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Life Cycle Environmental Impacts Assessment of Post-Combustion Carbon Capture for Natural Gas Combined Cycle Power Plant in Iraq, Considering Grassroots and Retrofit Design

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Abstract: In this work, the Life Cycle Assessment (LCA) methodology is used to examine the implications of CO_2 capture from a natural gas combined cycle power plant with post-combustion carbon capture (NGCC-CCS) in Iraq, taking into account two different design scenarios. In the first scenario (retrofit), the carbon capture unit is considered as an end pipe technology that can be linked to an existing power plant. The second scenario considers a grassroots design, in which a new power plant equipped with a carbon capture unit needs to be constructed. The LCA is carried out based on different impact assessment (LCIA) methodologies of ReCipe 2016 Midpoint (H), TRACI 2.1, and IMPACT 2002+ to investigate whether the chosen LCIA method influences the LCA scenario analysis for decision support in process development. The results of three impact categories applied to both scenarios reveal a 28% reduction in Global Warming Potentials (GWPs) and a 14% and 17% increase in the Particulate Matter Formation Potential (PMFP) and Acidification (AP) potential in the grassroots scenario, respectively. Finally, an uncertainty analysis is performed to more accurately reflect the influence of uncertain factors on the statistical significance of the environmental impact evaluation in this research, indicating that these uncertainties may significantly affect the ultimate decision.

Keywords: life cycle assessment; carbon capture; global warming; environmental impacts; retrofit and grassroots design

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1. Introduction

1.1. Background

Global warming is the world's most challenging concern nowadays. Energy demand is rising due to population growth and industrial activities [1]. Apart from natural causes, human activities such as burning fossil fuels (coal, lignite, and natural gas) increase carbon dioxide emissions into the atmosphere, increasing the earth's natural greenhouse effect. Due to rising electricity demand and a growing population, Iraq increasingly relies on fossil fuels to produce its electricity [2]. The absence of a steady power supply is a major barrier to Iraq's growth. Power plants in Iraq now produce more power than ever, but there is still not enough to satisfy demand [3]. Iraq's long-term mitigation plans aim to cut greenhouse gas (GHG) emissions through sector and national plans, aligning with the country's development aspirations and employing the appropriate tools to lower costs and bring about transformational and long-lasting improvements [4]. The Intended Nationally Determined Contributions (INDC) were submitted by Iraq to the UNFCCC in 2015 to set targets for reducing emissions of greenhouse gas (GHG) equivalent to 14% below business-as-usual (BAU) emissions during the period between 2020 and 2035 [4]. In the OECD countries, natural gas contributes about 31.6% of the energy source used in the electric power

generation mix, indicating a strong relationship between economic growth and natural gas demand [5]. Natural Gas Combined Cycle Power Plants (NGCC), in particular, have lower emissions than other fossil fuel-based power plants. In this regard, switching from coal and oil to natural gas could be a key solution considered for future sustainable energy systems, which could be realized by combining NGCC power plants with CO_2 capture and storage systems [6,7]. Nonetheless, despite advantages over conventional nonrenewable energy sources, hazardous pollutants are released into the environment during the operation of NGCC power plants [8].

Carbon capture and storage (CCS) has emerged as a medium-term mitigation strategy for reducing CO_2 emissions from power plants [9]. The benefits from the CO_2 capture and utilization chain are twofold: first, mitigating climate change and reducing harmful environmental effects, and second, creating economic value by using captured CO_2 to produce other valuable materials and enhancing oil production before being stored. Global interest is growing in new CO_2 use pathways for the manufacture of fuels, chemicals, and construction materials. The fertilizer industry has the largest consumer share, with 130 Mt CO_2 utilized in urea production, followed by the oil and gas industry, with consumption of (70–80) Mt CO_2 for enhanced oil recovery [10]. Food and beverage processing, cooling, metal fabrication, fire suppression, and stimulating plant growth in greenhouses are some of the other commercial applications of CO_2. The environmental implications of Carbon Capture and Utilization (CCU) technologies and Carbon Capture and Storage (CCS) are generally examined using a widely established process among industrial practitioners and academics known as Life Cycle Assessment (LCA).

LCA is a process for evaluating possible benefits as well as different environmental consequences through a product's or service's life cycle. The LCA is based on the defined approaches of ISO 14044 [11] and ISO 14040 [12]. The standard LCA analysis is based on choosing the functional unit, background processes, system boundaries, or environmental impact assessment. During the Life Cycle Impact Assessment (LCIA) stage, a specific set of methods and models is used to estimate the environmental impacts based on flows into and out of the environment from the Life Cycle Inventory (LCI). Typically, these methods characterize and classify emissions, using impact-related reference indicators. Thus, the environmental effects of a projected system can better comprehend at an early stage by quantifying the possible environmental implications. The life cycle assessment method evaluates the environmental impacts of a CCS or CCUS plant throughout its life cycle, in different stages (extraction, production, transportation, processing, and storage), in addition to recycling and final disposal of waste materials [13]. A clear distinction should be made between carbon capture and utilization chain utility (CCU) and storage technologies (CCS), as shown in Figure 1. When evaluating the environmental performance of power plants using CCS, it is implied that upstream (e.g., extraction of fuel, transportation) and downstream activities (e.g., CO_2 transport, injection, and storage) must be involved in the CCS chain designs [14].

1.2. Literature Review

LCA is recognized as a valuable method in identifying various environmental impacts over the life cycle in different phases and regions [15]. Research on LCA assessment of the CCS has been conducted to identify and evaluate the environmental implications of CCS [16]. However, the existing methodologies are inadequate, and there are discrepancies in data quality and basic assumptions that make it difficult to compare. For LCA to be widely accepted, comprehensive and specific data inventories are necessary. Data used in the LCA depend on assumptions that are unlikely to be accurate across all data sources; therefore, there will be some data with an unavoidable higher level of uncertainty. For example, unlike photochemical smog or human toxicity, data required to address various GHG emissions and acid rain precursors have been reasonably well produced for the power generation industry [17].

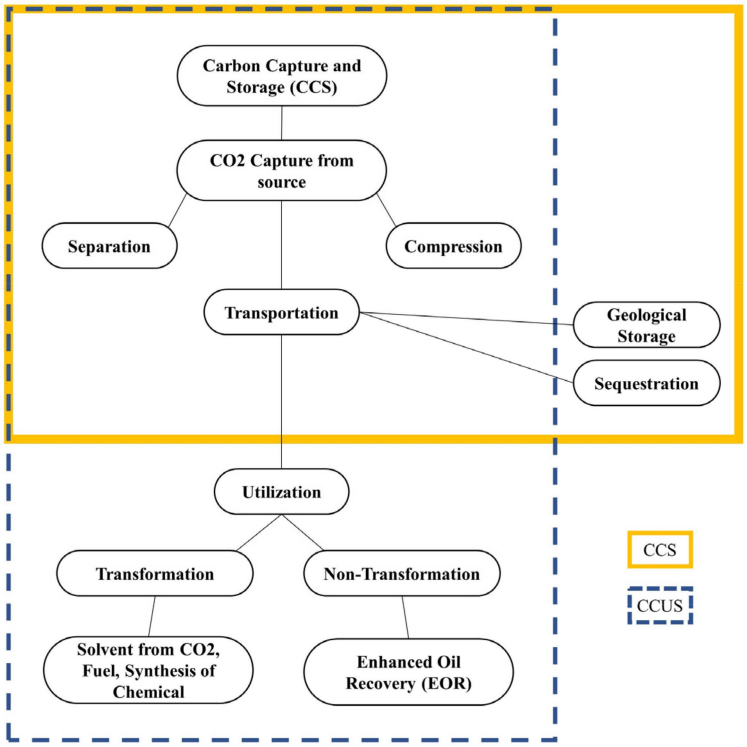

Figure 1. Difference between the CCS and CCUS plant.

More life cycle assessments have been performed in the last decade to examine the environmental impact of power production systems combined with CCS. These studies take into account not only the global warming potential (GWP) connected with climate change but also other types of environmental impacts. GWP is a measure to compare the climatic impact of various greenhouse gas emissions. It is calculated by aggregating the radiative climatic forcing of a greenhouse-gas emission over a certain time horizon [18]. All these studies have revealed a trade-off regarding global warming potential, chemical effects, resource depletion, and waste treatment of CCS technologies. The focus of many of these studies has shifted away from early climate change impacts toward a variety of non-climate issues such as human health potential (HTP), eutrophication potential (EP), and acidification potential (AP) [19]. Several characterization models and category indicators are proposed for various effect categories. The Impact categories range from only GWP, as in [20], to a more extensive set of other environmental categories [21]. Therefore, studies dealing with the same effect category but using distinct categorical indices may not be directly comparable. A complete understanding of all emissions is required to convert the data into the same indicator, yet such knowledge is largely unavailable. Although CCS is a proven technology, its depiction in the literature differs significantly. The projected process performance figures for various applications represent a wide range of plants, from bench-scale studies to full-scale commercial plants.

Depending on the type of power plants under study, values for energy penalties and net efficiencies vary significantly due to specific technical and technological representation concerning the fuels used [17]. For natural gas post-combustion, efficiency values fall between 42% [22] and 61% [23] while for hard coal post-combustion, efficiency is 29.6% [24]–49% [25]. The difference between the lowest and highest efficiency for lignite power plants is even more significant [17]. Since it can be retrofitted to existing power plants without requiring major changes, post-combustion carbon capture (PCC) is an ideal technology for reducing environmental emissions [26]. Although widely acknowledged, the high energy requirements for the CO_2 separation process and its repercussions (such as increased operating costs) have always been significant barriers to the scaling-up of PCC power plant

development [27]. In this regard, the amine-based PCC is one of the commercialized CO_2 capture technologies that use an amine solvent to absorb CO_2 molecules into a liquid solution. However, adding an amine-based carbon sequestration system to an existing power plant reduces the power plant's efficiency [28]. PCC and oxyfuel combustion CCS systems can reduce GWP by 78.8% and 80%, respectively, while other environmental effects, such as acidification, human toxicity, and ecotoxicity, differ significantly when compared to power plants without CCS [29]. Amine and ammonia-based flue gas absorption and the impact of capture efficiency on supercritical and subcritical coal-fired power plants were assessed by [30] to evaluate the environmental effects of CO_2 capture using life cycle analysis. Their studies investigated how different environmental impact categories were affected by amine concentrations of 20%, 30%, and 40%, using the LCIA methods of ReCiPe 2016 Midpoint (H)V1.03, IPCC 2013 GWP 100a, TRACI 2.1 V1.05, and AWARE V1.02. The added CCS unit offered significant environmental advantages regarding global warming. Their findings showed that for additional effect categories such as ozone depletion, water footprint, fossil fuel depletion, marine eutrophication, smog, and ionizing radiation, plants with a CCS unit had a higher impact than those without it. In terms of water and carbon footprints, the MEA-based CO_2 capture unit outperforms the ammonia-based CCS unit.

Using MEA for post-combustion CO_2 capture, a comparative LCA study was conducted comparing chemical absorption and membrane separation techniques [31]. According to this study, LCA outcomes of CCS, based on a membrane separation technique, were highly dependent on the type of membrane used and the dense active layer thickness, both of which impact the amount the size of the membrane needed and net power used.

Previous studies have used various LCIA methods, including CML, ReCiPe, IMPACT 2002+, TRACI, and IPCC. The impact categories that have been studied range from just one in [32] and [29] to ten environmental categories in [33]. Additionally, the impact categories appear to differ between studies. However, some of them are used more frequently [34] in the midpoint characterization of LCA studies for electricity generation, such as global warming potential (GWP), acidification potential (AP), human toxicity potential (HTP), eutrophication potential (EP), and ozone layer depletion potential (ODP). Among the studies, the most commonly used database was Ecoinvent, providing information on possible environmental impacts.

Table 1 displays the recent LCA studies on CCS in NGCC power plants and the methods used for the impact analysis.

1.3. Research Gap and Originalities

Despite the diversity of LCA modeling approaches highlighted in Table 1, the following challenges exist with all the aforementioned studies: (1) most studies relied on a single LCIA method to assess the environmental impact of the process. However, LCIA methods differ in several aspects. A key distinction between the LCIA methods is that they use different approaches and data sources in the chain of cause-and-effect to calculate impact. Therefore, variations between methods should be recognized, and whether these variations might influence outcomes should be evaluated, which is vital for decision support in process development. (2) A drawback of the LCAI methods is their statistical uncertainties. Data gaps and assumptions mount up throughout the cause-effect chain, so the further the environmental impacts are expressed and assessed, the lower the reliability of the results. Previous studies have not covered the uncertainty analysis of data used in their methods. (3) When dealing with the LCA of power plants, it is important to consider whether the CCS plant is linked to an existing power plant (retrofit design) or whether it should be considered from the first level of power plant construction (grassroots design). This is because the grassroots design covers the environmental impacts of the power plant construction stages, which is not seen in a retrofit design as previous studies have not addressed this issue.

Table 1. Previous LCA studies and methods used for LCIA on CCS in NGCC power plants.

