The environmental impact of cycling 1,600 MWh electricity

A Life Cycle Assessment of a lithium-ion battery from Greener Power Solutions

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Abstract

Energy storage is an important step for reducing peak energy demand and can contribute to reducing the fossil fuel energy demand by storing renewable energy. Off grid applications can have a fluctuating energy demand that is most of the time delivered by a Diesel generator set. However, it is also possible to deliver this energy demand by an Energy Storage System. Although storage systems often have no direct GHG emissions, indirect emissions can lead to problem shifting by for example a reduction of direct CO_2 emissions but an increase in land use, fine dust formation, or abiotic depletion. This can also be the case with a relative new technology, developed by Greener Power Solutions, a 330 kWh mobile battery system. A Life Cycle Assessment method is applied for this technology and compared with a Diesel generator set, a technology that has direct emissions and can be used in the same applications as the battery. The aim for this study was to provide a transparent inventory for both the battery and the generator set, to create a detailed overview of the environmental impact from cradle-to-grave. In order to create a fair comparison, multiple factors are taken into account e.g. lifetime of both technologies, efficiency due to internal losses of the battery, and efficiency of the genset due to a non-optimal operating point. In the most realistic scenario, the Global Warming Potential of the Greener battery is 53.3% of the total CO_2 emissions from the Diesel generator set. The Fine Particulate Matter Formation is 27.5% PM2.5 eq compared to the total FPMF emissions from the Diesel generator. The robustness of the study was tested by creating scenarios for the production and the use phase with different charge methods and electricity sources. The use phase has the largest environmental impact for both technologies. Therefore it is advised to Greener Power Solutions to charge the battery by renewable energy wherever possible and to avoid charging it by a Diesel generator set, although this can run at a more efficient operating point when using a battery system. This study is executed in the hope of mitigating climate change by analysing the potential of a widely used energy storage system to reduce GHG emissions.

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List of abbreviations

APOS = Allocation at the Point of Substitution

CO_2 = carbon dioxide

DC-AC = Direct Current - Alternating Current

EC = European Commission

EES = Electrical Energy Storage

EoL = End-of-Life

EV = electrical vehicle

EQ = equivalent

FPMF = Fine Particulate Matter Formation

ft = feet

GHG = Green House Gas

GJ = Giga Joule

Greener = Greener Power Solutions

GWh = Giga Watt hour

GWP = Global Warming Potential

kg = kilogram

kVA = kilo Volt Ampère

kW = kilo Watt

kWh = kilo Watt hour

L = liter

LCA = Life Cycle Assessment

MJ = Mega Joule

MWh = Mega Watt hour

NMC = Nickel Manganese Cobalt

SoC = State-of-Charge

SoH = State-of-Health

1. Introduction

1.1. Societal background

Off-grid electricity supply systems can be used at sites where the energy demand cannot be delivered by a local grid connection or when the local grid connection is not the correct size for the energy demand. A common solution to overcome this problem is by using a Diesel generator set which are mobile and thereby suitable for locations where electricity demand is temporarily on e.g. a construction site. Although the electricity demand can often be met with a Diesel generator set, it can also have negative effects e.g. odor and noise nuisance, direct Green House Gas emissions, and the need for fossil fuel supply for refuelling. Electrical Energy Storage (EES) is a common technology that allows energy producing processes e.g. wind-power, photovoltaic-power, tidal-power to store energy after which it is converted back to electricity (Chen et al., 2009). The mismatch between electricity supply and demand may result in wasted or a shortage of electric power if it is not stored. Large fluctuations in electricity production due to solar and wind generation characteristics result in grid instability. These are two examples where EES can be applied to increase the share of sustainable electricity resources in the energy mix and to improve grid stability (Medina et al., 2014).

According to Munuera & Fukui (2019) of the International Energy Agency, energy storage capacity reached over 8 GWh in 2018. This was nearly a doubling of capacity compared to 2017. Excluding pumped hydro, lithium-ion battery storage is the most widely used storage technology with 85% from the total installed capacity (2016). The remaining 15% is a combination of different types of batteries, compressed air, flywheels, and capacitors. This is interesting for this research, since it will focus on lithium-ion batteries that are produced commissioned by the company Greener Power Solutions.

In the hope of mitigating climate change, this research contributes to the discussion if storage of electricity has a smaller, equal, or even larger environmental impact compared to the now still widely common fossil fuel combustion. Increasing the share of renewable energy sources is decreasing dependency on fossil fuel based electricity (Medina et al., 2014). However, what is the effect on the environmental impact if renewable energy is stored using a storage system whenever these systems need to be produced, used, and recycled?

1.2. Scientific background

The type of EES is dependent on the application it is used for. For example, EES can be used in smart grids to match electricity users and suppliers to efficiently deliver sustainable, economic and secure electricity supply. Hydro power is one of the oldest EES where kinetic energy of water is used to generate electricity in periods of electricity shortage. In periods with an electricity surplus, water is pumped to a higher elevated lake where it is stored. This decreases wasted electric power (Wade et al., 2010). There are five types of EES: mechanical, electric, electro-chemical, thermal, and chemical. This research will focus on the electro-chemical storage technique in the form of batteries.

The main component of the Electrical Energy Storage system that is analysed in this research is a battery pack that consists of eight lithium-ion batteries from the electrical vehicle (EV) industry. Various studies showed difference in CO_2 emissions of battery electric vehicles and internal combustion vehicles over the complete lifetime, where battery electric vehicles have lower GHG emissions compared to internal combustion vehicles (Bauer et al., 2015; Küfeoğlu & Khah Kok Hong, 2020; Ma et al., 2012). However, Qiao et al., (2017) states the importance of a complete life cycle assessment, since solely the production phase will increase emissions of electric vehicles by 50% to 15 tCO_2 eq compared to 10 tCO_2 eq for an internal combustion engine vehicle due to the production of the battery and the additional weight necessary for an electric vehicle. This is a topic of interest for this research since the battery from Greener is equipped with 8 electric vehicle batteries produced by BMW with the use of lithium-ion cells from Samsung.

Greener Power Solutions (Greener) is a company based in Amsterdam that delivers batteries of 330 kWh storage capacity with a maximum power output of 285 kW. There are more companies that deliver mobile battery systems. These battery systems range from a capacity of 2 kWh to 1 MWh. Greener not only rents out batteries to locations where the necessary electricity demand cannot be met, it also provides software for other battery companies that allows live monitoring of the complete system and a forecast of the expected power demand. Greener batteries can be used in different sectors e.g. the building sector and for grid stabilization purposes. The most used application for the batteries is in the event business. A fundamental question that is often asked by costumers of Greener is: "Are the batteries actually better compared to a Diesel generator regarding CO_2 emissions when taking the production, charging, and recycling into account?". This research aims to provide a substantiated answer to this question with a report that makes a fair comparison between a Greener battery and a Diesel generator set.

1.3. Research goal & research question

This study will research the environmental impacts of a battery with 285 kW rated power and 330 kWh energy capacity, used at locations for temporary power supply; after which it is compared with the environmental impact of a 200 kVA Diesel generator. This represents a standard type of Diesel generator at locations where the Greener battery is applicable. Also, due to the low average load during the use phase, the efficiency of the diesel generator will decrease if a type with a larger capacity is used for the comparison. This is further elaborated in the methodology, section 3.2.1.

The results will be used by Greener Power Solutions to give an insight in the environmental impact of the battery compared to a Diesel generator. This will provide a substantiated answer that is used to communicate to stakeholders, investors, and costumers. This will increase awareness about electricity use and what the impacts are of generating and storing (renewable) electricity.

The main and sub research questions that will be answered in this research are:

What is the environmental impact of a 330 kWh, 285 kW Greener Power Solutions battery compared to a Diesel generator set from Aggreko concerning production, use, and end-of-life phase?

1. *What is the environmental impact during the production phase?*
2. *What is the environmental impact during the use phase?*
3. *What is the environmental impact during the End-of-Life phase?*

Answering these research questions will contribute to environmental impact insights of this relatively new market of mobile battery systems. The impact categories are elaborated in the methodology, chapter 3. The goal for this research is to calculate a break-even point, the time it takes before the battery has an equal and after that smaller environmental impact compared to a Diesel generator that delivers the same quantity of electrical energy. The break-even point will be calculated after the three sub-research questions.

1.4. Functional unit

This research will focus on the total delivered electricity over the lifetime of the Greener battery as guaranteed by the manufacturer under standard testing conditions. One Greener battery of 330 kWh capacity contains eight BMW I3 batteries. These batteries have a capacity decrease of 30% after 200,000 kWh energy throughput according to the official terms and conditions of new BMW high-voltage batteries (Alfen, 2018). It is expected that the capacity will decrease to 70% after 10 years of operation time, corresponding with ± 4,850 charge cycles. This results in 4850 x 330 kWh = 1,600,000 kWh throughput for the Greener battery. The maximum allowed capacity degradation for Greener of the current application for one battery is 30%, so the functional unit of 1,600 MW is equal to the standard performance of the lifetime of one Greener battery.

