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Selecting Indonesia's Iron and Steel Industry Mitigation Pathways Based on AIM/End-use Assessment

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ABSTRACT

The measurement of mitigation pathways is important for Indonesia's iron and steel industry in terms of reducing GHG emissions. This study conducted a cost-effectiveness analysis to assess the economic impacts with associated emission reduction potential of different mitigation strategies by developing an Abatement Cost Curve (ACC) that selects the mitigation option based on the logic of the AIM/End-use model up to 2050. The model was established through the baseline scenario, and the following appropriate mitigation options: adjusting the production structure (CM1), increasing energy efficiency by promoting low carbon technology and non-blast furnace technology that is un-implemented early in modeling years in Indonesia will be included for future reference (CM2), and switching from fossil fuels to low emission fuels (CM3). Results show that the selected technology roadmap from the abatement cost curve below carbon tax 110 US$/tCO2e in 2050 could lead to the most optimal emission reduction of 19.8 MtCO2e, 50.2 MtCO2e, 54.84 MtCO2e with investment costs 93.55 million US$, 1086 million US$, and 1183 million US$ in the scenarios CM1, CM2, and CM3, respectively. The effectiveness of each mitigation action reveals that energy savings and emission reduction from energy will rely mostly on promoting low-carbon technologies. The most effective strategy to reduce emissions from IPPU is to adjust the production structure.

1. INTRODUCTION

In recent years, addressing climate change and reducing emissions has become a crucial global priority. In line with this, Indonesia taking significant steps to strengthen its commitment to addressing climate change. Submitting an enhanced NDC sets a higher emission reduction target compared to the previous NDCs. Unconditionally, Indonesia aims to achieve a 31.89% reduction in emissions, up from the previous target of 29%. Additionally, with conditional support, Indonesia aims to further reduce emissions by 43.20%, compared to the previous target of 41%. These targets reflect Indonesia's commitment to transitioning towards a more sustainable and low-carbon future. By aligning its Second NDC with the Long-Term Low Carbon and Climate Resilience Strategy (LTS-LCCR) 2050, Indonesia is ensuring that its efforts are in line with long-term sustainability goals. Furthermore, has set an ambitious goal to achieve net-zero emissions by 2060 or earlier showcasing its determination to play a significant role in global climate action. This commitment is crucial in mitigating the impacts of climate change and creating a more sustainable and low-carbon future (Government of Indonesia, 2021). Nearly half of Indonesia's energy consumption and 18% of the nation's greenhouse gas (GHG) emissions are attributed to the manufacturing industry sector., making it a key focus area for implementing sustainable practices(Government of Indonesia,2021; MEMR, 2022). As an intensive energy-consuming and carbon-emitting industry, the iron steel industry is a major sector of GHG emission not only from

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energy use, which includes stationary fuel combustion and purchased electricity, but also from IPPU (Industrial Process and Product Use) activities which are primarily from non-energy use in the iron reduction process ($Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$) (Sodsai and Rachdawong,2012). In 2016, the Iron steel industry in Indonesia contributed a totaled 11.25 $MtCO_{2e}$ or 9.17% of the total industrial emissions (Widowati et al.,2018). As a result, the iron and steel industry's rapid expansion could lead to environmental issues.

A comprehensive quantitative evaluation utilizing a bottom-up Approach has also been investigated. Hasanbeigi et al., (2013), using ECFC and FCFC model to analyze 23 energy efficiency technologies from 2010-2030. The study concludes that the Chinese iron steel industry has potential for energy efficiency improvements and emissions reduction, and that the cost-effective measures include automated monitoring, cogeneration, and targeting systems. Supported by Morrow et al., (2014) emphasizes the importance of investing in and promoting the adoption of low-carbon technologies, due to the adoption can also lead to cost savings for industries and improve their competitiveness in the global market. Chen et al., (2014) modeling of steel production and energy efficiency scenarios in China using TIMES (The Integrated MARKAL-EFOM System), with simulation results showing the potential for energy and CO_2 intensity reductions related to the steel production structural adjustments. The review study by Mallett and Pal., (2022) identified factors affecting the potential for innovation within the steel industry in India, including the need for a diversified technological approach and the importance of considering social implications when transforming to sustainable green steel production. Another study by Ma et al., (2016) using LEAP (Long-range Energy Alternative Planning System) assess the technologically feasible GHG mitigation potential at the system level. BPPT., (2013) discussed the energy-saving technology roadmap for Indonesia's steel industry using the LEAP model. The results show a significant energy saving projection of up to 31% or 47.5 million BOE was obtained. However, this study examines the medium-term (2030) roadmap with limited efficient technology. Moreover, the result of GHG emissions in these studies mainly results from energy activity only. The study here looked at the impact of emission reduction strategies on energy savings and GHG emissions reductions that focus on deep decarbonization through the application of low-carbon technologies that are not limited to efficient technologies, but also include advanced technologies. A long-term (2050) projection of the iron steel industry's mitigation technology roadmap using the AIM/Enduse model is required. The quantified result of carbon emission in this study served separately, emissions from energy and IPPU activities that have never been done in the studies that focus on the bottom-up modeling for the iron steel industry. Furthermore, this study conducted a cost-effectiveness analysis to assess the economic impacts of different mitigation strategies. This involves comparing the costs of implementing different measures with the associated emission reductions achieved.

2. METHODS

2.1 AIM/Enduse

The AIM was developed to forecast GHG emissions and evaluate environmental policy options in the Asian-Pacific area. It's also one of the best-known energy system modeling platforms. The AIM model has been applied in various countries to analyze energy demand, identify energy-saving opportunities, and inform policy development such as Japan's carbon tax's effects on carbon-emitting technologies(Kainuma et al, 2003), policy analysis on climate change in Thailand's energy sectors(Chunark and Limmeechokchai, 2015), consider the potential synergies between India's CO_2 and SO_2 emission reduction goals(Kainuma et al, 2003). identify the most cost-effective strategies for reducing CO_2, SO_2 and NO_2 emissions in different economic sectors of Vietnam (Shrestha and Tung, 2003). AIM/Enduse utilization of the GAMS (General Algebraic Modeling System) optimization modeling interface allows for a comprehensive analysis of the energy system, considering various constraints and objectives, and facilitating the identification of least-cost energy to select the technology.