Area	Life Cycle Inventory	LCIA Method	Impact Categories	Ref.
Norway	Norway 2000 statistical database, modeling data, Ecoinvent v2	ReCiPe 2008	GWP, AP, MEP, POFP, PMFP, HTP, TETP, FAETP, MAETP	[35]
Taiwan	Ecoinvent database	IPCC 2007, IMPACT2002+	GWP, PM_{10}, SOx, NOx, and CO	[36]
Canada	Ecoinvent 3.7.1 database, specific regional data	ReCiPe 2016 Endpoint, Cumulative Energy Demand (CED)	PMFP, FRS, MEC, MRS, TEC, FEC, FEU, LU, GWP, HCT, HnCT, IR, MEU, OFHH, OFTE, SOD, TWC, and TAC	[37]
Turkey	Ecoinvent, Öko Institute, Sphera database	CML 2001	ADP, AP, EP, FAETP, GWP, HTP, MAETP, ODP, POCP, TETP	[38]
Italy	Italian power plants, Eurostat, TERNA, INECP, Ecoinvent 3.3	Different methods applied	GWP, FEU, MAETP, MEP, POFP,PMFP, HTP, TETP, FAETP, ODP	[39]
Germany	Umberto LCA database, Ecoinvent v1.01	UBA-Verfahren	GWP, PMFP, HTP, POFP, ADP	[40]
Bangladesh	Plant authority, Ecoinvent database V3	CML 2001 and Eco-Indicator 99 (H)	GHG, CCP	[41]
India	Plant Visit, Ecoinvent Database V2.2	Eco-Indicator 99 (H), CML 2001	GWP, AP, EP HTP, MAETP, FAETP	[42]
Indonesia	Industrial data	CML, ILCD. and ReCiPe IPCC 2013, IPCC 2007	GWP, AP, POCP, EP, PMFP	[43]
Singapore	Literature	IPCC 2000	GWP	[44]
Algeria	Ecoinvent V2.2	Not mentioned	GWP, AP, TETP, MAETP, FAETP, MEP, POFP	[45]

To fill the previous research gaps, a comprehensive environmental lifecycle assessment is carried out for an existing power plant (Hartha Power Plant) in Iraq, with 90% CO_2 capture efficiency, denoted as a retrofit scenario, utilizing traditional monoethanolamine (MEA), compared with another scenario of building a new power plant referred to as grassroots scenario. In order to find the impact of CCS implementation on the existing power plants process parameters, the Integrated Environmental Control Model (IECM) software developed by Carnegie Mellon University was used for the detailed process simulation of the proposed MEA capture process. The LCA analysis is founded on various LCIA methods such as ReCipe 2016 Midpoint (H) [46], TRACI 2.1 [47], and IMPACT 2002+ [48], using SimaPro software, 9.1.0.11. To create a robust LCA model, uncertainty analysis was performed on both retrofit and grassroots cases, as it is one of the major elements affecting the reliability of LCA outcomes. The research methodology used in this research is shown in Figure 2.

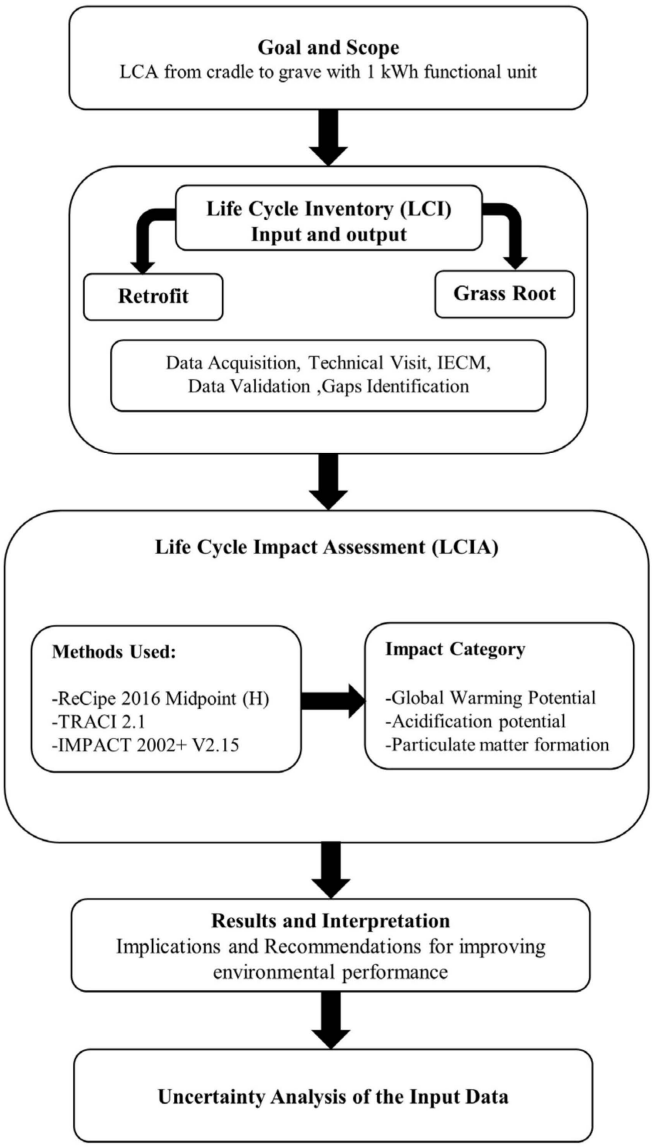

Figure 2. LCA framework employed in this study to evaluate the environmental Impact assessment of NGCC with carbon capture system.

The rest of the paper is structured as follows: Section 2 presents the comparative developed framework models and the application of the model in a real case study in Iraq. Section 3 shows the life cycle data inventory. Section 4 discusses the assessment results and the sensitivity analysis.

2. Materials and Methods

2.1. Case Study

The key performance indicators of the reference plant without a CO_2 capture plant studied in this research are given in Table 2. Hartha Power Plant Project provides an essential source of power for the region, frequently subjected to undesirable power outages. Figure 3 shows the proposed location of the capture plant. The selected power plant has three pressure levels of impulse-reaction turbines. The low-pressure turbine cylinder is a double flow chest; therefore, the turbines are two cylinders, single reheat, condensing double flow chest.

Table 2. Key parameters of the Hartha power plant.

Parameter	Value [1]
Net power output (MW)	371
Annual load (hours)	7451
Net power plant efficiency (%)	33
Number of stacks	4
Height of stack, (m)	100
Natural gas Specific gravity	0.7076
Natural gas consumption rate (kg/kWh)	280
Lifetime (years)	10
Industrial wastewater effluents discharge (m^3/h)	350 [2]
Flow rate of cooling water (m^3/h)	101,400 [2]
CO_2 flue gas (1000 m^3/h)	252 [2]
CO flue gas (1000 m^3/h)	194 [2]
SO_2 flue gas (1000 m^3/h)	15 [2]

[1] Power plant data [49]; [2] [50].

Figure 3. Hartha power plant location.

With a nominal capacity of 200 MW and a condenser pressure of 0.08 to 0.156 bar, the two turbines have six steps of steam bleeding. The rotor gland is a part of the turbine cylinder that insulates it from the output, preventing the HPT (high-pressure turbine) steam from venting into the environment. Due to the vacuum in the condenser, a similar gland in the LPT (low-pressure turbine) prevents air from entering the condenser. The generator is an AC type that uses hydrogen for cooling and operates at a constant speed of 3000 rpm to produce 50 Hz at 18 KV, which is subsequently transformed to a high voltage of 400 KV by the transformer. The power station's boiler section is a natural circulation water tube boiler with a forced draught that generates steam at 538 °C and 125.5 bar pressure, using a gas and oil-fired system. The boiler is also used to reheat the steam that comes out of the high-pressure turbine to a temperature of 538 °C. The Rehabilitation construction of the 200 MW Unit-1 of the Hartha Power Station began in October 2019. When GAMA Power

Systems and Mitsubishi Hitachi Power Systems (MHPS) complete the renewal process, it is hoped that the power plant's operating life will be extended by up to ten years [51].

2.2. Proposed CO_2 Capture Unit

The process of amine scrubbing is well-known among the alternatives because of the reversible interactions with CO_2; thus, it is regarded as the most suitable and cost-effective choice for use in a capture plant [52]. Although utilizing the MEA method for CO_2 capturing is common, the majority of current research focuses on this method due to its proven technique of capturing [53], while other studies are attempting to overcome the downsides of amine scrubbing by developing novel amines and mixes [54].

In this study, the KM-CR process provided by the Mitsubishi Heavy Industries (MHI) company is considered as the proposed CO_2 capture unit, which typically comprises an absorber, a quencher, and a stripping column [55]. As shown in Figure 4, the amine solvent passes into the packed absorber column, absorbing the CO_2 from the cold flue gas in a counter-current flow. A high level of CO_2 absorption by the solvent (>90%) is guaranteed by using multiple tiers of spray zones, trays, and packing. Before being supplied to the solvent, flue gas must be cooled in addition to any remaining acid gases being removed. This is brought on by the solvent's increased absorption capacity at lower temperatures. To provide this cooling, the polishing scrubber also serves as a quencher. The flue gas from the quencher/scrubber is cooled to about 37 °C. The semi-rich solvent is cooled by passing in an intercooler and sent back to the absorber regulating its temperature. A water wash is located at the top of the absorber to remove entrained solvents in the flue gas. The clean gas is discharged from the absorber via a fresh stack situated on top of the absorber. A weak link will form between the amine solvent and the dissolved CO_2; to break that link, heat energy is required. This process occurs at the top of the packed stripper column at a counter-current flow when the CO_2-rich solvent enters it. Low-quality steam is used in the reboiler at the bottom of the stripper as an energy source to evaporate water in the diluted solvent. The level of the water vapor increases in the CO_2 stripper, supplying energy to help with amine-solvent regeneration and CO_2 stripping. The CO_2-free hot-lean (or regenerate) solvent is delivered back to the absorber. The hot-lean solvent is delivered to the rich and lean heat exchanger by recovering the sensible heat and preheating the rich and cool solvent from the absorber. Preheating assists in recovering a portion of the energy used during regeneration, lowering the process's total energy consumption, particularly during the regeneration stage. The top of the stripper releases a mixture of steam and CO_2, which is then transferred to the compressor system, where it is compressed and dehydrated. To compress the CO_2 product stream into the pipeline, the compressor is intended. This method uses an intercooler after each of the compression stages. This procedure involves the removal of extra moisture in order to deliver a CO_2 product purified to 99% at 2215 psia pressure. Amine solvents are reactive with SO_2 and SO_3 particles in the flue gas and are sensitive to contaminants. Such reactions pollute the solvent that produces intermediate salts, increasing the need for solvent regeneration and the operating expenses. Therefore, the CO_2 capture system is equipped with further SO_3 and SO_2 removal for extra effective functioning, which is accomplished by passing the flue gas through a caustic scrubber. This scrubber utilizes a 10% (by weight) caustic soda (NaOH) solution to eliminate leftover acid gases. The scrubber reduces the flue gas to about 1 ppmv SO_2 by passing it through a counter-current packed column with a recirculated NaOH solution. As the caustic solution is recycled, residual particles, water, sulfates, and other soluble components will accumulate; as a result, a backwash stream is necessary to lower the pollutant concentrations and total liquid volume. The energy required for the capture process is for solvent regeneration, solvent pumps, flue gas blower, cooling water pumps, and CO_2 compression, resulting in a 7.9% energy penalty [56]. The thermal energy demand for CO_2 recovery is lowered by 9% compared to KS-1^{TM} [57]. By attaching the CCS system to the power plant, other resource (such as water, chemicals, and

reagents), as well as environmental emissions in the form of solid waste, liquid waste, and air pollutants that the CCS system does not collect will be released [17].

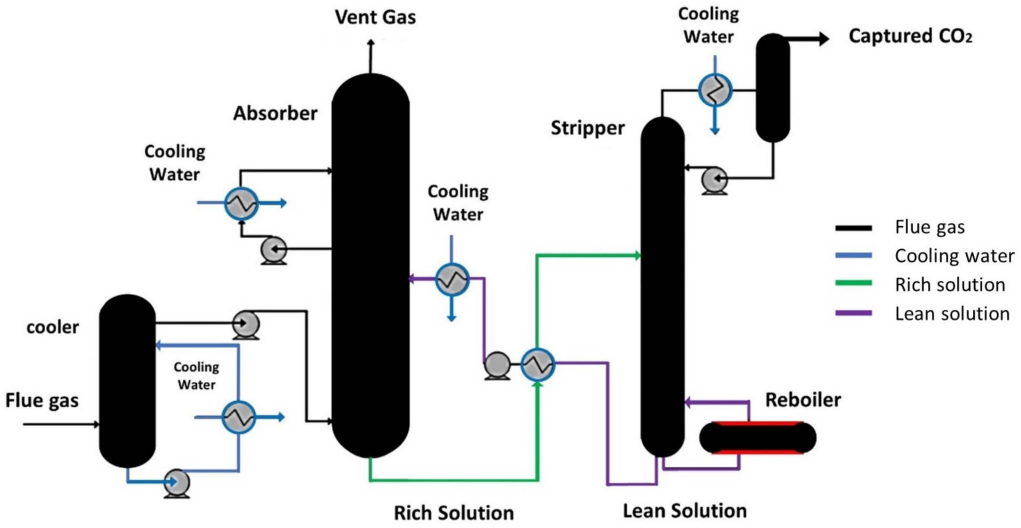

Figure 4. Amine scrubbing unit.