1.5. Relevance of this study

This study will investigate the lifetime environmental impact of a 285 kW / 330 kWh battery that is compared with direct emissions from a Diesel generator. It will contribute to the ongoing field of research of the electrification of society. The increase of electrification is accelerated under climate policy to reduce dependence of fossil fuels (Sugiyama, 2012). Electric Energy Storage systems can contribute to the share of renewable resources in the electricity mix and this research will show the environmental impact of the use of one of the storage systems: the Greener Power Solutions battery.

This research is relevant for Greener Power Solutions and similar companies to answer a fundamental question if the use of their battery is reducing CO_2 emissions when all life cycle phases are considered compared to the technology that is replaced by the battery. Since this study will research not only the environmental impact of the batteries, but also of the other components e.g. the refrigerating container, electronic equipment, and the transformer, the study can be applicable for companies that have a similar technology. However, the Greener battery is uniquely designed for the company and the manufacturer Alfen does not supply the same system to other companies. This research can be generalized for other battery storage systems, however, it will only give insight in the estimated environmental impact and the results of this research will not be directly applicable for other battery storage systems due to the difference in size and components.

1.6. Literature gap

Although the literature is extensive when it comes to analysing the environmental impact of electric vehicles, an impact assessment of a battery pack with as main component multiple electric vehicle batteries is not performed. Greener batteries consist, next to eight electric vehicle batteries, of electrical components that make the battery unique compared to battery electric vehicles and other battery systems. There are other companies that have mobile battery storage systems. The BMW batteries inside the Greener battery use a lithium-ion Nickel Manganese Cobalt (NMC) technology, where other companies use a different type of lithium-ion technology. Also, the capacity for mobile battery systems varies from a few kWh, up to 1 MWh.

Greener batteries are manufactured by the company Alfen commissioned by Greener Power Solutions. Battery lifetime and recycling rate are expected to be the two components that reduce the environmental impact the most. The results from this study can be compared with emissions from alternatives of EES, e.g. Diesel generators, but it can also be used to compare the emissions of the battery to the emissions of the energy mix in The Netherlands. In 2017 the average emission of electricity production, delivered by the Dutch power system was 450 grams of CO_2 / kWh. Decline is expected due to the increasing share of renewable energy resources. For example, wind energy has an average emission of 12 grams of CO_2 / kWh. An increase in share of wind energy will decrease the average emissions of the total energy mix (Bosch et al., 2019).

1.7. Company background

Greener started using one battery in the summer of 2018. The company is fast growing and expanded their current capacity to 13 batteries. In spring 2021, 30 new batteries will be delivered. Because of the short lifetime of the company, the exact lifetime of the batteries is unknown and the degradation of the battery can only be calculated by the data that is available from the past 1.5 year. Because of this, the exact lifetime is unknown and therefore estimated to be equal to the lifetime of the EV batteries that are installed in the Greener battery.

Next to the current applications of the batteries, mostly construction sites and festivals, Greener is also making the an inventory for second-life applications after the battery capacity is degraded with 30%. Greener is cooperating with Kite Power, a start-up that is researching the possibilities for renewable electricity generation using kites to extract wind energy. A combination of kite electricity and a battery storage system can deliver a constant electricity output for remote areas that do not have the resources for a grid connection. Kite energy consists of two phases, a generation phase and a recovery phase. During the generation phase, the kite makes a figure-eight motion that unwinds the rope, driving the generator rotor, generating electricity. During the recovery phase, the generator works as a motor and consumes electricity to rewind the rope so the kite can generate electricity again in the generation phase (Cherubini et al., 2015). Because this system uses electricity during the recovery phase, a stable electricity output is only possible in combination with an EES system. The combination of kite power with a battery to generate a constant power output is an example how the second-life of a Greener battery can look like. A second-life will reduce the need for alternative electricity producing technologies that use fossil fuels e.g. a Diesel generator set.

1.8. Justification of chosen LCA method

A Comparative Life Cycle Assessment is executed for this research to give an extensive insight in the difference in environmental impact between a Greener battery and a Diesel generator. The type of Diesel generator used for this research is a 200 kVA generator since this is according to the experienced operative staff the most common equipment used at the sites where a Greener battery is placed. Also, this type of generator can still provide the peak energy demand for the applications where it is used, e.g. a festival or construction site, while it is not the largest type of mobile generator set available. This is beneficial since the mass increases with an increase of power, which means less raw material is used for a 200 kVA genset compared to a larger genset. An even smaller generator set would use less raw materials. However, it would be an unfair comparison with the Greener battery since the smaller genset cannot deliver the peak electricity demand necessary.

2. Theory

2.1. Battery setup

The batteries can be installed in three different setups: off-grid, peak shaving, and coupled (figure 1) (Greener, 2019).

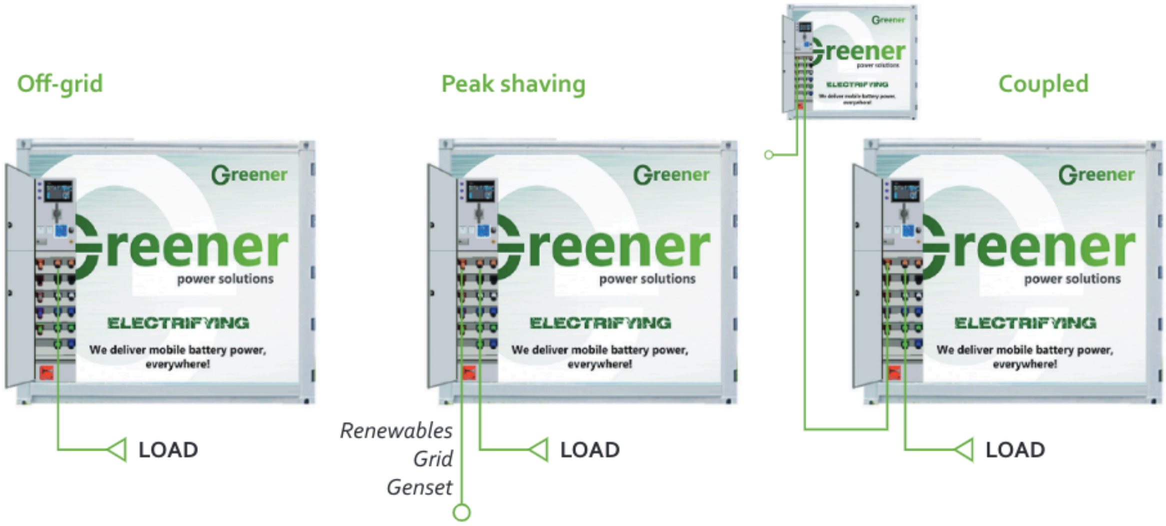


Figure 1 - Battery setup options

The first setup, off-grid, the battery is not recharged and the power output is limited by the State-of-Charge of the battery. With the second setup, peak shaving, the battery can be recharged by different electricity resources: renewables, the grid, or a Diesel generator. This reduces GHG emissions since e.g. a Diesel generator is most of the time not used on the most efficient load at festivals and construction sites because of the fluctuating electricity demand. With a battery, the exact electricity demand is delivered as power output. A Diesel generator can recharge the battery at the generator's optimal efficiency, and is then switched off. This prevents running a Diesel generator that uses fossil fuels in times when there is low or even no electricity demand. This is currently the most common application for Greener.

The coupled setup, where batteries are connected in series to double the capacity, is the least frequently used setup. However, it is expected by one of the founders of Greener that this setup will be used more often to completely eliminate the need for Diesel generators as used in the peak shaving setup. This research will focus on the second setup as seen in figure 1, and will include multiple scenarios regarding charging methods of the Greener battery.

The capacity decrease is based on a discharge rate and temperature of the battery. The terms of conditions of the BMW I3 battery is based on standard test conditions: a discharge rate of 1/3 C and 25 degrees Celsius. The discharge current, or C rate, is a measure to the rate at which a battery is discharged relative to its maximum capacity (Piernas Muñoz & Castillo Martínez, 2018). According to Cui et al. (2015), the discharge rate is one of the four stress factors that affect the length of the cycle life of a battery. For the Greener battery, the maximum C rate is 0.86 due to the maximum power discharge of 285 kW. However, it is not clear what the average discharge has been. This is elaborated in the discussion (section 5.2) of this research where the importance of the State-of-Health (SoH) is explained. Also, the batteries are protected for deep discharging that affects the SoH. The minimum SoC setpoint is 20%, after which it needs to be charged before the Greener battery can deliver energy output.