The analysis structure of the AIM/Enduse model consists of (i) evaluating future demand for steel according to socioeconomic factors (industrial structure, future technology development, economic growth, etc); (ii) determining technologies to meet the future demand relies on a database of energy technologies, which includes information on energy efficiency, emissions factors, energy and technology price, and other relevant parameters. The selection process aims to identify the technologies that can meet the demand at the least cost, while considering energy efficiency and environmental factors; (iii) estimation of energy consumption and CO_2 emissions; (iv) Environmental Target Analysis to meet the feasibility of emission reduction goals and identify the most effective pathways; and (v) estimate emission reduction and associated AC (Abatement Costs) under various technology combinations. In the ACC analysis, total cost (TC) includes all expenses for that year, including the total annualized initial investment cost, operational expenses, and energy and emission taxes. Based on the criterion of minimizing the total cost of an energy system, recruitment and operational decisions are made for all feasible technological combinations. The technology which satisfies minimum TC and has a lower abatement cost value than the selected carbon price will be selected. In addition, the energy tax parameter is not utilized for total cost minimization in ACC due to the energy tax in Indonesia is included in energy prices.

2.2 Overview of production processes and identification of emissions mitigation strategies

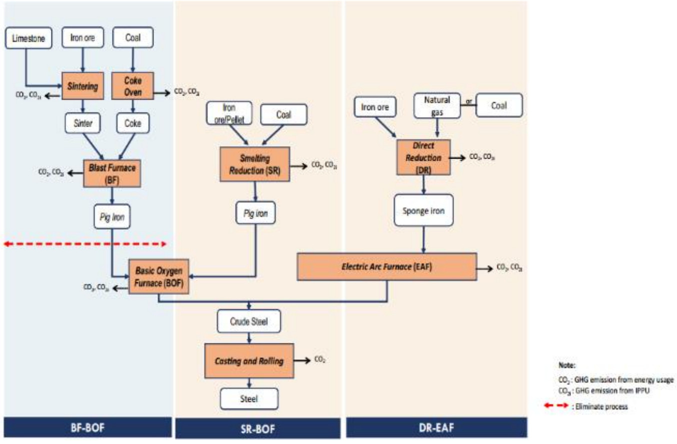
The Indonesian iron and steel industry employs two main routes the integrated steel route and the EAF route. The integrated steel route follows the traditional method of steel production and involves the following processes: (i) Raw Material Preparation: This stage includes the preparation of raw materials such as coking coal, iron ore, and limestone. It involves processes like coke oven operations, and sintering; (ii) Blast Furnace (BF); (iii) Basic Oxygen Furnace (BOF); (iv) Final Product Manufacturing, after steel is produced in the BOF, it goes through various manufacturing processes such as casting, rolling, and finishing to shape it into the desired products.; (v) On-Site Electricity Production. On another side, the EAF route involves the following processes: (i) Palletizing: Similar to the integrated route, the EAF route also includes the preparation of raw materials through processes like palletizing; (ii) Direct Reduction (DR);(iii) Electric Arc Furnace (EAF); (iv) Final Product Manufacturing, once the steel is produced in the EAF, it undergoes final product manufacturing processes such as casting, rolling, and finishing to create the desired steel products.

As described above, steel production in Indonesia is a complex process that involves several processes to convert raw materials with intensive energy-consuming and carbon-emitting. Implementation of mitigation strategies aims for the production process to become more efficient in energy consumption which leads to more competitive costs and therefore less emissions. Several mitigation actions can be implemented in the iron steel industry:

1. Adjusted the production structure

Adjusting the production structure through increasing scrap use is also found to be an effective measure for reducing carbon emissions. Steel scrap utilization in both BF-BOF and EAF routes can eliminate the needs of previous processes that consume a large amount of fuel and reductant as shown in Figure 1.

2. Technological improvement potential to increase energy efficiencies in the iron and steel production process.
3. Shifting towards low carbon emission fuel as well as renewable energy sources for electricity generation within the steel industry, such as biomass, RDF that can reduce the carbon footprint associated with energy consumption



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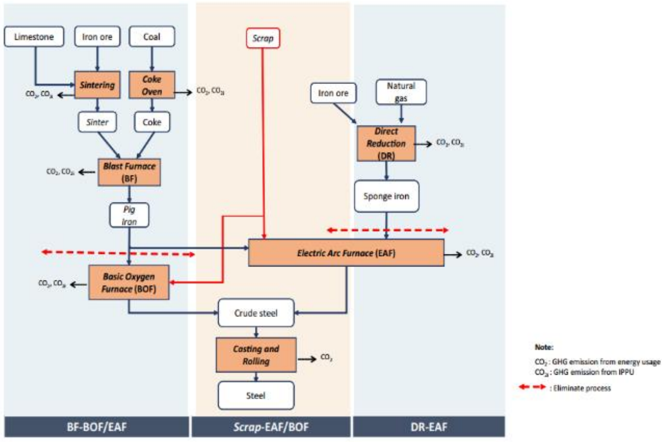


(b)

Figure 1. Alternative mitigation (a) Scrap utilization in both BF-BOF and EAF routes; (b) Non-Blast Furnace Technology

2.3 Indonesia's Iron Steel Industry Framework

The framework for analyzing the potential for long-term GHG mitigation in Indonesia's iron and steel industry is illustrated in the figure. 2. In the integrated steel production process, coal is a crucial component used in the coke-making process, which is essential for the operation of the BF (Gri and Hammond, 2019). Iron ore and coke are charged to the sinter plant to form sinter and then are fed into the BF. It's important to note that the integrated steel route, which relies heavily on coal and coke in the BF, is associated with significant carbon emissions.

As shown in the figure.2 this model structure was also considered to evaluate the potential of non-blast furnace technology (smelting reduction) that has not been implemented in Indonesia during the early modeling years. After the pig iron is separated from the iron ore in the BF (including non-blast furnace processes), it is further processed to produce crude steel in the BOF to reduce its carbon content and convert it into crude steel (S. Zhang et al, 2019), then further processed into casting and rolling to produce the final product steel (slabs, billets, and blooms).

