# Nickel Life Cycle Analysis Update and Additions in the GREET® Model

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## ACRONYMS

| | |
|---|---|
| BC | black carbon |
| HPAL | high-pressure acid leaching |
| LCA | life cycle analysis |
| LCI | life cycle inventory |
| MHP | mixed hydroxide precipitate |
| MSP | mixed sulfide precipitate |
| NI | Nickel Institute |
| OC | organic carbon |
| PM | particulate matter |
| $PM_{10}$ | particulate matter 10 micrometers or less in diameter |
| $PM_{2.5}$ | particulate matter 2.5 micrometers or less in diameter |
| tpy | metric ton per year |
| USGS | United States Geological Survey |

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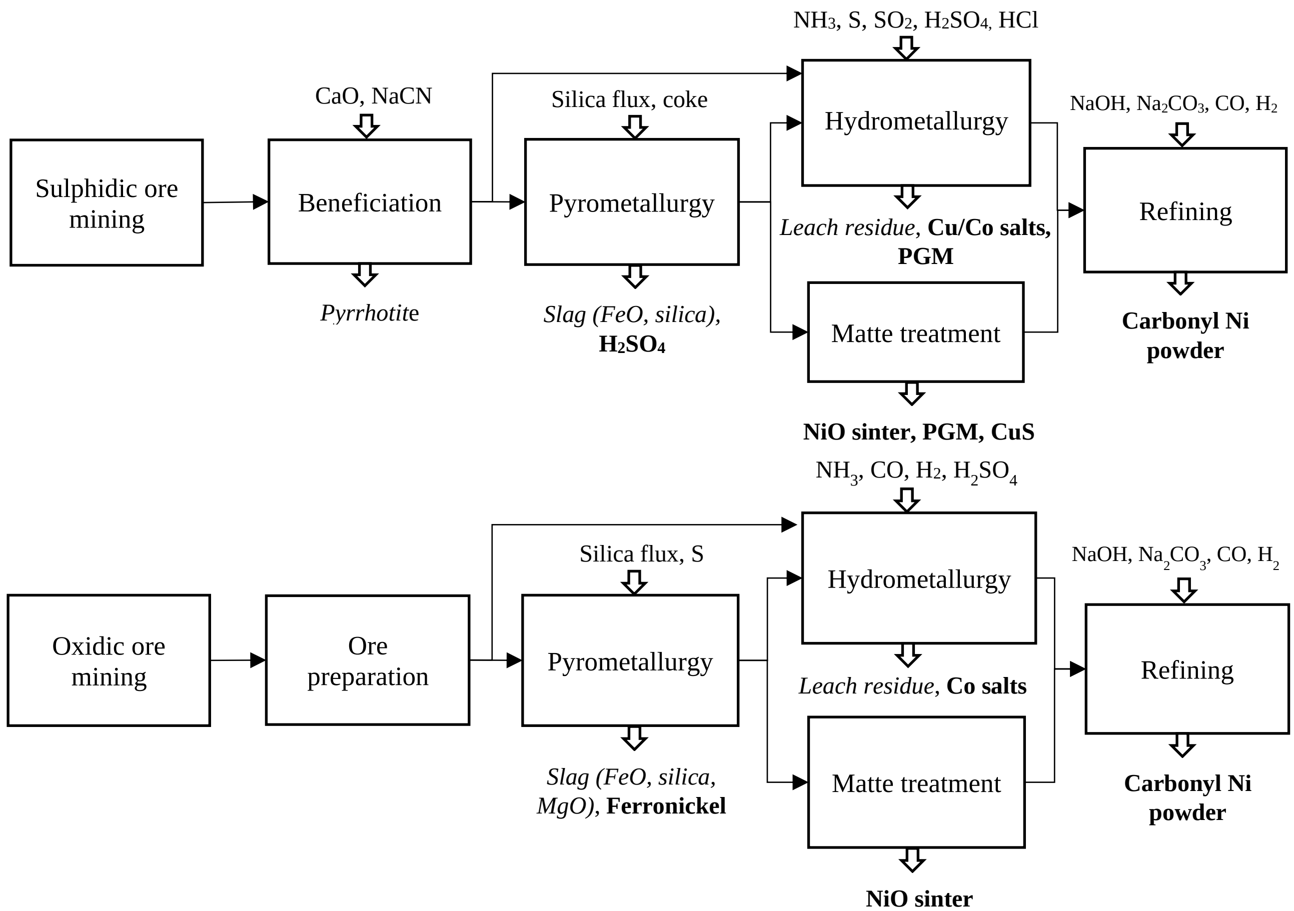
This memo documents the updates for life cycle analysis (LCA) of Class 1 nickel and battery-grade nickel sulfate ($NiSO_4$) production in the GREET® model. The updated life cycle inventory (LCI) covers material and energy flows associated with nickel ore mining and beneficiation, battery-grade $NiSO_4$ production, and Class 1 nickel production. Based on recent literature, industry statistics, and company reports, these updates represent the practices of the global nickel industry at the time of the analysis and were incorporated into GREET 2020.

