Gate-to-gate approach in life cycle assessment of steel pipe products

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Abstract: The iron and steel industry is of great strategic importance in Indonesia and is expected to continue its growth. One sector within this industry that is projected to see increased production is the steel pipe manufacturing sector. However, the significant emissions produced during steel pipe production have prompted many countries to seek ways to reduce these emissions. One such method is the implementation of the Life Cycle Assessment (LCA) technique, which assesses the environmental impact and serves as a valuable decision-making tool alongside other important methods. This approach aims to enhance sustainable production and consumption effectively and efficiently. In a specific case study, two types of steel pipe products were analyzed using LCA, focusing on various stages from material transportation to steel pipe production and delivery. The study assessed the environmental impact using the midpoint impact category, which includes factors like Global Warming Potential (GWP), Photochemical Ozone Creation Potential (POCP), Acidification Potential (AP), and Ecological Toxicity Potential (ETP) using the CML2001 characterization methods. The findings revealed that the production of SAWH pipes has a higher environmental impact in terms of GWP, AP, and POCP compared to HFW pipes, while HFW pipes had a greater ETP value. GWP was identified as the most significant potential impact for both products, with the pipeline production stage contributing the most to GWP. Overall, these results offer an initial understanding of the sustainability levels of steel pipe production, serving as a foundation for the development of pollution control measures to maintain the competitiveness of the industrial plant.

1 Introduction

Steel is a low-carbon iron that is widely used in the industrial sector. Its better properties compared to other types of iron, in terms of strength and toughness, make this material the first choice in the manufacture of pipelines both in clean water distribution systems, drainage systems, and oil and gas transport systems. The need for steel pipes on a national scale continues to increase in line with government policies that encourage industry to increase the use of domestic products. The Indonesian Iron and Steel Industry Association (IISIA) [1]

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calculated the projected development of the steel pipe industry nationally in accordance with the National Steel Industry Roadmap*,* where it is estimated that there will be an increase in steel pipe production capacity to 3.1 million tons in 2025 from 2.4 million tonnes in 2020.

The World Steel Associations [2] state that steel material can be fully recycled without losing its quality but, in the process of processing it into steel pipes, several potential negative impacts on the environment can occur. The steel industry sector is said to contribute at least 6% of anthropogenic CO_2 emissions annually globally [3]. The reasons for this high number of emissions are: (1) high energy consumption and (2) high carbon requirement to act as a reducing agent for iron ore [4]. In her research, Nandyala found that of the entire steel pipe manufacturing process, the pipe manufacturing phase gives the highest CO_2 equivalent - emissions [5]. The same results were also shown when comparing the CO_2 equivalent emissions produced during the steel pipe manufacturing process with concrete pressure pipe.

Efforts to reduce CO_2 emissions from iron and steel industry activities have been carried out in various countries. Several research and development initiatives related to this include: ULCOS (European Union), AISI (America), POSCO (Korea), and COURSE50 (Japan). All these activities have the same vision towards environmentally friendly and sustainable iron and steel production activities [3]. For example, ULCOS is one of the research programs of a consortium of 48 companies from 15 European countries with the aim of reducing CO_2 emissions by at least 50%. This program focuses on finding solutions to the threat of global warming by developing technology to be able to efficiently use energy and the waste it produces [6]. One of the methods used in the ULCOS project to assess the impact of metallurgical processes on the environment and the selection of new technologies is the Life Cycle Assessment (LCA).

LCA is a structured, comprehensive, and internationally standardized method that aims to quantify all emissions and resource consumption, as well as environmental and health impacts and resource scarcity issues related to goods and services (products). This method is also a powerful decision support tool, complementing other methods, which are equally important to help effectively and efficiently make production and consumption more sustainable [7]. In its application, LCA is widely used to compare the environmental impact of a product.

