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CLIMATE CHANGE IN INDONESIA: GREEN STEEL*

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Abstract: Most studies of Indonesian Green House Gas (GHG) emission deal with land, forestry, electricity and construction, and exclude iron and steelmaking as such, which emits a sizeable 2.75t CO_2equivalent/ton of steel. This paper focuses on GHG emissions of Indonesian iron and steel industry, now existing and under construction - and that projected to 2060. It gives actual steps of how to start reducing the industry's GHG immediately using charcoal and employ ordinary people in environmental plantations and help poor people in towns and villages to earn some money by buying wood cuttings from them and processing it in distillation plants. It considers Indonesian ways and culture. There is no modelling of any process and activity, so everything can be checked from first principles or by reference to the source. One contentious conclusion is that to reduce the steel industry's GHG to near zero, it is imperative to use nuclear energy. Its use in Indonesia has been committed to by President Prabowo at the G20 Summit in Brazil in November 2024 and its actual start with 29 reactors was announced the following month (December 2024). This elicited immediate protests with a slogan of: "Indonesia bukan Chernobyl". A useful response by the government could be: We strongly agree. We are also Indonesians. That is why we will build a Mitsubishi gas reactor, because it is impossible for such a reactor to melt down like the Chernobyl reactor.

Keywords: Indonesia, green steel, direct reduction, plantations, biomass, nuclear power, Near-zero emissions, International Energy Agency (IEA), 2020 average emissions, World Steel Association.

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1. Introduction

At the G20 Summit in Brazil in November last year (2024), President Prabowo emphasized Indonesia's commitment to achieving net-zero emissions by 2050 (later corrected by others to Jokowi's 2060 net-zero emissions). President Prabowo outlined an ambitious strategy to build 75 Gigawatts (GW) of renewable energy, including geothermal, wind, and solar, along with 5 GW of nuclear power. The real plan is to gradually reduce coal dependency, rather than immediately shut down coal plants.

Patunru and Resosudarmo (2024), in a detailed and well documented paper, show that in Indonesia, land use and forestry is by far the largest Green House Gas (GHG) emission source at 950 million tonnes per year (mty) of CO_2e (CO_2equivalent), electricity and heat as second (350mty CO_2e) and manufacture and construction as fifth (150mty CO_2e). Iron and steelmaking, as such, are not mentioned, so this paper may be viewed as new information. It is noted that Agriculture, Forestry, and Other Land Use, (AFOLU), unlike in Indonesia, is not the largest GHG emissions contributor globally, but second largest, after electricity and heat production. The sector accounts for around 23% of global GHG emissions, Rocha et al (2021).

Blast Furnace-Basic Oxygen Furnace (BF- BOF) steelmaking route emits 2.75t CO_2e/ton of steel and Electric Arc Furnace (EAF) emits 1.71t CO_2/ton of steel, Kullman, (2023). Therefore, at today's Indonesian BF-BOF steelmaking of 9mty and the same of EAF steelmaking, Indonesia produces 24.8mty CO_2e, and 15.3mty CO_2 from EAF, making a total of 40.1mty CO_2e. Indonesia is on track to reach 45mty of steel by 2035, IISIA (2022) and on a 50-50 basis produce 100.4mty CO_2e, – a big enough proportion of the total emission to make sizeable difference.

Indonesian developments show backtracking to the traditional BF-BOF route, compared with two neighbouring countries which show significantly higher EAF investment compared to Indonesia's 1.7mt, Vietnam of 17.2mt and the Philippines of 12.8mt, or both over 10-fold, daCosta (2024).

Once all Indonesian iron and steel projects are completed, national capacity will increase by 125% for steelmaking and 55% for ironmaking. Out of the 24.5mt steel-making capacity in the pipeline, 22.8mt are using BOF, contradicting net zero commitments, and, as noted above only 1.7mt are using EAF. Meanwhile, from the 5.8mt of ironmaking expansion in construction now, all use BF, daCosta (2024). To achieve zero CO_2 by 2060, steelmaking – especially the BF-BOF route, being a very big emitter of CO_2, needs to be "greened" as quickly as possible, and completely so by 2060. In this "greening" activity, hydrogen plays a dominant role.

There are three commonly distinguished hydrogens: Green, Blue and Grey. Green produces no CO_2, Blue is made by steam reforming of natural gas with CO_2 capture, and Grey is produced in the same way, but without the CO_2 capture. Unit costs are the highest for the green hydrogen and lowest for the grey one. This paper examines how it can be done under actual Indonesian conditions, culture and social habits. The examination is based on basic fundamentals of theory in the Appendix, and the author's practical experience of 50 years, including 15 years in PT Krakatau Steel, Cilegon Plant.

2. IRONMAKING

Analysis of ironmaking processes used in various parts of the world show that currently (2024) there are just two main processes, Blast Furnace (BF) and Direct Reduction Iron (DRI). BF ironmaking is generally followed by BOF, and DRI is followed by EAF – thereafter, refining, casting and rolling to make coils, plates, billets and other steel products are identical in both cases.

The current world production of steel is nearly 2 billion tonnes per year, equating to some 1. 7 billion tonnes per year of iron. The BF-BOS route accounts for about 75% of that – the rest, mainly by shaft DRI reactors of which Midrex reactors are the most numerous.

