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RESEARCH ARTICLE

Global Warming Potential from the Life Cycle of Fischer-Tropsch Fuel from Carbon Capture for Passenger Cars in Jakarta

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Abstract

This study evaluates the environmental impact of Fischer-Tropsch (FT) Fuel Synthesis from carbon capture (CCU) for passenger cars compared to battery electric vehicles (BEV) and internal combustion engine vehicles (ICEV) in Jakarta. Using life cycle assessment (LCA) principles and the openLCA application, carbon dioxide (CO_2) emissions per unit lifetime of passenger cars are assessed. FT Fuel Synthesis from CCU, reliant on a fossil fuel-dominated Java-Bali power system, exhibits a high global warming potential (GWP) compared to conventional fuels for ICEV and even electrical energy for BEV from the same power system. However, scenarios with increased renewable energy sources, especially solar photovoltaic (PV), could significantly reduce GWP. Additionally, FT Fuel Synthesis from coal liquefaction presents moderate GWP impacts. This study highlights the complexities of fuel synthesis methods, electricity sources, and environmental impacts in climate change mitigation, providing insights for transitioning towards sustainable transportation systems in Indonesia.

Keywords: Life Cycle Assessment, Carbon Capture and Utility, Fischer-Tropsch Synthesis

1. Introduction

Global warming is evident from various climate indicators [1]. Temperature changes occur not only in the atmosphere but also on the earth’s surface and in the oceans. This warming includes changes in surface temperature, atmosphere, oceans, glaciers, snow cover, sea ice, sea level, and atmospheric water vapor. This phenomenon has been ongoing since the 19th century.

Global warming is caused by various factors, including the greenhouse effect resulting from greenhouse gas emissions [1]. Various types of gases contribute to the greenhouse effect, with carbon dioxide (CO_2) being the most dominant greenhouse gas [2]. Cumulative anthropogenic CO_2 emissions worldwide from 1850-2021 amounted to 670±65 gigatons of carbon (GtC) or 2,455±240 gigatons of CO_2 ($GtCO_2$), with 70% occurring since 1960 and 33% since 2000 [3]. CO_2 emissions, driven by fossil fuel consumption and cement production, show a continuous upward trend.

In 2019, Indonesia’s greenhouse gas emissions amounted to 1,866,552 Gg CO_2-eq, with 638,808 Gg CO_2-eq from the energy sector, including 273,523 Gg CO_2-eq from electricity generation [4]. 93% of these emissions were CO_2. Compared globally, Indonesia’s CO_2 emissions constituted about 1.67% of global emissions in 2021 [3]. These emissions, stemming from various sectors, particularly highlight that the fuel consumed in the power generation sector amounted to 539 million BOE (barrel of oil equivalent) [5] with coal accounting for 76.22% of this consumption.

Anthropogenic emissions are the primary determinants of CO_2 levels in the atmosphere, leading to global warming [6]. World leaders have taken mitigation steps to limit global warming by reducing greenhouse gas emission growth annually, aiming for decarbonization [7]. These measures necessitate cross-national and cross-sectoral cooperation. Annex 1 countries, classified by the United Nations Framework Convention on Climate Change (UNFCCC), have commitments to undertake further mitigation efforts [8]. Indonesia, a non-Annex 1 country, determines its commitment level based on scenarios [9].

Indonesia’s mitigation and climate change adaptation plans outlined in its updated Nationally Determined Contribution (NDC) aim to reduce emissions by 31.89% unconditionally or 43.2% conditionally by 2030 compared to a business-as-usual (BAU) scenario [9]. These plans focus on various sectors such as energy, waste, Industrial Process and Product Use (IPPU), agriculture, and Forestry and Other Land Use (FOLU).

In the energy sector, planned mitigation actions include renewable energy penetration, increased energy efficiency, low-emission carbon use, clean coal and gas-fired power plant technologies, and mine reclamation [9]. Specifically, Indonesia aims for a 23% share of New and Renewable Energy in the power system by 2025 [10], [11], increasing to 31% by 2050 [10]. However, coal-fired power plants (CFPP) will continue to dominate with a projected capacity of 15.9 GW by 2030 [11]. Consequently, greenhouse gas emissions from the electricity generation sector are estimated to increase by 39% by 2030 compared to 2021.

Decarbonization poses a challenge for Indonesia due to its archipelagic nature, resulting in non-connected national energy systems. Mitigation actions relying on renewable energy penetration are heavily contingent on resource availability in specific areas that might not benefit other regions lacking interconnected electrical grids.

Carbon capture technology is a potential decarbonization tool [12]. Broadly, carbon capture involves trapping CO_2 from the air or industrial emissions, including power plants, before releasing it into the atmosphere. In 2021, global facilities captured over 40 million tons of CO_{22} [13]. Currently, Indonesia has expressed interest in investing in carbon capture but has not included its implementation in its mitigation plans [14].

Promoting electric vehicle usage is also part of Indonesia's climate change mitigation scenario [9]. Ideally, this mitigation action would parallel an increased renewable energy mix. That is because electric vehicle's main source of energy is electricity. While the consumption of energy from electricity does not emit CO_2, the electricity itself might be sourced from a CO_2-emitting electrical power generation, and this is the case for the determination of electric vehicle's lifecycle CO_2 emission. Considering Indonesia's dominance of fossil fuel-based power generation, electric vehicles usage in Indonesia will rely on dirty energy sources, causing CO_2 emissions throughout their lifecycle [15]. In fact, during their lifecycle, electric vehicles may produce higher CO_2 emissions than fossil fuel vehicles, particularly when powered by "dirty" energy grids dominated by fossil fuels [16]. As of 2021, renewable energy only constituted about 12.5% of Indonesia's energy mix [11].

Climate change mitigation is a long-term plan requiring significant time and concerted effort to achieve preset targets and transition toward a carbon-neutral society. During this energy transition phase, CO_2 emissions from fossil fuel consumption cannot be eliminated, especially in sectors like aviation, shipping, and heavy transport [17]. Moreover, as one of the world's largest coal reserves, Indonesia faces a geopolitical challenge in transitioning energy sources [18]. Hence, alternative fuels need consideration in this context.

Fischer-Tropsch Fuel (FT Fuel) is an alternative fuel synthesized from syngas (carbon monoxide (CO) and hydrogen (H_2)) [19]. This is an established process, which now has a commercially operating plant [20]. The process, developed in 1926 at Kaiser Wilhelm Institute for Coal Research [21], involves CO, which could be produced from processes like reverse water gas shift (RWGS), where CO_2 becomes the input [22]. CO_2 used in this process can originate from carbon capture from point sources or direct air capture [12]. However, RWGS is not widely scaled to commercial yet [22], although there were economic analyses [23], [24], techno-economic analysis [25], and thermo-economic analysis [26] already carried out in order to make it commercially feasible.

Utilizing CO_2 emissions could serve as a solution in Indonesia's energy transition and climate change mitigation, especially in the power generation and transportation sectors, where transportation is predicted to be among the last sectors to reduce its emissions below current levels [27], [28]. Process analysis [29] and simulation of a process concept [22] for the production of synthetic fuel from CO_2 has been conducted. The final consumption of this kind of synthetic fuel would still cause emission. In relation to this, using direct air capture of CO_2, techno-economic and life cycle assessment of sustainable aviation fuel [30], analysis for the energy and climate impact [31] and economy [32] of producing synthetic fuel, has been done.