Several previous studies have been conducted to evaluate the environmental impact during the steel production process on the steel pipe production process. The iron and steel industry uses LCA as a tool to comprehensively evaluate processes, material choices, and the effect of greenhouse gas emissions throughout their life cycle [8]. In a study involving 3 types of steel pipe products, it was found that the Global Warming Potential (GWP) is the most significant environmental impact in the steel pipe manufacturing process. The potential for CO_2 emissions during production processes that use electrical energy is generally higher than that of other energies as a result of the fossil fuels used in power plants [9]. The use of coke and coal as carbon sources for reducing iron ore is also a large source of CO_2 emissions during the steel production process [4].

LCA studies can help companies to identify the most significant environmental impacts throughout the process of transportation of raw materials, pipe production, to distribution of steel pipes as carried out by PT X. PT X is one of the national industries that produces steel pipes for piping system needs in onshore conditions as well as offshore. Information related to the environmental impact of a product's life cycle will assist companies in determining policies related to environmental management systems. Not only that, an evaluation of the steel pipe production process at PT X can be used as a reference for the development of a production process that is more towards the concept of cleaner production.

2 Methods

2.1 Research sites

The research was conducted at PT X which is located in Manyar District, Gresik Regency, East Java. PT X is a steel pipe manufacturing industry that produces pipes for the oil and gas industry, water pipes, pipe structures and piles, pipe accessories and other construction needs in accordance with national and international industry standards. Steel pipe production activities at PT X include the pipe manufacturing stage with two welding facilities (submerge-arc welding/SAW and high frequency welding /HFW), inspection stage (quality control), and coating stage with various facilities including anti-corrosion coating, internal coating/lining, heat insulation, concrete weight coating, and custom coating.

PT X has six SAWH pipe making machines and one HFW pipe making machine with a total installed capacity of 320,000 MT per year. SAWH pipe production machines manufacture steel pipe in sizes from 114.3 mm (4 inches) to 2032 mm (80 inches) and offers various combinations of standard and intermediate sizes (wall thickness, diameter, and material grade). For HFW pipe production machine produces 6 inches to 16 inches line pipe and casting pipe. The production of SAWH and HFW pipes from 2019 to 2020 is shown in Table 1.

Table 1. PT X steel pipe production in 2019-2020

No.	Year	Total SAWH (tonnes)	Total HFW (tonnes)	Total Production
1	2019	37164.54	7043.65	44208,19
2	2020	20163,78	20732,9	40896.68
Average		28664,16	13888,28	42552.43

2.2 Life cycle assessment method (ISO 14040:2006)

The research will be carried out following the stages of the LCA method [10], namely determining objectives and scope, inventory analysis, impact assessment, and interpretation of results. This research aims to identify the amount of material and energy used in the production of steel pipes, also determines the amount and magnitude of the environmental impact associated with the life cycle of steel pipe products produced by PT X based on the *Life Cycle Assessment* (LCA) Method. LCA system boundary for the steel pipe production shown in Fig. 1. The functional unit specified in this Life Cycle Assessment (LCA) study is 1 (one) ton of uncoated steel pipe ready for distribution. Two types of products are considered, namely, High-Frequency Welded (HFW) steel pipes and Submerged Arc Welded Helical (SAWH) steel pipes. The life cycle of steel pipe products is divided into three subsystems:

1. Transportation Material Subsystem Processes in this subsystem include the transportation of HRC material from suppliers to PT X. Emission calculations for the vehicles used to transport the material are conducted considering vehicle type, fuel type, distance from the HRC manufacturer to PT X, and the number of rotations. In this subsystem, the types of vehicles are limited to land transportation.
2. Steel Pipe Production Subsystem Processes in this subsystem include coil preparation, forming processes, inspection, and the final phase. The final products under consideration are uncoated steel pipes with high-frequency welding and submerged arc welding. Energy consumption considered in this subsystem includes the use of water and electricity

throughout the process. Calculations account for the emissions of air pollutants, liquid waste, and solid waste generated during the steel pipe production process. Waste treatment by third parties and recycling activities for the residual products are excluded from the scope.

3. Product Delivery Subsystem The delivery process takes into account the average distance from PT X to consumers, vehicle types, fuel types, and delivery rotations. In this subsystem, the types of vehicles are limited to land transportation.