Blast furnace sizes these days range from 2mty (million tonnes per year) to a few of 5mty. So, to just compete, any "green iron" reactor has to be in the same size class. Of all currently operated DRI reactors, the shaft reactors have a proven record over many years – and size-wise only Midrex Megamod, at 2.5mty is by far the biggest. It is noted that a fluidised bed reactor that has operated in Korea on an industrial basis is the Posco's FINEX, with 2mty of DRI.

Indonesia currently produces about 18mty of steel, of which about half uses molten iron from blast furnaces, Kullman (2023), so if Midrex Megamods are chosen, then four would be sufficient.

As already noted, the use of green hydrogen for DRI production, followed by green EAF melting, is now being strongly promoted in many countries.

Except for small amounts for special uses, there are as yet (2024) no tonnage hydrogen producing plants as such, in Indonesia, but PT PLN has combined with PT HDF, with the aim to produce hydrogen using water electrolysis, for power generation in Pulau Seribu to replace a 500 MVA diesel plant, SAMATOR (2024).

Also, in November 2022, PT Gunung Raja Paksi (GRP) and Australia's Fortescue Future Industries (FFI) signed an MOU to investigate the use of green hydrogen to help decarbonize GRP's steelmaking factories. According to The Jakarta Post of November 6, 2023, the company aims to replace natural gas with hydrogen sourced from FFI.

There has been a follow-up to this of a $60m loan from the International Finance Corporation (IFC) last year (2024) that also includes exploring different financing options to support GRP's decision to entirely decommission the company's newly built but never operated blast furnace, IFC (2024).

If this decision to decommission a newly built blast furnace is to help reduce GHG emission – and not as by Krakatau Steel, because as its then Dirut, Silmy Karim said its BF is uneconomic, Karim (2022), then Indonesians should be optimistic of reaching zero carbon by 2060.

As the blast furnace produces big amounts of molten iron in a short time, it needs to be replaced with something as productive, but very much greener, that is, with much less CO_2 emission but about as economic. Let's also keep in mind here that the only true economics is the totality of Run Of Mine (ROM) ore cost, grade processing, agglomeration, reduction, melting, refining, casting and hot rolling to end-products of Hot Rolled (HR) coils, plates, and such like.

So, we can now make a conclusion that barring a large economic superiority and accelerated start of Posco's HyRex hydrogen fluidised bed reactor, Indonesian green steel production will follow the DRI – EAF, or DRI – ESF route using Midrex (Megamod) reactor and as much green hydrogen as the LeChatelier's principle and the economics allow. .

ESF stands for Electric Smelting Furnace – a very recent project by BHP and others, designed to use the more plentiful lower grade iron ores of Pilbara, WA. Unlike EAF, ESF operates continuously producing molten (pig)iron, which is then processed as currently, namely, refined in BOF, cast into billets and slabs and rolled to produce products for sale. It has been tested in New Zealand and in December 2024 a 40,000 tpy pilot plant was about to be built in Western Australia. Its GHG emission has not been indicated by BHP, or by others.

Next, we have to decide on how this DRI-EAF route may be carried out in Indonesia economically and safely in practice with minimum compromises. Unfortunately, there are immediate problems.

Indonesia is a big country. One problem associated with this and identified by Pak Thohir in BUMN News 12/12/24, is: "Indonesia merupakan negara yang besar, sehingga masalah transportasi yang harus diperbaiki bukan hanya angkutan udara."

Another problem is, as of September 2024, 93 of the country's 201 coal plants supply energy to sectors like mining and smelting. While critical for industrial growth, these plants contribute significantly to emissions, complicating Indonesia's path to greener energy, Bimo (2024).

Out of these, 33 plants in Central, South, and Southeast Sulawesi power Chinese-owned nickel smelters, fuelling a key part of the global electric vehicle battery supply chain. This underscores China's strategic involvement in Indonesia's nickel processing sector, leveraging coal power to drive industrial operations, Bimo (2024). These power facilities are indispensable for processing nickel ore but rely on coal and therefore, as above, add significantly to GHG emissions.

Coupled with this is a note that "Adding 75 GW of renewable energy by 2040 will only generate fossil-free electricity for about 35% of projected national electricity demand. To meet President Prabowo's vision, Indonesia must more than double this target", Tachev (2024).

Indonesia's internationally agreed Nationally Determined Contribution (NDC) and Control of Carbon Emissions in Development (CCED), regulations serve as the legal framework for domestic carbon pricing regulations intended to help Indonesia meet the climate targets to reduce greenhouse gas emissions and adapt to climate change. Indonesia's NDC includes targets to reduce emissions by 31.89% unconditionally and 43.2% conditionally by 2030, UNDP (2022). The NDC also includes targets to restore 2 million hectares of peatlands and rehabilitate 12 million hectares of degraded lands. NOTE: Carbon emission targets with decimal points are always interesting!

Other problems are: Developing green steel can take five to six years just to get official permission, driven by lengthy approval and planning processes. Long lead times and regulatory uncertainty can deter investment in energy projects.

The status of the Indonesia's iron and steel industry in the last few years is, paradoxically, – a jump from a 17th exporter in 2019 to world's 4th biggest in 2023 and also an importer of about the same amount, USDC (2023).