The EAF pathway uses recycled scrap steel and sponge iron (produced by direct reduction) outside of integrated steel. The primary source of energy for this process is electricity, which is partially generated on-site and the remains are purchased from the Indonesian national power grid. The total GHG emissions (energy and IPPU) produced within the system boundaries were calculated in this study, while direct emissions from BOF slag integrated into the cement plant, purchased electricity, and purchased pellets are not counted due to the emissions are generated elsewhere which are not under the direct control of the steel industry.

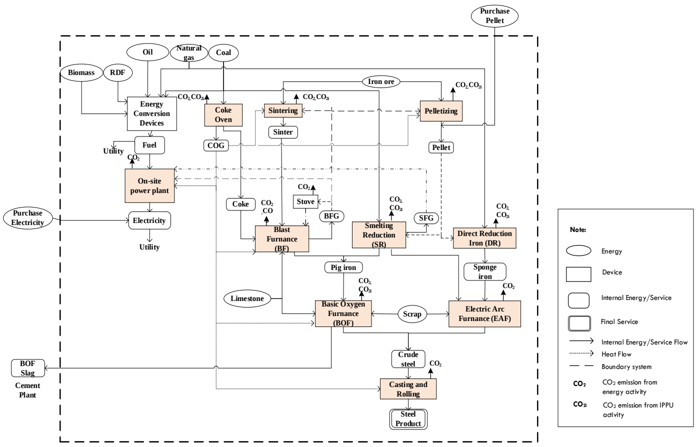


Figure 2. Indonesia's iron and Steel model structure and emissions sources

2.4 Data collection and parameter

The energy and material consumption parameter in this study was obtained from Ramakrishnan (2013) who estimated the material and energy balance based on international references of the steel production process using ASPEN plus. Indonesia's domestic technologies specification refers to data published by the Indonesia Agency for the Assessment and Application of Technology (BPPT, 2013).Technical and emission parameters are among the parameters that are considered, the emission parameters take into account emission variables for various fuel sources as well as the electricity used. Aside from energy emission considerations, some main or secondary fuels may be utilized for non-fuel purposes (reducing agent), then should be recognized as IPPU emissions. These emission factors are shown in Tables 1, 2 and 3. Specific technical factors, including data from 58 selected technologies, are incorporated in the primary process of producing iron steel. table A.1-3 shows information for each measurement, such as fixed investment cost, OM cost, lifetime, energy input-output, and energy savings, based on relevant research (Li and Zhu, 2014; Lu et al, 2016.; He and Wang, 2015; Q. Zhang, Li, et al, 2018.; Hasanbeigi et al, 2013). Among these selected technologies, It is worth noting that CCS (carbon capture storage) is one of the interesting options for reducing emissions that receiving a lot of attention worldwide (Q. Zhang 2018; Zhao, et al., 2017). However, CCS technology wasn't analyzed in this quantitative scenario due to natural gas-based DR technology which produces high purity of CO_2 from the processing of iron steel has not operated since 2014. This makes implementation of CCS not interesting and not economically profitable.

Table 1. Emission Factors of Fuel

	Emission factors		
	(tCO_2/toe)	**(tCH_4/toe)**	**(tN_2O/toe)**
Fuel [a]			
- Raw coal	4.1750	0.0009	0.0195
- Coking coal	3.9607	0.0009	0.0195
- Fuel oil	3.1010	0.0026	0.0078
- Natural gas	2.4116	0.0009	0.0013

[a] CO_2 emission factor of fuel is adapted from Indonesia's Mineral and Coal Technology Research and Development Centre, and other data are extracted from IPCC guidelines for national GHG inventories

Table 2. Emission factors of electricity

	2010	2014	2020	2025	2030
Electricity (tCO_{2e}/toe)[b]	8.62	9.77	11.86	13.40	14.93

[b] CO_2 emission factor of electricity was taken from the JAMALI (Jawa-Madura-Bali) regional grid, published by the Directorate General of Electricity-Ministry of Energy and Mineral Resources and emission factor for 2020-2030 from regression results.

Table 3. Emission factors of IPPU[c]

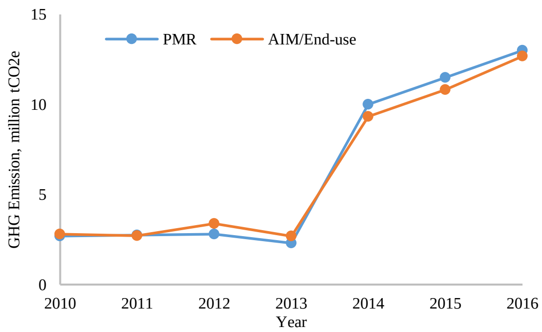
Iron production	Emission factors		Steel production	Emissions factor
	($t CO_2/t$ product)	($t CH_4/t$ product)		($t CO_2/t$ product)
Sinter production	0.2	$7e^{-5}$	BOF	1.46
	0.03		EAF	0.08
Pellet production	0.56	$1.e^{-7}$		
	1.35			
Coke oven	0.7	1*		
Iron production				
Direct reduction				

*unit for CH_4 emission factors of the Direct reduction process is kg/TJ

[c] CO_2 emission factor of fuel is adapted from IPCC guidelines for national GHG inventories volume 3 for IPPU

2.5 Model validation

Data validation is a critical step in any data workflow that ensures the conceptual simulation model is an accurate representation of the actual system being modeled. The data were validated by comparing the results of the GHG emission level from the AIM/end-use model with the historical data (2010-2016) reported in the Partnership for Market Readiness (PMR) Indonesia database (Widowati et al, 2018). As shown in the figure. 3, the results for both energy and IPPU emissions are in line with the historical data with 2.1% and 5% for average and maximum error, respectively. Therefore, the model that was built can be used to represent the real conditions in Indonesia's iron steel industry.