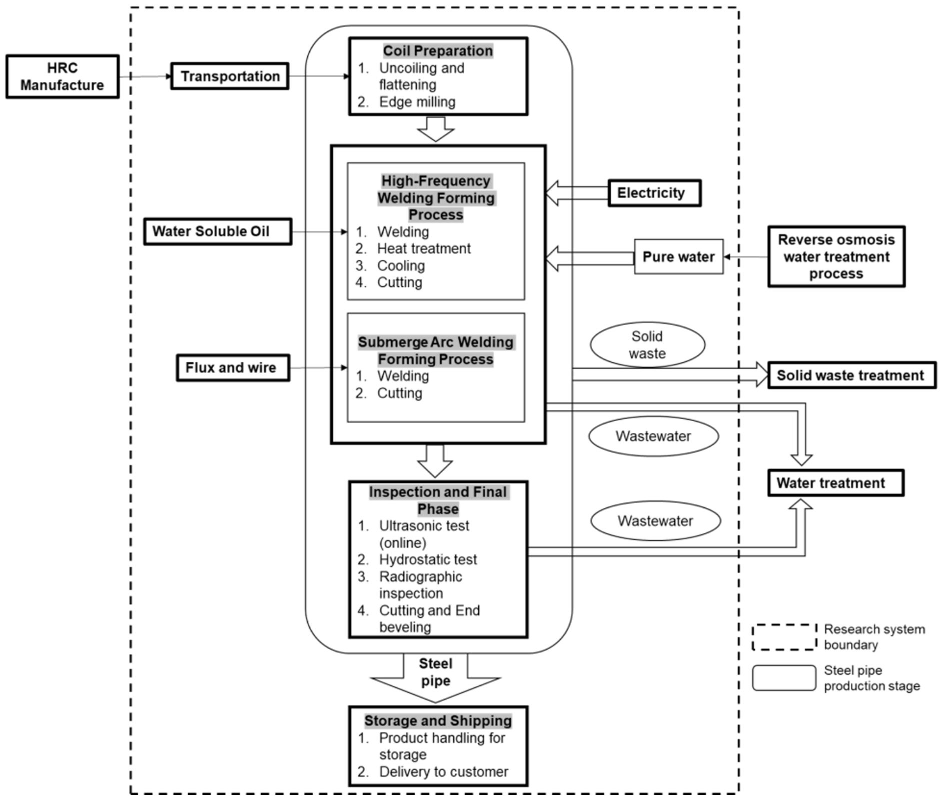

Fig. 1. System boundary of the research for steel pipe manufacturing in PT X.

2.2.1 Life cycle inventory

The data used is secondary data sourced from PT X for HFW and SAWH steel pipe production activities in 2019 – 2020. Emission calculations are carried out using several approaches:

a. The calculation of the inventory of emissions originating from vehicles (raw material transportation and distribution stages) is carried out based on the Vehicle Kilometers Traveled (VKT) with the emission factors from 2019 EMEP/EEA *emission inventory guidebook* [11]. Emission factors are determined based on vehicle category, fuel, and technology. The calculated distance between the location of the raw material supplier and PT X and between PT X and the customer's delivery point. The number of products shipped follows PT X's purchasing and shipping data. The estimated emissions follow the following formula:

$$E_{a} = \Sigma(VKT_{b,c}\, x\, FE_{a,b,c}) \qquad (1)$$

Where:
E_a = Pollutant load for pollutant a
$VKT_{b,c}$ = Total annual trip length of category b motorized vehicles using type c fuel
$FE_{a,b,c}$ = The amount of pollutant a emitted for each [kilometer] trip made by a category b motorized vehicle that uses type c fuel or also known as the emission factor.

b. The estimated emission load from electricity use is based on electricity consumption multiplied by the *ex post* 2019 GHG emission factor for the Java, Madura and Bali interconnection systems of 0.87 tons CO_2 /MWh. The equation used is:

$$\text{Electricity emission} = \text{electricity consumption (kWh)} \times \text{emission factor (tonnes/MWh)} \quad (2)$$