This makes decarbonizing the Indonesian steel industry even more important because steel exports to the European Union will be charged "carbon tariff" via Carbon Border Adjustment Mechanism (CBAM), effective next year (2026), if the suppliers cannot prove that the steel is "green". This will have a negative effect on the exports of the Indonesian steel industry. For this reason, the steel industry needs to undergo transformation to a GHG emission-free industry.

Farid Wijaya of IESR, explained that decarbonization for the steel industry will bring prospects for economic growth, although currently (2024) there are still quite a lot of challenges. There are also national laws and rules and international ones to which Indonesia is a signatory, that have a bearing on Indonesia's march to zero carbon by 2050/60.

CSR (Corporate Social Responsibility) is mandatory as mandated under Company Law and GR 47/2012, any company must implement CSR to comply with Indonesia's prevailing laws and regulations.

Mandatory Carbon Reporting is the law in 40 countries across the World. AASB S2 Climate-related Financial Disclosures and metrics and targets, including information about scenario analysis and Scope 1, Scope 2 and Scope 3 greenhouse gas emissions, where:

- Scope 1: Direct emissions from sources owned or controlled by the company.
- Scope 2: Indirect emissions from the purchase and use of energy, such as electricity, steam, heating, and cooling.
- Scope 3: All other indirect emissions that occur in the company's value chain, including both upstream and downstream emissions.

However, IFRS (International Financial Reporting Standards) Sustainability Disclosure Standard IFRS S2 Climate-related Disclosures issued by International Sustainability Standards Board (ISSB) is important, as non-compliance with IFRS standards can create barriers to cross-border capital movements, making it challenging to attract international investors or secure business credit. Indonesia is preparing to join IFRS S2.

Related to the economic issues in Indonesia is the observation that Indonesia's economy grapples with challenges like dependence on natural resource exports, infrastructure gaps, regional disparities, and a need for skilled labour. Corruption, complex regulations, environmental issues, and income inequality also impede growth, Triatmanto and Bawono (2023).

To sum up. Currently, the domestic steel production capacity is 27mty (million tonnes per year) and is increasing, and on track to reach over 45 million by 2035 and planned to be 207mty by 2060 with associated carbon emission if nothing is done, of an eye-watering 600mtCO_2, Fathurrahmi and Wardhana (2024).

Clearly this is unacceptable, and the industry must decarbonize to reach the zero carbon by 2060.

There are already many good rules, steps and lists of activities that would normally be included in such projects, such as the World Economic Forum's, Energy Transition, giving a framework built around four key solutions to help reduce carbon emissions in industrial clusters. They are: 1. Systemic efficiency and circularity; 2. Direct electrification and renewable heat; 3. Hydrogen, and 4. Carbon capture, utilization and storage (CCUS). Please note that hydrogen is a key solution, too.

We will not repeat them here, but instead propose decarbonizing steps for iron and steel industry in Indonesia considering Indonesian culture and traditions and typical

Indonesian ways of doing things – recognising, as noted by Patunru and Resosudarmo (2024), that "a uniform national policy may not work universally across regions".

The EAF way of steel production is the green steel way, if – and only if, the electricity for melting, casting and rolling to make steel products, eg coils, sections and bars, comes from GHG-free sources.

INDONESIAN IRON AND STEEL INDUSTRY

Indonesia has nearly 50 years of experience producing DRI, melting it in EAFs, casting and rolling – starting as Krakatau Steel in 1976 with a simple HyL1 batch process plant and ending with the high-technology, high pressure HyL3 process. For many years, the reducing gas was made by nickel catalysed steam reformed natural gas, but recently this was replaced by the "zero reformer" process, in which the heated natural gas, injected into the reactor where its in-situ reforming is catalysed by the freshly reduced iron.

Because Midrex reactors operate at ambient pressure, efficient in-situ reforming is still being investigated. This means it still needs external reforming of natural gas.

For economic reasons current Midrex practice is to do it with recycled top gas water and CO_2, even though the reaction is endothermic. However, if plentiful oxygen is readily available – which would be its case as a by-product of water electrolysis of making reduction hydrogen – it will be a big plus because oxygen reforming of CH_4 is exothermic,

$$CH_4 + \frac{1}{2}O_2 \rightarrow CO + 2H_2 + \text{heat}$$

Oxygen reforming requires a smaller reactor vessel. Exothermic also means that we will not need as much energy in preheating the reduction gas before it is injected into the reactor.

It is noted that in 1995, the partial combustion technology according to the above equation was incorporated in the HYL3 plant in PT Krakatau Steel, by injecting O_2 at the transfer line between the reducing gas heater and the inlet of the reduction reactor. This scheme allowed an important increase in the reducing gas temperature, as well as in-situ reforming. This decreased the reformed gas consumption by around 25 % and increased the productivity of the shaft furnace. In 1998 the total natural gas feed and O_2 injection to the shaft furnace led to the 'HYL self-reforming scheme', where the reformed gas make-up was reduced to zero.

As was said earlier; to reduce our carbon footprint, we must use "chemical hydrogen". Of course, if it is economical to have hydrogen for energy also, we can use it there, too.

Hydrogen is assumed to be produced through electrolysis using low emissions energy.

Until low carbon hydrogen is readily available, DRI shaft furnaces, like HyL and Midrex can use natural gas as a transition pathway.