2. The Life Cycle of Passenger Car Fuel

The study focuses on evaluating the environmental impact of FT Fuel synthesis from CCU for passenger cars in comparison to battery electric vehicles (BEV) and internal combustion engine vehicles (ICEV). This comparison involves analyzing the fuel derived from CCU against similar reference applications used for passenger vehicles but differing in elements and chemical compositions. The functional unit considered here is CO_2 emissions per unit lifetime of a passenger car, denoted by the distance traveled within a lifecycle, set at an assumed lifetime of 160,000 km [33]. The passenger car fuel product here is assumed to be used in the Jakarta area, Indonesia.

Considering the cradle-to-grave approach, this research encompasses resource extraction, transportation, passenger car manufacturing, fuel consumption in Jakarta, and the operation and maintenance of passenger cars. It aims to investigate these systems' life cycles in response to global warming, climate change, greenhouse gas emissions, and the transition toward a net-zero emission era.

By applying the Life Cycle Assessment (LCA) principles, the study intends to assess the life cycle of environmentally friendly passenger vehicle fuels. This involves evaluating three product systems—FT Fuel from CCU, BEV, and ICEV—as reference systems. Employing LCA guidelines based on ISO 14040 [34] and 14044 [35], the study will compute CO_2 emissions within each life cycle, considering the factors that most impact emissions in the supply chain of the reviewed systems. Additionally, alternative scenarios from the reference fuel life cycle will be explored to gauge their influence on the overall CO_2 emissions of the reference systems.

The three product systems mentioned above will be modeled using LCA to evaluate their life cycle impacts, as well as the alternative scenarios. The selected alternative scenarios are as follows:

1. FT Fuel synthesis using the projected Java-Bali power system for 2030.
2. FT Fuel synthesis using a power system entirely supplied by Solar PV Power Plants.
3. Electric energy for BEV using a power system entirely supplied by Solar PV Power Plants.
4. FT Fuel synthesis originating from coal liquefaction.
5. FT Fuel synthesis originating from coal liquefaction using a power system entirely supplied by Solar PV Power Plants.

The life cycle impact assessment in this study is constrained based on the ReCiPe2016 method indicators [36]. The chosen characterization factor is the midpoint climate change impact category, specifically global warming potential (GWP). GWP signifies the integrated increase in infrared radiation strength from greenhouse gases, expressed in kg CO_2-eq [37], [38].

The life cycle modeling is performed using the openLCA application version 2.0.3 [39]. The life cycle model relies on the conducted Life Cycle Inventory (LCI), which gathers data from all stages within the life cycle scenarios. Much of this LCI data is accessible to the public.

This research utilizes the ecoinvent dataset version 3.9.1, namely Preprint Submitted to IJECBE "ecoinvent_391_cutoff_upr_n3_20230629" [40]. Besides the LCI data available in the ecoinvent database, the modeling is also referenced from other relevant sources as required for the life cycle model. Processes in ecoinvent database and other sources that is not directly fit with the model in this research and need modifications have LCA models that can be found in Appendix.

2.1 Life Cycle of FT Fuel Synthesis for ICEV

The life cycle of FT Fuel Synthesis for ICEV first consists of raw materials extraction, which in this context is CO_2 production at CFPP, then production, which is carbon capture and FT Fuel synthesis, then product distribution, and at the final stage is the consumption of FT Fuel by ICEV and end-of-life treatment, as shown in 1. The power plant used as the LCA model in this study is Suralaya Power Plant Unit 7.

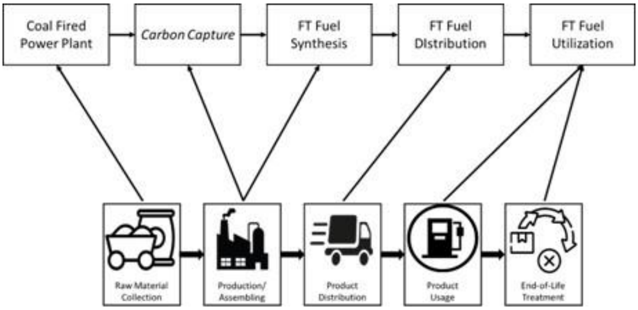


Figure 1. Life Cycle of FT Fuel Synthesis for ICEV

2.1.1 Coal Fired Power Plant

The CFPP serves as a source of CO_2, which becomes the feedstock for carbon capture and FT Fuel synthesis. This is considered the raw material acquisition stage. The CFPP itself has a life cycle, with raw materials extraction, too, along with production, product transportation, and product utilization.

Coal is the raw material for CFPP operations. Within the coal subsystem, there are stages of raw material acquisition: the coal mining process and transportation, which involves transferring coal from the mine to the CFPP location.

The coal acquisition model refers to the database in ecoinvent [40], with certain values adjusted based on assumptions in this research. It is assumed that the coal originates from domestic coal trading sourced from mines in Muara Enim Regency, South Sumatra [41], [42], and is directly available at the railway station. Initially, the coal is transported via train from Muara Enim to Tarahan Port in Lampung Province, covering a distance of 420 km, with a carrying capacity of 60 wagons, and each wagon is capable to hold 50 tons [43]. From the port, shipment continues using a coal carrier ship [44] with a carrying capacity of 80,000 DWT [45] to the dedicated dock at the Suralaya Power Plant, a distance of 100 km, measured using Google Maps [46]. At the dock, the coal is assumed to be immediately used as the CFPP feedstock.

CO_2 is emitted from CFPP operations, which is considered a product in this context. Coal fired power plant primarily produces another main product: electricity. In LCA, CO_2 emissions are used as an environmental impact category. Having more than one product from this product system, along with CO_2 acting as feedstock and an environmental impact category, renders this product system multifunctional. Uncaptured CO_2 emissions from CFPP will be allocated to each product, namely emissions from electricity generation and emissions from captured CO_2 Preprint Submitted to IJECBE products.

The operational model of Suralaya Power Plant Unit 7 refers to the database in ecoinvent, with some values adjusted based on assumptions in this research as shown in Table 1.

Table 1. Suralaya Power Plant Unit 7 Characteristics

Characteristics	Value	Unit	Reference
Power	600	MWe	[47]
ThermalEfficiency	33	%	[47]
Lifetime	150,000	hour	[31]
Operating Time	8,000	hour/year	[31]
PowerPlantCO_2Emissions	1.048	kg CO_2/kWh	[47]
%Carbonof Subbituminous	49.5	%	[47]
CoalNCV	18.9	MJ/kg	[47]

According to [31], the electricity demand for FT Fuel synthesis is mainly from hydrogen production via electrolysis, which is higher compared to the electricity produced by the power plant. Therefore, all electricity generated by the power plant will be channeled for electrolysis operations. Meanwhile, the carbon capture process will use 10% of the plant's capacity [48]. The remaining electricity demand will be supplied by the Java-Bali power system and will be detailed in the Fischer-Tropsch Process. This model encompasses the end-of-life treatment processes of the power plant. CO_2 products will be captured by the retrofit carbon capture subsystem at CFPP. Hence, it is assumed the transportation process for CO_2 products has no life cycle impact. CO_2 products will be utilized by capturing and separating CO_2 from flue gas through carbon capture.

2.1.2 Carbon Capture (CC)

Carbon capture involves capturing carbon by retrofitting the referenced CFPP. The raw material for carbon capture is the output from CFPP, namely flue gas containing CO_2. The production refers to the CO_2 capture process, where uncaptured CO_2 becomes emissions. The captured CO_2 product will be directly processed for FT Fuel synthesis at the same location. Thus, it is assumed the transportation process for the CO_2 product has no life cycle impact. The carbon capture model refers to [31], where the chosen carbon capture rate is 90%, using monoethanolamine (MEA) as an absorbent. The end-of-life treatment model for the carbon capture facility is assumed to be nonexistent due to data limitations.