2.2.2 Life cycle impact assessment

In this research, the impact categories were selected based on the potential impacts generated by steel pipe manufacturing activities, namely Global Warming Potential (GWP), Photochemical Ozone Creation Potential (POCP), Acidification Potential (AP), and Ecological Toxicity Potential (ETP). The selected characterization method is the CML 2001 methods. In general, the characterization value of the impact on LCIA is calculated using the following equation:

$$I\text{c} = \Sigma CF_{\text{c,s}}\ x\ m_{\text{s}} \quad (3)$$

Where:
I = Result of the indicator for the impact category c
CF_{s} = The characterization factor of compound s towards the impact category c

2.2.3 Interpretation of results

Interpretation of the results of the LCA is a stage of consideration of the findings of the inventory analysis and impact assessment. The findings in this interpretation can be in the form of conclusions and recommendations for decision making, also intended to provide a presentation of the results of the LCA in accordance with the objectives and definition of the research scope [10].

3 Results and discussion

3.1 Life cycle inventory

The inventory carried out in this study includes the subsystems of material transportation, steel pipe production, and product delivery. In calculating energy consumption, the approach taken to obtain the amount of energy is to calculate the electric power or the volume of water used to produce one ton pipe. The results of *the gate-to-gate* inventory analysis of steel pipe products with the HFW and SAWH types are shown in Table 2 where the inventory value is a combination of each process stage. Inventory values for the process of material transportation and product delivery are written separately to facilitate further analysis.

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Table 2. *Gate-to-gate* inventory of HFW and SAWH steel pipe products

HFW pipe			**SAWH pipe**		
Input	**Unit**	**Total**	**Input**	**Unit**	**Total**
Hot Rolled Coils	tons	1.0 52	*Hot Rolled Coils*	tons	1.027
Lubricants	kg	8.73E-04	*Flux*	tons	2.79E-03
Material transport fuel	kg	7.70E-02	*Wire*	tons	4.95E-03
distribution fuel	kg	1.25	Material transport fuel	kg	1.00E-01
Electricity	kWh	5.28E-02	distribution fuel	kg	1.25
Water	L	7 6,88	Electricity	kWh	8.72E-02
Output	**Unit**	**Total**	Water	L	43.75
CO_2			**Output**	**Unit**	**Total**
Electricity	kg	4.59E-02	CO_2		
Fuel	kg	2.42E-01 [a] + 3.93 [b]	Electricity	kg	7.59E-02
CO	kg	5.32E-04 [a] + 8.42E-03 [b]	Fuel	kg	3.15E-01 [a] + 3.93 [b]
NMVOC	kg	1.03E-04 [a] + 1.62E-03 [b]	CO	kg	5.63E-04 [a] + 8.42E-03 [b]
NOx	kg	2.95E-03 [a] + 4.66E-02 [b]	NMVOC	kg	1.11E-04 [a] + 1.62E-03 [b]
N_2O	kg	3.72E-06 [a] + 5.98E-05 [b]	NOx	kg	3.18E-03 [a] + 4.66E-02 [b]
NH_3	kg	9.24E-07 [a] + 1.44E-05 [b]	N_2O	kg	4.02E-06 [a] + 5.98E-05 [b]
HFW Pipe			**SAWH Pipe**		
Output	**Unit**	**Total**	**Output**	**Unit**	**Total**
SO_2	kg	2.61E-04 [a] + 4.08E-03 [b]	NH_3	kg	1.22E-06 [a] + 1.44E-05 [b]
CH_4	kg	2.71E-05 [a] + 4.23E-04 [b]	SO_2	kg	3.45E-04 [a] + 4.08E-03 [b]
Cu	kg	1.24E-07	CH_4	kg	3.57E-05 [a] + 4.23E-04 [b]
Zn	kg	8.37E-08	Cu	kg	8.02E-08
CD	kg	1.00E-07	Zn	kg	5.40E-08
Ni	kg	9.23E-08	CD	kg	6.47E-08
Pb	kg	3.30E-07	Ni	kg	5.95E-08
Solid waste	kg	5.21E-02	Pb	kg	2.13E-07
HFW pipe	tons	1,000	Solid waste	kg	2.07E-02
			SAWH pipe	tons	1,000