Typical reformed gas into the reactor is: H_2 – 70%, CO – 15%, CO_2 – 10%, CH_4 – 5%, and the exit gas is: H_2 – 40%, H_2O – 20%, CO – 20%, CO_2 – 15%, CH_4 – 4%, N_2 – 1%.

H_2O and CO_2 in the exit gas are scrubbed away and about 2/3rd of H_2 and CO are recycled as reducing gas and the rest used as the heat source for gas preheating. Currently, H_2O and CO_2 are partially recycled, and the rest of CO_2 is sold.

The production of green DRI formally requires replacing the reformed gas with 100% green hydrogen. This will produce carbon free DRI, aligned with the first requirement of theory of making iron, but against the practical experience of DRI operators and EAF steelmakers.

Reasons for having carbon in DRI are: 1) pure iron DRI is pyrophoric and having carbon in it, usually as a cementite (Fe_3C) surface, will prevent spontaneous fire of DRI; 2) melting in EAFs needs foamy slag to reduce consumption of expensive graphite electrodes and wall refractories, and, of course, making high carbon steel; 3) If CO is also added to the DRI bed, the resulting exothermic reactions provide extra energy to counter endothermic reactions.

It should be said that EAF steelmakers would like to use DRI with about 4%C. In my view, to ensure all of the above 1) – 3), DRI carbon should be around 2%.

EAF gases contain significant amounts of chemical and sensible heat that is currently not recovered because of the batch or periodic nature of the process. On average, the gases contain about 20%CO and 5%H_2, as well as various amounts of CO_2, O_2 and N_2, depending on the practice used. Additionally, there is always steam formed from the water-cooling parts of the EAF.

In green steel making, recovering anything useful that can reduce the use of fresh material, is most important, so EAF's sensible heat and CO and H_2 gases will be recovered.

It is possible to design the DRI process for a zero-make-up water requirement mainly because water is a by-product of the reduction reaction ($FeO + H_2 = Fe + H_2O$) and is condensed and removed from the gas stream. As a consequence, with the adoption of a closed-circuit water system based on the use of water heat exchangers instead of conventional cooling towers, there may be no need for fresh make-up water and actually a small stream of water may be left available.

As to using much H_2, Midrex has reported that it has experience using various reducing gases with H_2/CO = 0.5 to 3.5 in commercial plants and using reducing gas with H_2/CO = 4.2, in a pilot plant.

3. RESULTS AND DISCUSSION

It has been demonstrated that to reduce Indonesia's Green House Gas (GHG) emission, it is worthwhile reducing it as such in the steel industry, as well as to avoid the steel exports from having tariff applied if the steel is not "green".

Because Indonesian steel industry has many years of experience of producing about 2mty of DRI pellets in a shaft reactor and melting it in EAFs in Krakatau Steel Plant in Cilegon and melting about another 10mty of scrap in EAFs in many other plants in Indonesia, there is no need to start with a pilot plant – instead, go directly to full size. Except for tonnage hydrogen, all other parts already have government regulations.

The Ministry ESDM has been in the process (2024) of drafting regulations on incentives and tax relief to green hydrogen developers, aiming to speed up the growth of the country's green hydrogen industry. In addition, the government is also evaluating a national hydrogen strategy expected to reduce fossil fuel usage, Dokso (2024). Actually, the government has just (May, 2025) launched the National Hydrogen and Ammonia Roadmap (RHAN) 2025–2060 as a derivative of the national hydrogen strategy. According to the Minister of Energy and Mineral Resources Bahlil Lahadalia the roadmap should be an opening signal to create a market and attract investment.

Whilst waiting for the implementation of the above RHAN roadmap and actual production of hydrogen, Indonesia can start building shaft furnaces of Midrex size, and companies with blast furnaces can start investigating the economics of altering them into DRI reactors – and if tonnage hydrogen is still not available, reforming natural gas and using it in the reactor, AND not allowing any CO_2 to escape, thereby ensuring production of "green" DRI.

What is envisaged is a single national charcoal industry consisting of biomass/wood processing plants and three wood supplying parts: 1. Plantations designed by a team of environmental scientists, arborists, forest scientists, agronomists, town planners AND Rural Fire Service (RFS) modelled on Australian RFS and its Volunteer part – all importantly under one minister! Maybe Transmigration and its Patriot Scholarship programs (22 October 2024 Antara Press) could also participate; 2. City and town councils' horticultural departments; 3. Corner drop-off places where ordinary people can bring bundles of wood to sell.

In plantations the workers will live in town planners' villages built for the purpose, presumably with schools ("SD" and maybe "SMP"), shops, "Puskesmas", fire stations and village office. Depending on the plantation design team's advice, after the initial mechanical planting of millions of appropriate trees, workers will use only "cangkul" and manual handling to do the rest, like clear the weeds and prune the branches to send to the nearest distillation plant. It is of interest to note Setiawan and Iswati's (2019) research finding that receiving a PROPER Award "have affected positive and significant impacts carbon emissions in the plantation industries."

City and town councils have many parks and trees on roads and streets that need pruning all year round. The clippings and cuttings that before were burned, will now be taken to a central store via a weighbridge, for sorting and compressing and transported to the nearest distillation plant.