Table 3 summarizes the projected CO_2 capture facility requirements and estimated utility consumption for 90% capture efficiency.

Table 3. KM-CDR CO_2 capture facility and quality requirements.

Parameter	90% Capture
Purity of CO_2 stream (%)	≥95
Temperature of CO_2 product (°C	95
Stream pressure of CO2 product (psia)	2215
CO_2 emissions (lb/MWh)	193
Steam [1] (ton/tCO_2)	1.19
Cooling Water [2] (ton/tCO_2)	105

[1] [57]; [2] [58].

2.3. Life Cycle Impact Assessment Model

Figure 5 represents the life cycle boundaries of the proposed two cases in this study, which are designed for the LCA analysis in SimaPro software.

Global warming potentials (GWPs) are utilized as characterization elements to analyze and combine the interventions for the climate change impact category (referred to as "increased greenhouse effect") [59], as expressed by the following equations:

$$Climate\ change = \sum_i GWP_i \times m_i \quad (1)$$

where m_i (kg) is the mass of the element i released and GWP_i is the global warming potential of the element indicator. Climate Change is expressed in kg CO_2 equivalent. To compare the consequences of emissions, each greenhouse gas is assigned a global warming potential (GWP) index.

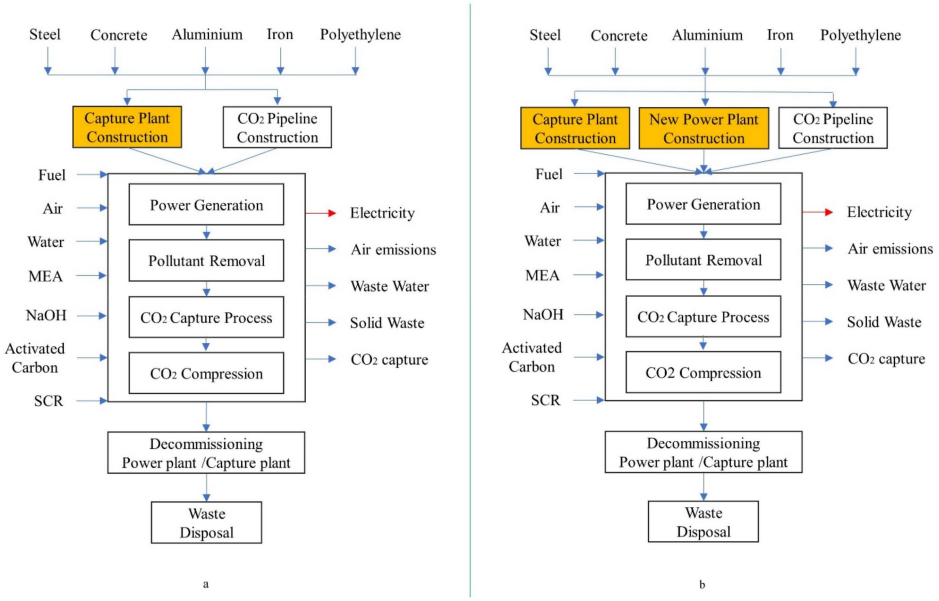

Figure 5. (**a**) Life cycle boundaries for attaching existing NGCC power plants with CO_2 Capture Plant (**b**) Life cycle boundaries for construction of new NGCC power plants with CO_2 Capture Plant.

The GWP index compares the increased infrared absorption of carbon dioxide caused by the instantaneous release of 1 kg of the element to that caused by an equal instantaneous emission of CO_2 combined with integration over time value:

$$GWP_{T,i} = \frac{\int_0^T a_i c_i(t)dt}{\int_0^T a_{CO_2} c_{CO_2}(t)dt} \quad (2)$$

where a_i is the rise in greenhouse gas i concentration's radiative forcing (w.m^{-2}·kg). $c_i(t)$ is the concentration of GHG i at time t after the release of (kg·m^{-3}), and T is the duration of integration (year). *GWP* integrates fate-related factors and measures an element's potential impact on climate change. It only gives an overall idea of the potential climatic effects of such emissions because these depend not only on total atmospheric heat absorption but also on how that heat is distributed over time. As a baseline method of characterizing climate change, the GWPs for 100 years are recommended [60]. The intake of a pollutant is significant for the midpoint characterization factors of human health damage from $PM_{2.5}$, since the consequence and damage are precursor element-independent. The primary $PM_{2.5}$ equivalents of particulate matter formation potentials (PMFP) are calculated by dividing $iF_{x,i}$ by the emission-weighted global average iF of $PM_{2.5}$:

$$PMFP_{x,\,\mathrm{j}} = \frac{iF_{x,\,i}}{iF_{pm2.5\ world}} \quad (3)$$

.

The sum of the changes in the intake rate of $PM_{2.5}$ in each receiving area j as a result of a change in the emission of a precursor element in region i was used to establish the region-specific intake fraction (d$M_{x,i}$) [61]. The population (N_j) in the receptor area i, the average breathing rate per each person (BR), and the change in $PM_{2.5}$ concentration in each receptor area (d$C_{k,j}$) can all be used to compute the intake rate:

$$iF_{x,\,i} = \frac{\sum_j dC_j.N_j.BR}{\mathrm{d}M_{x,i}} \quad (4)$$

.

Since the effect is precursor element-independent, the pollutant's fate in the soil and atmosphere is significant for the characterization of the midpoint for the terrestrial ecosystem damage caused by acidification emissions [62]. According to the precursor x, the acidification fate factor (FF) brought on by emissions in grid *i* is calculated ($FF_{x,i}$). By dividing $FF_{x,i}$ by the emission-weighted global average FF of SO_2, the acidification potential (AP), expressed in kg SO_2 equivalents, is determined by:

$$AP_{x,i} = \frac{FF_{x,i}}{FF_{\text{SO2,world average}}} \quad (5)$$

.

3. Data Inventories

Characterization and quantification of material, energy, and emission input and output flow inside the specified system boundary are crucial elements in the gathering and processing of LCI data. As explained before, an amine-based commercially existing technology known as KM-CR Process by Mitsubishi Heavy Industries (MHI) using the KS-1^{TM} solvent is considered as the foundation for the capture technology with 90% capture, treating 100% of flue gas [63]. In this study, the Ecoinvent database [64] was used to inventory the construction, operation, and electricity generation processes. Table 4 represents the basic components used in the LCA. The available data inventory structural flows used in the database are shown in Figures A1–A3 in Appendix A.

Table 4. Basic components used in the power plant and MEA capture plant in this study.

Component			Ref.
Construction			
Power Plant	Eoinvent Database, Gas power plant, combined cycle, 400 MW construction		[64,65]
MEA plant [1] [tonne]			
Stripper	Stainless steel	4107.1	[66]
Absorber	Stainless steel	2657.4	[66]
Reboiler	Stainless steel	3060.1	[66]
Pre-scrubber	Stainless steel	1911.4	[66]
Amine recovery tank	HDLPE [2]	945.8	[66]
Condensate tank	HDLPE	1527.5	[66]
Amine storage tank	HDLPE	1436.5	[66]
Reclaimer polyethylene tank	HDLPE	3874.3	[66]
NaOH storage polyethylene tank	HDLPE	792.1	[66]
Piping and small equipment	Stainless steel	4107.1	[66]
Concrete	Reinforced	191.6	[66]
Operation (Chemicals) [kg/t_{CO_2}]			
Activated carbon	0.059		[67,68]
MEA input	1.65		[69]
NaOH	0.1565		[67,70]
Water	655		[68,70]
Utility (kWh/t_{CO_2})			
Electricity [3]	230		[68]

[1] Based on MHI design; [2] (HDLPE) High Density Linear Polyethylene; [3] Equivalence of heat used for CO_2 capture.

4. Results and Discussions

4.1. MEA Capture Unit Simulation Results

The detailed process simulation of the proposed MEA capture process was performed using the Integrated Environmental Control Model (IECM) software developed by Carnegie Mellon University [71]. Table 5 summarizes the simulation outcomes of the CO_2 capture plant in this study. For this LCA estimation, the reliability of secondary data from the IECM software is assessed based on real data from the power plant and literature citations. Data for operational and stack characteristics at the Al-Hartha power plant were collected from the technical visit, and detailed information was given in [49]. The following are some of the primary outputs of the proposed performance model for the amine system in the Hartha power plant with a net power capacity of 371 MW: (1) MEA requirement: exhaust gas CO_2 mass flow rate, MEA concentration, and CO_2 capture efficiency. To purify the flue gas from impurities such as NO_2, SO_x and acid gases, an extra loss in solvent might occur relative to the contamination level [72]. (2) Energy requirements: the heat required for solvent recovery is determined by the lean sorbent loading. Additionally, the compression of CO_2 products, circulation of solvent, as well as other system requirements demand an amount of electrical energy. (3) Emissions into the environment: the model accounts for the CO_2 control system's production of many additional waste products, primarily ammonia gas (produced by the breakdown of monoethanolamine) and possibly hazardous solid waste at the bottom of the reclaimer generated from the recovery process of spent sorbent. On the other hand, the CO_2 capture technique also reduces emissions of PM and HCl, NO_2, and SO_2.

Table 5. Simulation results of the proposed CO_2 capture plant for the Hartha power plant.

Simulation Results	Nominal Value
CO_2 removal efficiency [a]	90%
NO_2 removal efficiency [a]	25%
SO_2 removal efficiency [a]	99%
PM_{10} removal efficiency [a]	50%
MEA concentration (wt) [a]	32%
Activated Carbon Flow Rate (tonne/h)	0.007245
Cooling water Make-up (tonne/h)	0.0228
Captured CO_2 Flow Rate (tonne/h)	96.62
Scrubber Solids Disposed Flow Rate (tonne/h)	0.01969
Flue Gas Fan Use (MW)	3.742
Sorbent Pump Use (MW)	0.1916
CO_2 Compression Use (MW)	8.985
Sorbent Regen. Equiv. Energy (MW)	28.16
Amine Steam Use (Elec. Equiv.) (MW)	28.16
CO_2 Pressure (MPa)	13.74

[a] IECM 11.5 default.

4.2. LCA Analysis Results

The SimaPro 9.1.0.11 software was used to perform the LCA in this study. The impact scores are calculated for the three environmental impacts under study, which are: the global warming potential (GWP), particulate matter formation potential (PMFP), and acidification potential (AP), using three different life cycle impact assessment (LCIA) methods shown in Table 6. Regionalized characterization factors (CFs) of air pollution developed by [61] were used for the impact assessment stage of an environmental life cycle assessment as in Equation (3). In order to derive the regionally-specific damage factors and effects,

background concentrations, mortality rates, and years of life lost data have been used [61]. The recommended average breathing rate (BR) of 13 m^3/d has been used based on [73]. Population data were collected from [74]. The two examined scenarios of grassroots and retrofit design and their contributions to the selected category with an expansion on the modeling findings, similarities from the literature with sensitivity analysis are analyzed as shown in Table 6.

Table 6. Absolute characterization scores using various methods.

Impact Categories		GWP (kg CO_2 eq)			PMFP (g $PM_{2.5}$ eq)			AP (g SO_2 eq)		
Life Cycle Impact Assessment Method (LCIA)		ReCipe 2016 Midpoint (H)	TRACI 2.1	IMPACT 2002+ V2.15	ReCipe 2016 Midpoint (H)	TRACI 2.1	IMPACT 2002+ V2.15	ReCipe 2016 Midpoint (H)	TRACI 2.1	IMPACT 2002+ V2.15
Total Impact	**Retrofit**	0.178	0.175	0.172	0.21	0.045	0.1	0.69	0.82	0.82
	Grassroots	0.127	0.125	0.123	0.24	0.051	0.1	0.81	0.9	0.93
Infrastructure	**Retrofit**	0.0041	0.00408	0.00398	0.006	0.004	0.004	0.01	0.014	0.014
	Grassroots	0.0024	0.00239	0.00233	0.005	0.003	0.004	0.011	0.013	0.014
Direct Emissions [1]	**Retrofit**	0.0964	0.09520	0.09360	0.042	0.006	0.042	0.132	0.234	0.234
	Grassroots	0.0721	0.07150	0.07060	0.036	0.004	0.038	0.116	0.212	0.212
Natural Gas Production	**Retrofit**	0.0753	0.07390	0.07220	0.159	0.035	0.053	0.537	0.566	0.566
	Grassroots	0.0503	0.04940	0.04820	0.198	0.043	0.06	0.677	0.696	0.696
Indirect Emissions [2]	**Retrofit**	0.0021	0.00206	0.00195	0.003	0.002	0.002	0.007	0.008	0.008
	Grassroots	0.0021	0.00206	0.00195	0.003	0.002	0.002	0.007	0.009	0.010

[1] Direct emissions include flue gas emissions directly from the power plant and capture plant operation (Direct consumption of the Natural gas and electricity required for the operation of the capture plant). [2] Indirect emissions include monoethanolamine, sodium hydroxide, water used and activated carbon production chain.