The functional unit of 1,600 MWh is based on the assumption that the battery is discharged according to testing condition, this means a temperature of 25 degrees Celsius and a discharge rate of 1/3C. The discharge rate is also visible in figure 2 which represents a typical power output delivered by the Greener Battery at a festival. The maximum peak power output is approximately 150 kW (green line). This is also why a diesel generator type of 200 kVA is chosen for the comparison with a Greener battery, since this is approximately the maximum power output for this generator (160 kWh).

2.2. Example of the battery use

At the moment most of the batteries are used at festivals for temporarily power supply in combination with Diesel generators. Figure 2 represents the power output curve from a battery of the Boomtown festival in summer 2019. The red line represents power output of a Diesel generator, this is the power input for the battery. In this setup, a Diesel generator was charging the battery with a maximum capacity of at least 230 kW. This graph is interesting since it show three settings of the battery in combination with a Diesel generator: cycling (first blue oval), peak shaving without input setting from the generator (second blue oval), and peak shaving with input setting from the generator (third blue oval). During cycling, the generator switches on to charge the battery once the State-of-Charge (SoC) is at the minimum setpoint of 20%; and switches off at the maximum setpoint of 85%. During peak shaving without input setting from the generator, the power output is connected to the Diesel generator and peak loads are flattened out using the battery. Peak electricity demand are short periods where power deviates frequently and significantly from the average (Barker et al., 2012).The last battery mode uses an average power output setting of the Diesel generator. If the power output is lower compared to average, the battery is charging, otherwise, the battery is used for power supply. These settings are optimized by the developer software team of Greener. By optimizing the software, it is possible to monitor the battery system with more precision, give insight in the total power demand, and anticipate on the expected power demand. These processes are called 'forecasting' and 'nowcasting' and are also applicable for other mobile battery systems.

Daily Energy Consumed (kWh)

	7/24	7/25	7/26	7/27	7/28	7/29	7/30	7/31	8/1	8/2	8/3	8/4	8/5
Output (kWh)	775	740	775	747	703	757	897	110	935	1032	1063	1195	1229
Peak (kW)	125	132	121	130	114	115	135	43	121	144	148	141	147
Peak (time)	10:31	10:32	16:57	05:50	13:07	04:59	17:47	20:03	06:34	17:14	17:24	11:03	18:15

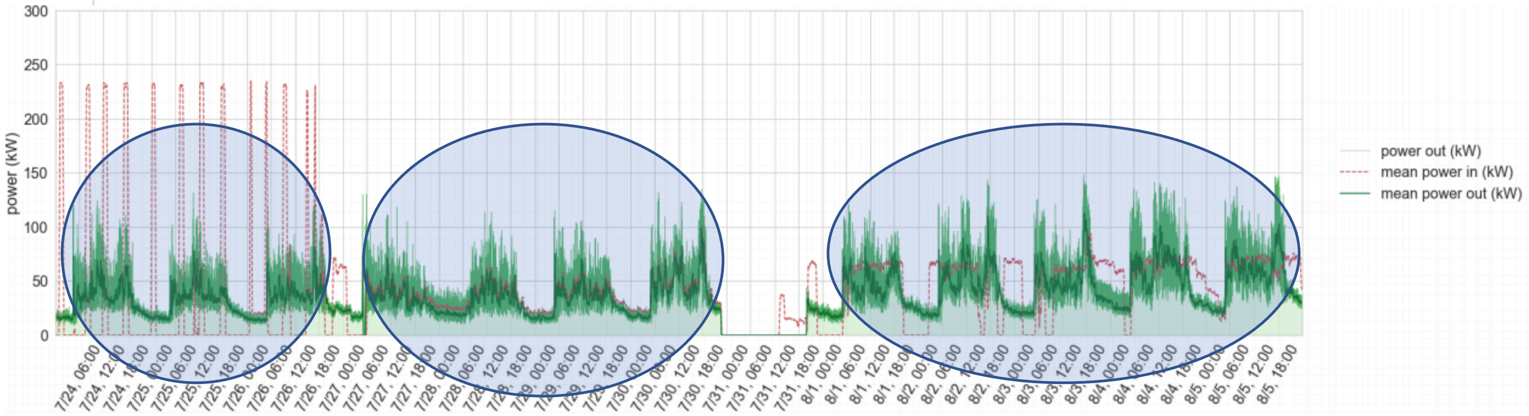


Figure 2 – Power output distribution

3. Methodology

For this research, the LCA software programme SimaPro is used to compared the environmental impact of a Greener battery with a 200 kVA Diesel genset. This is a commonly used software program that implements the results of science-based literature for more than 30 years to create a transparent tool that makes it possible to calculate the environmental impact of a product or process. This research uses two methods, the CML-IA baseline method, developed by Leiden University to calculate the Global Warming Potential 100; and the global method 'ReCiPe 2016 midpoint hierarchist' to calculate the Fine Particulate Matter Formation. The midpoint method is selected over the endpoint method since the midpoint method gives a more specific environmental impact per impact category, where the endpoint method gives a more overall impact of the combined impact categories. For example, the endpoint impact category 'human health' combines the midpoint impact categories a.o. 'Fine Particulate Matter Formation, Ozone Depletion, Water Use, and Toxicity' (SimaPro, 2019).

Figure 3 visualizes the steps undertaken in this research. All steps are explained in this section of the report, the methodology.

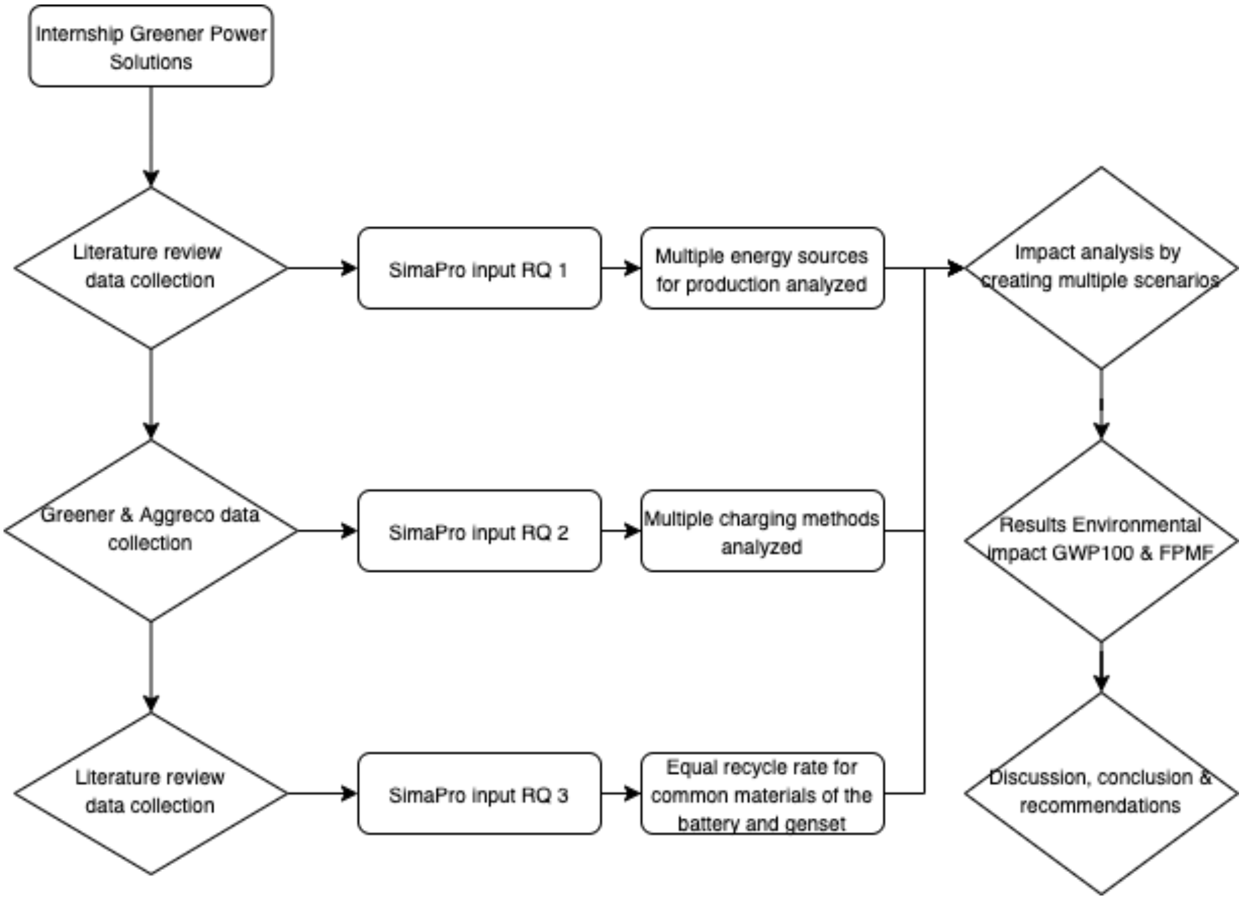


Figure 3 – Flowchart undertaken steps

3.1. Sub research question 1: Environmental impact of the production phase

The first sub research question is answered using existing academic literature as input for the environmental impact of the 200 kVA Diesel genset and for the three components and one component group (electronic equipment) of the Greener Battery: BMW I3 batteries, transformers, refrigerating container, and electronic equipment. The materials and energy as described in section 3.1.1 to 3.1.6 are used as input in SimaPro for the production phase.