2.1.3 FT Fuel Synthesis and Distribution

FT Fuel synthesis involves inputting CO_2 from carbon capture and adding H_2 from water electrolysis. This process produces FT Fuel equivalent to gasoline for passenger cars. Subsequently, distribution occurs using fuel tanker trucks from Suralaya Power Plant Unit 7 to Jakarta. The main raw material for FT Fuel synthesis in this study is

CO_2 from capture, with secondary raw material H_2 from water electrolysis. FT Fuel is produced by synthesizing syngas in a reactor using a catalyst. Syngas is obtained from the RWGS process of CO_2 and H_2. The resulting FT Fuel product is distributed to Jakarta, and then consumed by passenger cars.

The FT process model comprises three main stages to convert captured CO_2 into fuel: electrolysis, RWGS, and FT Fuel synthesis.

Electrolysis is a process to produce H_2 from water using electricity. In this study, the Preprint Submitted to IJECBE electrolysis model refers to [31], where the process involves hydrogen production via an electrolyzer, followed by compressing H_2 gas to 25 bars as input for RWGS and FT Fuel synthesis. The end-of-life treatment model for the electrolysis facility is assumed to be nonexistent due to data limitations.

According to [31], the electricity demand for this process surpasses the power generated by the power plant. Therefore, additional electrical energy is required from an external source. In this study, it is assumed that the extra electricity demand will be supplied from the Java-Bali power system. The Java-Bali power system model will be further detailed in latter chapter.

CO_2 from carbon capture and H| from electrolysis undergo the RWGS process to obtain carbon monoxide. In this research, the RWGS model refers to [31], where the RWGS reaction is modeled in a fixed bed reactor, utilizing the Südchemie Shiftmax 240 catalyst, consisting of 57% CuO, 31% ZnO, and 11% Al2O3. The end-of-life treatment model for the RWGS facility is assumed to be non-existent due to data limitations.

CO from RWGS is combined with H_2 from electrolysis for FT Fuel synthesis in the FT plant. The FT Fuel synthesis model refers to [31], including the hydrocracking process to obtain the desired fuel. In this study, the FT Fuel produced is assumed equivalent to conventional gasoline used for motor vehicles, with a net calorific value (NCV) of 43.2 MJ/kg. The end-of-life treatment model for the FT Fuel synthesis facility is assumed to be non-existent due to data limitations.

The FT Fuel product is then distributed to the FT Fuel utilization location in Jakarta. Delivery is carried out using tanker trucks assumed to have a capacity of 16,000 liters, meeting EURO 4 emission standards [49]. The distance traveled is assumed to be 120 km [50]. This model includes the end-of-life treatment process of the tanker.

2.1.4 FT Fuel Utilization

FT Fuel will be used as gasoline for vehicles. In using FT Fuel, LCA also encompasses the life cycle of the intended passenger cars. The raw material for passenger cars is FT Fuel synthesized from captured CO_2 from CFPP. Utilization includes the manufacturing process of passenger cars used to consume FT Fuel during the vehicle's lifetime, or in other words, mileage. The background process of ICEV manufacturing is not included in this research scope.

The utilization of FT Fuel is assumed to begin from the same point in the city of Jakarta, to be used throughout the lifetime of a passenger car, which is 160,000 km. The FT Fuel usage model refers to the database in ecoinvent [40], with adjustments to values according to assumptions, encompassing fuel consumption, passenger car manufacturing and maintenance, and road construction and maintenance.

2.2 Life Cycle of Electric Energy for BEV

The life cycle of electric energy for BEVs comprises the Java-Bali power generation, the transmission and distribution system, and the utilization of electricity for BEVs, as shown in Fig. 2.

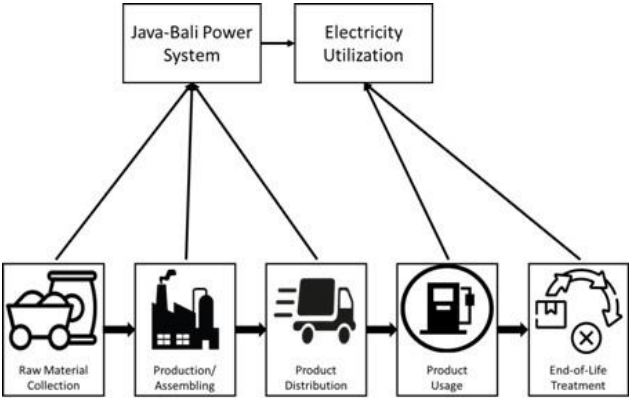


Figure 2. Life Cycle of Electricity for BEV

In this scenario, electric vehicles will be used in Jakarta. Therefore, the electricity used for charging will originate from the power generation system in Java-Bali. The Java-Bali power generation comprises various types and capacities of power plants scattered across different regions. Thus, for electricity consumption in Jakarta, the power generated by these plants will be transmitted using the Java-Bali transmission system and distributed through Jakarta's distribution system.

The Java-Bali power generation system model refers to [11], where the energy mix is assumed to be the same as the 2021 energy mix, consisting of 76.6% coal, 16% natural gas, 4.1% geothermal, 3.1% hydropower, 0.2% petroleum, and 0.1% other renewable energy sources. The transmission and distribution system model refers to the ecoinvent database [40], encompassing high-voltage transmission systems, high-voltage to medium-voltage transformation, medium-voltage transmission systems, medium-voltage to low-voltage transformation, and low-voltage distribution systems. This low voltage electricity will be utilized for charging BEVs.

The electricity usage here refers to the consumption for charging BEVs, encompassing the manufacturing of electric vehicles aggregated over their lifetime.

Similar to the life cycle model of FT Fuel Synthesis for ICEVs, the use of electric energy for BEVs is assumed to originate from the same point in Jakarta, to be utilized over the passenger vehicle's lifespan of 160,000 km. The model for electric energy use for BEVs refers to the ecoinvent database [40], adjusted according to assumptions, covering electric energy consumption, manufacturing and maintenance of passenger vehicles, battery manufacturing for BEVs, and road construction. The background processes of both Java-Bali power system and BEV manufacturing are not part of the scope of this study.

2.3 Life Cycle of Conventional Gasoline for ICEV

The life cycle model for conventional gasoline for ICEV consists of the global conventional gasoline market and the utilization of conventional gasoline for ICEV, as shown in Fig. 3.

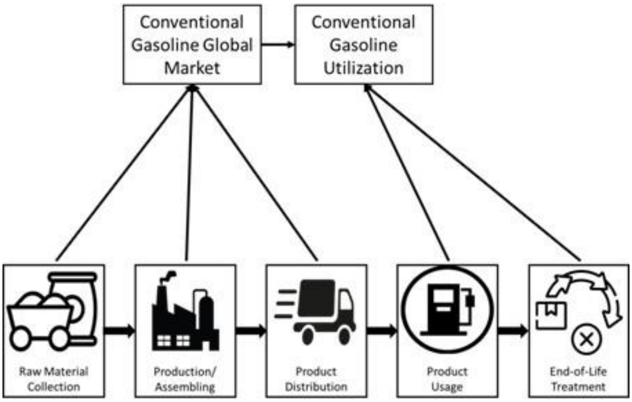


Figure 3. Life Cycle of Conventional Fuel for ICEV

The global conventional gasoline market model refers to the ecoinvent database [40], specifically the "market for petrol, low-sulfur | petrol, low-sulfur | Cutoff, U". Meanwhile, the use of conventional gasoline for ICEV is similar to the use of FT Fuel described in Chapter 2.1. The background process of global conventional gasoline market is not part of the scope of this study.