4.2.1. Global Warming Potential (GWP)

As can be shown in Figure 6, outcomes for the grassroots scenario demonstrate a considerable decrease in GWP. Generally, in the case of the grassroots design, the proposed NGCC-CCS would emit 0.123–0.127 Kg CO_2 eq, while 0.172–0.178 Kg CO_2 eq would be emitted in the retrofit design, when producing 1 kWh of electricity based on different impact assessment methods. This is 76% lower than base-case NGCC without a capture system, as reported by [45]. The capture plan is assumed to capture 90% of CO_2 in the flue gas for both cases. In order to integrate a CO_2 capture process into an existing power plant, measures must be taken to guarantee a sufficient steam supply for solvent regeneration. It is evident that CO_2 capture is an energy-intensive process as the heat required for solvent regeneration in the retrofit scenario has the most significant influence on the total process power output. Compared with the grassroots scenario, in the retrofit scenario the natural gas required to generate steam for the regeneration column in the capture unit cannot be supplied internally, which is basically due to the limited existing capacity of the power plant. Thus, the GWP score for natural gas production is higher for the retrofit scenario in all methods.

The three methods applied to calculate the GWP used in this study show a slight difference between the estimations since these methods use the common CO_2 equivalency

factors published in the Intergovernmental Panel on Climate Change report with a 100-year time horizon [46,48,75]. The process contribution reveals that natural gas production accounts for 40–42% of the total GWP score. The share of indirect emissions (mainly the monoethanolamine production chain) is between 2–4%, while infrastructure is responsible for less than 3%. Direct emissions (the largest share is from the natural gas consumption and energy requirements from the auxiliary capture plant) from both scenarios, Grassroots, and retrofit, account for 27% and 33%, respectively. These findings correspond to what was previously reported in many studies on NGCC with an amine capture system attached [20,42,76].

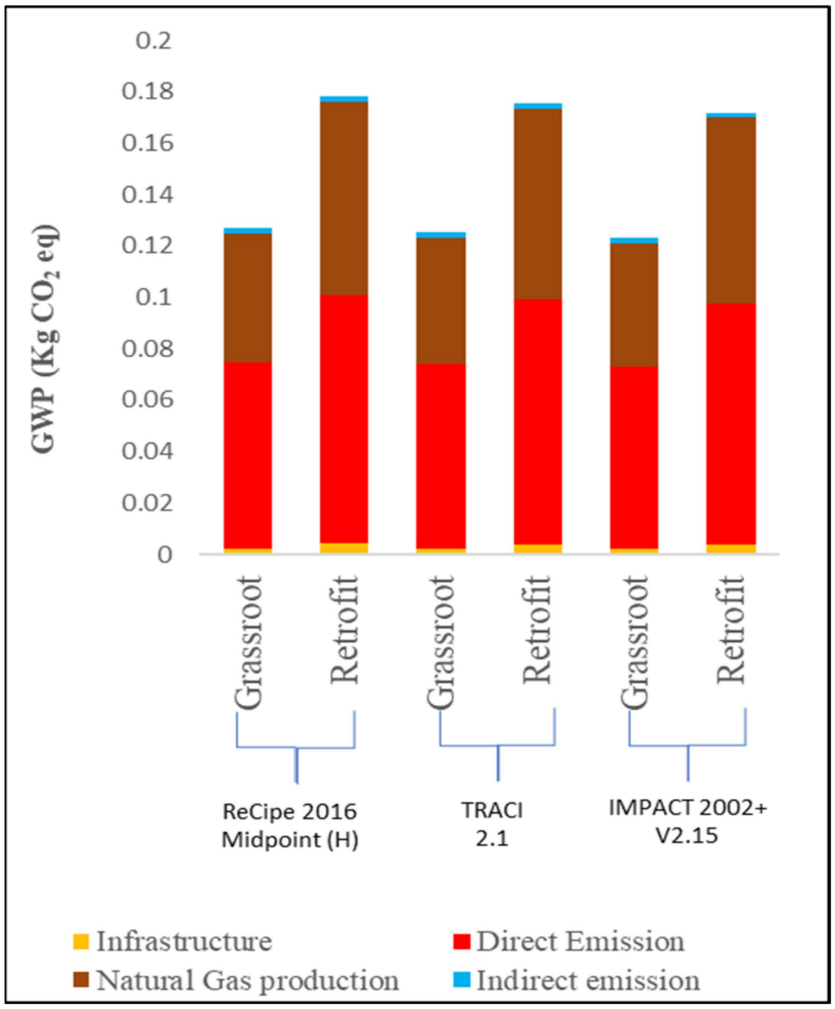

Figure 6. GWP Impact score and process contribution.

4.2.2. Acidification Potential (AP)

Results demonstrate that the ReCipe 2016 Midpoint (H) method had the most negligible impact scores for both scenarios, with the total score from the life cycle increasing by 11% for the grassroots scenario compared to the retrofit scenario. The SO_2 and NO_2 direct emissions are significantly reduced throughout the capture process; however, this reduction is insufficient to offset the effects of increased emissions due to the related activities, such as construction phase requirements of the grassroots scenario. The contribution analysis in Figure 7 demonstrates that the site's direct emissions are responsible for 23% and 26%, respectively, of the overall acidification along the entire chain.

As shown in Table 6, the direct acidification impact caused by NH_3 and MEA vapor discharged from the absorber is 2%. Natural gas production is another significant factor in both scenarios, contributing 73% and 67% of the total contribution to acidification poten-

tial, respectively. Using various impact assessment methods, it is evident that the TRACI 2.1 and IMPACT 2002+ have higher scores than the ReCipe 2016 Midpoint (H). For the last method mentioned, country-specific characterization parameters of terrestrial ecosystem damage owing to acidifying emissions were used. Since the effect is precursor element-independent, the fate factor of a pollutant in the soil and atmosphere is significant. TRACI 2.1 employs an acidification model that accounts for the rising hydrogen ion potential in the environment without taking into account site-specific factors such as the capacity of some environments to act as buffers [75]. Notably, characterization factors (CFs) for IMPACT 2002+ are given for emissions into the air only, and no CFs are presently available for emissions into water and soil [48].

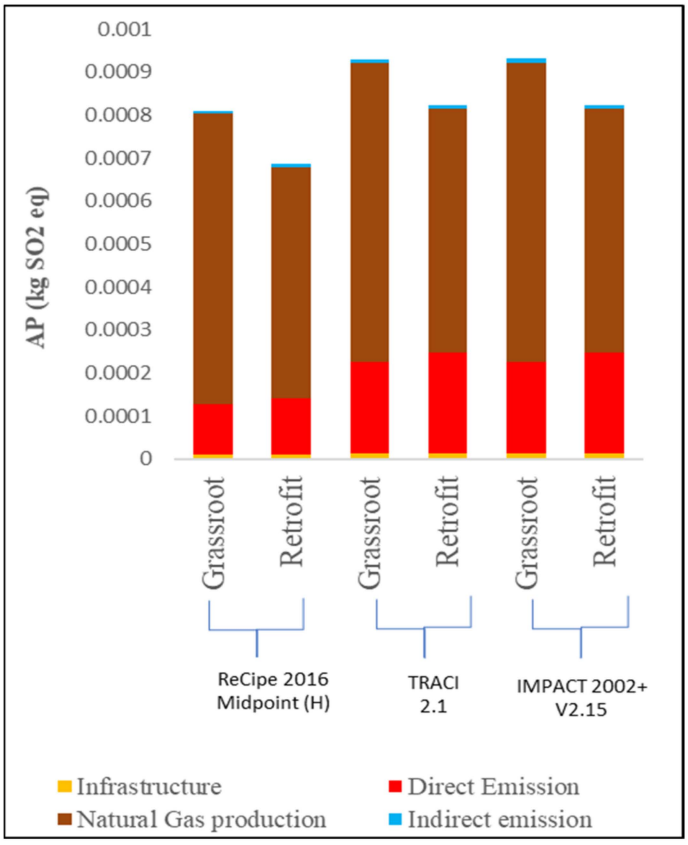

Figure 7. AP Impact score and process contribution.

4.2.3. Particulate Matter Formation Potential (PMFP)

According to Figure 8, direct emissions from the plant facility are responsible for 17–19% of the overall PMFP impact for both scenarios, with NO_x emissions from fuel combustion accounting for the majority of around 77%. Infrastructure demand accounts for 6% of the impact. As can be seen from the results of the three methods, the ReCipe 2016 Midpoint (H) has the higher impact scores, compared with the IMPACT 2002+ method and the TRACI method for both scenarios considered, with a higher impact on the retrofit scenario. The power plant in the grassroots scenario appears to emit more $PM_{2.5}$ into the atmosphere than in the retrofit scenario. In TRACI 2.1, the reference element, $PM_{2.5}$, was used to classify the elements [77]. However, the IMPACT 2002+ is based on a thorough review of CFs and intake fractions, primary PM, and secondary PM from SO_2, NO_x, and NH_3 between 2008 and 2010, resulting in updated intake factors for respiratory inorganics [77,78]. Value choices in modeling the effect of fine particulate matter formation in Hierarchist ReCipe 2016 Midpoint are the primary and secondary aerosols from SO_2 [47]. The evaluation of the environmental contribution reveals that natural gas production accounts for 40% of the total GWP score in the grassroots case, followed by direct emission (30%) and the opera-

tional energy requirements (27%), as represented in Figure 9a, while these shares are 42%, 33%, and 22%, respectively, for the retrofit scenario (Figure 9b). For the AP score, 73% of the environmental contribution comes from natural gas production, 23% from direct emission, and 2% from the energy consumption for capturing in the grassroots scenario (Figure 9c), while contributing 67%, 26%, and 5%, respectively, for the retrofit scenario as shown in Figure 9d. Figure 9e,f show the share of PMFP, indicating more than 70% of environmental contribution by the natural gas production for both scenarios; however, the share of the direct emission is estimated at 17% and 19% in the grassroots scenario and retrofit scenario, respectively.

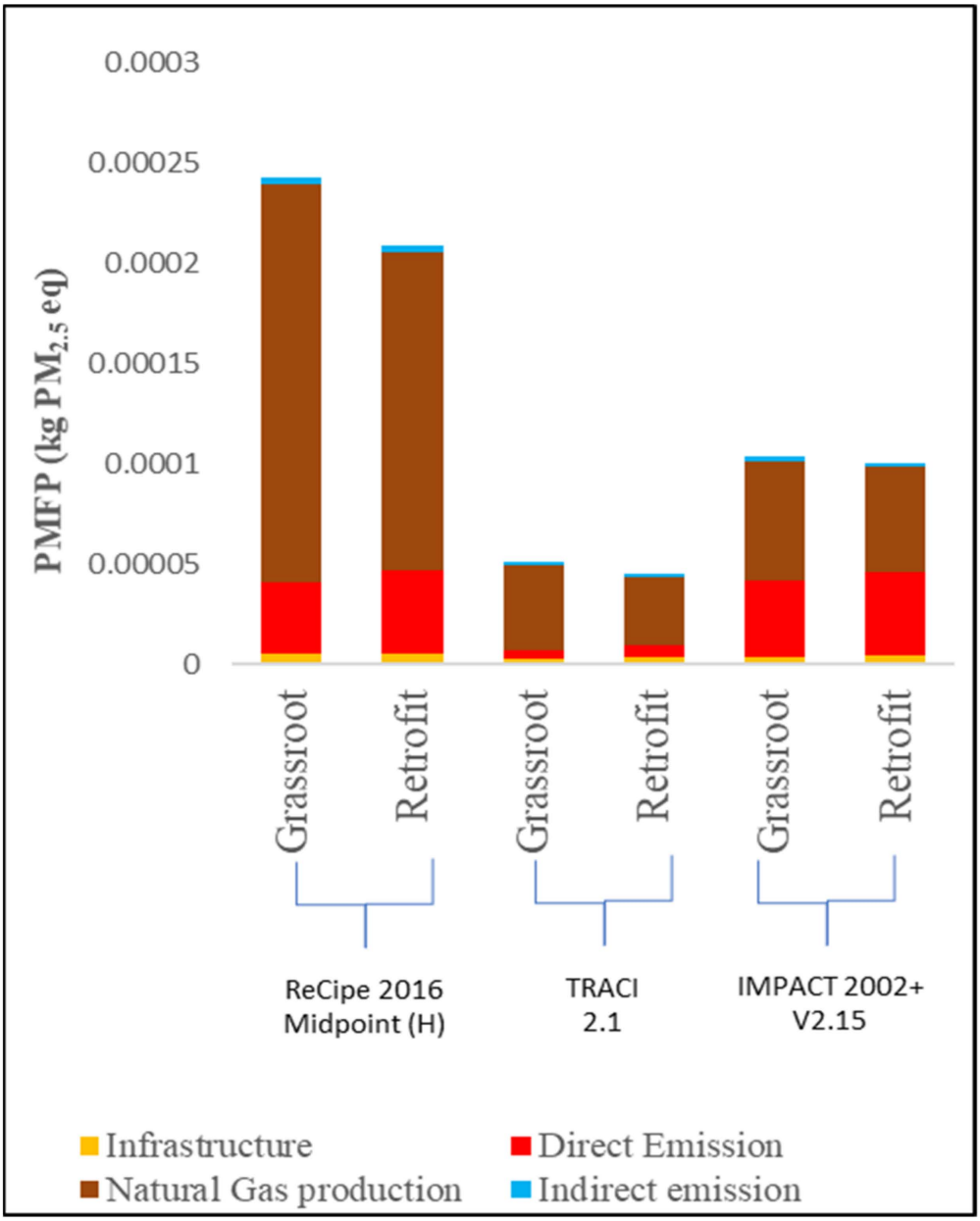

Figure 8. PMFP impact score and process contribution.