Information:

[a] Material transport process inventory value

[b] Value of product distribution process inventory

3.2 Impact analysis (life cycle impact assessment)

The impact categories related to steel pipe production activities at PT X have been determined, namely: Global Warming Potential (GWP), Photochemical Ozone Creation Potential (POCP), Acidification Potential (AP), and Ecological Toxicity Potential (ETP). Quantification of data inventory results and compound classification was carried out CML2001 characterization methods. The results of the characterization of the gate-to-gate life cycle based on potential impacts are shown in Fig. 2.

Based on the results of characterization calculations, SAWH pipe products have a greater GWP potential impact compared to HFW pipes with a value of 80.221 kg CO_2 eq/ton SAWH pipe. The largest potential impact calculations for AP and POCP are also found in SAWH products with successive values of 0.00534 kg SO_2 eq/ton SAWH pipe and 0.0000515 kg Ethylene eq/ton SAWH pipe. Whereas in the ETP impact category, the biggest potential impact comes from the life cycle of HFW pipe products with a value of 0.000606 kg 1.4-DCB eq/ton HFW pipe.

The value of the potential impact is related to the energy and emissions resulting from the steel pipe manufacturing process. The use of electrical energy in the steel pipe manufacturing process contributes CO_2 emissions to the potential impact of GWP, with a value for each product of 50.2 kg CO_2 eq/ton HFW pipe and 80.2 kg CO_2 eq/ton SAWH pipe. This also causes the value of the potential impact of GWP on SAWH products to be higher compared to HFW products.

The potential impact of AP gets the biggest contribution from SO_2. The characterization results show a value 0.00524 kg SO_2 eq/ton HFW pipe and 0.00534 kg SO_2eq/ton SAWH pipe. Direct emissions from material transportation activities are one of the contributors to the potential impact of AP. In the SAWH pipe, the distance traveled to deliver raw material per ton of SAWH pipe from the supplier to PT X is farther than the HFW pipe resulting in a higher AP impact potential value.

The formation of photochemical ozone generally occurs due to the photochemical reaction of NO_x and volatile organic compounds (VOC and NMVOC). CML2001 method makes SO_2 the main contributor to the formation of photochemical ozone. The SAWH pipe is the product with the greatest potential for POCP impact compared to the HFW pipe with CO compounds became the largest contributor with a value of 5.15E-05 kg Ethylene/ton SAWH pipe. Direct emissions from the material transportation process become a source of emissions on the potential impact of POCP.

Wastewater generated during the pipe forming process at PT X can contain metals in certain amounts that can risk the environment. metal compounds can be highly biologically active [12], and emissions of metal compounds are considered as priority compounds [13]. In this study the potential impact of ETP assessed the contribution of wasted metal compounds to the environment which was then compared to the equivalent of 1,4-DCB. Products with higher value of ETP, nickel (Ni) have the biggest characterization with value of 0.000295 kg 1,4-DCB eq/ton of HFW pipe.