2.4 Altenative Life Cycle of Fuels for ICEV and BEV

2.4.1 Life Cycle of FT Fuel Synthesis with the Projection of the Java-Bali Power System in 2030

The life cycle model is the same as the life cycle model presented in Chapter 2.1. However, the additional electricity required for the electrolysis process is supplied from the projection of the Java-Bali electricity system for the year 2030 according to [11]. Its energy mix comprises 73.5% coal, 12.1% natural gas, 8.3% geothermal, 4.5% hydro, 0.5% solar PV, 0.5% wind, 0.5% waste, and 0.1% other renewable energy sources. In this model, the "other" renewable energy source is assumed to be included within the solar PV mix, making solar PV account for 0.6%.

2.4.2 Life Cycle of FT Fuel Synthesis with Entire Electricity Supply from Solar PV

The life cycle model is the same as the life cycle model presented in Chapter 2.1. However, the additional electricity required for the electrolysis process is entirely supplied by solar PV. The solar PV model used refers to the ecoinvent database

[40], specifically the "electricity production, photovoltaic, 570kWp open ground installation, multi-Si | electricity, low voltage | Cutoff, U".

This model is designed to assess the significance of renewable energy use in the life cycle emissions of FT fuel synthesis.

2.4.3 Life Cycle of Electric Energy for BEV with Entire Electricity Supply from Solar PV

This life cycle model is identical to the one in Chapter 2.2. However, the additional electricity needed for the electrolysis process is entirely supplied by solar PV. The solar PV model used refers to the ecoinvent database [40], as in Chapter 2.4.2.

This model is designed to assess how significant the use of renewable energy is in the life cycle emissions of electric energy for BEVs.

2.4.4 Life Cycle of FT Fuel Synthesis with Coal Liquefaction and Electricity Supply from the Java-Bali Power System

The life cycle model is the same as the life cycle model in Chapter 2.3. However, in this case, the FT fuel synthesis is not done from the carbon capture process in the CFPP and the subsequent RWGS process, but rather from coal liquefaction.

Coal liquefaction is a method for the conversion of solid coal into liquid fuels. This is a wellestablished technology, which has two methods of conversion, direct liquefaction and indirect liquefaction [51]. Direct liquefaction, as its name implies, is a direct process of converting solid coal into liquid fuels via hydrogenation, while indirect liquefaction has an intermediate process which is coal gasification before converting the gasification product, that is syngas, into liquid fuels.

The coal liquefaction model refers to the commercial-scale FT fuel synthesis from the Secunda Synfuel Operations in South Africa found in the ecoinvent database [40], titled "synthetic fuel production, from coal, high-temperature Fischer-Tropsch operations | petrol, unleaded | Cutoff, U." The distinction for the model on this research from the database lies in replacing the "hard coal" parameter with "lignite" to match the type of coal used in the FT fuel synthesis from carbon capture in this study.

This model is created to compare CO_2 emissions from different FT fuel synthesis methods, particularly on a commercial scale.

2.4.5 Life Cycle of FT Fuel Synthesis with Coal Liquefaction and Entire Electricity Supply from Solar PV

This life cycle model is the same as the life cycle model in Life Cycle of FT Fuel Synthesis with Coal Liquefaction and Electricity Supply from the Java-Bali Power System. However, in this case, the electricity required for the coal liquefaction process is entirely supplied by solar PV. The solar PV model used refers to the ecoinvent database [40], as in Chapter 2.4.2.

This model is created to assess the significance of renewable energy utilization in the life cycle emissions of FT fuel synthesis with coal liquefaction.

3. Global Warming Potential of The Life Cycle of Passenger Car Fuel

The usage of passenger vehicles, whether ICEV or BEV, encompasses various life cycle scenarios that exhibit differing environmental impacts. These scenarios established in this research are modeled for their life cycle using the openLCA application. The selected impact assessment is the midpoint impact category of climate change using the ReCiPe 2016 method, specifically the GWP expressed in kg CO_2-eq, with the functional unit being the lifespan of a passenger vehicle.

The life cycle modeling generates environmental impact parameters, both comprehensively and for each subsystem. The environmental impact assessment results from each scenario model that can be compared and analyzed are grouped.

It is noteworthy that apart from the FT Fuel synthesis life cycle model, the GWP impact from the subsystems of raw material extraction, production, and distribution cannot be distinctly differentiated. Therefore, all processes except consumption are considered as a single production process.

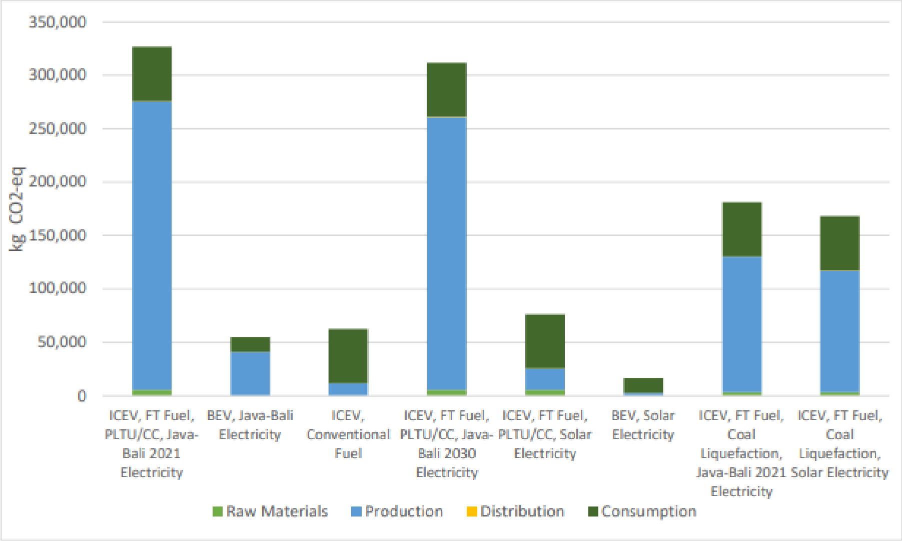


Figure 4. Summary of Global Warming Potential of the Life Cycle of Passenger Car Fuels. Apart from the FT Fuel synthesis life cycle model, all processes except consumption are considered as a single production process.

3.1 *FT Fuel Synthesis for ICEV*

The synthesis of FT Fuel for ICEV is the main scenario of concern in this study. FT Fuel from carbon capture is expected to offer a solution to the issues addressed in this research. This FT Fuel product is assumed to be used as a substitute for conventional gasoline used by ICEVs.

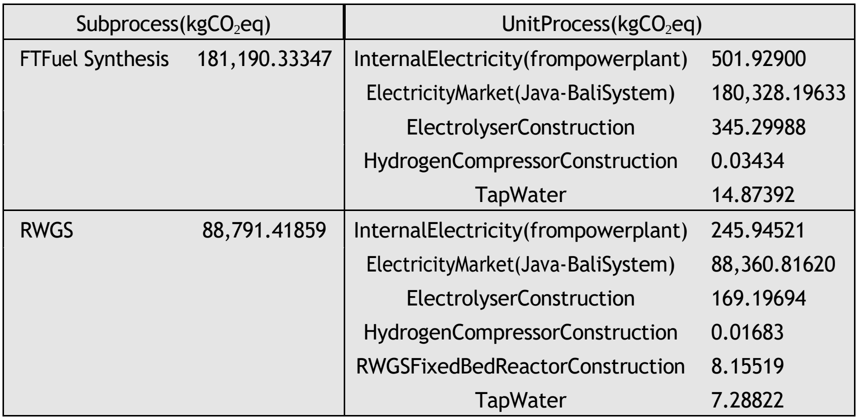
It was found that within the lifetime of a vehicle, the life cycle model of FT Fuel synthesis for ICEVs yields a GWP impact of 326,480 kg CO_2-eq (Fig. 4). When examining each subsystem, the FT Fuel synthesis system generates the largest CO_2

emissions, amounting to 270,006 kg CO$_2$-eq, followed by the use of FT Fuel by passenger vehicles at 50,681 kg CO$_2$-eq. Meanwhile, the carbon capture process contributes a GWP impact of 5,484 kg CO$_2$-eq, and the distribution of FT Fuel to consumers amounts to 308 kg CO$_2$-eq.