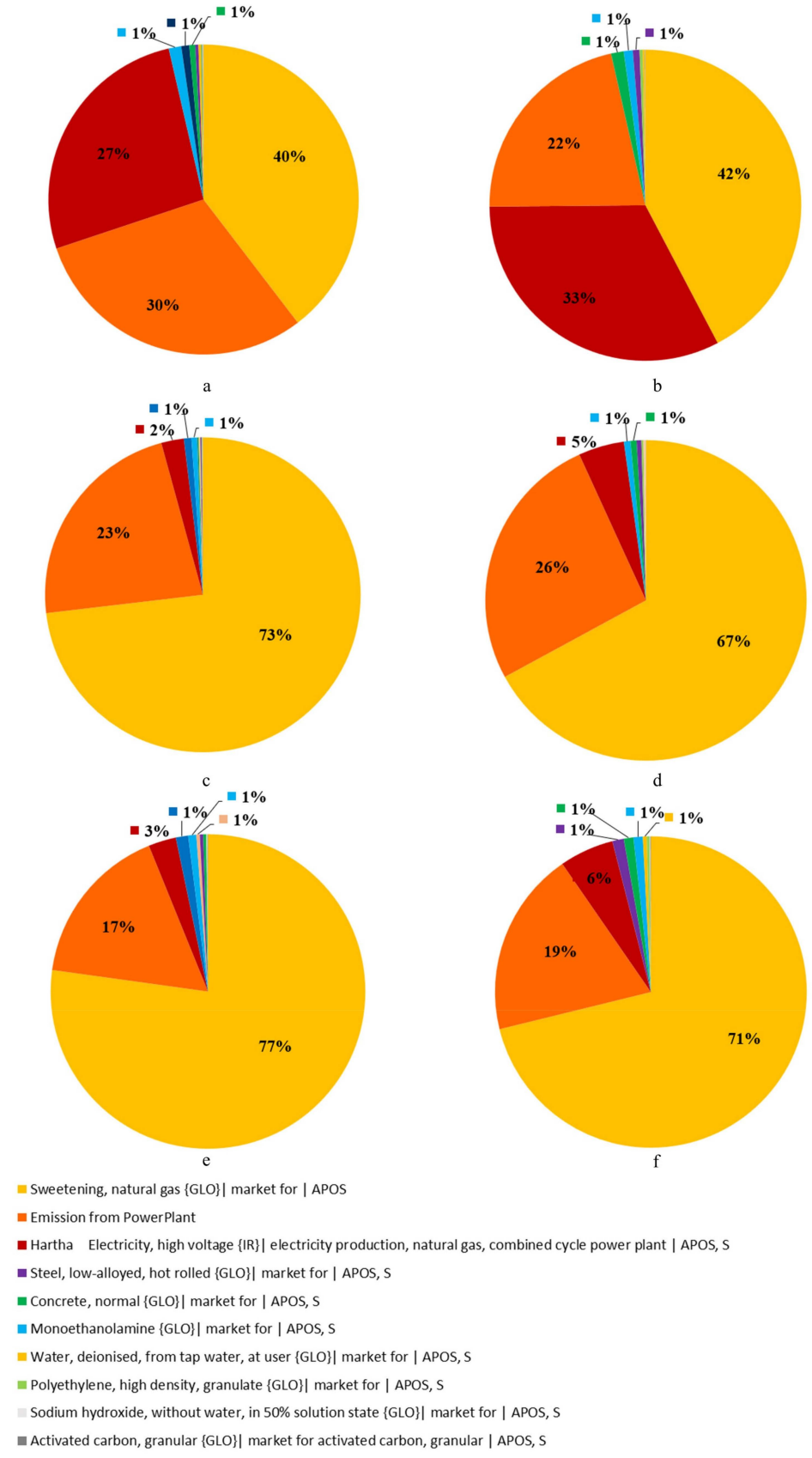

Figure 9. Process contribution (**a**,**c**,**e**) is the share of GWP, AP, PMFP for the grassroots scenario, respectively, (**b**,**d**,**f**) is the share of GWP, AP, PMFP for the retrofit scenario, respectively.

4.3. Sensitivity Analysis of the Impact Categories

The sensitivity of the consequences of life cycle impacts was evaluated by changing the corresponding values of the main parameters from a lower limit to an upper limit in the retrofit design scenario (See Table 7).

Table 7. Values for the parameters in the sensitivity analysis.

Variables	Lower Limit	Upper Limit
Activated carbon [a] (kg/tone CO_2)	0.038	0.081
MEA input [b] (kg/tone CO_2)	0.2	3.2
NaOH [a] (kg/tone CO_2)	0.014	0.3
Ammonia emissions [a] (kg/tone CO_2)	0.036	0.32
MEA emissions [a] (g/tone CO_2)	0.0628	0.064
Water [a] (kg/tone CO_2)	210	1100
Formaldehyde emissions [a] (g/tone CO_2)	0.0002	0.263
Acetaldehyde emissions [a] (g/tone CO_2)	0.0001	0.168

[a] [69]; [b] [21].

The two scenarios investigated in this study are then compared with the impact of the grassroots scenario to determine the relationship between behavior and variation in system performance. SimaPro does not show overlapping distributions due to the possibility of incorrect interpretation. Instead, it uses an (A-B) strategy. This method determines the difference between scenarios A (here referring to the grassroots scenario) and B (referring to the retrofit scenario) in each iteration. Then it displays the relative impact of instances where scenario (A) scores worse than scenario (B). The results shown in Figure 10 indicate that the impact score of GWP is highly sensitive to the changes compared to the other impact scores. PMFP has the lowest sensitivity indicator at 5% of the system performance compared to 9% for AP, while the 17% sensitivity ratio indicator recorded for GWP is between the lower and the upper limit. Emissions from the capture processes and materials (e.g., activated carbon, MEA input) consumption account for a large portion of this difference in GWP. The key factors influencing this increase in AP are the ammonia and MEA emissions during the capture process.

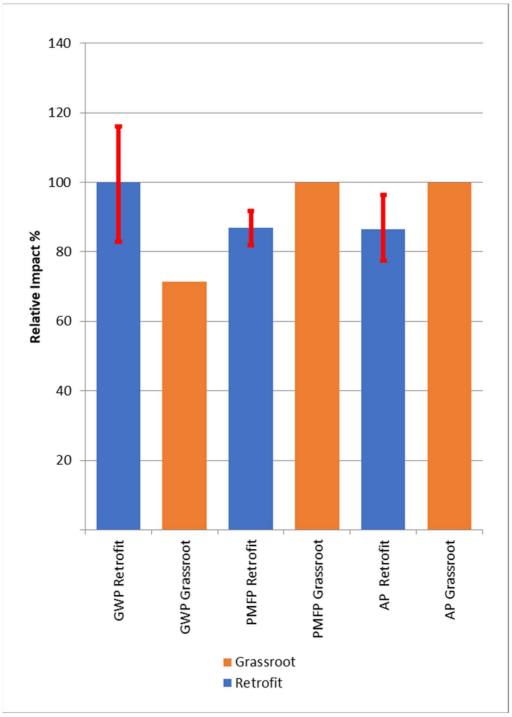

Figure 10. Relative impact analysis for both scenarios.

As previously mentioned in the results of the PMFP, NO_x emissions from fuel combustion have the largest share. They therefore have the lowest sensitivity range as it was not considered in the sensitivity variation limits. Accordingly, this analysis shows that the reduction in MEA, formaldehyde, and acetaldehyde emissions released during the capture process, will have significant control over all trade-offs.

4.4. Uncertainty Analysis of the Input Data

The uncertainty analysis was conducted to reflect more accurately the influence of uncertain factors on the statistical significance of the environmental impact evaluation in this research. The uncertainties in this study are viewed based on the method presented by the Ecoinvent database [64] as a combination of basic and additional uncertainties. The basic uncertainty is linked to the processes, potential fluctuations in quantities, and construction techniques. The uncertainty derived from the input data ranges is quantified and described using probability distributions for variable data; this rule-based procedure considered the knowledge and procedural ambiguity pertaining to the variable. The former might be evaluated either statistically or empirically, whereas the latter was often estimated using the data quality indicators (DQI) process. To convert DQIs into additional variances with respect to a lognormal distribution of data, Ecoinvent provides the default variances for fundamental uncertainty and the pedigree matrix. As a result, the total uncertainty of the input data might be calculated by adding the basic and additional variances. The data quality indicators (DQIs) are quantified in the pedigree matrix, which includes completeness, reliability, geographic correlation, temporal correlation, and additional technological correlation. The DQI assessment can be performed depending on the compilation of the preliminary data inventory to determine the significance of input data. Values ranging from low to high indicate how uncertain each category is. Table 8 shows the DQI matrix developed in this research, taking into account the fundamental characteristics of the materials in use by [79,80]. It can be seen that the distribution for DQI = 5 is significant narrower and more centralized than the one produced from DQI = 1. As stated in the screening methodology study of [75], less ambiguity or variability suggests the data are of higher quality.

Table 8. DQI evaluation system.

Quality Score	Data Quality Indicators				
	Reliability	**Completeness**	**Geographic Factor**	**Technological Correlation**	**Temporal Factor**
5	Measurable data that have been verified	Date from all sources related to the market considered	Date from the study area	Process-related data related to enterprises and the identical technology	More than 15 years or unknown
4	Data either validated based on assumption or measurements-based data	Date from ≥50% of relevant sources for the considered market	Average data from which the study area is included	Process data from different enterprises with identical technology	Less than 15 years
3	Data that has not been verified and is based on qualified estimations	Data from ≤50% of relevant sources for the considered market	Regional data	Technologically different data but with same materials and process	Less than 10 years
2	Qualified estimate, data derived from theoretical information	Data from a single relevant source	National data	Data from the process studied of the enterprise with similar technology on the laboratory scale	Less than 6 years
1	Non-qualified estimate	Data from a small number of sources during a short period	Unknown data or other international data	Laboratory scale of different technology	Less than 3 years to the baseline year

The following formula is used to calculate the overall uncertainty for a flow with a lognormal distribution:

$$SD_{g95} = \sigma_g^2 = e^{\sqrt{[\ln(U_1)]^2 + [\ln(U_2)^2] + [\ln(U_3)]^2 + [\ln(U_4)]^2 + [\ln(U_5)]^2 + [\ln(U_b)]^2}} \quad (6)$$

where: SD_{g95} is the square of geometric standard deviation (95% interval); U_{1-5} are the uncertainty factors for the completeness, reliability, geographical correlation, temporal correlation, additional technological correlation; and U_b is the basic factor for uncertainty. The above formula computes the geometric standard deviation, σ_g^2, resulting from adding independent variables with lognormal distributions. It also demonstrates that the added uncertainty causes the original data's basic uncertainty dispersion to rise. Bigger scores correspond to higher variances and lower quality data, and each level of the quality indicator is transformed into an uncertainty factor [81]. It should be highlighted that only additional uncertainties were taken into consideration with the material amounts. It is because including the basic uncertainties would require a probabilistic approach in all phases of the capture plant design, which was outside the scope of the current study. Table 9 shows the data quality assessment matrix formed based on the basic uncertainty and additional uncertainties in the Ecoinvent database.

Table 9. Data quality assessment matrix DQI.

Phase	Dataset	Reliability	Completeness	Temporal Correlation	Geographical Correlation	Additional Technology Correlation	σ^2 *
Raw materials	Cement	2	1	4	2	1	3.05
	Steel	1	2	4	3	1	3.05
	Polyethylene	2	3	3	2	1	3.02
	Concrete	1	2	4	4	1	3.05
Air emissions	Carbon dioxide	1	2	3	1	1	1.12
	Methane	1	2	3	2	1	1.52
	Carbon monoxide	1	3	4	2	2	5.06
	Hydrogen dioxide	1	2	3	2	1	1.52
	Sulfur dioxide	1	3	4	3	1	1.21
	Nitrogen dioxide	1	2	4	2	1	1.56
	Ammonia	1	2	3	1	1	1.52
	PM 2.5 µm	2	2	3	5	1	3.05
	PM 10 µm	1	2	4	2	1	2.05
Water emissions	COD	1	4	5	5	1	1.59
	Ammonia	1	2	3	4	1	1.52
Soil emissions	Lead	1	2	2	4	2	1.51
	Chromium	1	2	3	4	1	1.52
	Arsenic	2	1	4	2	1	1.56
	Cadmium	1	2	4	3	1	1.57
	Mercury	2	3	3	2	1	1.53
Waste treatment	Water	1	2	4	4	1	5.06

* Square of the standard deviation, which indicates if the data used are appropriate for this investigation. Color gradients represents the chosen DQI index from (1–5).