3.1.1. BMW I3 batteries

The batteries inside the Greener battery are from the car manufacturer BMW and are used in their model I3. The batteries have a capacity of 42.2 kWh (BMW, 2018). There are multiple technologies for a lithium-ion battery. These technologies refer to the material of the cathode and anode inside the battery cell. BMW I3 batteries use the NMC technology, Nickel-Manganese-Cobalt-Oxide, for the cathode; and graphite for the anode. Literature to set a value for the environmental impact of these batteries is based on solely NMC technology. In general, the NMC technology has the largest environmental impact compared to other lithium-ion technologies. However, the NMC technology has a longer lifetime compared to e.g. iron phosphate (LFP) regarding total energy throughput (Popp et al., 2014). Table 1 represents the used academic literature to measure the environmental impact of the NMC battery. Since there is no previous study or data regarding the BMW I3 battery specifically, a combination of LCA literature is used for NMC batteries.

Table 1 – Literature analyzed for environmental impact BMW I3 battery

Author and year	**Title**	**Specifications**	**Environmental impact**
(Romare & Dahllöf, 2017)	The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries	*Mining processing and assembly/manufacturing* Independent of the cell chemistry NMC, LFP or LMO. Largest part of emission (50%) from energy of battery manufacturing Near linear scale up of greenhouse gas emissions when the battery size increases Ambrose and Kendall (2016): NMC: cumulative energy demand: likeliest 960 MJ/kWh. Battery production: 254 kg CO2-eq/kWh. Battery material production including mining and refining: 60-70 kg CO_2-eq/kWh Manufacturing (component and cell + battery assembly): 70-110 kg CO_2-eq/kWh	160 kg CO_2 eq/kWh
(Qiao et al., 2017)	Cradle-to-gate greenhouse gas emissions of battery electric and internal combustion engine vehicles in China	Total energy consumption for NMC batteries: 59514 MJ/t	2896 kg CO_2eq / battery
(Dai et al., 2019)	Life Cycle Analysis of Lithium-Ion Batteries for Automotive Applications	Focus on NMC $LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$ li-ion batteries. Major contributors to the energy and environmental impacts are: active cathode material,	72.9 kg CO_2-eq/kWh 1.126 MJ energy use / kWh 0.8 kg SOx / kWh

		aluminium, and energy use for cell production. 23.5 kWh NMC111 cathode graphite anode li-ion battery, 165 kg, 140 46-Ah prismatic cells. Scaling is done linear Locations of production facilities and origins of the battery materials can significantly affect the cradle-to-gate energy and environmental impact	0.0969 kg NOx / kWh 0.0479 kg PM2.5 / kWh 752 l water use / kWh
(Majeau-Bettez et al., 2011)	Life cycle environmental assessment of lithium-ion and nickel metal hydride batteries for plug-in hybrid and battery electric vehicles	Mining and metallurgy activities required for production of the nickel in the electrodes and the current collectors are responsible for more than 70% of the toxicity and ecotoxicity impacts and more than 80% of particulate matter formation, terrestrial acidification, and metal depletion potential impacts. Manufacture energy requirements are a major cause of GWP. Polytetrafluoroethylene as binder in the electrode paste responsible for 14-15 % of the GWP, mostly due to halogenated methane emissions.	NMC battery production: 196 kg CO_2-eq/kWh (GWP) 0.15 kg FE-eq/Wh $4.6*10^{-4}$ kg PM2.5-eq/Wh
(Kawamoto et al., 2019)	Estimation of CO_2 Emissions of internal combustion engine vehicle and battery electric vehicle using LCA	NMC values from 3 different studies Majeau-Bettez et al. 200 kg CO_2 eq/kWh. Amarakoon et al 121 kg CO_2 eq/kWh. Elingsen et al 172 kg CO_2eq/kWh.	Average of NMC batteries: 164 kg CO_2eq/kWh
(Anna et al., 2019)	Energy and environmental assessment of a traction lithium-ion battery pack for plug-in hybrid electric vehicles	Case study, Mitsubishi outlander LEV40 LMO-NMC battery pack. Nominal capacity: 11.4 kWh battery pack. One LMO-NMC cell dismantled and sorted per material.	313 kg CO_2 eq/kWh = upper mid-range of estimates found in the literature review 190 kg CO_2 eq/kWh, produced with European energy mix.

		Electricity required for cell assembly is responsible for the main impacts.	Electricity used for cell assembly: 586 MJ/kWh.
(Kim et al., 2016)	Cradle-to-Gate Emissions from a Commercial Electric Vehicle Li-Ion Battery: A Comparative Analysis	NCM battery cradle to gate emissions from reviewed studies: 121-196 kg CO_2-eq/kWh. Mainly because of the higher energy demand during the cell an pack manufacturing phase. Energy used during cell manufacturing was measured in South Korea (energy mix)	140 kg CO_2 eq/kWh for the Ford Focus NMC battery. 45% of GHG emissions is from the use of utilities (electricity, natural gas, and water) in cell manufacturing.
(Ellingsen et al., 2014)	Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack	NCM battery, 253 kg, capacity: 26.6 kWh. Normal use: battery efficiency 95 – 96 %. 60 % of the battery are cells. Cells consist of: anode, cathode, separator, electrolyte, and cell container. Energy required for battery manufacturing is 51% of total emissions.	Lower Bound Value: 172 kg CO_2-eq/kWh Asymptotic value: 240 kg CO_2-eq/kWh Average Value: 487 kg CO_2-eq/kWh Lower Bound Value: 5.8E-1 kg PM2.5 eq Asymptotic value: 6.7E-1 kg PM2.5 eq Average Value: 9.7E-1 kg PM2.5 eq

From this literature review, the environmental impact of lithium-ion NMC batteries ranges from the lowest value of 72.9 kg CO_2 equivalent/kWh (Dai et al., 2019) to the highest value of 487 kg CO_2 equivalent/kWh (Ellingsen et al., 2014). This large different is due to the different approaches that the authors use to analyse the environmental impact of lithium-ion batteries. Multiple studies analyse the environmental impact per single component, where other studies analyse the complete assembled battery as one component. For this research, the average value for the environmental impact found in the literature review is 213.5 kg CO_2 equivalent/kWh. Half of this value is used as input in SimaPro for the production phase of the batteries, the other half of the emissions is from electricity used during production. As stated in multiple reviewed articles, at least half of the emissions comes from the energy used during production, this is elaborated in the next paragraph. The average Fine Particulate Matter Formation (FPMF) from the reviewed literature is 0.493 [kg PM2.5 eq/kWh]. Also there, half of this value is used as input in SimaPro for the production phase of batteries.

Anna et al., 2019; Dai et al., 2019; Ellingsen et al., 2014; Kim et al., 2016; Majeau-Bettez et al., 2011; and Romare & Dahllöf, 2017 highlight the large share of environmental impact that is related to the energy use for battery manufacturing and assembly. According to these studies, 50 % of the environmental impact relates to this. Therefore, the environmental impact during the production phase is a combination of half the environmental impact from the reviewed literature and from the energy used during the production phase. The average quantity of electricity used for production from the reviewed literature is 890.7 MJ/kWh. Multiplying this with the capacity of the Greener battery gives the total electricity used for the production phase, 300.7 GJ.

The batteries are assembled in the BMW factory in Leipzig, Germany. Since BMW not only wants to increase the share of electric vehicles on the road, but also wants to produce the electric vehicles by using electricity with a low carbon content, the company invested in a factory which is powered by four wind turbines. These turbines, together with 700 second-life BMW I3 batteries, make the factory completely self-sufficient for the total electricity demand (Behrmann, 2017). The turbines are manufactured by Nordex in Germany and have a rated power of 2.5 MW (Bosch-Rexroth & Eickhoff, 2020). The data for an onshore 2.5 MW wind turbine is used as input in SimaPro for the electricity demand in the production phase of the battery. The wind turbines deliver the 300.7 GJ energy necessary for production of the battery packs.