In corner drop-off places ordinary people will bring wood on motorbikes; when sufficient volume is collected it is transported to local storage centres; when sufficient volume is collected there, it is transported to the nearest biomass distillation plant. These drop-off places will have weighing balances and "one-way-in" designed wood receivers from which no wood can be stolen and resold. To prevent people saturating the wood and leaves with water to increase the weight to sell it and get more money, will be told "we don't buy wet wood, go back home, dry it in the sun and then come back". There will also be CCTV to watch that no money is pocketed by the drop-off government wood buyers. Naturally, the town council workers may bring some of the council clippings to sell in spite of each truck being weighed there, and this is something to watch against as it is impossible to ever stop.

These activities of helping poor people in towns and villages to earn some money, will be seen as being the same as the objective of Patunru and Resosudarmo (2024) of eradicating poverty.

Biomass is a clean, renewable energy source with CO_2 emission close to zero. Its use in Indonesia is already covered by existing government laws and regulations, so we can go directly to our distillation and production of charcoal for green steel, and a range of chemicals for sale, and syngas that can also be used instead of natural gas for "green DRI" making.

There is a net zero emission, self-sustaining exothermic pyrolysis technology making high-grade green charcoal/biochar for metallurgical use, MetChar (2024) that would be just right for Indonesian conditions.

In making "green steel", charcoal will be used for: 1) making CO, 2) converting CO_2 to CO, 3) purifying recycled water for electrolysis, and 4) selling any excess to gold mines for CIP treatment.

Making CO with carbon of some sort is an old process of making town gas in so called "gas works". Converting CO_2 to CO, is the endothermic Boudouard reaction ie. $CO_2 + C = 2CO$. Purifying water is an everyday process in homes and towns and using charcoal for CIP (Carbon-In-Pulp) recovery of gold, is a lucrative business.

At first, before hydrogen making by electrolysis starts and its by-product oxygen becomes available to take care of heat deficiencies in the DRI reactor and converting CO_2

to CO, some CO_2 in the top gas will not be converted, but be sold, as is the current practice in PT Krakatau Steel.

The above processing steps take care of making "green DRI". Apart for the normal power use to operate pumps, blowers, pellet feeding equipment and process control equipment, this "green" step does not require any electric power for iron oxide reduction itself.

This is so very different to the next step of EAF melting, which is opposite, that is, it requires most of the power used for the main part of melting. In the steel making industry, EAFs are considered as one of the operations with the largest consumption of electrical energy, Logar and Shkrjank (2021).

For melting DRI in EAFs, the best that can be expected with all the energy saving additions and hot charging, is about 500 KWh/tls (ton of liquid steel). For its current production of about 18mty of steel, Indonesia will need to generate 9,000,000,000 KWh or have a power station of 1,000 MW capacity. For complete processing to steel bars, coils, plates, etc, add another 1,500KWh/t, making a total power generating capacity of 6,000 MW. As Indonesia is on track to reach 45mty of steel by 2035 this will require 135x1015KWh day and night, or a power station of 15,000 MW.

If all of the 135x1015KWh required is to be supplied by solar, wind and hydro and have power available at night and 24/7, the number of batteries to achieve it is astronomical. The sheer area required for solar panels, wind turbines and batteries is astronomical, too, and the total cost of all this is astronomical also. Then think of the projected 207mty of steel by 2060 – more panels, more batteries and more wind turbines – and much2 more of land to put them on. No people in any country would agree to this being done and pay for it – climate change, or not!

Current knowledge and experience suggest that nuclear energy can be the answer. In fact, as noted in the first paragraph of this paper, "At the G20 Summit in Brazil last year (2024), President Prabowo committed Indonesia to include 5 GW of nuclear power in achieving net zero emission." As noted above, to make Indonesian steel on track to reach 45 mty by 2035 "green" by using this nuclear energy, the 5GW will need to be trebled and increased to 70GW for the 207mty by 2060.

It should be pointed out that from a regulatory perspective, all relevant nuclear laws and procedures are already in place in Indonesia, and this, with President Prabowo's commitment at the G20 Summit explains a sudden activity in nuclear power.

PT Thorcon Power Indonesia announced it had signed an agreement with Indonesia's nuclear regulator to investigate building a 500 MW molten-salt reactor demonstration plant on Gelasa Island in Bangka-Belitung province.

In December 2024 Indonesia Energy Council has proposed 29 sites for nuclear power plants in a bid to secure reliable energy sources and reduce carbon emission. The sites stretch from North Sumatra, south-east across the archipelago to West Papua, Salim (2024).

In the latter case protesters have been immediately active with slogan of "Indonesia bukan Chernobyl", which is simply normal ignorance of ordinary people world-wide about nuclear power, and consequently their fear of it. Yet nuclear waste has many uses and benefits that extend to many consumer products, like fire alarms, medical apparatus, printers, watches, etc.

In defence of this decision, Agus Puji Prasetyono, member of Indonesia National Energy Council said, "The earthquake fault line would have to be more than 5 kilometres away [from the plant] to minimise significant impact on construction." Defending building nuclear reactors in Indonesia in this way is counterproductive and causes more fear than decreases it – and must not be repeated!

The best response by government is as follows:

We totally agree. We are also Indonesians. That's why together we will build Mitsubishi gas reactors because there is absolutely no way they will melt down like the Chernobyl reactors.