## 1. Introduction

In the GREET® model, Class 1 nickel is used for the production of nickel metal hydride batteries, as well as various catalysts, while $NiSO_4$ is used for the production of various cathode materials for lithium-ion batteries. Since existing data for secondary production of Class 1 nickel and $NiSO_4$ in GREET 2020 still represents the best industrial data available at the time of the analysis, this study focuses only on primary production. The system boundary is cradle-to-gate. The updated LCI for Class 1 nickel production is based on the most recent LCA of nickel products commissioned by the Nickel Institute (NI) that represents 52% of global production in 2017 (NI, 2020). The LCI for $NiSO_4$ represents laterite ore mining and processing in Papua New Guinea and the refining of mixed hydroxide precipitate (MHP) in China.

## 2. Primary Class 1 Nickel Production

Class 1 nickel is produced from sulfide and/or oxide ores via pyrometallurgical and/or hydrometallurgical pathways. Nickel production technologies have been described in our 2015 report (Benavides *et al*., 2015) and are summarized in Figure 1. Since the 2020 LCA study by the NI covers Class 1 nickel production from both sources and pathways and represents 52% of global production in 2017 (NI, 2020), we have adapted this LCI for GREET (summarized in Table 1).




### Figure 1. Process Flow Diagram for Class 1 Nickel Production

Class 1 nickel production processes also produce other metals in addition to nickel. To be consistent with the NI study, economic value-based allocation is used to convert the gate-to-gate LCIs reported in this study into an LCI specific to Class 1 Ni production in GREET. The unit prices for metals reported in the NI study are used for the economic value-based allocation. In addition, mass-based quantities of diesel, gasoline, coal, residual oil, natural gas, and liquefied natural gas from the NI LCA study were converted into energy values (in MJ) based on their respective lower heating values in GREET. Also, since LCIs from the NI LCA study do not include emissions of black carbon (BC), organic carbon (OC), and nitrous oxide ($N_2O$), we have estimated these emissions by multiplying the quantities of fuels consumed by their respective emissions factors for BC, OC, and $N_2O$ from GREET.