Next to the battery cells, every electric vehicle battery pack includes one converter. Since there are eight battery packs in the Greener container, eight 'converters for electric passenger car' are used as input in SimaPro with a total weight of 100 kg. The converters are already installed in the BMW battery packs and therefore are not installed as separate units in the Greener battery. The combined mass of the eight battery packs minus the converters is 3799.12 kg.

3.1.2. Transformer

Every Greener battery is equipped with a three phase transformer. The transformer operates in both ways, during charging and discharging of the battery. A transformer is a static piece of equipment, meaning that it has no moving parts, that adjusts the voltage to the desired input or output, depending on charging or discharging of the battery. Next to the connection for input and output voltage, the transformer is also connected to the DC-AC inverter. According to the battery manufacturer of Greener, Alfen, the three phase transformer inside the battery has a total weight of 1500 kg and an efficiency of 98.31 %. Alfen does not specify the raw materials used to produce the transformer. Therefore, the standard 'transformer, high voltage use' in SimaPro is adjusted by altering the core material from ferrite to steel. As SimaPro indicates, ferrite is used in smaller type of transformers e.g. in the information and communication technology. Since ferrite is not used in large three phase transformers as core material, this material is changed to ‘steel, low-alloyed’. The quantity of steel for the core and copper for the windings has an approximate ratio of 1:1 which is common for a three phase transformer (Winders, 2002).

3.1.3. DC-AC Inverter

Direct current from the lithium-ion battery packs is converted by a DC-AC inverter to generate an alternating current of 50 Hertz. Technical specifications of the converter specify a weight of 100 kg (Fell et al., 2012). The exact converter is not available in SimaPro, therefore a converter for an electric passenger car is used as input for the battery converter since it is assumed that the raw materials used to produce a converter do not vary significantly depending on the type of converter. Since every BMW battery pack is already equipped with one converter, the total weight of all converters inside the Greener battery is 200 kg. This is a DC/DC converter that regulates the maximum voltage levels to match the minimum and maximum input and output currents for the BMW batteries (Sakka et al., 2011).

3.1.4. Refrigerating container

All technology as described above is mounted inside a standard size refrigerating (reefer) container. To protect the batteries and all electronic components inside the container, the temperature is kept constant at 18 degrees Celsius in winter and 22 degrees Celsius in summer. The refrigerating container has a standard size of 10 feet and has an build in air-conditioning unit. Together with isolated walls, roof, and floor, the energy loss for cooling inside the container is minimized. The air-conditioning unit uses power from the battery pack itself. This can be seen as one of the losses of the Greener battery. Another loss for example is the efficiency of the three phase transformer.

From technical specification of a standard refrigerating container, the weight of a 10 feet reefer is 2030 kg with as main components aluminium and steel for the plating and cooling unit (Reeferco, 2011). In SimaPro, inputs from nature of a standard ‘Reefer, intermodal shipping container, 40-foot, carbon dioxide liquid as refrigerant (GLO)’ are adjusted so they are suitable for a 10 feet carbon dioxide liquid as refrigerant reefer container. The weight difference between a 40 feet and a 10 feet reefer without air-conditioning unit (530 kg) is 5440 kg. The air-conditioning unit in reefer containers are uniform regardless the size of the container.

The weight difference of the container is allocated to: 4750 kg steel, 400 kg aluminium, 200 kg isolation foam, and 90 kg polypropylene. The quantity of materials that are adjusted in SimaPro are according to the standard composition of a reefer container by the ratio of materials used as input. Also, the amount of zinc coat and steel welding are adjusted to 25% of the initial value since the 10 ft container is four times smaller compared to the 40 ft container.

3.1.5. Electronic equipment

Since the total weight of electronic equipment is unknown, it is assumed that the difference between the total weight of the Greener battery and the total weight of the components as described above is assigned to electronic equipment. Examples of electronic equipment that is installed in the battery are: fuses, print boards, raspberry-pies, WIFI routers, a fire detector, busbars, and relays. Most of this equipment is part of the Battery Management System (BMS). The BMS is additional equipment next to the battery packs that manages the power input and output through the battery in a safe environment. Safety measures as fuses are installed to prevent damage to people operating the battery and damage to the battery itself from e.g. heat or fire.

The sum of weight of the components mentioned above is expressed in table 2. The Greener battery has a total weight of 8100 kg. This is measured by the truck that transports the batteries to the operation site, for example a festival.

Table 2 – List of components Greener battery

Equipment	Weight	Quantity	Total weight
BMW I3 battery pack (inverter excluded)	474.89 kg	8	3799.12 kg
EV built in inverter	12.5 kg	8	100 kg
Transformer	1500 kg	1	1500 kg
DC-AC inverter	100 kg	1	100 kg
Refrigerating container	2030 kg	1	2030 kg
Sum of total weight, electronic equipment excluded			7519.12

The sum of total weight of all components without electronic equipment is 7519.12 kg. Therefore the total weight of the BMS is: 8100 kg – 7519.12 kg = 580.88 kg. This weight is used as input for the Greener battery in SimaPro under ‘electronics for control unit’. This is a combination of cables, injection moulded plastics, different types of printed wiring boards, and steel; and is representative for the equipment installed in the Greener battery.

3.1.6. Diesel generator set

This research will compare the environmental impact from the Greener battery with a Diesel generator set (genset). Depending on the type of setup used at the location for temporary electricity demand, the Greener battery replaces a genset or is installed between the genset and the power demand. This research will focus on the type of genset that is most often used at similar locations as the Greener battery according to one of the co-founders of Greener[1], a 200 kVA Diesel generator. Technical specifications from a genset of the company Aggreko are used for the production and use phase of the LCA and as input for the software SimaPro.

For the production phase of the genset, the shares of raw materials and energy quantities are used described by Smith et al., (2015). The main components of a genset are: steel, cast steel, aluminium, copper, and plastic. Table 3 provides an overview of input data that is used for a standard 200 kVA Diesel generator from Aggreko with a weight of 3522 kg without fuel.

Table 3 – Material composition Diesel generator

Raw materials	Components percentages	Mass [kg]
Steel	30 %	1056.6
Cast steel	30 %	1056.6
Aluminium	35 %	1232.7
Copper	3 %	106.66
Plastic	2 %	70.44

Smith et al., (2015) also consider energy use for the production phase of a genset. Table 4 provides an overview of the two types of energy sources and total energy used for the production of a 200 kVA genset. It is assumed that the genset is produced in China. Therefore, the electricity mix from China is used as input in SimaPro. The production phase also includes a scenario where all consumed energy will be generated using wind turbines to give insight in the environmental aspects of the energy used during the production phase.

Table 4 – Energy use for production 200 kVA Diesel generator

Type of energy	Quantity used for production [GJ/ton generator]	Total energy consumption for production of 200 kVA genset

[1] Dieter Castelein, personal communication, March 6, 2020

Natural gas	54	190.188
Electricity	16	56.352

3.2. Sub research question 2: Environmental impact of the use phase

3.2.1. 200 kVA Diesel generator

The second sub research question is answered using a combination of previous research regarding efficiencies in Diesel generator sets and new data from Greener Power Solutions. The Greener battery can be seen as an additional or replacing piece of equipment in a whether or not temporarily electricity grid. The battery is also applicable at locations where the grid connection is too small for the peak electricity demand, but large enough to continuously charge the Greener battery. For example, during a festival where electricity demand is provided by Diesel generator sets, a battery can be placed between the demand and supply side. Using this technology, it is possible to store electricity at times that demand is low, and deliver electricity during high demand. This can be beneficial if the load on a Diesel generator set is not on its most efficient level. Therefore, the hypothesis for the production phase is that the environmental impact using a Diesel generator to deliver 1,600 MWh is larger compared to delivering the same quantity of electricity with using a Greener battery.

The optimum load for a Diesel generator set is between 60 and 90% of its maximum load so the fuel consumption will be close to optimal (Dwi Atmaja et al., 2018). This means that the Diesel generator set is most efficient when the load is close to its maximum capacity. Therefore, Diesel generator sets are designed to deliver the maximum power demand. However, earlier research from Greener Power Solution shows an average load of Diesel generators during operation of 12%. These are representative Diesel generator sets that can be replaced by battery systems. An average load of 12 % is far from optimal and therefore the fuel consumption of the genset is large compared to the power output. However, the 12 % is an average load and the Diesel generator still needs to deliver close to its maximum load if the electricity demand is large, for example during the main show at a festival. The results will include multiple scenarios where the generator set runs on the 12% load. In the result section will also be a calculation for the use phase if the Diesel generator operates half of the time on a 12% load and half of the time on a load that is more efficient, 80%. This will give insight in the importance of running a Diesel generator set on a more optimum load.