The Monte Carlo simulation method (MCS) was used to model the uncertainty and incorporate it into the LCA framework [65]. MCS provides a quantifiable measure of what is known and what is unknown, as well as the inherent unpredictability of a process, as it is essential for creating defendable criteria for review [82]. According to [80], the underlying normal distribution variances that reflect the LCI input sample data define the lognormal

distribution as the probability distribution where the natural logarithm of the observed data values is normally distributed. The outcomes of 1000 simulation iterations (and 95% confidence intervals) display all interval variations in detail, including the mean, median, standard deviation (SD), variability coefficient (CV), and standard error of the mean (SEM), as shown in Table 10.

Table 10. Uncertainty analysis of two scenarios, method: ReCipe 2016 Midpoint (H), characterization at 95% confidence level.

Impact Category	Scenario	Unit	Mean	Median	CV	SD	SEM
GWP	Retrofit Grassroots	(kg CO_2 eq)	0.178 0.127	0.176 0.126	9.32% 8.34%	0.0166 0.0106	5.26×10^{-4} 3.34×10^{-4}
PMFP	Retrofit Grassroots	(kg $PM_{2.5}$ eq)	2.24×10^{-4} 2.57×10^{-4}	2.19×10^{-4} 2.51×10^{-4}	15.2% 16.8%	3.41×10^{-5} 4.32×10^{-5}	1.08×10^{-6} 1.37×10^{-6}
AP	Retrofit Grassroots	(kg SO_2 eq)	8.04×10^{-4} 9.27×10^{-4}	7.91×10^{-4} 9.06×10^{-4}	15% 15.9%	1.21×10^{-4} 1.47×10^{-4}	3.81×10^{-6} 4.66×10^{-6}

The key negative impact was presented in a small CV by GWP of (CV = 9.32%) for the retrofit scenario and (CV = 8.34%) for the grassroots scenario (see Table 10). Categories with a low impact yet a high CV value on both scenarios were caused by the uncertainty in the database used and materials by acting mainly on PMFP and AP with more effect on the grassroots scenario, as this scenario requires more assumptions to develop. The graphical representations of the probability distribution of the three environmental impacts for both scenarios are shown in Figures 11–13. The result of AP impact has the highest probability index, while the results of the GWP show a minor index with a lognormal distribution for both. It is noteworthy to highlight the divergence in the sensitivity curve for the AP impact score in the two scenarios (retrofit CV = 15%, grassroots CV = 15.9%). Uncertainty in AP is due to the uncertainty in releasing NOx emissions data [83]. The uncertainty of the related activities of the grassroots scenario that emits SO_2 and NO_2 as direct emissions are significantly reduced throughout adding the capture process; however, this reduction is insufficient to offset the effect in the retrofit scenario. PMFP probability index score results indicate that the retrofit case has a higher score than the grassroots case (CV = 15.2%, CV = 16.8%).

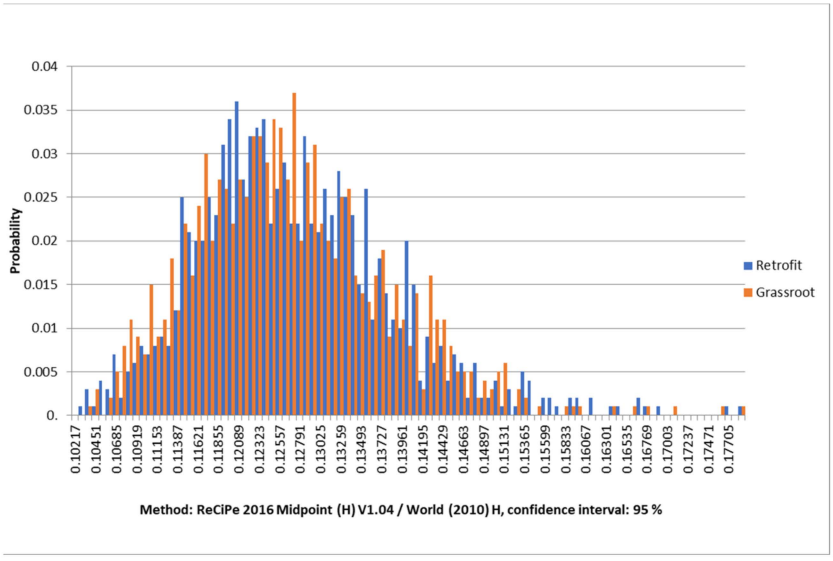

Figure 11. Distribution of probability index of GWP.

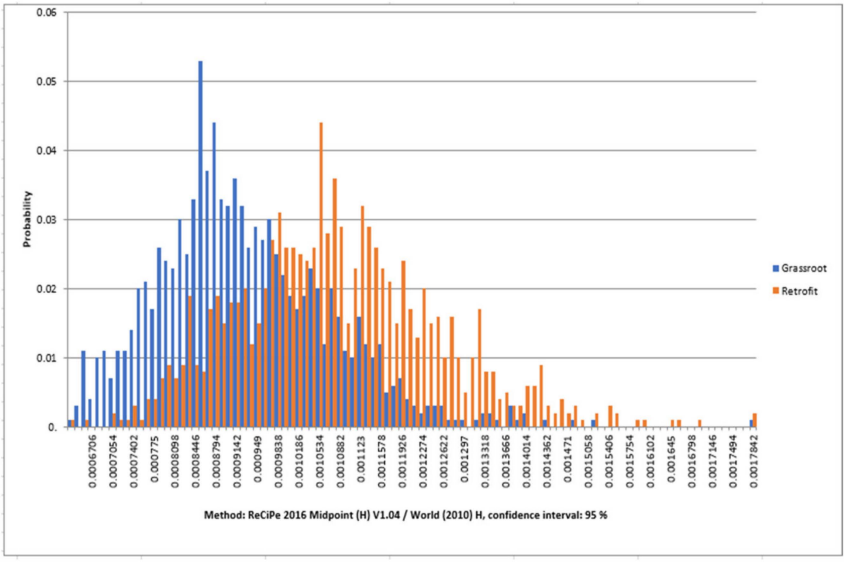

Figure 12. Distribution of probability index of AP.

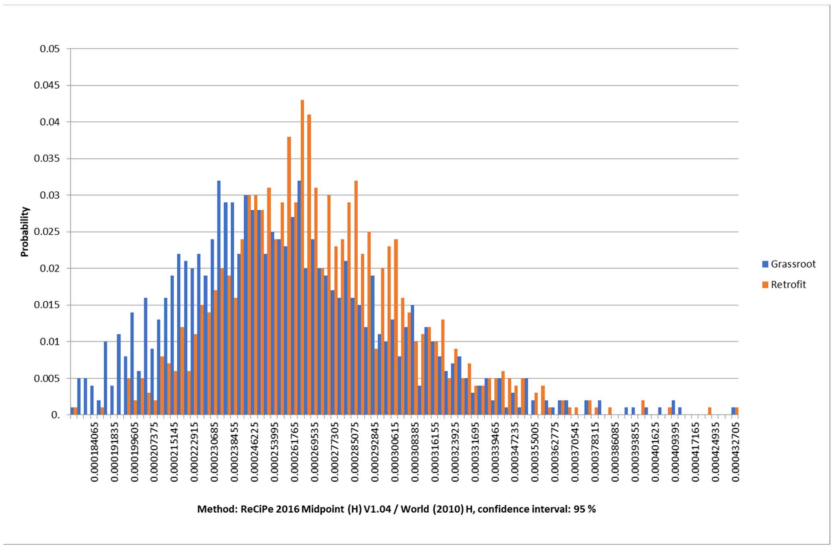

Figure 13. Distribution of probability index of PMFP.

However, it is noted that the risk values related to chemical transportation and storage (e.g., MEA), CO_2 transport and storage, and infrastructure land occupation are not currently accounted for in the model. In addition, due to data restrictions, energy requirements for production and dismantling, energy and material requirements for infrastructure maintenance, and recycling after dismantling as well as waste processing, have not been considered.

5. Conclusions

This study evaluated the environmental impacts of a NGCC power plant coupled with post-combustion CO_2 capture, using monoethanolamine as the solvent, for both retrofit and grassroots design scenarios. Applying three LCIA methods of TRACI 2.1, ReCipe 2016 Midpoint (H), and IMPACT 2002+ for three environmental impacts of GWP, PMFP, and AP, the results revealed that, the grassroots scenario would emit 28.6% less compared to the retrofit scenario. However, in the case of PMFP and AP impacts, the grassroots scenario has a higher environmental impact (14.2%, 17.3%) than the retrofit scenario. Utilizing a variety of impact assessment methods, it is clear that scores are different due to different

concepts considered in each method. Comparing three LCIA methods, the ReCipe 2016 Midpoint (H) method had the most negligible impact scores for both scenarios. This study also identified several critical data limitations for the CO_2 capture process's environmental performance. This is mainly owing to a lack of specific process emission data for the CO_2 capture process and, particularly, the procedure's effect on trace elements that flue gas contains. The Uncertainty of the LCI input data effects on the LCA outcomes was explored. The probabilistic methodology used in this study allowed for a comparative evaluation and an understanding of the overall variation in the environmental impact footprint for the two scenarios considered. LCA evaluation has an influence on scenario selection based on their desirability and sustainability, hence, the vast range of LCA results indicates the crucial requirement and importance of handling the impact of uncertainty on the evaluation process appropriately. The sensitivity analysis results show that these uncertainties can have a considerable impact on the ultimate decision. According to the results, priority should be given to reducing the uncertainty in the PMFP and AP data compared to GWP.

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Conflicts of Interest: The authors declare no conflict of interest.

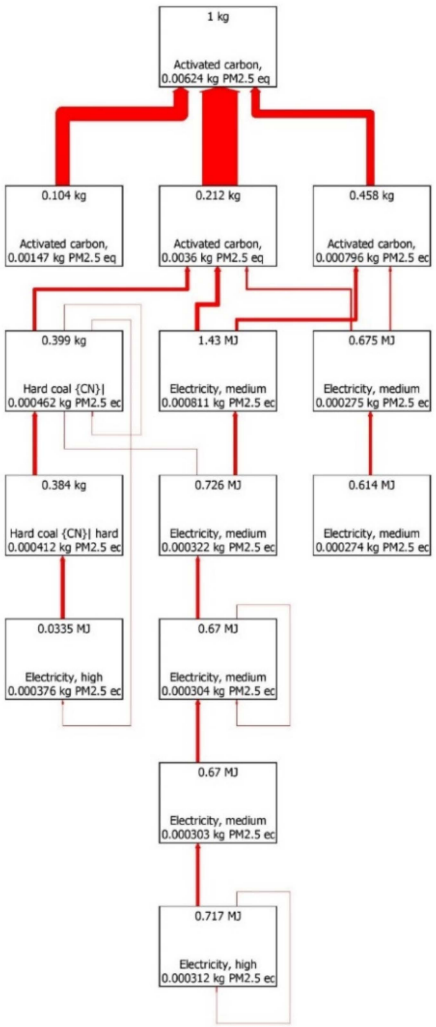
Nomenclature

ADP	Abiotic Depletion Potential
AP	Acidification potential
CCP	climate change potential
CCS	Carbon capture and storage
CCUS	Carbon capture, utilization, and storage
CCU	Carbon capture and utilization
CED	Cumulative energy demand
CO	Carbon monoxide
CO_2	Carbon dioxide
DQIs	Data quality indicators
EOR	Enhanced oil recovery
FEC	Fresh water ecotoxicity
FAETP	Fresh aquatic ecotoxicity potential
FEU	Freshwater eutrophication
FRS	Acidification potential fossil resource scarcity
GWP	Global warming potential
GHG	Greenhouse gas
HCT	Human carcinogenic toxicity
HDLPE	High Density Linear Polyethylene
HETP	Height Equivalent to One Theoretical Plate
HnCT	Human non-carcinogenic toxicity
HPT	high-pressure turbine
HTP	Human toxicity potential
IEA	International Energy Agency
IECM	Integrated Environmental Control Model
INDC	Intended Nationally Determined Contributions

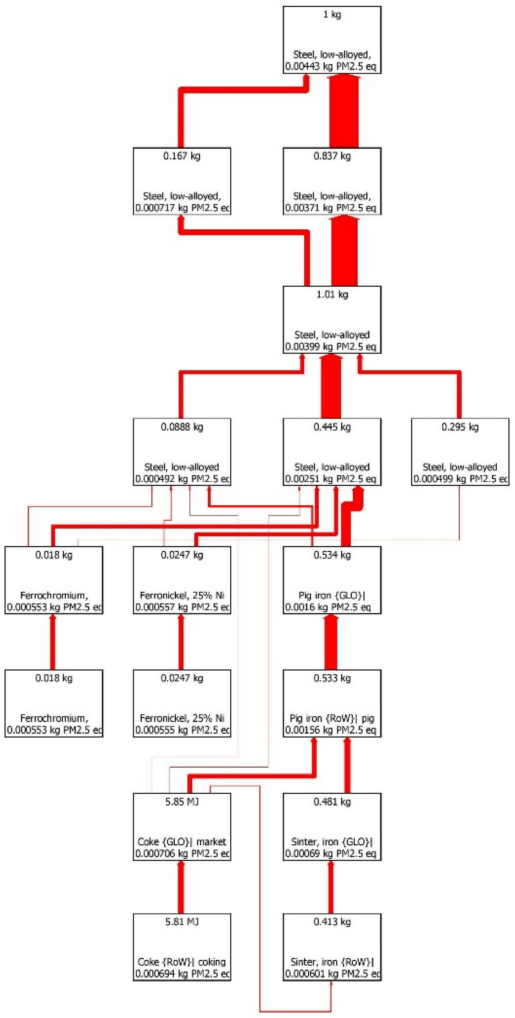
IPCC	Intergovernmental Panel on Climate Change
IR	Ionizing radiation
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LCI	Life Cycle Inventory
LPT	Low-pressure turbine
LU	Land use
MAETP	Marine/aquatic ecotoxicity potential
MEA	Monoethanolamine
MEC	Marine ecotoxicity
MEP	Marine eutrophication potential
MEU	Marine eutrophication
MRS	Mineral resource scarcity
NG	Natural Gas
NGCC	Natural Gas Combined Cycle
ODP	Ozone layer depletion potential
OFHH	Ozone formation affecting human health
OFTE	Ozone formation affecting terrestrial ecosystems
PCC	Post-combustion carbon capture
PMFP	particulate matter formation potential
POCP	photochemical ozone creation potential
POFP	Photochemical oxidant formation potential
SDg95	Overall uncertainty for a flow with a lognormal distribution
SO_2	Sulfur dioxide
SOD	Stratospheric ozone depletion
TWC	Total water consumption
TETP	Terrestrial ecotoxicity potential
TAC	Terrestrial acidification
LCI	Life Cycle Inventory
LPT	Low-pressure turbine
LU	Land use

Appendix A

The general structure of the data inventory flows in the database.