**Table 1. LCI for Class 1 Nickel Production (per ton of Class 1 Ni produced)**

| | Mining | Beneficiation and ore preparation | Primary extraction | Refining |
|---|---|---|---|---|
| **Materials input (ton/ton)** | | | | |
| Ammonium nitrate | 0.092 | 0.000 | 0.000 | 0.000 |
| Steel | 0.000 | 0.087 | 0.000 | 0.000 |
| Lime | 0.000 | 0.096 | 0.128 | 0.021 |
| Limestone | 0.000 | 0.000 | 1.745 | 0.000 |
| Sulfur | 0.000 | 0.000 | 0.611 | 0.000 |
| Coke | 0.000 | 0.000 | 0.127 | 0.000 |
| Sodium hydroxide | 0.000 | 0.000 | 0.007 | 0.111 |
| Sand | 0.000 | 0.000 | 2.459 | 0.001 |
| Ammonia | 0.000 | 0.000 | 0.001 | 0.119 |
| Oxygen | 0.000 | 0.000 | 3.093 | 0.333 |
| Sulfuric acid | 0.000 | 0.002 | 0.698 | 0.159 |
| Soda ash | 0.000 | 0.021 | 0.004 | 0.190 |
| **Water (gal/ton)** | | | | |
| Water | 0.000 | 1.369 | 608.302 | 85.542 |
| **Energy input (mmbtu/ton)** | | | | |
| Residual oil | 0.000 | 0.348 | 3.273 | 0.218 |
| Diesel | 4.903 | 1.372 | 0.409 | 0.014 |
| Gasoline | 0.006 | 0.003 | 0.054 | 0.002 |
| Natural gas | 0.675 | 3.888 | 28.813 | 9.549 |
| Coal | 0.000 | 2.319 | 2.935 | 4.706 |
| Liquefied petroleum gas | 0.000 | 0.000 | 0.001 | 0.042 |
| Electricity | 10.913 | 17.052 | 16.370 | 12.277 |
| **On-site process emissions (g/ton)** | | | | |
| NMVOC | 29.503 | 21.588 | 66.202 | 79.154 |
| CO | 863.502 | 79.154 | 5540.802 | 1583.086 |
| $NO_x$ | 1288.057 | 489.318 | 3324.481 | 745.490 |
| $SO_x$ | 388.576 | 410.163 | 2518546.294 | 65482.204 |
| $CH_4$ | 719.585 | 25.185 | 68.361 | 42.455 |
| $PM_{10}$ | 302.226 | 107.938 | 15830.862 | 5396.885 |
| $PM_{2.5}$ | 30.942 | 20.148 | 10793.770 | 1.511 |
| $CO_2$ | 424,555 | 359,792 | 1,942,879 | 791,543 |
| BC | 3.104 | 3.625 | 20.855 | 6.306 |
| OC | 7.819 | 8.486 | 47.647 | 15.577 |
| $N_2O$ | 5.013 | 6.761 | 30.138 | 11.786 |

# 3. Primary Nickel Sulfate Production

Although the NI LCA study also covers nickel sulfate ($NiSO_4$) production, it represents only 15% of global production in 2017. In addition, the study has reported LCI and LCA results for nickel sulfate hexahydrate, ($NiSO_4.6H_2O$), and it is not clear as to why the emission impacts for $NiSO_4$ production are significantly higher than that for Class 1 nickel production (on a per-kg basis). Hence, we have not adopted NI's LCI for nickel sulfate production, and we only include it in GREET as a reference (referred to in GREET 2020 as "Generic" $NiSO_4$) after converting the LCI for $NiSO_4.6H_2O$ production into that for anhydrous $NiSO_4$production. The LCI is summarized in Table 2.

### Table 2 LCI for Generic Nickel Sulfate Production (per ton of $NiSO_4$ produced)

| | | | | |
|---|---|---|---|---|
| **Materials input (ton/ton)** | | | | |
| Ammonium nitrate | 0.038 | 0.000 | 0.000 | 0.000 |
| Steel | 0.000 | 0.036 | 0.000 | 0.000 |
| Lime | 0.000 | 0.046 | 0.085 | 0.011 |
| Limestone | 0.000 | 0.000 | 0.196 | 0.000 |
| Sulfur | 0.000 | 0.000 | 0.017 | 0.000 |
| Coke | 0.000 | 0.000 | 0.129 | 0.000 |
| Sodium hydroxide | 0.000 | 0.000 | 0.003 | 0.064 |
| Sand | 0.000 | 0.000 | 1.356 | 0.000 |
| Ammonia | 0.000 | 0.000 | 0.000 | 0.031 |
| Oxygen | 0.000 | 0.000 | 2.097 | 0.224 |
| Sulfuric acid | 0.000 | 0.000 | 0.000 | 0.080 |
| Soda ash | 0.000 | 0.013 | 0.014 | 0.092 |
| Engine oil | 0.017 | 0.001 | 0.000 | 0.000 |
| Hydrochloric acid | 0.000 | 0.000 | 0.002 | 0.014 |
| Nitrogen | 0.000 | 0.000 | 0.000 | 0.025 |
| **Water (gal/ton)** | | | | |
| Water | 0.000 | 0.000 | 204.333 | 13.756 |
| **Energy (mmbtu/ton)** | | | | |
| Residual oil | 0.000 | 0.013 | 1.827 | 0.151 |
| Diesel | 0.273 | 0.005 | 0.002 | 0.000 |
| Gasoline | 0.000 | 0.000 | 0.191 | 0.000 |
| Natural gas | 0.000 | 2.163 | 8.980 | 4.359 |
| Coal | 0.000 | 0.505 | 0.054 | 1.803 |
| Liquefied petroleum gas | 0.000 | 0.000 | 0.000 | 0.048 |
| Electricity | 3.245 | 6.731 | 2.644 | 4.928 |
| **On-site emissions (g/ton)** | | | | |
| NMVOC | 1.395 | 0.456 | 17.752 | 1.090 |
| CO | 253.602 | 1.648 | 2662.819 | 849.566 |
| $NO_x$ | 284.034 | 11.412 | 1103.168 | 50.720 |