To make a fair comparison between a Diesel generator set and the Greener battery, the lifetime of the diesel generator set is important since the quantity of delivered power can be different compared to that in a lifetime of a Greener battery (1,600 MWh). The production and EoL phase can be adjusted accordingly. An expert[2] from the company of the 200 kVA diesel generator set that is analysed for this research, Aggreko, elaborated on the lifetime of this type of diesel generators. This is dependent on multiple factors, e.g. maintenance, size of the generator, and most importantly the load on the generator set. The rule of thumb for a typical size generator set is for a heavy load the lifetime is 40,000 running hours; and with a light load 60,000 running hours. The average 12% load on the generator set is a light load and therefore the lifetime of 60,000 running hours is used to calculate the power output of a 200 kVA Diesel generator set, with a power factor of 0.95. The total power output during the lifetime of the Diesel generator set is:

0.12 [%] * 200 [kVA] * 0.95 (power factor) * 60,000 [hours] = 1,368,000 kWh

With an average load of 12%, the delivered power during the lifetime of a 200 kVA Diesel genset is 1,368 MWh, this is less compared to the Greener battery. This indicates that more than 1 Diesel generator set needs to be used to deliver 1,600 MWh electricity on a 12% load. However, for this research it is assumed that one 200 kVA diesel generator set can deliver 1,600 MWh electricity due to the large difference in running hours depending on the load and due to the light load of only 12%. This would mean the genset has a lifetime of approximately 70,000 running hours which is, according to Aggreko, possible whenever the genset is properly maintained and not heavily loaded or worn out. Therefore, for this research it is assumed that the power output during the lifetime of a 330 kWh Greener battery is equal to the power output during the lifetime of a 200 kVA Diesel generator set.

The calorific value of Diesel is assumed to be 42.21 [MJ/kg] and the density of Diesel is 0.832 kg/l (Raheman & Phadatare, 2004). With data from Aggreko combined with the calorific value and density of Diesel, calculations regarding energy efficiency of a 200 kVA genset are made (table 5). As expected, the efficiency of the genset increases as the load increases (figure 3).

Table 5 – Efficiency data 200 kVA Diesel generator

Load	**Fuel consumption [l/kWh]**	**Energy output [kWh/l]**	**Energy output [MJ/l]**	**Efficiency [%]**
10%	0,51	1,996	7,186	20,5
12%	0,46	2,156	7,761	22,1
20%	0,36	2,778	10,00	28,5
30%	0,34	2,941	10,58	30,1
40%	0,32	3,125	11,25	32,0
50%	0,32	3,125	11,25	32,0

[2] Mark Reijnders, personal communication, May 4

60%	0,32	3,125	11,25	32,0
70%	0,30	3,333	12,00	34,2
80%	0,28	3,571	12,85	36,6
90%	0,28	3,571	12,85	36,6
100%	0,27	3,704	13,33	38,0

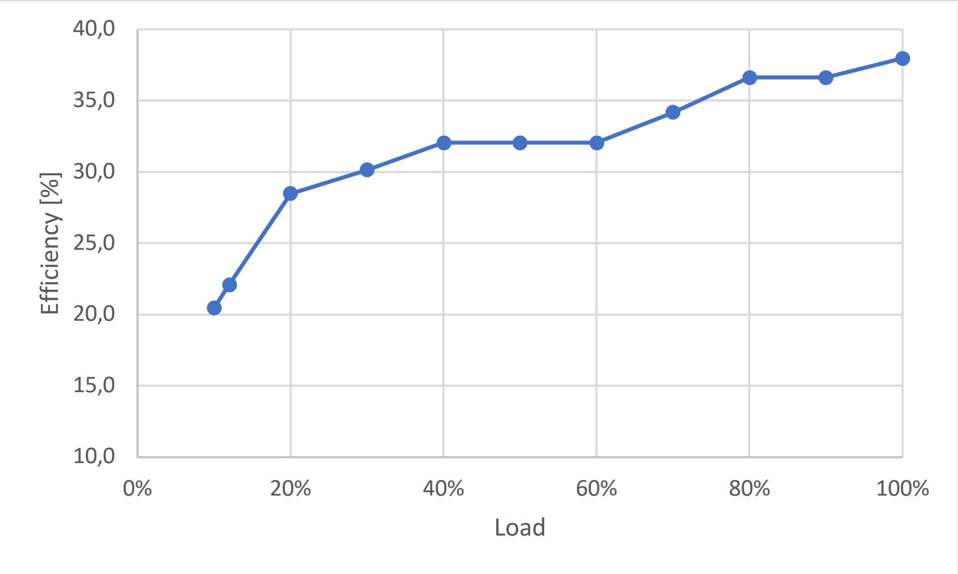


Figure 4 – Load Efficiency curve 200 kVA Diesel generator

The average load of 12% on a Diesel genset gives an efficiency of 22.1% energy output, meaning 1 kilogram Diesel is converted by the genset to 9.328 MJ useful energy output.

An energy output of 1,600,000 [kWh] equals 5,760,000 [MJ] (1,600,000 * 3.6). Therefore, the total fuel consumption during the use phase of a Diesel genset is equal to 5,760,000 [MJ] / 9.328 [MJ/kg] = 617,468.57 [kg] of Diesel. This quantity of Diesel is used as input in SimaPro for the LCA of the Diesel generator.

3.2.2. Greener battery

State of health

The lifetime of the battery is dependent on the State-of-Health (SoH) of the battery. This indicates the total power output as a percentage of the originally designed power output. The total power output will decrease in time due to multiple factors: temperature, Depth of Discharge (DoD), C rate, and throughput. Due to the combinations of these four factors, all with its own variable characters, accurately calculating the SoH for a battery system can be challenging. The SoH is important for e.g. Greener because it indicates whenever a battery is still profitable and applicable for the current types of locations where the battery is deployable. The BMW batteries lose, according to the technical specifications, 30% of the initial capacity after 200,000 kWh throughput at testing conditions. However, a variation in the throughput value for the same degradation percentage means the lifetime of the battery is changing. For example, a degradation of 30% initial capacity after only 150,000 kWh throughput means the lifetime of the battery is less compared to the technical specifications.

There are multiple methods for this calculation, e.g. the Coulomb Counting Method, the Voltage Method, and the Kalman Filter Method (Murnane & Ghazel, 2017). The accuracy for these methods varies and is dependent on the calculation of the State-of-Charge (SoC). The Coulomb Counting Method is the mostly used method. This method uses open-circuit voltages or loaded voltages, obtained by tests of the lithium-ion battery, where after the found data is used as input for an algorithm that continuously calculates the best approximate SoH. This type of data is obtained by sensors in the battery that measure the releasable charge and the stored charge during one cycle (the efficiency) and the voltage losses caused by self-discharging (Soon et al., 2009). Due to the many pieces of equipment in the Greener Battery, more then 160, that all affect the performance of the battery; and the missing data from e.g. open circuit tests, it was not possible to accurately calculate the SoH in this research. This is a limitation of this research, since the LCA is based on theoretical throughput according to the testing conditions. The lifetime of the Greener battery is expected to be 10 years. However, this lifetime can also be less whenever the battery is not used according to the standard testing conditions.

Greener battery efficiency

The power input for the Greener battery is not equal to the power output due to losses during energy conversion from AC to DC and back, losses inside the lithium-ion batteries, and the cooling unit inside the reefer container that prevents the battery from overheating. The energy efficiency of the transformer is 98.31%. According to one of the founders of Greener[3], the cooling unit of the battery is constantly in use when the battery is in operation. This is not in the advantage of the Greener battery since the cooling unit consumes electricity and therefore the efficiency of the Greener battery will be reduced whenever the cooling unit is on. Even though, it is assumed that the cooling unit is continuously on whenever the Greener battery is in use, to prevent to be biased in advantage for the Greener battery. The cooling unit from the reefer container consumes on average 2.0 kW electricity, which gives an energy consumption of 2.0 kWh. The average discharge cycle duration is 4 hours. The total energy consumption by the cooling unit is: 4 [hours] * 2.0 [kW]= 8 kWh,

[3] Klaas Akkerman, personal communication, May 13

this is 2.37% of the total capacity of the Greener battery. This means the 2.4 % of the power input is used to run the cooling unit.

The lithium-ion batteries also have an efficiency for charging and discharging, depending on the C-rate. Although this efficiency is high, it is taken into account for the total efficiency of the Greener battery. Charging a lithium-ion with a C-rate of 0.8 has a maximum efficiency of 99.9% and a minimum efficiency of 99.0%. Discharging a battery has a maximum efficiency of 99.8% and a minimum efficiency of 99.2% (Soon et al., 2009). For this research the lowest efficiencies are chosen to create an fair comparison with a Diesel generator set without choosing benefits for the battery.