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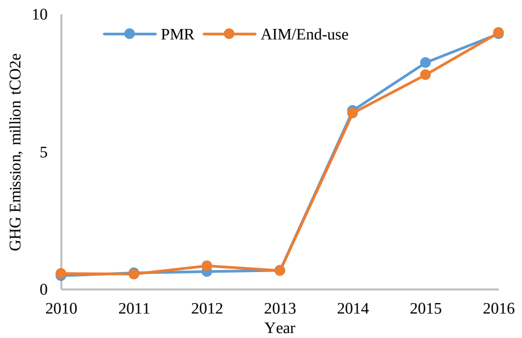


(b)

Figure 3. Validation model for (a) energy (b) IPPU

2.6 Future annual Indonesia's iron steel industry production and Mitigation Scenario

The estimation of energy and associated emission projection are based on certain levels of steel production that are related to the macroeconomic assumption. Indonesia's GDP was projected to expand at an average annual rate of 5.5% from 2010 to 2060, and its overall GDP was projected to be 5.2 times more in 2050 than it was in 2010. From 2010 through 2050, the population is projected to increase by 0.8% per year, reaching 328 million. As described in the earlier steel demand projection articleYin and Chen (2012), with the same GDP assumptions, industrial product levels and predicted lifetimes will greatly alter long-term steel demand. Steel production forecast in the iron steel industry is the first stage of the whole analysis process Ma et al.(2013). The forecast of GHG emissions is based on the level of steel production. In the following analysis, the assumption that the crude steel production rate (2010-2050) is applied to all scenarios to clarify differences between scenarios.

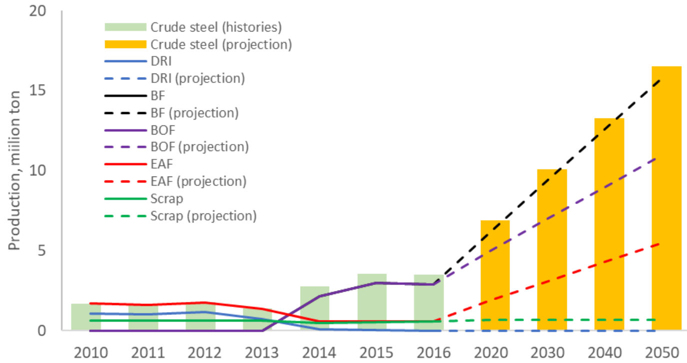


Figure 4. Projection of crude steel products

In figure. 4, the crude steel production rate (2010 to 2016) refers to historical data published by the Indonesia Ministry of Industrial. The projection of crude steel up to 2050 refers to the planning of steel production capacity development. The Indonesian Iron and Steel Industry Association (IISIA) projects a production level of 50 Mt in 2050, assuming all domestic steel demand is met by domestic production without imports. However, this study applies a pessimistic scenario with a level production of 16.5 Mt (33% of IISIA projections) in 2050. This assumption considers the conditions of availability of raw material resources, market potential due to limited domestic production by imported steel, and imported advanced technology need high cost. The level of installed production capacity of Indonesia's iron steel industry cannot accommodate demand, so this sector requires the application of new technology to meet the increasing demand. As can be shown in Table 4, it will affect the structure of crude steel production and the technology that is applied.

Table 4. Steel production share in the BAU scenario

	2010	2014	2020	2030	2050
EAF production (%)	100	21.30	35.99	33.56	52.09
BOF production (%)	0	78.70	64.01	66.44	47.91

In this study was developed four scenarios, these scenarios are defined as BAU scenarios and alternative scenarios (CM1, CM2, and CM3). The baseline (BAU) scenario assumes that sector development will follow the historical trend, and there will be no major changes in energy efficiency improvement. It's important to note that the reference scenario is used as a baseline for comparison and does not consider potential changes in policy, technology, or other factors that could impact energy consumption and GHG emissions. Mitigation scenarios, which include energy-saving measures and emissions-reduction policies, are typically developed to assess the potential impact of implementing such measures. As scenario mitigation the option is adjusting the whole production process structure, such as increasing the proportion of EAF steel and BOF developed in the CM1 scenario. Based on this discussion, two other energy efficiency scenarios and changing fuel mix were introduced (see table 5).

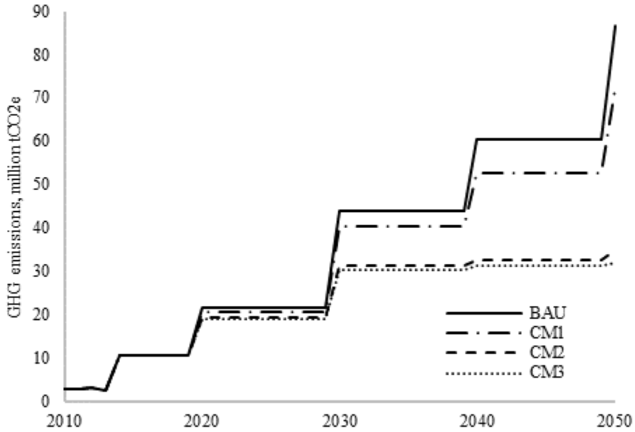
Table 5. Scenario definition

Scenarios	Scenario description
BAU	The share of energy in 2030 & 2050 are the same as that of 2010, efficiency of equipment in 2030 & 2050 are the same as that of 2010, and no addition of scrap
CM1 (Adjusted the production structure)	The modified production structure consisted of BOF and EAF routes, which increased material efficiency with scrap used
CM2 (CM1+ promoting low carbon technology)	CM1 condition is being applied with promoting low carbon technology and non-BF technology (direct and smelting reduction), which were not yet established in Indonesia during the early modeling years
CM3 (CM2+ substitution fuel)	Reducing carbon emissions by switching from high- to low-emission fuels under the CM2 scenario condition