In the FT Fuel synthesis system, FT Fuel synthesis itself has the highest GWP impact with 181,190 kg CO$_2$-eq, followed by RWGS at 88,791 kg CO$_2$-eq, and FT plant construction at 25 kg CO$_2$-eq.

Upon closer look, each RWGS and FT Fuel Synthesis subprocess has detailed components contributing to GWP impact, as shown in Table 2. The primary contributor to GWP impact from both processes is the Electricity Market (Java-Bali System), each amounting to 88,361 kg CO$_2$- eq and 180,328 kg CO$_2$-eq, respectively.

Table 2. GWP of FT Fuel Synthesis and RWGS Subprocesses and Unit Processes



Subprocess(kgCO$_2$eq)		UnitProcess(kgCO$_2$eq)	
FTFuel Synthesis	181,190.33347	InternalElectricity(frompowerplant)	501.92900
		ElectricityMarket(Java-BaliSystem)	180,328.19633
		ElectrolyserConstruction	345.29988
		HydrogenCompressorConstruction	0.03434
		TapWater	14.87392
RWGS	88,791.41859	InternalElectricity(frompowerplant)	245.94521
		ElectricityMarket(Java-BaliSystem)	88,360.81620
		ElectrolyserConstruction	169.19694
		HydrogenCompressorConstruction	0.01683
		RWGSFixedBedReactorConstruction	8.15519
		TapWater	7.28822

Overall, the Electricity Market (Java-Bali System) contributes the most to the GWP impact of the FT Fuel synthesis life cycle for ICEV. This is primarily due to two interrelated factors. Firstly, both the RWGS and FT Fuel Synthesis processes involve electrolysis components that demand substantial electrical energy. The total electrical energy required for electrolysis amounts to 256,947 kWh per vehicle lifecycle, comprising 40,006 kWh from the internal system, namely Suralaya Power Plant Unit 7, and 216,941 kWh from the Electricity Market (Java-Bali System). Secondly, it pertains to the source of electrical energy itself. In this FT Fuel synthesis life cycle model for ICEV, the chosen generation system is the 2021 Java-Bali power generation system, dominated by fossil fuel power plants, accounting for over 90% of the total generation. The high demand for electrical energy, coupled with the predominance of fossil fuel power generation, results in the substantial GWP impact from the FT Fuel Synthesis process within this FT Fuel synthesis life cycle model for ICEV.

3.2 Baseline

The baseline scenario group comprises the reference scenarios in assessing the GWP impact, namely FT Fuel synthesis from carbon capture for ICEV, BEV, and conventional gasoline vehicles. The modeling results indicate that FT Fuel synthesis for ICEV generates a GWP impact 5.9 times higher than electric energy for BEV (54,987 kg CO_2-eq) and 5.2 times higher than conventional gasoline for ICEV (62,326 kg CO_2-eq) (Fig. 4).

This baseline group demonstrates that FT Fuel synthesized from carbon capture has not yet served as climate change mitigation, either in the transportation sector or in power plant operations. The amount of CO_2 captured from CFPP is disproportionate to the CO_2 emissions resulting from the energy demand for FT Fuel synthesis, as shown in FT Fuel synthesis for ICEV.

Comparing the GWP impacts of electric energy for BEV and conventional gasoline for ICEV, ICEV with conventional gasoline generates 1.1 times higher impact than BEV. ICEV results in higher CO_2 emissions during vehicle operation due to gasoline combustion emitting CO_2 compared to BEV, which does not emit any. Meanwhile, BEV produces higher CO_2 emissions during fuel production because the electricity system used for charging is the JavaBali system, as previously explained, still dominated by fossil fuel power plants.

3.3 FT Fuel Synthesis based on Electricity Energy Source

This scenario group compares the life cycle model of FT Fuel synthesis for ICEV based on its electricity source: the Java-Bali electricity system in 2021, the projected Java-Bali electricity Preprint Submitted to IJECBE system in 2030, and the entire electricity supply from solar PV (Fig. 4). The GWP impact of FT Fuel synthesis using electricity from the Java-Bali system in 2021 compared to 2030 shows no significant difference, decreasing by 4.4% to 311,995 kg CO_2-eq. This is due to the 2030 projected Java-Bali electricity system not having many additional renewable energy sources yet, resulting in FT Fuel synthesis still having a high GWP impact. Meanwhile, in the scenario where the entire Java-Bali electricity system is supplied by solar PV, the GWP impact decreases by 76.7% to 76,090 kg CO_2-eq. This demonstrates that CO_2 emissions from the electricity system have a significant influence on the GWP impact of FT Fuel synthesis from carbon capture.

3.4 FT Fuel Synthesis based on Synthesis Method

This scenario group compares the life cycle model of FT Fuel synthesis for ICEV based on the synthesis method, namely FT Fuel synthesis from carbon capture and FT Fuel synthesis from coal liquefaction (Fig. 4).

The GWP impact of FT Fuel synthesis from coal liquefaction, using the Java-Bali electricity system in 2021, is 44.5% lower than FT Fuel synthesis from carbon capture (181,046 kg CO_2- eq).

Meanwhile, if the energy requirement for FT Fuel synthesis from coal liquefaction is entirely supplied by solar PV, the difference is not significant, only 7.3% lower than the Java-Bali electricity system in 2021 (167,901 kg CO_2-eq). This is because the largest CO_2 emissions from the FT Fuel synthesis from coal liquefaction come from the FT process (77.8%), compared to CO_2 emissions from electricity (11.1%) (Fig. 5).

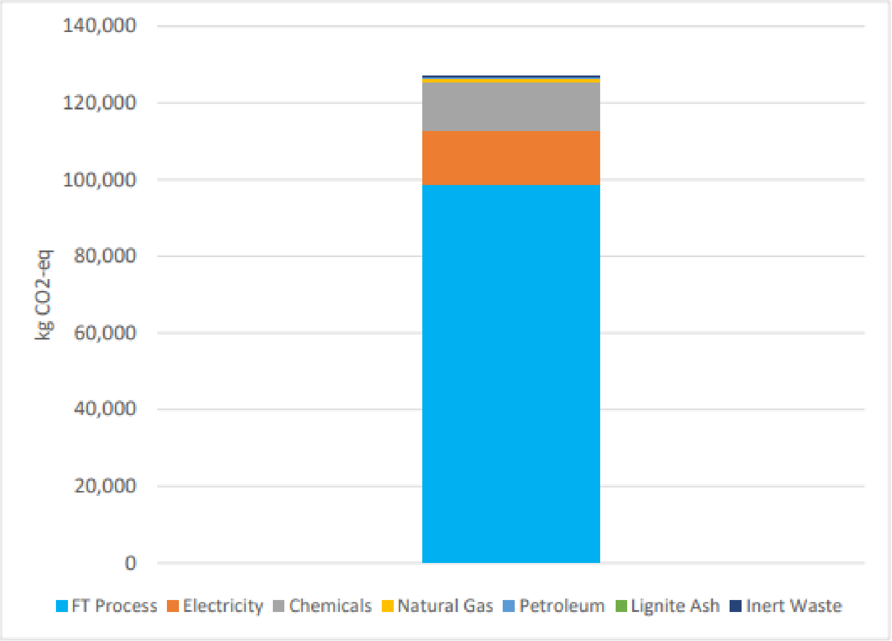


Figure 5. GWP - FT Fuel Synthesis Process with Coal Liquefaction

3.5 *Life Cycle of Vehicles Using Solar PV Electrical Energy Source*

This scenario group compares the life cycle models of ICEV and BEV passenger vehicles using solar PV electricity sources, namely FT Fuel synthesis from carbon capture, electric energy for BEV, and FT Fuel synthesis from coal liquefaction (Fig. 4).