Here, the reference is to the Mitsubishi Heavy Industries (MHI) High Temperature Gas Reactor (HTGR), which, unlike other common reactors, including the Chernobyl one, has a negative temperature coefficient. This means that with the increase in temperature caused by a greater number of nuclear reactions, the reactor automatically reduces the number of these reactions, returning to the previous and completely safe level. This is opposite to other reactors, and it also means that the maximum gas temperature leaving the reactor cannot be higher than 950^{o}C, which is still effective enough to generate power. Additionally, the gas used is helium, which cannot become radioactive, and this is opposite to other type of reactors currently used. And they can use spent fuel which means reducing its half-life further yet again and help with its eventual storage.

Additionally, using gas turbines to drive the alternators in a closed cycle, generating efficiency is higher than with steam as it uses Brayton cycle instead of the traditional Rankine cycle. Also, no water is necessary, which is very useful in arid areas and during times of drought.

There is a place in Japan called Takasago Hydrogen Park in the Hyogo Province and near its Capital City Kobe, where these HTG reactors are to produce tonnage hydrogen for Japan's zero carbon by 2050 and many to be sold overseas – some already booked to Sarawak, Indonesia's Kalimantan neighbour.

To further allay the fears of local people of building HTG reactors in earthquake-prone Indonesia it is important to recall the catastrophic Kobe earthquake of January 1995, which caused more than 6,000 deaths and over 30,000 injuries and fires following the earthquake that incinerated half of the city.

The importance of Kobe earthquake is that the HTG reactors are being built and hydrogen produced in Tagasako, only a 50 km distance away from Kobe – confirming that HTG reactors are fully safe and impossible to melt-down in the "Ring of Fire" countries that includes Japan, Philippines and Indonesia.

4. CONCLUSIONS

Indonesia is one of the world's largest emitters of greenhouse gases (GHG). Most studies deal with major emissions and exclude steelmaking as such, which ranks fifth and emits 2.75t CO_2e/ton of steel. This paper focuses on GHG emissions of Indonesian iron and steel industry, now existing and under construction - and that projected to 2060.

It gives actual steps of how to start reducing the industry's GHG immediately using charcoal and employ ordinary people in environmental plantations and help poor people in towns and villages to earn some money by buying wood cuttings from them and processing it in distillation plants.

It considers Indonesian ways and culture. There is no modelling of any process and activity, so everything can be checked from first principles or by reference to the source.

One contentious conclusion is that to reach nett zero, it is imperative to use nuclear energy. Its use in Indonesia has been committed to by President Prabowo at the G20 Summit and its actual start with 29 reactors was announced in December 2024 and elicited immediate protests with a slogan of: "Indonesia is not Chernobyl. The best response by the government is as follows: We totally agree. We are also Indonesians. That's why together we will build the Mitsubishi gas reactor because it is absolutely impossible for it to melt down like the Chernobyl reactor.

APPENDIX: FUNDAMENTALS OF MAKING IRON

Making iron from iron ores is chemistry. People generally write chemical equations and use them, without ever thinking of what a chemical equation says. Let me write a simple chemical equation to make iron.

$$FeO + H_2 = Fe + H_2O$$

This equation asserts that to make iron, two requirements must be satisfied:

1. There must be iron oxide (FeO).

If there is no iron oxide, or if it is impure, iron will not be made, or it will be made inefficiently.

2. It and the reducing gas (H_2) must contact each other. This is shown by the plus (+) sign.

If there is no contact, or contact is poor, iron will not be made, or it will be made inefficiently.

Also, every chemical reaction is accompanied by a heat effect that can be small or large - and heat may be given up, or it may be absorbed.

Reactions that give heat up are called "exothermic" – a good example being $C + O_2 = CO_2$ + lots of heat given off, so temperature rises. It is, of course, the well-known combustion reaction.

Reactions that absorb heat are called "endothermic". An everyday example is reaction of baking soda with spirits of salt: $NaHCO_3 + HCl = NaCl + H_2O + CO_2$ + heat absorbed, so temperature drops.

What happens to the progress of the reaction follows Le Chatelier's Principle, namely:

If a dynamic equilibrium is disturbed by changing the conditions,
the position of equilibrium moves to counter the change.

For example, the reaction, $FeO + H_2 = Fe + H_2O$ is endothermic, that is, it absorbs heat, so as we increase the temperature, the reaction moves to the right, to produce more Fe.

On the other hand, the reaction, $FeO + CO = Fe + CO_2$ is exothermic, that is, it releases heat, so as we increase the temperature the reaction moves to the left, to produce less Fe.

Thermodynamics tells us what reaction is possible and under what conditions. It was invented by practical men to stop people wasting time on inventing perpetual motion machines. Fundamentals of thermodynamics of iron oxides reduction with CO and H_2 are presented in Figs 1 and 2 in which the Y-axis is, respectively, CO and H_2 concentration, and the X-axis in both is temperature.

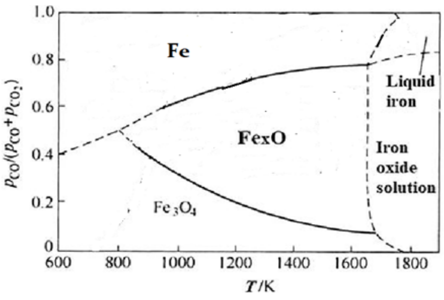


Figure 1. Reduction of iron oxides with CO.