3. RESULT AND DISCUSSION

3.1 Microplastic composition

GHG Emission Reduction



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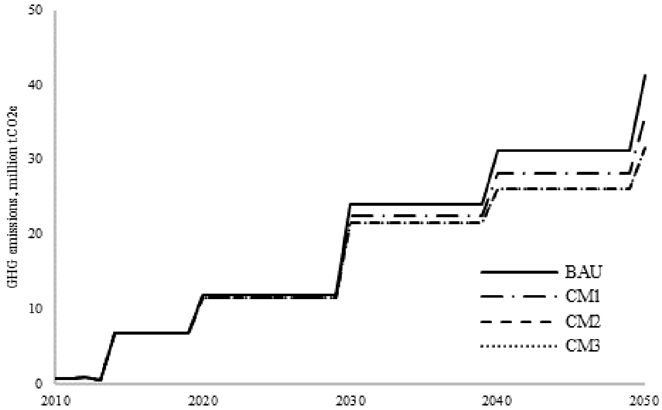
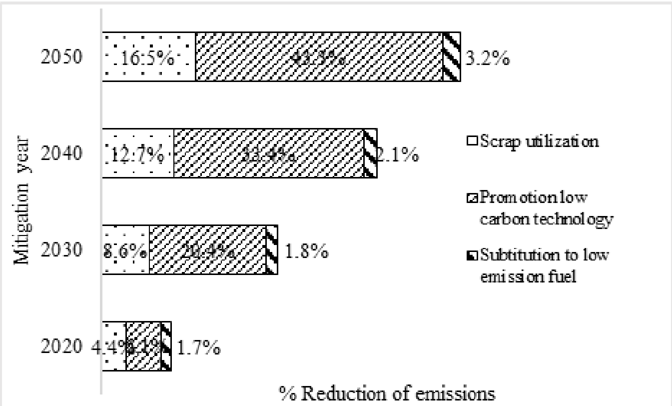


(b)

Figure 5. GHG emission forcast under different scenarios from (a) energy, (b) IPPU

Under BAU scenario in figure. 5, GHG emissions are likely to relatively low, from 3.03 million tCO_{2e} and 0.78 million tCO_{2e} in 2010 to 2.44 million tCO_{2e} and 0.56 million tCO_{2e} in 2013 respectively in the energy and IPPU sector. There has been a significant increased in 2014, the increase is mainly due to the replacement of DR technology through the implementation of BF/BOF and EAF technology. BF/BOF and EAF technology is speculative technology which expected to increase until 2050 because of this technology more flexible in the supply of raw materials and economics. Therefore, the use of coal as an energy source in this technology will significantly increase GHG emissions. The emission growth rate continues until 86.60 million tCO_{2e} and 41.20 million tCO_{2e} in 2050 respectively in the energy and IPPU sector.

In addition to the BAU scenario, other mitigation scenarios that include more aggressive energy conservation and emission reduction strategies provide comparable trends in GHG emissions. Compared with BAU, increasing scrap input rate (20% of total input) of the steel production process included BOF and EAF in the CM1 scenario intensively reduce emissions by 14.27 million tCO_{2e} (16.48%) and 5.52 million tCO_{2e} (13.39%) in 2050 respectively from energy and IPPU sector. After more energy conservation technologies are applied in the CM2 scenario, can reduce GHG emissions up to 51.80 million tCO_{2e} (59.81%) and 9.64 million tCO_{2e} (23.40%) in 2050 respectively from energy and IPPU sector, compared with BAU scenario. Further shifting to the use of natural gas, RDF, and biomass as energy sources in the CM3 scenario could bring cumulative emissions reduction of 54.58 million tCO_{2e} (63.02%) and 9.64 million tCO_{2e} (23.40%) in the energy and IPPU sector.



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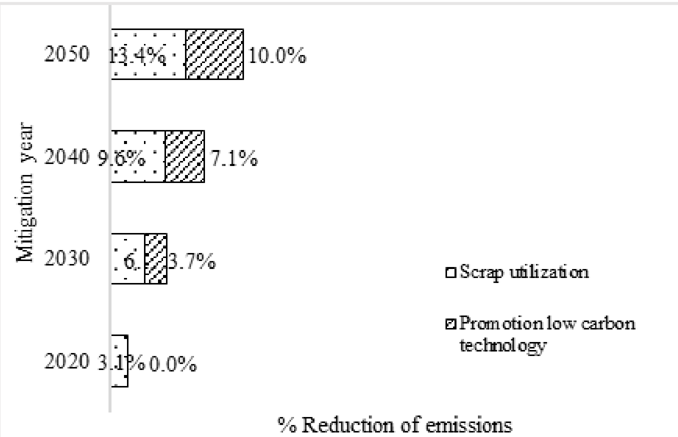


(b)

Figure 6. Potential for GHG emission reduction under different scenarios from (a) energy and (b) IPPU activities in Indonesia's iron steel industry, 2020-2050

The effectiveness of each mitigation actions reveals that energy savings and emission reduction from energy and IPPU sector during mitigation year (2020-2050) shown in figure. 6, emission reduction occurred in both sectors maximum 16.5% and 13.4 % from energy and IPPU sector, respectively as the proportion of scrap input rate increased. This reduction in emissions is referred to as scrap utilization that obtained from the difference in emissions at BAU and CM1 scenario. Promotion low carbon technology determined from the difference in emissions at CM1 and CM2 scenario effective reduce emissions up to 43.3% and 10% from energy and IPPU sector, respectively. While potential GHG emission from substitution of low emission fuel obtained from the difference in emissions at CM2 and CM3 scenario. This mitigation measure is not related to steel production process activities. Therefore, there is no reduction in emissions for IPPU sector, only reduce emissions related to energy activities 3.2% in 2050. Consequently, with the above three strategies, the low carbon technology promotion is the main driver for GHG emissions reduction from energy sector. In the sector IPPU, some strategies focused on the scrap utilization will be obtained the most significant emissions reduction due to reducing the consumption of pig iron, this also has an impact on the reduced need for coke as a reductant.