The GWP impact from electric energy for BEV with the entire electricity supply from solar 0 20,000 40,000 60,000 80,000 100,000 120,000 140,000 kg CO_2-eq FT Process Electricity Chemicals Natural Gas Petroleum Lignite Ash Inert Waste Preprint Submitted to IJECBE PV is the lowest, amounting to 16,577 kg CO_2-eq, which is 60.8% lower than FT Fuel synthesis from carbon capture (76,090 kg CO_2-eq) and 87.6% lower than FT Fuel synthesis from coal liquefaction (167,901 kg CO_2-eq).

Here, the GWP impact from FT Fuel synthesis from carbon capture can be lower than that of FT Fuel synthesis from coal liquefaction. As explained earlier, this can occur because the largest CO_2 emissions from the coal liquefaction FT process, compared to the CO_2 emissions from the electric energy. Meanwhile, CO_2 emissions from FT Fuel synthesis from carbon capture are primarily influenced by electric energy. Hence, the renewable energy mix significantly impacts reducing the emissions of FT Fuel synthesis from carbon capture.

3.6 Delayed Emissions Scenario

In the context of mitigating GWP impacts, there exists a distinguishing factor for FT Fuel synthesis from carbon capture compared to other scenarios, namely, emission timing. In the scenario of FT Fuel synthesis from carbon capture, the resulting FT Fuel product is a secondary energy production process, where primary energy production occurs in the power plants generating electric energy. Under these conditions, it can be said that there is a difference in the final emission timing in FT Fuel synthesis from carbon capture would be at a later time compared to other scenarios. This delayed emission is one of the related issues to the question of timerepresentativeness of a process, and this can be considered quantitatively as it is the needs of the goal of this study [52]. In another report, an avoided burden of emission reduction compared to the reference case is assumed as "avoided burden" or "emissions benefit", although there is no consensus on how this emissions benefit may be transferred to a product when that CO_2 finally utilised [53]. This section assumes that the CO_2 captured would count into the reduction of the life cycle emissions, while the consequent time of emission from it is not yet determined.

When delayed emissions are considered, then the GWP impact of all scenarios becomes as shown in Fig. 6.

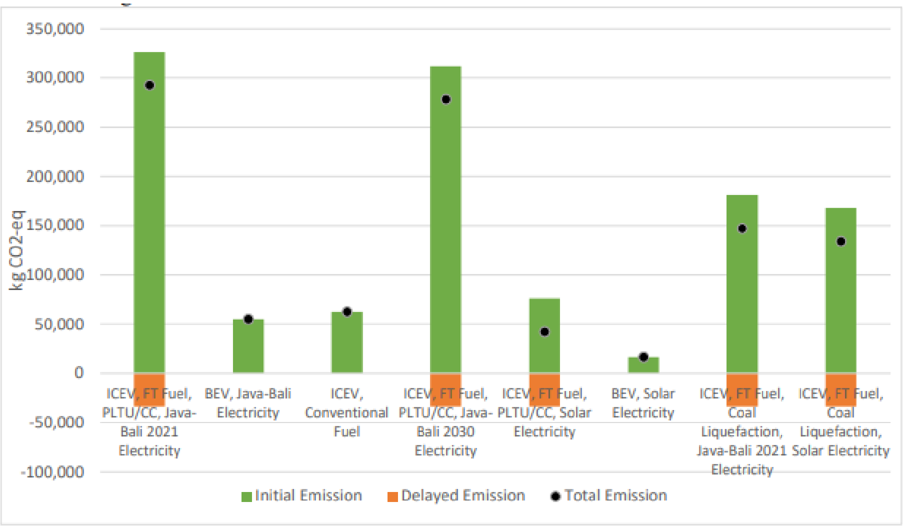


Figure 6. GWP - Scenario with Delayed CO_2 Emission

In scenarios with delayed emissions, the entire life cycle of FT Fuel synthesis receives attribution from emission delays. Specifically, for FT Fuel synthesis with all its electric energy supplied from solar PV, the total GWP impact (42,328 kg CO_2-eq) becomes lower than the system of electric energy products for BEV (54,987 kg CO_2-eq) and conventional gasoline for ICEV (62,326 kg CO_2-eq). This means that if the delayed CO_2 emissions from carbon capture prove to have a noticeable influence, the life cycle of FT Fuel synthesis from carbon capture could have scenarios that offer a better GWP impact than the existing conventional systems.

4. Conclusion

FT Fuel Synthesis is considered an alternative solution for mitigating the impact of climate change. Life cycle modeling of Synthesis FT Fuel is conducted to understand its GWP impact compared to the current conventional systems, i.e., electric energy for BEVs and conventional gasoline for ICEVs. Conclusions drawn from this research are as follows:

1. FT Fuel Synthesis from carbon capture using the Java-Bali power system results in a high GWP impact compared to conventional motor vehicle fuels. This is primarily due to the high demand for electric energy and the energy mix of the Java-Bali power system, which is still dominated by fossil fuel-based generators.
2. Nevertheless, any scenario involving a substantial increase in renewable energy mix would significantly reduce the GWP impact on the life cycle of passenger vehicle fuels, particularly those reliant on electric energy supply. Synthesis FT Fuel from carbon capture can compete with the GWP impact of current conventional systems (electric energy for BEVs, conventional gasoline for ICEVs) if all its electric energy is supplied by solar PV. Moreover, its GWP impact could be even lower than conventional gasoline if deferred emissions are considered in the impact calculations.
3. FT Fuel Synthesis from coal liquefaction results in moderate GWP impact. To lower its CO_2 emissions in its life cycle, further development of coal liquefaction Synthesis FT Fuel could be explored, such as integrating carbon capture. However, this scenario is beyond the scope of this study.

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Appendix 1. Life Cycle Inventory for FT Fuel Synthesis for ICEV

Appendix 1.1 Coal Resource

Life Cycle Inventory Data for the synthesis of FT Fuel process for ICEV refers to the ecoinvent database [40], specifically the "market for hard coal | hard coal | Cutoff, U". The distinction lies in the transportation input flow, where coal is transported by train from Muara Enim to Lampung and then continued by coal ship to CFPP Suralaya.

With a capacity of 60 wagons, 50 tons per wagon, and a distance of 420 km, the train is capable of transporting coal at a rate of 3.57 tons/km. Thus, the transport unit is 0.28 km/ton.

Meanwhile, for the coal ship, with a carrying capacity of 80,000 DWT, a distance of 100 km, and two round trips for one transport, the transport unit is 0.0025 km/ton.

Table 3 is the model for coal acquisition.