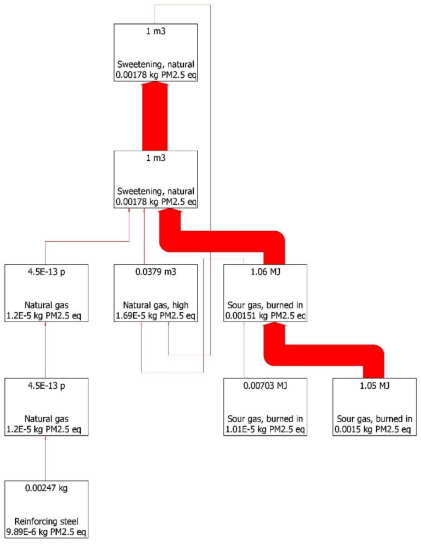


Product: Activated carbon;
Method: ReCiPe 2016 Midpoint (H) V1.04;
Chosen indicator: Characterization, PMFP (kg $PM_{2.5}$ eq);
Indication mode: Cumulated;
Long-term emissions are not excluded;
Node cut-off: 4%.

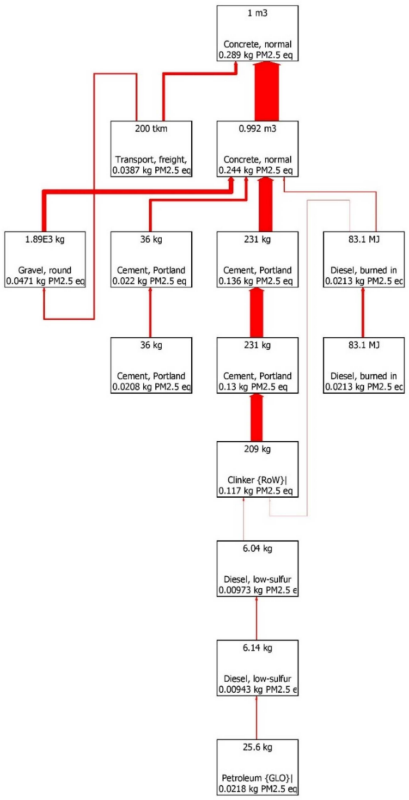


Product: Steel, low-alloyed, hot rolled ;
Method: ReCiPe 2016 Midpoint (H) V1.04;
Chosen indicator: Characterization, PMFP (kg $PM_{2.5}$ eq);
Indication mode: Cumulated;
Long-term emissions are not excluded;
Node cut-off: 9%.

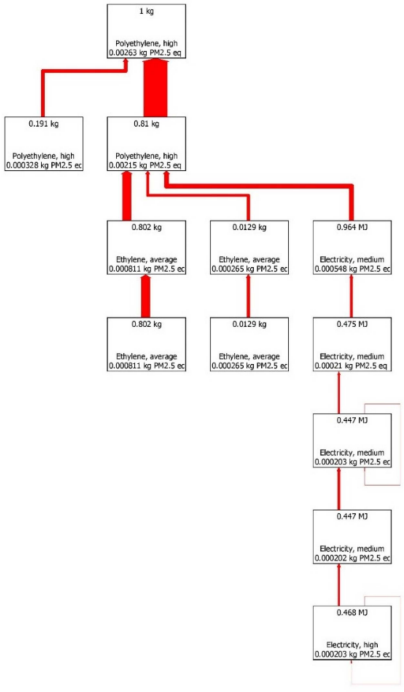
Figure A1. *Cont.*



Product: Sweetening, natural gas;
Method: ReCiPe 2016 Midpoint (H) V1.04;
Chosen indicator: Characterization, PMFP (kg $PM_{2.5}$ eq);
Indicator mode: Cumulated indicator;
Long-term emissions are not excluded;
Node cut-off: 0.5%.

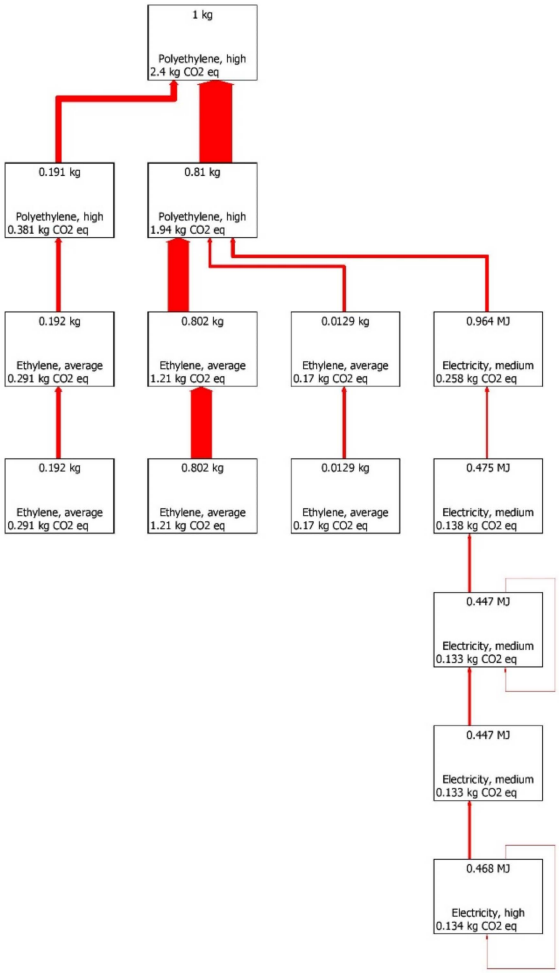


Product: Concrete;
Method: ReCiPe 2016 Midpoint (H) V1.04;
Chosen indicator: Characterization, PMFP (kg $PM_{2.5}$ eq);
Indication mode: Cumulated;
Long-term emissions are not excluded;
Node cut-off: 7%.

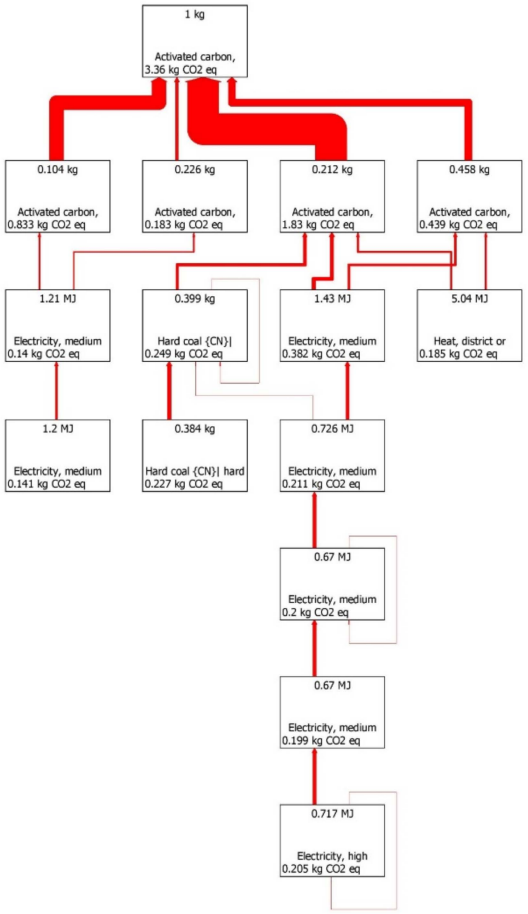


Product: Polyethylene, high density, granulate;
Method: ReCiPe 2016 Midpoint (H) V1.04;
Chosen indicator: Characterization, PMFP (kg $PM_{2.5}$ eq);
Indication mode: Cumulated;
Long-term emissions are not excluded;
Node cut-off: 7.5%.

Figure A1. Structural data inventory flows used in the Ecoinvent database in for the PMFP in (kg $PM_{2.5}$ eq).

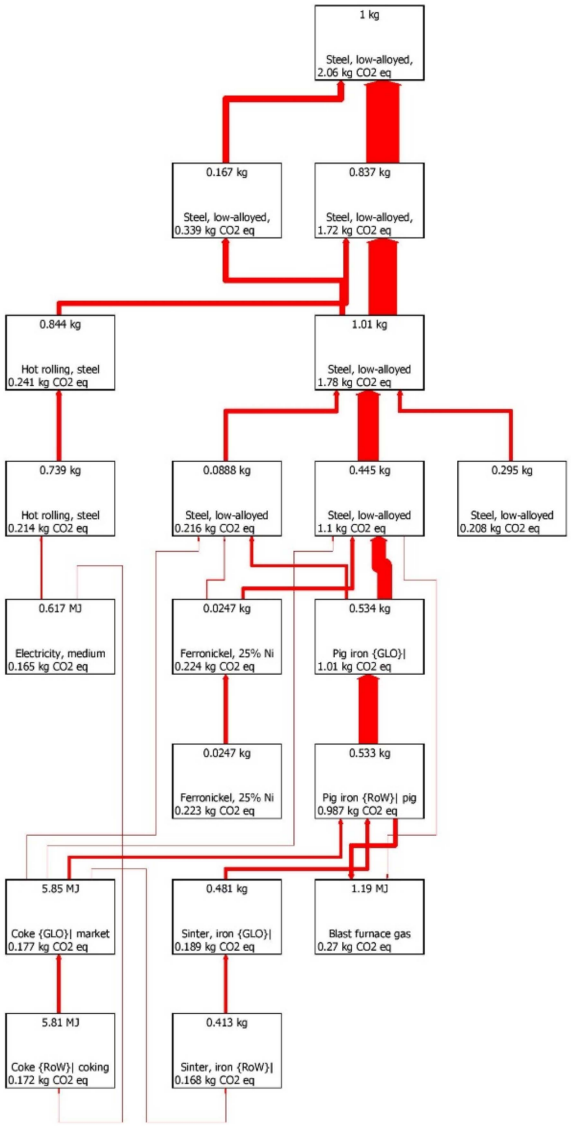


Product: Polyethylene, high density, granulate;
Method: ReCiPe 2016 Midpoint (H) V1.04;
Chosen indicator: Characterization, GWP (kg CO_2 eq);
Indication mode: Cumulated;
Long-term emissions are not excluded;
Node cut-off: 5%.

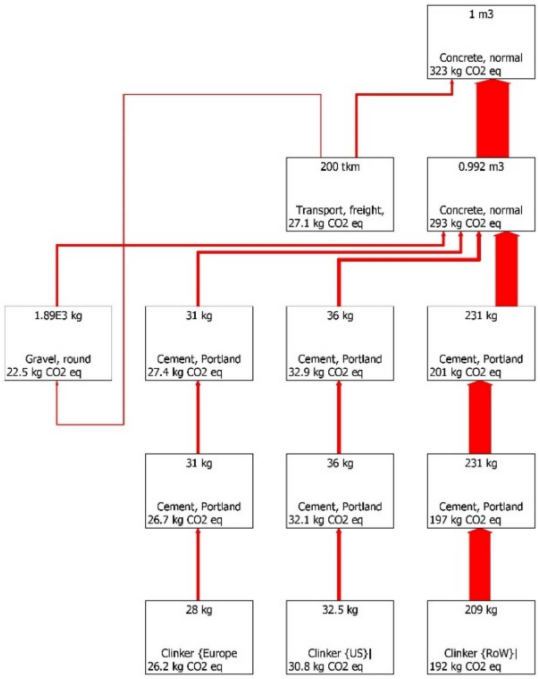


Product: Activated carbon;
Method: ReCiPe 2016 Midpoint (H) V1.04;
Chosen indicator: Characterization, GWP (kg CO_2 eq);
Indication mode: Cumulated;
Long-term emissions are not excluded;
Node cut-off: 4%.