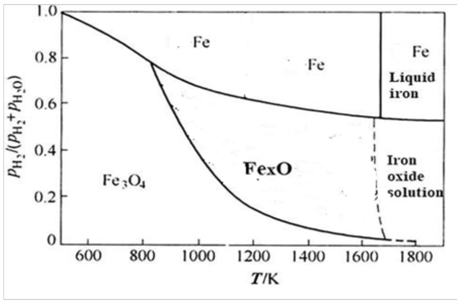


Figure 2. Reduction of iron oxides with H_2.

First, the figures do not show Fe_2O_3. It is not an omission. It is just that the Fe_2O_3 line almost coincides with the X-axis. Or, more colourfully, there is enough CO in a smoker 's breath to change Fe_2O_3 to Fe_3O_4.

In Figs 1 and 2, each line is an equilibrium line. Thus, with CO, to go from FeO to Fe at, say, 1200oK, CO concentration ratio is 0.70, and at 1400oK it is higher (= 0.75). But, with H_2, to go from FeO to Fe at 1200oK, H_2 concentration ratio is 0.65, and at1400oK it is lower (= 0.55). This result is just Le Chatelier's Principle in action!

The above thermodynamics tells us that to go from Fe_2O_3 to Fe is a stepwise process:

$$Fe_2O_3 \rightarrow Fe_3O_4 \rightarrow FeO \rightarrow Fe.$$

Let's look at the properties of each oxide. Table1, gives molecular weight, specific gravity, melting point, oxygen to iron ratio and crystal shape, of each, while Table 2 highlights what it all means in industrial practice.

Table 1. Physical Properties of Iron Oxides.

Compound	MW (-)	SG (-)	MP (ºC)	O/Fe	Shape
Iron (Fe)	55.85	7.86	1535	0	Cubic
Hematite (Fe_2O_3)	159.70	5.24	1565	2/3	Trigonal
Magnetite (Fe_3O_4)	231.55	5.18	1538	4/3	Cubic
Wustite (FeO)*	71.84	5.71	1420	1/1	Cubic

*Actually, wustite is what is known as a non-stoichiometric compound, . or (Fe_1-xO), where 0.833 < x< 0.957.

Table 2. Properties of Iron Oxides Affecting Industrial Ironmaking.

Compound:	Fe_2O_3	Fe_3O_4	FeO	Fe
The O/Fe ratios are:	1.5	1.33	1.0	0
Oxygen to be removed:		0.17	0.33	1.0
Or, as percentage:		11%	22%	67%

It is clear from Table 2 that no matter whether we use CO or H_2 to do the reduction, 2/3 of oxygen has to be removed in the final step, AND that's a lot! In case of CO reduction at 1,000oC (1273K), for example, CO concentration, as can be seen in Fig 1 has to be very high (>0.70%) – so we need to really work hard to make sure that everything within our control is at its highest performance level.

In the case of H_2 reduction, as Fig 2 shows, it is easier (<0.70%) – as long as we make sure that our temperatures are maintained!

The stepwise reduction process, $Fe_2O_3 \rightarrow Fe_3O_4 \rightarrow FeO \rightarrow Fe$, is also followed by the kinetics of reduction – in other words, by the rate, or speed, of the reduction, which is so important in the economics of ironmaking.

The stepwise, or topochemical, to use the technical word, is an onion-like, reduction, illustrated for the CO case in Fig 3. It is exactly the same onion-like reduction for H_2, with H_2 diffusing in and gaseous H_2O diffusing out.

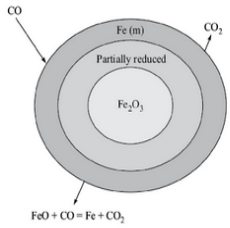


Figure 3. CO reduction of Fe_2O_3.

Hydrogen molecule and H_2O molecule are both smaller than CO molecule and CO_2 molecule, so diffusion-in of H_2 and counter-diffusion out of H_2O molecules are easier than CO molecules in and CO_2 molecules out, so H_2 reduction should be faster than CO reduction – this is true all other things being equal.

What does “all other things being equal” mean?

It means that the permeability structure of the starting oxide – and that of the other growing layers are the same. Because of different crystal structures, especially of hematite and magnetite, reduction of magnetite is much slower than that of hematite.

In fact, if the starting oxide is magnetite, it is standard industrial (economic) practice to heat it in air to convert magnetite to hematite and then use that product for reduction.

The reason is that the 16% of expansion in going from hematite (trigonal) to magnetite (cubic) creates cracks, as shown in Fig 4, that help gas diffusion.

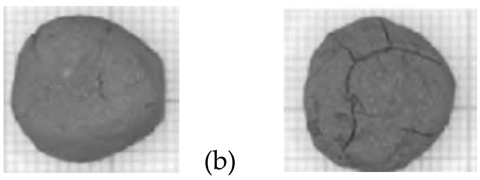
(a)

(b)

Figure 4. Insufficient cracking (a), and sufficient cracking (b).

Of course, if cracking is excessive and pellets disintegrate (They have high value of standard test for RDI – Reduction Degradation Index), then no matter how good their other properties, and price are, such pellets are simply, unacceptable.