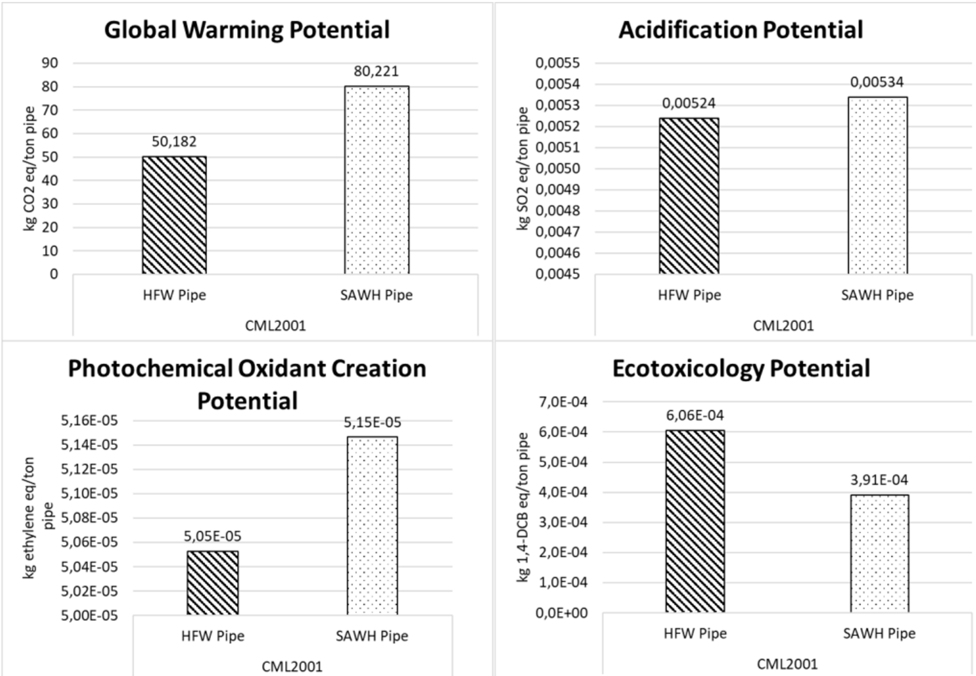

Fig. 2. The characterization value of the potential impact of each product

An analysis of potential impacts based on process stages on steel pipe production activities was also carried out in this study. Fig. 3 shows characterization values from every stage of steel pipe production. Based on the characterization results, the potential GWP impact on the two products gets the largest contribution from the pipe production process with a contribution of more than 91%. The potential impact of AP and POCP on both products gets the biggest contribution from the product delivery stage with a contribution of more than 93% for both products. As for ETP, the contribution comes entirely from pipe production activities.

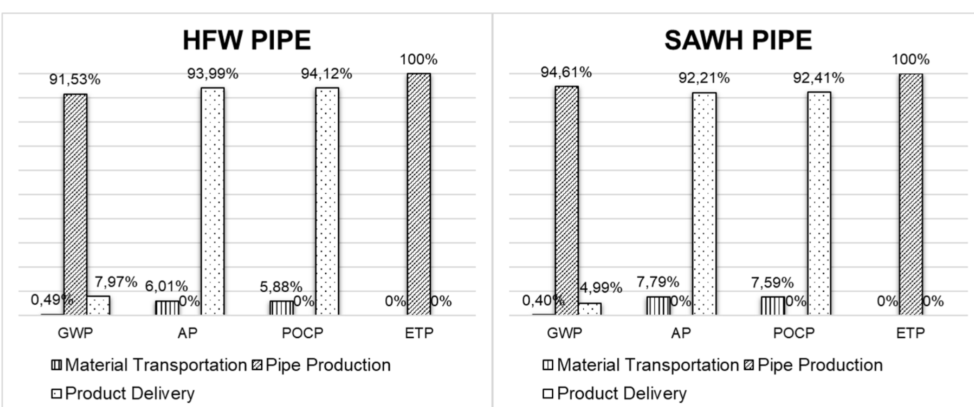

Fig. 3. Potential impacts based on process stages for HFW Pipe and SAWH pipe

3.3 Normalization

Normalization of characterization values is carried out to be able to compare the results of the impact analysis with the characteristic value units determined based on the normalization reference, thus facilitating the process of interpreting the LCA results. Normalization was carried out on the characterization results using the normalization reference CML, global impact per year, World 2000. The normalization results are shown in Fig. 4.