Energy and GHG Emissions Intensity

GHG emissions and total energy consumption in the iron and steel industry related to steel products. Therefore, the value of each energy consumption and emissions are expressed in units of intensity to obtain a more appropriate evaluation of mitigation strategies. The baseline and mitigation scenario in 2010, GHG emissions and energy intensity at the same level because there are no changes in the technology and product structure with value 0.44 toe/tonne of steel and 2.33 tCO_{2e}/tonne of steel respectively. However, in the baseline scenario, increasing steel production capacity using BF technology cause an increase energy and emissions intensity level to 1 toe/tonne of steel and 8.52 tCO_{2e}/tonne of steel in 2050 respectively. As shown in figure. 7, implementation of mitigation scenario shows the changing trends for energy and GHG emissions intensity. For scenario CM1 intensity levels decrease to 0.83 toe/ton of steel, about 83% of the baseline level and 7.20 tCO_{2e}/ton of steel in 2050. Scenario CM2 obtain the energy intensity level in 2050 is only 41% of the baseline level and the emissions intensity declines significantly to 4.42 tCO_{2e}/ton of steel. In the same period, a greater degree of decline will occur in CM 3 because of the accumulative of mitigation strategies (scrap utilization, promotion low carbon technology, and substitution to low emission fuel). Energy intensity level declines to 0.4 toe/tonne of steel, about 40% of the baseline level and emissions level to 4.24 tCO_{2e}/tonne of steel.

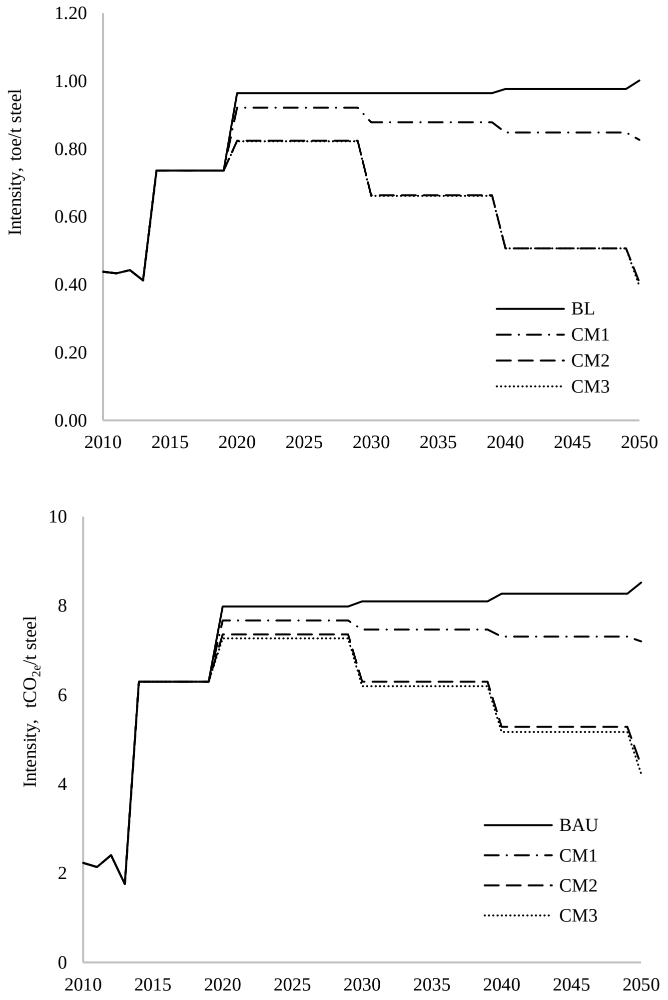


Figure 7. Intensity in Indonesia's iron and steel industry under different scenarios (a) GHG emissions (b) Energy

The development path of selected technology

The cost effectiveness of the implementation low carbon technology in this paper, was developed by ACC that select selects the technologies based on the logic of AIM/End-use model under a certain carbon price. As shown in figure. 8 the cost curve shows the range of emission reduction actions that are possible with abatement cost of technologies under 0 US$/t CO_{2e}. This ACC study indicates the abatement potential in the iron and steel industry can reach 8.96 million tCO_{2e} reductions per year by 2050. Low temperature rolling and automated monitoring and targeting system present 58.48% of mitigation potential and if all abatement potential in the abatement is implemented, the investment value will be -303 million US$ with an average cost of -39.26 US$/$tCO_{2e}$. It is worthy to note that a better industry competitiveness while implementing abatement opportunities.

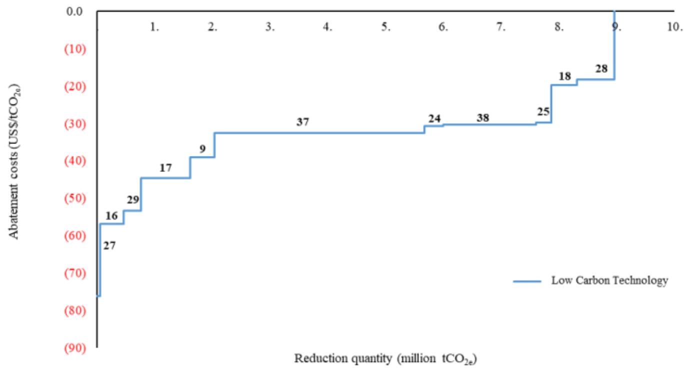
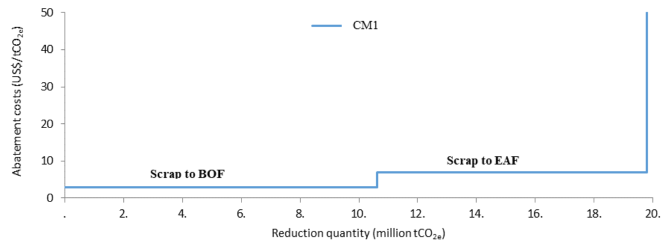


Figure 8. Abatement cost curve in the iron and steel industry for 0 US$/$tCO_{2e}$ carbon tax. Labels refer to the technologies specified in table A.1-3.

The increasing of carbon tax up to 50 US$/$tCO_{2e}$ will provide greater opportunity for the realization of low carbon technology, as selected technology paths are shown in figure 9. In the CM1 scenario, adjusting production structure through increasing scrap utilization in BOF and EAF reduced 19.79 million tCO_{2e} which requires an additional investment of 93.55 million US$. The adoption of low carbon technology in the CM2 scenario implies significant emissions reduction up to 34.3 million tCO_{2e} with investment cost 91.30 million USD less than that in the baseline scenario, it shows the economic benefits of developing low carbon technologies. The addition of low emission fuel substitution in CM3 scenario made 41.7 million tCO_{2e} emissions reduction. This abatement potential is also complemented by about USD 66.16 million US$ more than that baseline.