The round-trip efficiency of the Greener battery is:

98.31% (transformer AC-DC) * 97.63% (cooling unit) * 99.0% (charge efficiency) * 99.2% (discharge efficiency) * 98.31% (transformer DC-AC)= 92.67%

To deliver 1,600 MWh power output with an efficiency of 92.67% from the battery, the power input needs to be 1,726,611 kWh. In practice, this is done by charging the battery using a grid connection if available, or by using a Diesel generator that can run on its most efficient load.

3.2.2.1. Scenario 1: Power input by Diesel generator

To give insight in CO_2 emissions during the use phase, three scenarios regarding power input are chosen. In the first scenario the Greener battery is solely charged using a 200 kVA Diesel genset during the complete lifetime of the battery.

To charge the Greener battery, a Diesel generator can run on an optimum load, independent of the current energy demand. Therefore, the load to charge the Greener battery is chosen to be 80%. This will protect the Diesel genset from overload and according to operational staff from Greener this is a representative value. A load of 80% on a 200 kVA genset leads to an efficiency of 36.6% (figure 4), meaning 1 kilogram Diesel is converted by the genset to 15.45 MJ useful energy output. Because of the energy losses inside the battery, the power input is equal to 1,726,611 [kWh] *3.6 = 6,215,798 MJ.

If during the whole lifetime of the battery it is charged only by a 200 kVA genset, the total fuel consumption to charge the battery is: 6,215,798 [MJ] / 15.45 [MJ/kg] = 402,317 [kg] Diesel. This is used as input in SimaPro for the first scenario.

3.2.2.2. Scenario 2: Power input by grid

In the second scenario, the Greener battery is solely charged using a grid connection. Before a Greener battery is placed on the location where the battery will be operational, the site is inventoried for the type of power input that is possible. A grid connection is preferred over a Diesel generator as input since the CO_2 emissions from the grid are lower compared to a Diesel generator. This can easily be calculated using the efficiency data from figure 4 of the 200 kVA Diesel generator. The most efficient power output consumes 0.27 liter of Diesel for 1 kWh. 1 liter of Diesel emits 2640 gram of CO_2 (720 gram carbon + 1920 gram oxygen). 0.27 * 2640 = 712.8 gram CO_2 / kWh with the most efficient load, compared to an average 430 gram CO_2 / kWh from electricity of the grid in 2018 in The Netherlands (Bosch et al., 2019). Data from 2019 is not yet available at the Centraal Bureau voor de Statistiek (Central Statistical Office of The Netherlands). The power input of 6,215,798 MJ (or 1,726,611 kWh) is completely assigned to 'Electricity, medium voltage (NL)' in SimaPro. It is assumed that the battery is charged in The Netherlands since Greener has not yet accepted international projects until now, except for one project in England.

However, it is not always possible to use a grid connection as power input for the Greener battery due to practical objections e.g. too small grid connections, or not the right cable infrastructure. It is also possible that there is no infrastructure for a grid connection. In this case the use of a Diesel generator is unavoidable.

3.2.2.3. Scenario 3: Diesel generator and grid combined

The third scenario is a combination of charging the Greener battery partially by a grid connection and partially by a Diesel genset. The ratio of charging the battery using a Diesel generator versus the grid is calculated using charge data from the Greener database. At the moment, Greener has 13 batteries. Every second the data e.g. SoC, Power Input, Power Output, is stored for all batteries in the database since July 2019. To achieve a ratio for how often the battery is charged using the grid or a Diesel genset, the data is averaged for every 15 minute of power input. This is done for two representative batteries. Table 6 and 7 show the charge ratio from this data analysis.

Table 6 – charge ratio of battery 001 'Carmen'

Input type battery 001 "Carmen"	Total time of power input [hours]	Percentage
Genset	175,25	16.68%
Grid	876,25	83.32%

Table 7 – charge ratio of battery 009 'Izzy'

Input type battery 009 "Izzy"	Total time of power input [hours]	Percentage
Genset	457	32.06 %
Grid	968,5	67.94 %

The power input for the battery is divided according to the ratio from table 7 from the battery Izzy since this is the least in favour of the battery in order to give a fair comparison of the battery and genset. The total power input for the battery is 1,726,611 kWh. 32.06% is generated using a 200kVA genset, this is 553,551 kWh and used as input in SimaPro with the efficiency of 36.6% for a 80% load.

The other share of power input is delivered using a grid connection. This is 1,173,059 kWh and is used as power input in SimaPro as 'Electricity, medium voltage (NL)'.

3.2.2.4. Scenario 4: Wind energy

The final scenario for the use phase of the Greener battery is charging it by wind power. This is a relative new setup for Greener and therefore still in the testing phase. At a location in The Netherlands, a new storage location is built underneath multiple wind turbines. The storage location has three-phase power lock connections installed to connect the Greener batteries with local grid from the wind turbines. With this setup, it is now possible for Greener to access the electricity trading market. Also, it is possible to charge the batteries with power from the wind turbines whenever they are not used at e.g. a festival or a construction site. Therefore, this (future) scenario uses solely wind power in the use phase to charge the battery even though this is practically not yet implemented.

The total power input to charge the battery during its complete lifetime, 1,726,611 kWh, is assigned to 'Electricity production, wind, 1-3MW turbine, onshore' in SimaPro.

3.3. Sub research question 3: Environmental impact of the End-of-Life phase

3.3.1. Greener battery

The European Commission (EC) introduced the obligation for countries to recycle batteries. For lead acid batteries the obligated minimum recycle quantity is 90% while for lithium-ion batteries this recycle quantity is only 50% (European-Commission, 2019). The BMW I3 batteries that are installed in the Greener battery are assembled in Germany. However, the cells of the battery are produced in China by Samsung. Recycling the batteries in Europe creates three benefits: environmental, economic, and strategic. Recycling contributes to environmental benefits since it allows energy savings compared to mining, economic benefits since development of a recycling infrastructure and an industrial ecosystem linked to electricity storage will create jobs and value, and strategic benefit since it will allow the recovery of mineral resources which the EU does not exploit on its own lands (Danino-perraud, 2020).

However, the recycle market for Electric Vehicle (EV) batteries is rather new. Modern EV production significantly increased last years. For example in The Netherlands the share of electric vehicles compared to combustion engine vehicles was only 7% in 2019 (ETEnergyWorld, 2019). The lifetime of an EV is in some cases more than 15 years, therefore, recycling EV batteries is an upcoming market. The collection rate for batteries from electric vehicles is around 80% (Graedel et al., 2015).

Before the recycling process EV batteries can be used in applications where the energy demand is not as intense compared to the use in an EV. For example, 148 Nissan LEAF batteries are used for energy storage and grid balancing underneath the Amsterdam Arena Stadion (Koster, 2018), and as described in section 3.1.1 in the BMW factory for renewable energy storage. Greener is also investigating a business case to generate a second-life application in e.g. African countries where electricity grids are unstable or power is generated by Diesel generators. Peak loads are expected to be less high compared to the electricity demand with the current applications during e.g. festivals or construction sites.

Recycling of lithium-ion batteries is mostly focused on recovery of cobalt, nickel, copper, and steel. Recovery of materials from lithium-ion batteries takes primarily place in China and South Korea. Recycling lithium-ion batteries is a complex process that involves three methods that are often combined: mechanical, pyrometallurgical, and hydrometallurgical. These processes include e.g.: separation, thermal treatment, separation with acids, and bio-leaching. The recovery rate for lithium and cobalt are, according to Melin (2019) who researched 128 lithium-ion recycle studies, in more than 80 of these studies above 90%. However, the share of Lithium and Cobalt used in a NMC battery is on average only 2% and 4% of the total weight of the battery. Also, these are theoretic recovery rates from test conditions due to the unavailability of data from companies.

In Europe, there is one known company that recycles lithium-ion NMC batteries, Duesenfeld, located in Germany. The company combines the mechanical and hydrometallurgical methods to process the batteries. Given the complex route from collecting, distribution, pre-processing, and processing, it has been estimated that less than 40% of the materials contained in a battery can be recycled (Danino-perraud, 2020).

Several LCA studies regarding recycling of lithium-ion batteries did not include the End-of-Life phase due to the greater uncertainty as described above regarding collection rate and the type and share of material that can be recovered in the EoL phase (Ellingsen et al., 2014; Kim et al., 2016; Majeau-Bettez et al., 2011).

This research will conduct the recycle phase with the End-of-Life approach. This means that the recycled materials are not necessarily used in lithium-ion batteries, but can also be used for different applications after it is recycled.