| | | | | |
|---|---|---|---|---|
| $PM_{10}$ | 126.801 | 0.254 | 7227.652 | 3170.023 |
| $PM_{2.5}$ | 0.571 | 0.000 | 0.000 | 0.000 |
| $SO_x$ | 21.556 | 11.158 | 1394809.948 | 34236.244 |
| BC | 0.149 | 1.323 | 8.078 | 2.903 |
| OC | 0.373 | 3.366 | 17.999 | 7.096 |
| $CH_4$ | 431.123 | 0.773 | 24.092 | 0.533 |
| $N_2O$ | 0.250 | 2.082 | 10.025 | 5.305 |
| $CO_2$ | 21,556 | 11,412 | 532,564 | 202,881 |

For the analysis of the primary production of $NiSO_4$ in GREET, we have built our own LCI. In 2019, intermediates accounted for 60% of the feedstock for global $NiSO_4$ production (Roskill, 2021). These intermediates typically include mixed hydroxide precipitate (MHP) and mixed sulfide precipitate (MSP), which are intermediate products from laterite (oxidic) ore processing. The remaining feedstock for primary $NiSO_4$ production primarily came from different forms of Class 1 nickel, such as nickel powder and briquettes (Roskill, 2021). Therefore, in GREET 2020, we assume that 60% of primary $NiSO_4$ is produced from intermediates and the remaining 40% from Class 1 nickel.

$NiSO_4$ production from Class 1 nickel typically involves dissolving nickel in sulfuric acid. We did not consider the process to consume any significant amounts of energy, water, or reagents other than the raw materials, so the LCI for this production pathway only consists of stoichiometric amounts of Class 1 nickel and sulfuric acid.

For $NiSO_4$ production from intermediates, little information was available for MSP at the time of the analysis, so we have used $NiSO_4$ production from MHP as a proxy. Furthermore, we assume that MHP is produced in Papua New Guinea since it was the biggest producer of MHP from laterite during 2015-2019 (USGS, 2022). We also assume that MHP is refined to battery-grade $NiSO_4$ in China, which accounted for over 50% of $NiSO_4$ production in 2020, and is expected to dominate global $NiSO_4$ production through 2040 (Roskill, 2021). We discuss this analysis in the following sections.

## 3.1 MHP production from laterite

MHP is produced via high-pressure acid leaching (HPAL) of laterite ores. Ramu NiCo operates the laterite mines and MHP production plant in Papua New Guinea. The LCI for MHP production in GREET is based on a technical report for a Ramu NiCo project (Deng et al., 2019), supplemented by data from a journal article authored by researchers from the Harita Nickel Group in Indonesia (Gultom and Sianipar, 2020), which also uses HPAL to produce intermediates from laterites.

The Ramu NiCo project processed 3,660,000 metric tons (t) of dry laterite ores per year during 2017-2018 and produced 91,103 metric tons per year (tpy) of dry MHP. Its laterite ore contains 1.1% Ni and 0.11% Co, while the MHP contained 38.4% Ni, and 3.65% Co. The HPAL plant operates at 250 °C and 4.3 MPa for 7,500 hours per year (Deng et al., 2019). Figure 2 depicts the MHP production process, while Table 3 summarizes the annual material and energy requirements for mining and MHP production.