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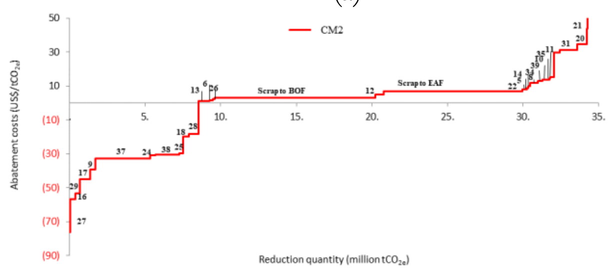

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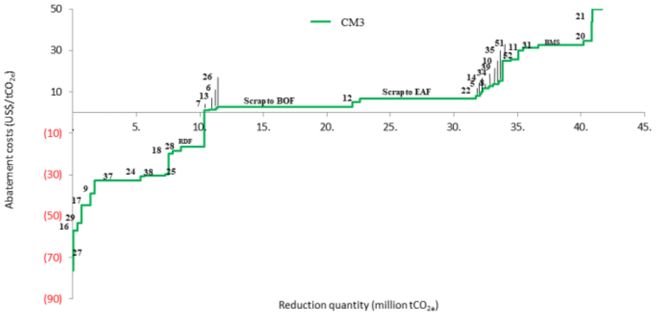
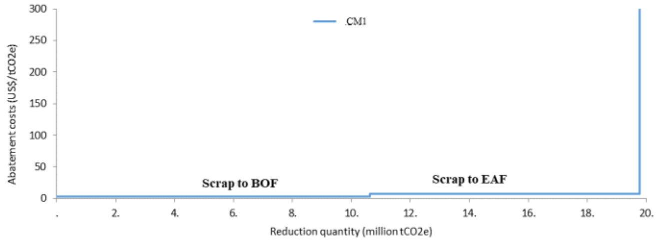


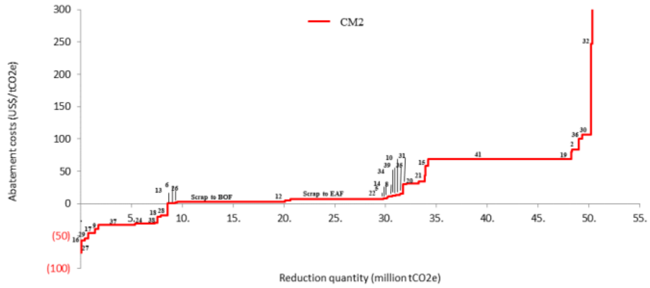
(c)

Figure 9. Abatement cost curve for 50 US\$/tCO_{2e} carbon tax (a) CM1 (b) CM2 (c) CM3. Labels refer to the technologies specified in table A.1-3.

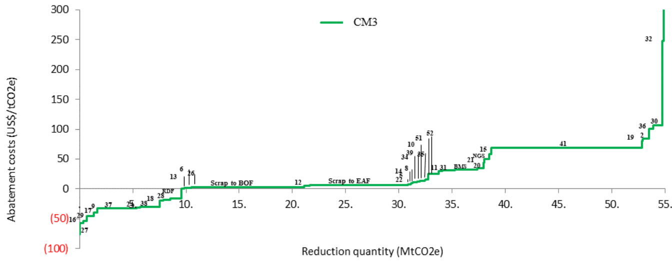
The increase in carbon tax up to 300 US\$/tCO_{2e} was chosen as many as 40 technologies which have an abatement cost under carbon tax. However, based on figure.10. the increasing of carbon tax above 110 US\$/tCO_{2e} does not significantly reduce emissions (0.08 million tCO_{2e}) with high abatement cost 274.4 USD, therefore, the investment cost at carbon tax above 110 USD/tCO_{2e} is not included. In the CM1 scenario, the value of emissions reduction and investment cost at the same level with carbon tax 50 US\$/tCO_{2e}. It should be noted that the abatement cost above 6.89 US\$/tCO_{2e} in the CM1 scenario was not included in the calculation since its abatement cost value at 6.89 US\$/tCO_{2e} will be obtained maximum reduction from scrap utilization as a raw material in the steel production (BOF and EAF technology) within the limit of 20% input scrap to preserve the quality of steel. In the CM2 scenario, there is an increase in reduction of up to 50.2 million tons of CO_{2e} with investment costs of 1086 million USD. While in the CM3 scenario through the addition of low-emission fuel use it is able to reduce emissions by up to 54.84 million tons of CO_{2e} by adding investment costs of 1183 million USD compared to baseline technology. It shows that the development of non-BF (smelting reduction) technology requires quite a high mitigation cost of 976 million USD, but this technology has a significant emission reduction potential (14.12 million tons CO_{2e}). If the carbon reduction in the CM3 scenario were to be implemented, the reduction in GHG emissions compared to that of the baseline would be 54.84 million tCO_{2e} with additional investment costs 93.55 million US\$.



(a)



(b)



(c)

Figure 10. Abatement cost curve for 300 US\$/tCO_{2e} carbon tax (a) CM1 (b) CM2 (c) CM3. Labels refer to the technologies specified in table A.1-3.

4. CONCLUSION

This study analyzes and develops the structure of an AIM/end-use model for the Indonesian iron and steel sector to identify optimal combinations of low carbon technologies and other mitigation possibilities. Scenario analysis results show that scenarios can achieve different levels of energy saving and emission reduction. Based on abatement cost curve of selected technology roadmap for the optimum carbon tax value of 110 USD/ton CO_{2e} was obtained potential emissions reduction up to 19.8 million tCO_{2e}, 50.2 million tCO_{2e}, 54.84 million tCO_{2e} with investment costs of 93.55 million USD, 1086 million USD and 1183 million USD, respectively in the CM1, CM2, and CM3. The high investment costs (976 million USD) in CM2 is caused by the application of non-BF (smelting reduction) technology, however this technology provides a significant opportunity to reduce emissions by 14.12 million tCO_{2e}.