At this stage we should make it absolutely clear that people talk about hydrogen and the “hydrogen economy” and lumping all hydrogens together. This must not be done, as it is not only not true, but it also interferes with talking about the economics of green steel production. We confirm that there are two principal kinds of hydrogen, namely: 1) energy hydrogen, and 2) chemical hydrogen.

For the reduction of iron oxides – and other metal oxides – we need chemical hydrogen, and for the production of energy for heating, melting, rolling, etc we need energy hydrogen – but only if its use for this, as such, or via electricity is economic . Of course, if it is advantageous or economic, we can use hydrogen for both at the same time.

By the way, there are three commonly distinguished hydrogen types: Green, Blue and Grey. Green is made with no CO_2 produced, Blue is made by steam reforming of natural gas with CO_2 capture, and Grey is produced in the same way, but without the CO_2 capture. Unit costs are the highest for the green hydrogen and lowest for the grey one.

The above principles of theory will help appreciate the overall view of iron oxide reduction, and any specific parts will be added at the time of need.

INDONESIA APPLICATION

Indonesian steel production in 2023 was 16mty, with about half from scrap melting in EAF (Electric Arc Furnace), and the other half from BF (Blast Furnace) and DRI (Direct Reduction Iron) plants.

The projected steel production by 2060 is 207 million tonnes per year (mty) with colossal GHG emission if nothing is done about it of 480,000,000 tonnes per year of CO_2-e!! So, it is obvious that all this has to be removed to reach zero carbon by 2060.

The EAF way of steel production is the green steel way, if – and only if, the electricity for melting, casting and rolling to make steel products like coils, sections and bars, comes from CO_2 -free sources.

It is clear that a green method of steel production has to be able to produce the same kind of amounts as a BF-BOF does. It also must be economic, safe and practical.

Current methods of mining iron ores produce many fines. In most cases these are of lower Fe content and usually preferred by the BF/BOF steel companies because they are cheaper and, in any case, feed to blast furnaces is usually agglomerated as sinter or sometimes as pellets.

Theory says that iron is produced by the contacting of molecules, such as illustrated by the equation $FeO + H_2 = Fe + H_2O$. In practical terms this means that the smaller are the iron oxide grains the faster is the reaction and more iron can be made. This points us to fluidized and semi-fluidized reactor types because they use only iron ore fines as feed.

Many fluidized and semi-fluidized reactors have come and gone. The one that has stayed and proven on an industrial basis is the Posco's Finex, with 2mty of DRI. Last year (2024) they announced development of HyRex, that extends Finex to use hydrogen. However, POSCO is demonstrating its HyRex process' performance in an ESF (Electric Smelting Furnace), mentioned on p 4, the molten iron from which is refined in BOF before casting. Just the same because of possible economic advantage of HyRex over Midrex, especially if Indonesia has to use its iron ore fines from various mines and those from its byproduct of nickel production from laterites and saprolites, we should follow its progress, in particular as it could then have potential to challenge Midrex.

To complete the overview of green steel processes, we should mention low temperature electrolysis of around 100oC. It uses ROM iron ore as feed. Fortescue is fully financing it. It is not known why.

Then there is BioIron – already at pilot plant scale of one tonne of DRI/hour. It uses biomass blended with iron ore reduced in a microwave furnace, followed by smelting in EAF to produce steel. Theory shows that bringing reactants FeO and C close together should really make the reaction proceed very fast, but it does not. The reason is that 2FeO + C = 2Fe + CO_2 , which then reacts with C as CO_2 + C = 2CO – the most endothermic reaction in ironmaking known as Boudouard reaction in textbooks . The ironmakers call it a "solution – loss" reaction, meaning "solution" of carbon and "loss" of heat. The famous graph of Standish (1991) in Fig 5 shows the difference between the carbothermic reduction of iron oxides at 1000oC in a laboratory furnace and in a microwave oven. The reason is that in a laboratory furnace the heat travels to the centre of the pellet from outside by the slow process of conduction, whereas microwave being volumetric heating

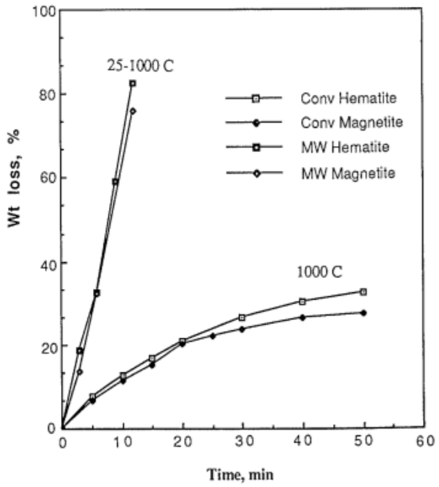


Figure 5. Conventional and microwave carbothermic reduction of Fe oxides.

the heat is available immediately in the centre, too, to cover the endothermic reaction. In other words, in laboratory furnace the pellets have "cold centres", and in a microwave oven they have not.

BioIron is funded ($215 million) by Rio Tinto. This is not understandable. My experience has been that apart from its niche application in drying, microwave processing of metals is only economic for high value metals.

Likewise, the low temperature electrolysis, funded by Fortescue, is not understandable also because it is impossible to have either process produce anywhere near the tonnages of steel required.

Needless to say, we don't talk about them for Indonesia at this time!

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