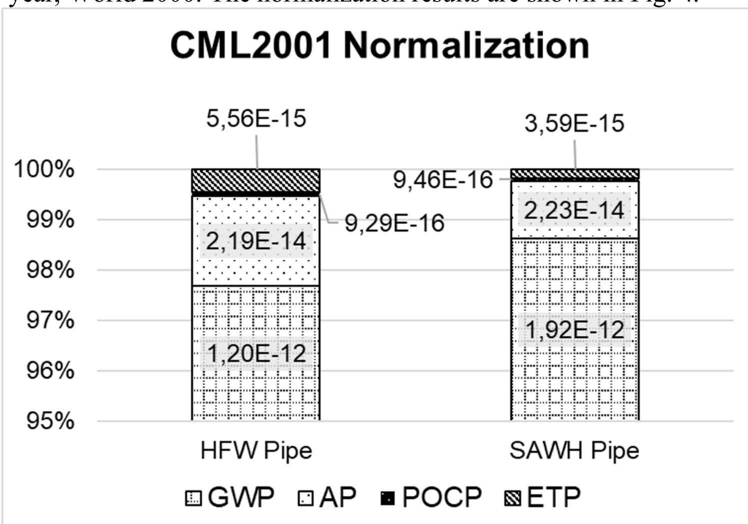

Fig. 4. Normalization of potential impact characterization results

GWP impact potential from gate-to-gate life cycle of steel pipe products shows the greatest value compared to other potential impacts. The potential normalization value for GWP is 1.20E-12 for HFW pipes and 1.92E-12 for SAWH pipes. Normalization is also carried out on the potential impact of each stage of the steel pipe manufacturing process. From Fig. 5, it is known that for the two products the largest GWP contribution comes from the pipe production process with a value of 1.10E-12 per ton of HFW pipe and 1.82E-12 per ton of SAWH pipe. As for AP and POCP, the largest contribution came from the product delivery process with values for the two products respectively 2.06E-14 per tonne of pipe and 8.74E-16 per tonne of pipe. For ETP, the largest contribution comes from the pipe production process with a value of 5.56E-15 per ton of HFW pipe and 3.59E-15 per ton of SAWH pipe.

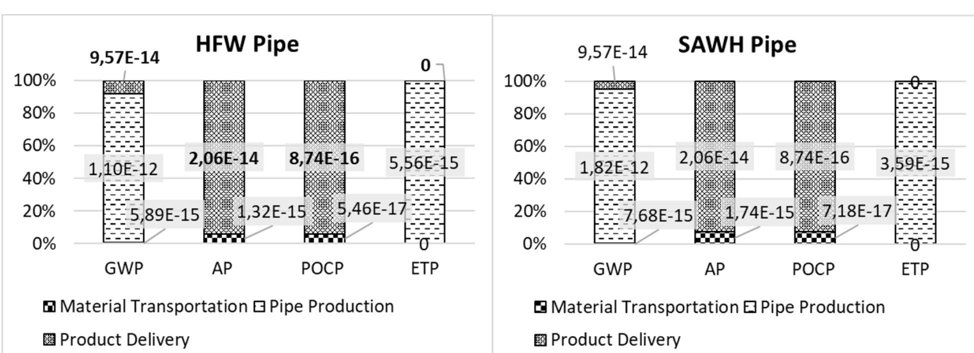

Fig. 5. Normalization of characterization values per process stage in the CML2001 method

3.4 Interpretation

Based on the normalization results, the Global Warming Potential (GWP) impact has the highest value compared to other impact potentials. The highest GWP impact potential is generated during the pipe production stage with values of 45.93 kg CO_2 eq/ton for HFW pipes and 75.9 kg CO_2 eq/ton for SAWH pipes. CO_2 emissions are the largest contributors to the GWP impact potential during the pipe production stage due to the significant electricity consumption during the pipe formation process.

4 Conclusion

Analysis of the potential impact on the two steel pipe products was carried out using CML2001 method. The characterization results show that the SAWH pipe has a greater impact characterization value than HFW for the potential impact of GWP, AP, and POCP. The greater use of energy in SAWH pipes is the reason for the large value of the potential impact. Whereas in terms of potential ETP impacts, HFW pipe products have a greater value, this is related to the production of more wastewater during the pipe manufacturing process.

Based on the results of normalization, the potential GWP impact has the greatest value compared to other potential impacts. The biggest GWP impact potential is generated at the pipe production stage with a value of 1.10E-12 per ton of HFW pipe and 1.82E-12 per ton of SAWH pipe. CO_2 emissions are the biggest contributor to the potential GWP impact at the pipe production stage due to the use of electrical energy during the pipe forming process.

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