The effectiveness analysis of each mitigation step shows that adjusted production structure (scrap utilization) will contribute to the significant mitigate GHG emissions in the IPPU activities with potential reduction of 0.37 tonCO_{2e}/ton steel. Therefore, the increased use of obsolete scrap in the BF-BOF route can become an interesting option for Indonesia iron and steel industry. Energy savings and GHG emission reduction from energy use, most depend on the strategy focused on the implementation of low carbon technology with potential reduction of 2.50 tons CO_{2e}/tons of steel by 2050. While, the substitution of low-carbon fuels only reduces emissions related to energy use with less significant values (0.185 tons CO_{2e}/ton steel) compared to other mitigations. Therefore, it will be necessary to provide the development of low-carbon technology for the steel industry's promotion of energy-saving strategies in future consideration.

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Appendix

Table A.1 Screened technologies related energy saving and cost component in iron steel industry

No	Process	Technology	Type	Fuel saving (toe/ t)	Electricity saving (toe/t)	Capital cost (US$ /t)	OM cost (US$ /t)
1	Coke making	Coal moisture control technology (CMC)	R	0.00406	0	78.68	0.00
2		Coke dry quenching (CDQ)	R	0.03368	0	94.02	0.77
3	Pelletizing	Grate klin	S	0.00693	0	53.22	0.00
4		Pellet waste heat recycling	R	0.00196	0	1.95	0.26
5	Sintering	Deep bed sintering technology	R	0.00191	0	0.44	0.00
6		Reducing air leakage (10%)	R	0.00430	0	0.15	0.00
7		Low temperatur sintering	R	0.00836	0	0.22	0.00
8		Sintering waste heat recovery	R	0.01310	-0.00239	3.31	0.00
9	BF	BAT	S	0.00481	0	180.5	0
10		Top gas recycling BF	S	0.02928	0	79.82	0.00
11		Recovery of blast furnace gas (BFG)	R	0.00096	0	0.44	0.00
12		Top Pressure Recovery Turbines (TRT)-wet	R	0	0.00263	32.33	0
13		Top Pressure Recovery Turbines (TRT)-dry	R	0	0.00396	29.46	0.00
14		Improved BF control system	R	0.00955	0	0.40	0.00
15		Preheating of fuel and air for hot blast stove	R	0.00597	0.00	2.14	0.00
16		Recuperator on the hot blast furnace	R	0.00717	0	6.69	0.00
17		Injection natural gas in Blast Furnance	R	0.00884	0	6.51	-2.87
18		Injection of Coke Oven Gas	R	0.00860	0.00159	6.51	-2.87
19		Pulverized Coal Injection (PCI) 130 kg/t hM	R	0.01552	0	7.89	-2.15
20	BOF	*Flue gas waste heat recovery*	R	0.002150	0	3.86	0.10
21		*Recovery BOF gas and sensible heat*	R	0.002197	0	24.28	0
22		*Dry gas cleaning system (wet to dry)*	R	0.003344	0	4.68	0.00
23	EAF	*LT-PR of converter gas*	R	0.016480	0	0.27	0.52
24		*Scrap preheating*	R	0	0.00525	8.39	-4.337
25		*Automated controls*	S	0	0.00263	1.05	0.00
26		*Post combustion*	S	0	0.00215	1.10	0.02
27		*UHP transformer*	R	0	0.00143	9.16	0.09
28		*Foamy slag practice*	R	0	0.00048	11.03	-1.99
29		*Oxy fuel burners*	R	-0.005732	0.00430	4.41	0.4

No	Process	Technology	Type	Fuel saving (toe/ t)	Electricity saving (toe/t)	Capital cost (US$ /t)	OM cost (US$ /t)
30		*DC furnace*	R	0	0.00430	4.304	-3
31	*Hot roliing and casting*	*Direct sheet plant*	S	-0.02830	0	199.55	0
32		*thin slab casting (TSC)*	S	0.010987	0.00836	220.70	-0.55
33		*Integrated casting and rolling (strip casting)*	S	0.0067	0.00000	354.25	-22.11
34		*waste heat recovery from cooling water*	R	0.000955	0	26.07	0.30
35		*recuperative burners*	R	0.001672	0	2.76	0
36		*hot delivery and hot charging*	R	0.005493	0	0.38	0.29
37		*process control in hot strip mill*	R	0.006688	0	18.54	0.00
38		*low temperatur rolling*	R	0	0.01565	0.43	0.00
38	*Cold rolling and finishing*	*Automated monitoring and targeting system*	R	0	0.00516	1.99	0
39		*heat recovery on annealing line*	R	0.007165	0.00026	4.41	0

R: retrofit, S: subtitusion

No	Process	Technology	Type	Fuel consumption (toe/ t)	Electricity production (toe/t)	Capital cost* (US$ /t)	Annual OM* (US$ /t)
40	*Non*-BF	COREX	S	0.54300	0.0756	367.18	.0
41		FINEX	S	0.37440		367.18	0
42		MIDREX	S	0.25301		399.10	0
43		Ulcored	S	0.18988		399.10	0
44		SL/RN	S	0.47916		344.39	0
45		Hisarna	S	0.41010		159.64	0

Table A.2 Screened technology of non-BF process

S: subtitusion; **Capital cost* and *annual OM cost* in 2030

Table A.3 Screened technology of on-site power plant

No	Process	Technology	Type	Efficiency thermal (%)	Capital cost* (US$ /t)
46	On site power plant	Coal, Stoker Boiler (existing)	S	60	1500
47		Coal, stoker boiler CHP	S	51	1000
48		Coal, IGCC	S	25	1770
49		RDF, PLTSA_MG	S	25	5915
50		RDF, PLTSA_CFB	S	40	2133
51		BMS, Direct combustion	S	60	2300
52		BMS, CHP	S	60	4040
53		cofiring, CHP	S	60	2500
54		cofiring, CFB	S	43	1440
55		cofiring, CFB +CHP	S	60	4260
56		cofiring, IGCC	S	40	2200
57		cofiring, Digester GT	S	50	1850
58		cofiring, Landfill gas	S	35	1350

S: subtitusion; **Capital cost* and *annual OM cost* in 2030