Table 3. GWP of FT Fuel Synthesis and RWGS Subprocesses and Unit Processes

Input flow	Amount	Unit
electricity, medium voltage	0.0072	kWh
lignite	1	kg
transport, freight train	2.80E-01	t*km
transport, freight, sea, bulk carrier fordry goods	0.0025	t*km
Occupation, industrial area	0.001	m2*a
Transformation, from unspecified	0.00001	m2
Transformation, to industrial area	0.00001	m2
Output flow	**Amount**	**Unit**
lignite	1	kg
Arsenicion	4E-11	kg
BOD5,BiologicalOxygen Demand	1E-07	kg
Cadmium II	1.00E-11	kg
Chloride	2.00E-06	kg
Chromium III	2.00E-10	kg
COD, Chemical Oxygen Demand	1.00E-07	kg
Copper ion	1.00E-09	kg
Dissolved solids	1.00E-04	kg
DOC, Dissolved Organic Carbon	3.70E-08	kg
Iron ion	2.00E-09	kg
Lead II	2.00E-10	kg
Manganese II	2.00E-07	kg
Nickel II	4E-10	kg
Particulate Matter, > 10 um	2.00E-03	kg
Selenium IV	2.00E-10	kg
Solids, inorganic	1.00E-05	kg

Sulfate	4.00E-05	kg
Tin ion	2.00E-10	kg
TOC, Total Organic Carbon	3.70E-08	kg
....		

Appendix 1.2 Coal Fired Power Plant

Life Cycle Inventory (LCI) data for the CFPP process refers to the ecoinvent database specifically identified as "electricity production, lignite | electricity, high voltage | Cutoff, U" [40]. The differences lie in the coal source, power plant construction, internal electricity usage Preprint Submitted to IJECBE for carbon capture, and CO_2 production as a result of carbon capture retrofitting.

Based on the characteristics of the Suralaya Power Plant Unit 7, the Net Calorific Value (NCV) of the coal used is 18.9 MJ/kg, which equals 5.3 kWh/kg. This implies that the electrical energy generated from 1 kg of coal is 1.7325 kWh/kg, meaning the coal used is 0.577 kg/kWh.

Regarding the construction of the power plant, the ecoinvent database assumes a service life of 150,000 hours. The energy generated during the power plant's service life is 90 million MWh, resulting in the power plant's energy usage per produced kWh being 1.111 x 10-11 units. With a power plant blend of 30% at 100 MW and 70% at 500 MW, the average capacity is 380 MW. Extrapolating for a 600 MW capacity, it is derived that the required construction is 1.57 times the ecoinvent database construction.

The internal electricity usage for carbon capture is 10% of the plant's capacity.

The emission factor from the power plant is 1.048 g/kWh, and the CO_2 capture rate is 90%. Table Table 4 represents the model of the power plant.

Table 4. Coal Fired Power Plant Model

Inputflow	**Amount**	**Unit**
electricity,high voltage	0.2	kWh
lignite	0.577200577	kg
lignitepowerplant	1.11E-11	Item(s)
petroleumcoke	0.001768198	kg
SOxretained,inlignitefluegas desulfurisation	0.00484	kg
water,completely softened	0.076325088	kg
water,decarbonised	2.544169611	kg
Water,cooling,unspecifiednatural origin	0.057116829	m3
Output flow	**Amount**	**Unit**
carbondioxide,gasproduct	CCRate*1.047619048	kg
electricity,high voltage	1	kWh
ligniteash	0.186996466	kg

residuefrom coolingtower	6.36E-05	kg
Antimonyion	6.64E-09	kg
Arsenicion	3.77E-08	kg
Barium II	1.97E-07	kg
Benzene	2.76E-06	kg
Benzo(a)pyrene	2.54E-12	kg
Boron	2.38E-05	kg
Bromine	8.41E-07	kg
Butane	2.42E-07	kg
Cadmium II	8.55E-09	kg
Carbon dioxide, fossil	(1-CCRate)*1.047619048	kg
Carbon monoxide, fossil	2.54E-04	kg
Chromium III	3.38E-08	kg
Chromium VI	4.08E-09	kg
Cobalt II	6.84E-09	kg
Copper ion	9.41E-08	kg
Dinitrogen monoxide	1.84E-05	kg
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	8.90E-14	kg
Ethane	5.22E-07	kg
Formaldehyde	7.38E-07	kg
Hydrocarbons, aliphatic, alkanes, unspecified	2.79E-06	kg
Hydrocarbons, aliphatic, unsaturated	2.75E-06	kg
Hydrochloric acid	7.19E-05	kg
Hydrogen fluoride	1.72E-05	kg
Iodine	6.11E-07	kg
Lead II	3.31E-08	kg
Lead-210	1.06E-04	kBq
Manganese II	1.08E-07	kg
Mercury II	6.88E-08	
Methane, fossil	1.27E-05	kg
Molybdenum VI	2.05E-08	kg
Nickel II	1.30E-07	kg

Nitrogen oxides	0.00412	kg
PAH, polycyclic aromatic hydrocarbons	1.27E-08	kg
Particulate Matter, < 2.5 um	0.0388	kg
Particulate Matter, > 10 um	0.00229	kg
Particulate Matter, > 2.5 um and <10um	0.00457	kg
Pentane	1.87E-06	kg
Polonium-210	1.95E-04	kBq
Potassium-40	3.69E-05	kBq
Propane	4.45E-07	kg
Propene	2.04E-07	kg
Radium-226	2.75E-05	kBq
Radium-228	1.64E-05	kBq
Radon-220	0.001615548	kBq
Radon-222	0.002862191	kBq
Selenium IV	1.56E-07	kg
Strontium	1.74E-07	kg
Sulfur dioxide	0.00357	kg
Thorium-228	8.87E-06	kBq
Thorium-232	1.40E-05	kBq
Toluene	1.39E-06	kg
Uranium-238	2.29E-05	kBq
Vanadium V	4.29E-08	kg
Water	0.00179926	m3
Water	0.057938063	m3
Xylene	1.17E-05	kg
Zinc II	2.21E-07	kg
....		

Appendix 1.3 Java-Bali 2021 Power System

Life Cycle Inventory (LCI) data for the Java-Bali 2021 power system process refers to the ecoinvent database specifically identified as "market for electricity, high voltage | electricity, high voltage | Cutoff, U" [40]. The differences lie in its energy mix.

Tables Table 5 to Table 8 represent the models for the Java-Bali 2021 power system.

Table 5. Java-Bali 2021 Power Generation and High Voltage Transmission Model

Input flow	**Amount**	**Unit**
electricity, high voltage	0.766	kWh
electricity, high voltage	0.031	kWh
electricity, high voltage	0.16	kWh
electricity, high voltage	0.002	kWh
electricity, high voltage	0.041	kWh
transmission network, electricity, high voltage direct current aerial line	8.15347E-09	km
Output flow	**Amount**	**Unit**
electricity, high voltage	1	kWh
Dinitrogen monoxide	0.000005	kg
Ozone	4.15773E-06	kg

Table 6. High-to-Medium Voltage Transformation Model

Input flow	**Amount**	**Unit**
electricity, high voltage	1.006618826	kWh
Output flow	**Amount**	**Unit**
electricity, medium voltage	1	kWh

Table 7. .Medium Voltage Transmission Model

Input flow	**Amount**	**Unit**
electricity, medium voltage	1	kWh
electricity, medium voltage	0.004579626	kWh
sulfur hexa fluoride, liquid	0.000000054	kg
transmission network, electricity, medium voltage	1.86278E-08	km
Output flow	**Amount**	**Unit**
electricity, medium voltage	1	kWh
Sulfur hexa fluoride	0.000000054	kg

Table 8. Medium-to-Low Voltage Transformation Model

Input flow	Amount	Unit
electricity, medium voltage	1.030218062	kWh
Output flow	**Amount**	**Unit**
electricity, low voltage	1	kWh

Appendix 1.4 Carbon Capture

LCI data for the carbon capture process entirely refers to [31].

