212.96/t (USD$ 48.40/t) and maximum cost of RM2,014.32/t (USD$ 457.80/t), at a conversion rate of USD$1.00 equals to RM 4.40. It is estimated that approximately 0.6 tonne of coal is needed to produce 1 tonne of steel, hence the lower and upper coal cost boundaries to produce 1 tonne of steel are RM 127.78/t and RM 1208.59/t, respectively. Then, we superimposed the cost of hydrogen to produce a tonne of steel based on the industrial E3 electricity tariff by Tenaga Nasional Berhad (TNB) [22]. Approximately 55 kg of hydrogen is required to produce 1 tonne of steel, which is equivalent to approximately 3 MW of electricity. We found that the cost of hydrogen is in the range of RM 11.11/kg H_2 (off-peak) to RM 19.52/kg H_2 (peak), which is equivalent to RM 611.05/t to RM 1073.88/t of steel. It can be seen that by comparing with the peak coal cost of RM 1,208.59/t and the range of hydrogen cost as the raw material to produce 1 metric tonne of steel, hydrogen could potentially save up to 59% of raw material cost with zero environmental cost, not mentioning the recent weakening of Ringgit Malaysia to US dollar.

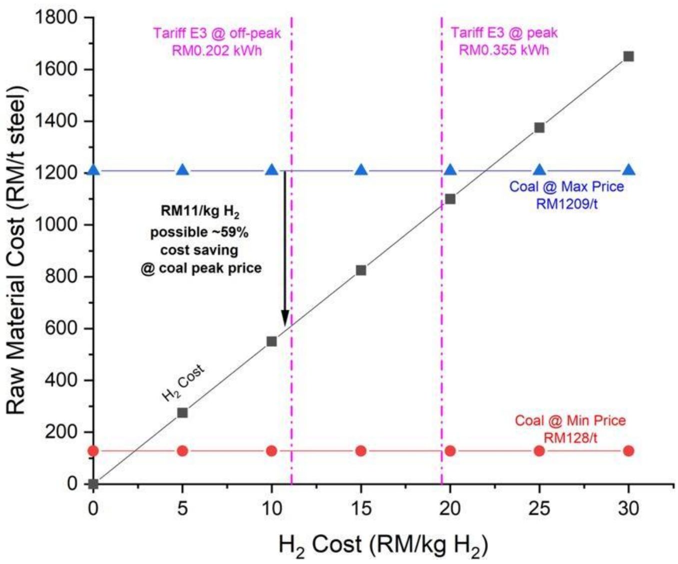

Figure 3 Comparison of Raw Materials Cost Between Coal and Hydrogen (Conversion rate USD$1 = RM4.40)

In addition to the raw material cost benefits, shifting to hydrogen in I&S production could also potentially mitigate the risk of coal price hike caused by supply-chain disruption, such as the recent coal export restriction by the Indonesian government because water (the raw material for green hydrogen) and renewable energies could be sourced locally. Coupled with long-term renewable energy power purchase agreement (PPA) model, the I&S sector could forecast utilities far more accurately, which enable the I&S sector to reduce its dependence of coal import, has better controlling of its production cost and eventually maximise its profit.

Carbon tax has been included in the 12th Malaysian Plan (2021-2025), which will inevitably increase the cost of coal usage across all sectors. Although, to date, the government has yet to announce the carbon tax framework, Penang Institute has proposed an introductory rate of RM 35/t CO_2e and subsequently increase to RM 150/t CO_2e by end of 2030 in year 2019. This carbon tax will increase the coal cost by RM 67/t to RM285/t (by 2030). Accordingly, this carbon tax is translated into an annual commitment of RM 254 million and RM 1.1 billion (by 2030), respectively, for the I&S sector. I&S industry should aim to repurpose this estimated carbon levy to invest in projects that could improve their ESG ratings and explore new clean business opportunities. Early adopters could also consider to adopt the voluntary carbon market (VCM) exchange which will be launched soon by Bursa Malaysia end of this year to earn and sell carbon/regulatory credits as a means to offset their OPEX. BloombergNEF [23] has predicted that green steel could capture 31% of market share by 2050.

5.0 Conclusion

As the ESG movement is increasingly important in the world of business and investment, green hydrogen could be a game-changing tool to decouple I&S and its down-stream industries from coal usage, making the business more sustainable and remains relevant with the change of the time. More importantly, removing carbon emission from I&S sector supports the Malaysia's pledge to reduce carbon emission intensity by 45% by 2030. It is expected that a complete transition towards zero-carbon steel and iron production would reduce the national carbon emission by 2-3%.The rise electric vehicle is expected to drive demand of steel. It is believed that green steel will play a vital role to make electric vehicle a truly 'green' product. Nevertheless, green hydrogen production is still expensive due to costly renewable electricity and small-scale electrolyser. High volume of hydrogen consumption by I&S sector could potentially drive down the production cost and accelerate the adoption of hydrogen economy.

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