### Table 3. Annual Materials and Energy Requirement for MHP Production

| | Mining | Ore beneficiation and preparation |
|---|---|---|
| **Materials** | | |
| Total $H_2SO_4$ (t) | | 900,000[a] |
| $H_2SO_4$ from sulfur (t) | | 886,500[a] |
| Purchased $H_2SO_4$ (t) | | 13,500[a] |
| Limestone (t) | | 694,471[b] |
| Sodium hydroxide (t) | | 59,706[b] |
| **Energy** | | |
| Electricity (MWh) | 225,000[a] | 405,000[a] |
| Steam (t) | | 675,000[a] |

a. Deng et al., 2019
b. Gultom and Sianipar, 2020

Since both mining and MHP production plants use electricity generated on-site using heavy fuel oil (Deng et al., 2019), we assume the electricity mix to be 100% petroleum without any transmission and/or distribution losses. Limestone is used to neutralize excess sulfuric acid in the process (Gultom and Sianipar, 2020), and its amount was estimated based on stoichiometric calculation. Sodium hydroxide is used to convert Ni and Co into their hydroxides in this process (Gultom and Sianipar, 2020), and its amount was also calculated stoichiometrically, assuming that the HPAL plant recovers 87% of the Ni and Co from the concentrated ore (Deng et al., 2019).

## 3.2 Battery-grade nickel sulfate production from MHP

The LCI for battery-grade $NiSO_4$ production from MHP is based on an environmental impact assessment report for a Huayou Cobalt project that can produce 30,000 tpy of $NiSO_4$ based on Ni content ((Huayou Cobalt, 2019). Figure 2 shows the concerned production process, while Table 4 provides the annual material and energy requirements for this plant. The plant is assumed to be powered by electricity generated using the average Chinese electric grid mix.

### Table 4. Annual Materials and Energy Requirement for MHP Refining Plant

| **Materials (t)** | |
|---|---|
| $H_2SO_4$ | 76,997 |
| HCl | 196.23 |
| NaOH | 21,960 |
| Kerosene | 325 |
| Soda ash | 289 |
| Lime | 2,845 |
| $O_2$ | 3,008 |
| $SO_2$* | 2,744 |
| $NaClO_3$ | 395 |
| Water | 187,990 |

| Energy | |
|---|---|
| Electricity (kWh) | 61,214,000 |
| Steam (t) | 54,020 |

*Excluded from LCI because it is not expected to have any upstream environmental impacts.

Both the MHP production and the MHP refining processes produce products other than nickel. To be consistent with the LCI for Class 1 nickel production, economic value-based allocation has been used to convert materials and energy requirements for these two processes to an LCI specific to $NiSO_4$ production. Again, unit prices for metals used in the NI LCA study (namely, $36/kg for Co and $11/kg for Ni) are used here. In addition, the MHP refining plant takes both MHP (containing 36.2% Ni and 3.5% Co) and nickel matte (containing 74% Ni and 0.94% Co) as feedstock (Huayou Cobalt, 2019). In order to link the two production processes, the total amount of feedstock for the MHP refining plant was converted into 78,172 tpy of Ramu NiCo-equivalent MHP, based on the Ni content. The resultant LCI is summarized in Table 5.

### Table 5. LCI for $NiSO_4$ production from MHP

| | Mining | Beneficiation and ore preparation | MHP Refining |
|---|---|---|---|
| **Materials Input (ton/ton)** | | | |
| Steel | | 0.336 | |
| Lime | | 0.220 | 0.028 |
| Limestone | | 5.767 | |
| Sulfur | | 2.404 | |
| Sodium hydroxide | | 0.496 | 0.220 |
| Oxygen | | | 0.030 |
| Sulfuric acid | | 0.112 | 0.771 |
| Soda ash | | | 0.003 |
| Hydrochloric acid | | | 0.002 |
| Kerosene | | | 0.003 |
| Sodium chlorate | | | 0.004 |
| **Water (gal/ton)** | | | |
| Water | | | 450.87 |
| **Energy (mmbtu/ton)** | | | |
| Natural gas | | 16.743 | 1.615 |
| Electricity | 5.784 | 10.411 | 1.896 |
| Total | 5.784 | 27.155 | 3.511 |