Appendix 1.5 Electrolysis

(LCI) of the electrolysis process refers to [31]. The difference lies in its electricity supply, as indicated in Table 9 and Table10.

Table 9. Electricity ConsumptionfromCoalFiredPowerPlantfor Electrolysis

Input flow	Amount	Unit
electricity, high voltage	1.25	kWh
Output flow	Amount	Unit
electricity,low voltage	1	kWh

Table 10. InternalElectricityAllocationandJava-BaliMarket

Input flow	Amount	Unit
electricity, low voltage	0.84430114	kWh
electricity, low voltage	0.15569886	kWh
Output flow	**Amount**	**Unit**

Appendix 1.6 RWGS

LCI data for the RWGS process entirely refers to [31].

Appendix 1.7 FT Fuel Synthesis

LCI data for the FT Fuel synthesis process entirely refers to [31].

Appendix 1.8 FT Fuel Distribution

The Life Cycle Inventory (LCI) of FT Fuel distribution refers to the database in ecoinvent, specifically to "transport, freight, lorry 7.5-16 metric ton, EURO4 | transport, freight, lorry 7.5- 16 metric ton, EURO4 | Cutoff, U" [40]. Table 11 is the FT Fuel distribution model

Table 11. FT Fuel Distribution Model

Input flow	**Amount**	**Unit**
FTFuel	1	kg
transport, freight, lorry 7.5 - 16 metricton, EURO4	120	kg*km
Output flow	**Amount**	**Unit**

Appendix 1.9 FT Fuel Utilization

The Life Cycle Inventory (LCI) of FT Fuel usage refers to the database in ecoinvent, specifically to "transport, passenger car, medium size, petrol, EURO 4 | transport, passenger car, medium size, petrol, EURO 4 | Cutoff, U" [40]. The difference lies in the type of fuel used.

The usage of FT Fuel is assumed to last throughout the vehicle's lifespan, estimated at 160,000 kilometers.

Table 12 is the FT Fuel utilization model, while Table 13 is a model to indicate the use of FT Fuel throughout the lifespan of a vehicle.

Table 12. FT Fuel Utilization Model

Input flow	**Amount**	**Unit**
FT Fuel	0.065356794	kg
passenger car maintenance	8.60E-06	Item(s)
passengercar, petrol/ naturalgas	0.010666667	kg
road	9.11E-04	m*a
road maintenance	2.65E-04	m*a
Output flow	**Amount**	**Unit**
transport, passenger car, medium size, petrol, EURO4	1	km
brake wear emissions, passenger car	7.55E-06	kg
road wear emissions, passenger car	1.66E-05	kg
tyre wear emissions, passenger car	9.72E-05	kg
1-Pentene	2.66E-08	kg
2-Methylpentane	7.42E-06	kg
Acetaldehyde	1.81E-07	kg
Acetone	1.48E-07	kg
Acrolein	4.60E-08	kg
Ammonia	1.96E-06	kg
Benzaldehyde	5.32E-08	kg
Benzene	3.85E-06	kg
Butane	7.47E-06	kg
CadmiumII	6.54E-10	kg
Carbondioxide, fossil	0.207834604	kg

Carbonmonoxide, fossil	3.88E-04	kg
ChromiumIII	3.27E-09	kg
Benzene	3.85E-06	kg
Butane	7.47E-06	kg
CadmiumII	6.54E-10	kg
Carbondioxide, fossil	0.207834604	kg
Carbonmonoxide, fossil	3.88E-04	kg
ChromiumIII	3.27E-09	kg
ChromiumVI	6.54E-12	kg
Copperion	1.11E-07	kg
Cyclohexane (forallcycloalkanes)	2.76E-07	kg
Dinitrogen monoxide	8.50E-06	kg
Ethane	1.09E-06	kg
Ethylene	2.65E-08	kg
Ethyleneoxide	1.77E-06	kg
Formaldehyde	4.11E-07	kg
Heptane	1.79E-07	kg
Hexane	3.89E-07	kg
LeadII	9.80E-11	kg
m-Xylene	3.21E-06	kg
MercuryII	4.57E-12	kg
Methane, fossil	1.80E-05	kg
Methylethylketone	1.21E-08	kg
NickelII	4.57E-09	kg
Nitrogenoxides	4.13E-05	kg
NMVOC, non-methane volatile organic compounds	6.74E-05	kg
o-Xylene	7.57E-07	kg
PAH, polycyclicaromatic hydrocarbons	2.27E-09	kg
Particulate Matter, <2.5 um	1.03E-06	kg
Pentane	8.69E-06	kg
Propane	5.61E-06	kg
Propene	1.48E-07	kg

Propylene oxide	9.24E-07	kg
Selenium IV	6.54E-10	kg
Styrene	2.44E-07	kg
Sulfur dioxide	1.31E-06	kg
Toluene	7.44E-06	kg
Zinc II	6.54E-08	kg
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Table 13. Vehicle Lifetime Model

Input flow	**Amount**	**Unit**
transport, passenger car, medium size, petrol, EURO 4	160000	km
Output flow	**Amount**	**Unit**
Vehicle Life time	1	Item(s)

Appendix 2. Life Cycle Inventory for Electric Energy for BEV

LCI of the life cycle of electric energy for BEVs comprises the Java-Bali power system, the use of electric energy for BEVs, and the vehicle lifetime. The Java-Bali power system and vehicle lifetime are already covered in Life Cycle Inventory for FT Fuel Synthesis for ICEV. The model for the use of electric energy for BEVs refers to the ecoinvent database, specifically the "transport, passenger car, electric" [40], as depicted in Table 14.

Table 14. Electric Energy for BEV Model

Input flow	**Amount**	**Unit**
battery, Li-ion, Li Mn 2O4, rechargeable, prismatic	0.00262	kg
electricity, low voltage	0.199	kWh
maintenance, passengercar, electric, withoutbattery	6.67E-06	Item(s)
passenger car, electric, without battery	0.006121467	kg
road	4.87E-04	m*a
Output flow	**Amount**	**Unit**
transport, passenger car, electric	1	km
brake wear emissions, passenger car	1.05E-06	kg
road wear emissions, passenger car	1.16E-05	kg
tyre wear emissions, passenger car	6.76E-05	kg
used Li-ion battery	0.00262	kg

Appendix 3. Life Cycle Inventory for Java-Bali Power System for year 2030

LCI of the Java-Bali power system in 2030 for the FT Fuel synthesis with the Java-Bali power system in 2030, as shown in Table 15.

Table 15. Electric Energy for BEV Model

Input flow	**Amount**	**Unit**
electricity, high voltage	0.121	kWh
electricity, high voltage	0.006	kWh
electricity, high voltage	0.735	kWh
electricity, high voltage	0.045	kWh
electricity, high voltage	0.083	kWh
electricity, high voltage	0.005	kWh
electricity, high voltage	0.005	kWh
transmission network, electricity, high voltage direct current aerial line	8.15E-09	km
Output flow	**Amount**	**Unit**
electricity, high voltage	1	kWh
Dinitrogen monoxide	5.00E-06	kg
Ozone	4.16E-06	kg