Figure A2. *Cont.*

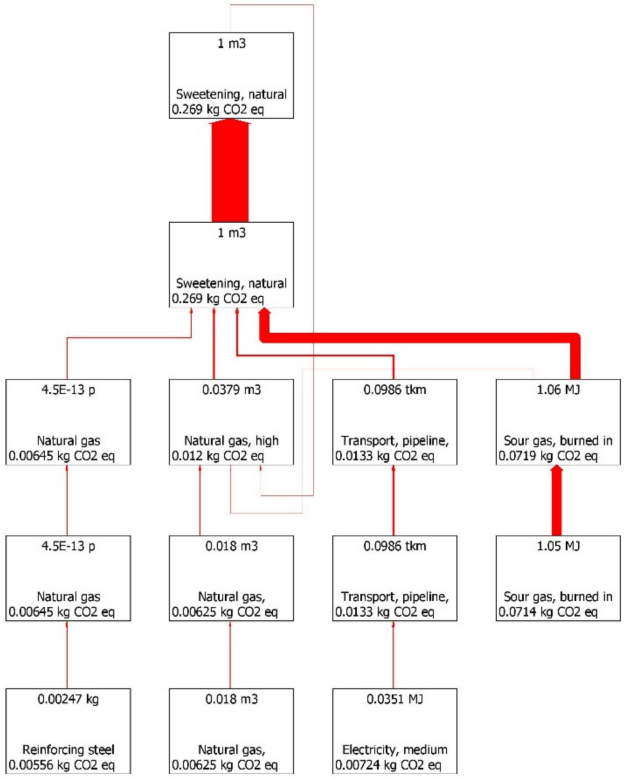


Product: Steel, low-alloyed, hot rolled;
Method: ReCiPe 2016 Midpoint (H) V1.04;
Chosen indicator: Characterization, GWP (kg CO_2 eq);
Indication mode: Cumulated;
Long-term emissions are not excluded;
Node cut-off: 8%.



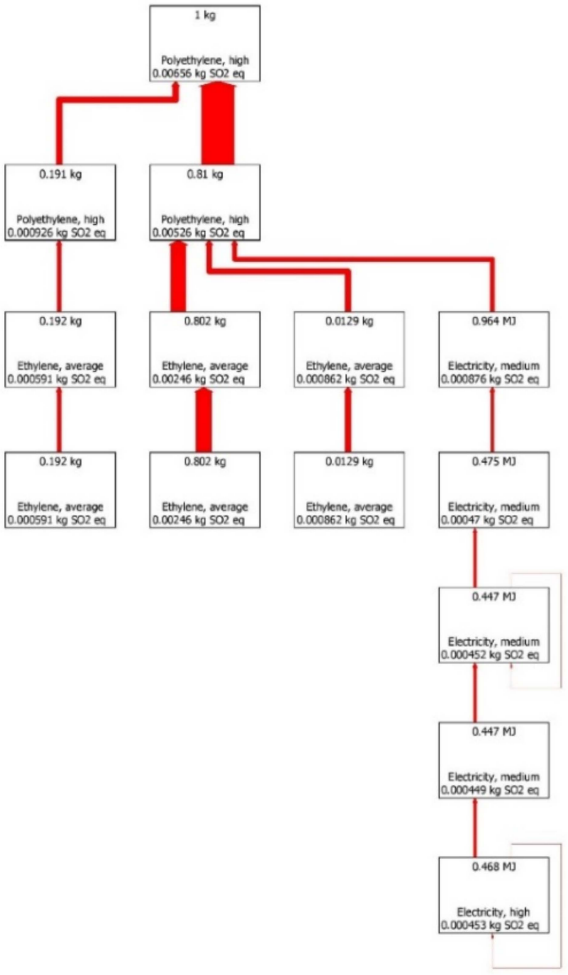
Product: Concrete, normal;
Method: ReCiPe 2016 Midpoint (H) V1.04;
Chosen indicator: Characterization, GWP (kg CO_2 eq);
Indication mode: Cumulated;
Long-term emissions are not excluded;
Node cut-off: 6%

Figure A2. *Cont.*

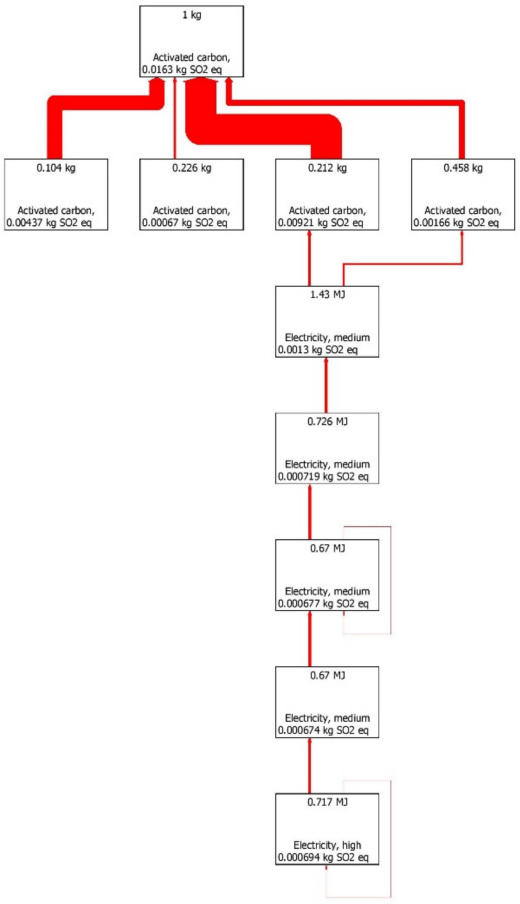


Product: Sweetening, natural;
Method: ReCiPe 2016 Midpoint (H) V1.04;
Chosen indicator: Characterization, GWP (kg CO_2 eq);
Indication mode: Cumulated;
Long-term emissions are not excluded;
Node cut-off: 1.5%.

Figure A2. Structural data inventory flows used in the Ecoinvent database in for the GWP in (kg CO_2 eq).

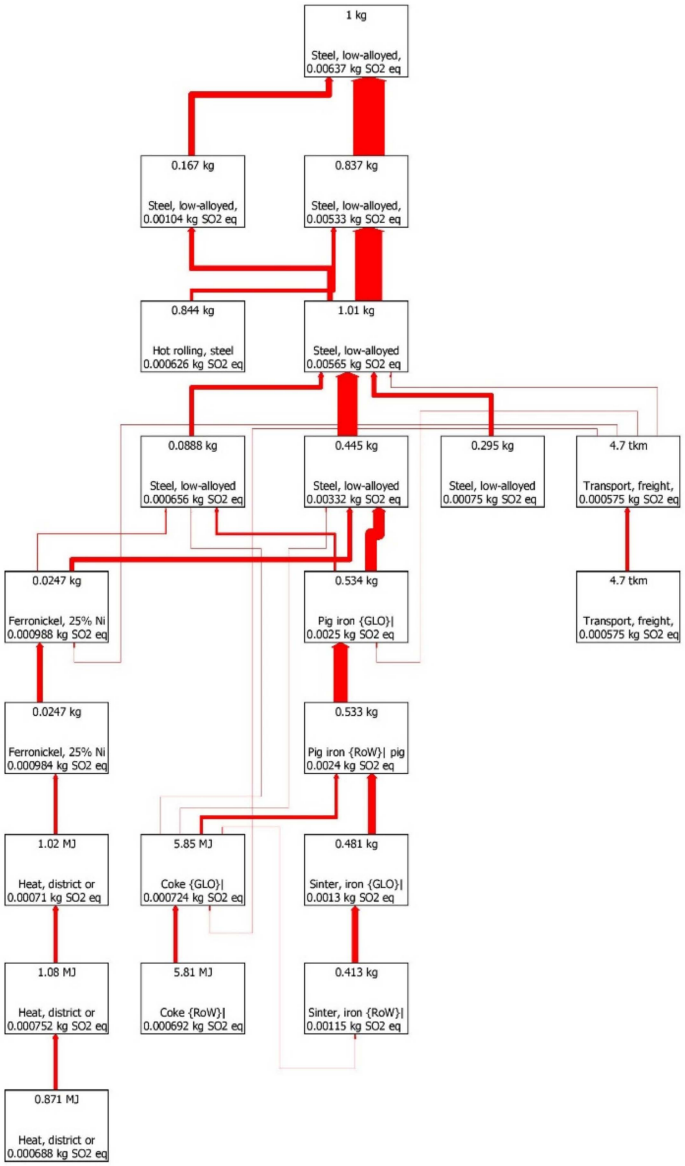


Product: Polyethylene, high density;
Method: ReCiPe 2016 Midpoint (H) V1.04;
Chosen indicator: Characterization, AP (kg SO2 eq);
Indication mode: Cumulated;
Long-term emissions are not excluded;
Node cut-off: 6.8%.

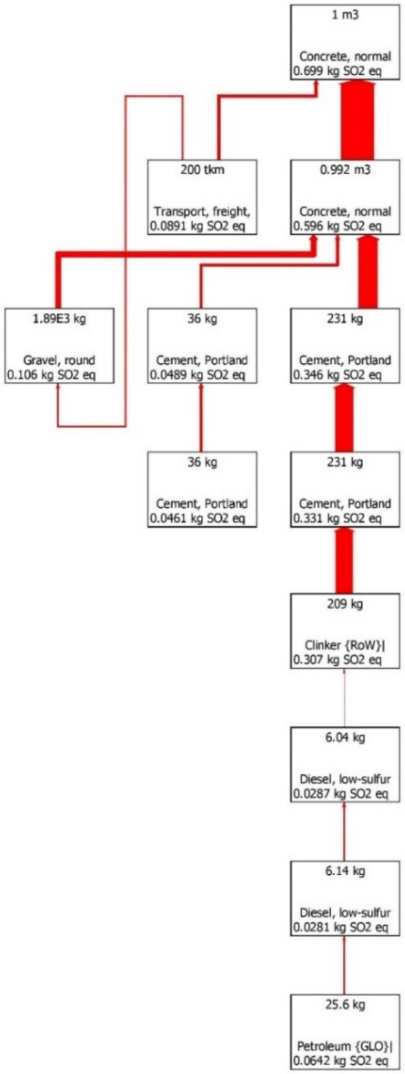


Product: Activated carbon, granular;
Method: ReCiPe 2016 Midpoint (H) V1.04;
Chosen indicator: Characterization, AP (kg SO2 eq);
Indication mode: Cumulated;
Long-term emissions are not excluded;
Node cut-off: 4%.

Figure A3. *Cont.*

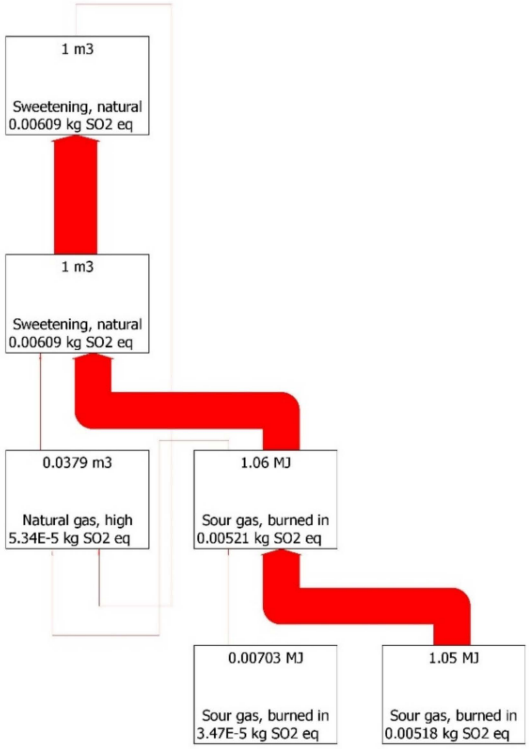


Product: Steel, low-alloyed, hot rolled;
Method: ReCiPe 2016 Midpoint (H) V1.04;
Chosen indicator: Characterization, AP (kg SO_2 eq);
Indication mode: Cumulated;
Long-term emissions are not excluded;
Node cut-off: 9%.



Product: Concrete, normal; Project: Ecoinvent 3;
Method: ReCiPe 2016 Midpoint (H) V1.04;
Chosen indicator: Characterization, AP (kg SO_2 eq);
Indication mode: Cumulated;
Long-term emissions are not excluded;
Node cut-off: 6.5%.

Figure A3. *Cont.*



Product: Sweetening, natural gas;
Method: ReCiPe 2016 Midpoint (H) V1.04 ;
Chosen indicator: Characterization, AP (kg SO_2 eq);
Indication mode: Cumulated;
Long-term emissions are not exclude;
Node cut-off: 0.5%.

Figure A3. Structural data inventory flows used in the Ecoinvent database in for the AP in (kg SO_2 eq).

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