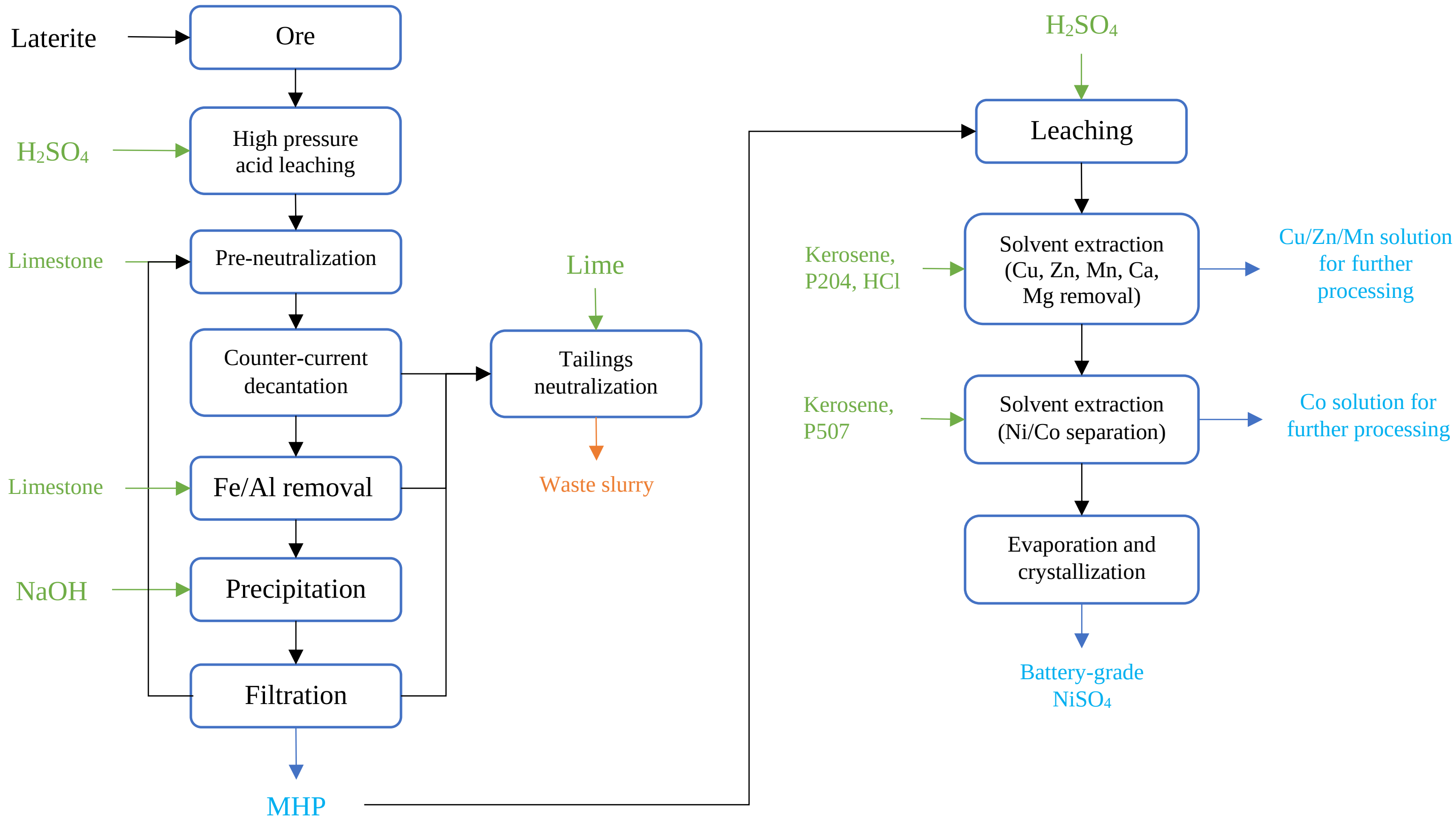



**Figure 2. Process Flow Diagram of $NiSO_4$ Production from MHP**

# Appendix A: Converting Steam Use into Natural Gas Use

The conversion of steam use into natural gas use is based on heat balance. It is assumed that the heat released from natural gas combustion was used to produce steam in the boiler at 250 °C and 4.3 MPa . The default boiler efficiency in GREET (80%) is used in this study. The natural gas consumption for the production of 1 kg steam is, therefore, calculated as follows:

$$Natural\ gas\ use = \frac{h_{g@250℃,4.3MPa}}{\eta_{boiler}} = \frac{2779kJ/kg}{0.8} = 3474kJ/kg$$

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