The method used for the recycling phase is: allocation at the point of substitution (APOS). This model has the underlying philosophy that it uses a combination of multiple underlying processes (Ecoinvent, 2020). For example, the incineration of waste generates GHG emissions, electricity, and heat. These output can be used for other processes, e.g. heat can be used in a district heating system to reduce and prevent fossil fuel use for space heating. APOS provides an average share of e.g. electricity and heat that is used in different applications. These treatment activities are grouped and aggerated into one single dataset that is represented as the treatment process in SimaPro, specified for the desired material. Grouping and aggregation is based on the EcoInvent database. The advantage for this method compared to for example the ‘cut-off’ method is that there are no parts excluded of the product system.

The materials that are recoverable are: cobalt, nickel, manganese, copper, and steel, which are approximately 55% of the total weight of the battery. This is done using a combination of two highly complex technologies: hydrometallurgical and pyrometallurgical. The electricity used for these technologies are obtained from the reviewed literature regarding NMC lithium-ion battery recycling. Using the current technologies, it is not possible to recover the other components of the battery that make up 45% of the total weight. These components are plastics, binder material, electrolyte, and graphite, and are lost during recycling (Cusenza et al., 2019).

Table 8 – reviewed literature EoL phase

Author and year	Paper	Specifications	Environmental impact
(Qiao et al., 2019)	Electric vehicle recycling in China: Economic and environmental benefits	Functional unit: 27 kWh NMC battery Battery weight: 164 kg Most energy and CO_2 are saved by recycling of NMC and aluminium Unknown what total energy use and GHG emissions is	Recycling credits: Energy consumption: 15.2 MJ/kg GWP: -4.21 kg CO_2 eq/kg For Greener battery: Energy use: 56226.62 MJ GWP: -15573.3 kg CO_2 eq
(Cusenza et al., 2019)	Energy and environmental assessment of a traction lithium-ion battery pack for plug-in hybrid electric vehicles	Capacity of the battery: 11.4 kWh Environmental benefits could be increased if other cell components were recovered Land use and water resource depletion impact categories excluded due to low availability and high uncertainty of data	Recycling: Energy consumption: 3151 MJ GWP: -360 kg CO_2 eq PM: -0.502 kg PM2.5 eq For Greener battery: Energy use: 93313.8 MJ GWP: -10661 kg CO_2 eq PM: -14.866 kg PM2.5 eq
(Hao et al., 2017)	Impact of recycling on energy consumption and greenhouse gas emissions from electric vehicle production: The China 2025 case	CO_2 saved mainly due to NMC (1652 kg CO_2 eq) steel (134.6) and copper (79.2). from 1865.7	Energy used for recycling a 212 kg battery: 12.1868 MJ/kg GHG saved 8.800471698 kg CO_2 / kg For Greener battery: Energy use: 45080.44 MJ GWP: -32554 kg CO_2 eq

A literature analysis is executed to give insight in the known literature about recycling. This is used as input for SimaPro for the EoL phase. It is stated by multiple authors that the EoL phase is the most difficult phase to analyze due to the complex research area, the relative new market, and therefore missing the availability of data. This makes the EoL phase the most uncertain phase of this research. Table 8 provides an overview of the reviewed literature for the EoL phase. The quantities for the environmental impact from the articles are adapted to match the battery pack from a Greener battery (8 * BMW I3 batteries). The results are adapted according to the capacity of the Greener battery. All reviewed papers apply for the specific type of battery that is used in a Greener battery, the lithium-ion NMC technology.

After averaging the results from the reviewed literature, the energy use for recycling is 64873.62 MJ for the Greener battery. The GWP100 average results in a reduction of 19,596 kg CO_2 eq. Fine Particulate Matter Formation is calculated in only one paper (Cusenza et al., 2019) and therefore highly uncertain. However, more scientific data regarding FPMF is absent and therefore this value is applied for recycling the BMW I3 batteries, which results in a reduction of FPMF 14.866 kg PM2.5 eq for the Greener battery.

3.3.2. The reefer container

The standard recycling process of a 40 ft reefer container is adjusted so it can be applied for a 10 ft reefer container. This means the quantity of materials as 'output to technosphere' are adjusted according to the ratio of materials used to construct a reefer container (see section 3.1.4 of this report). Therefore, the main components steel and aluminium are adjusted by 2700 kg and 215 kg.

3.3.3. Electronic equipment

Recycling electronic equipment recovers metals that are used in equipment e.g. copper and nickel. This is executed using a copper smelter with as main input electricity. The standard SimaPro 'electronic treatment of scraps, recovery in copper smelter' is used for a quantity of 780 kg. This quantity is a combination of the 'electronics for control unit' (580 kg) and the 'converter for electric vehicle passenger cars' (200 kg).

3.3.4. Transformer

The transformer consists of a combination of steel and copper with a ratio of 1:1, as described in the production phase, section 3.1.2. The total mass of the transformer is 1500 kg, of which 1400 kg is copper (700 kg) and steel (700 kg). For steel, 700 kg is used as input for 'waste reinforcement steel' which is a combination of steel collection, sorting and recycling. The ratio of these three processes are established by the EcoInvent database for global steel treatment.

Table 9 provides an overview of the materials that are recycled per component. The recycle rate is based on European data from J.H. Schmidt (2010). To keep the comparison also for the recycle phase equal, the same recycle rate is taken for the materials that have the Greener battery and the genset in common. The share of materials that cannot be recycled is used as 'output to technosphere' in SimaPro and is treated as waste processing.

Table 9 – recycled components of the Greener battery

Components	Materials	Materials in battery [kg]	Recycle rate	Saved material [kg]	Waste material [kg]	Energy consumption for recycling [MJ]
Reefer container (2030 kg)	Steel	1115	66 %	735.9	379.1	2787.5
	Aluminium	608	58 %	352.6	255.4	4316.8
	Plastics	307	23 %	70.6	236.4	2977.9
Transformer (1500 kg)	Steel	700	66 %	462	238	1750
	Copper	700	47 %	329	371	7000
	Plastics	100	23 %	23	77	970
Electronic equipment & transformer for electric vehicle (780 kg)	Steel	156	66 %	103	53	390
	Copper	156	47 %	73.3	82.7	1560
	Plastics	468	23 %	107.6	360.4	6285.6

3.4. 200 kVA Diesel generator set

The materials used to produce the Diesel generator can be dismantled, sorted and recycled. For every material, there is a specific recycle rate. This is the share of material that is recovered from the disposed material after sorting. Table 10 provides an overview of the materials used to produce the genset and the recycle rate of the individual materials. The material that cannot be recycled is used as 'output to technosphere' where the waste process is a combination of waste incineration and waste dumped in a landfill (J. H. Schmidt, 2010). Since the recycling rate for steel and cast steel are equal and SimaPro does not distinct separate waste flows for these materials, it is assumed that both waste flows are 'scrap steel'.

Table 10 – Recycled material Diesel generator set

Material	Mass in genset [kg]	Recycling rate	Mass recycled [kg]	Waste [kg]	Energy consumption for recycling [MJ]
Steel	1056.6	66%	697.4	359.2	2641.5

Cast steel	1056.6	66%	697.4	359.2	2641.5
Aluminium	1232.7	58%	715.0	517.7	8752.17
Copper	106.7	47%	50.1	56.6	1067
Plastic	70.4	23%	16.2	54.2	682.88

The recycling process consumes energy by e.g. melting metals. The energy used for recycling is dependent on the process per material. Therefore, the EoL phase has an ‘input from technosphere’ in the form of electricity. The energy consumption for recycling of the iron-steel industry is 2.5 [MJ/kg], for aluminium 7.1 [MJ/kg], and copper 10 [MJ/kg] (Cumbul Altay et al., 2011). The average energy consumption for recycling plastic is 9.7 [MJ/kg] (Arena et al., 2003). The last column of table 10 represents the total energy consumption for recycling the initial quantity of materials, using the energy values as described above. Combined, recycling the materials uses 15,785 MJ energy, which is used as input in the EoL process as ‘medium voltage electricity consumption in The Netherlands’.

4. Results

In this section the results per sub-research question are described using the calculation methods CML-IA and ReCiPe 2016. The main impact categories that will be focused on are: Global Warming Potential 100 (GWP100) and fine particulate matter formation (FPMF). There are only two impact categories since the output from the reviewed literature of the NMC lithium-ion battery for the production and the EoL phase does not specify e.g. land use, ecotoxity, acidification etc. (section 3.1.1).

4.1. Production phase

This section will show the results of the production phase of a Greener Battery and a 200 kVA Diesel generator set for the three impact categories.

4.1.1. Impact category: Global Warming Potential 100 (GWP100)

Global Warming Potential is an impact category that measures climate change with kilograms carbon-dioxide equivalent as unit. However, it does not solely focusses on carbon-dioxide, but also for example the greenhouse gas methane, since this has an equivalent of ~25 times the heat collecting impact compared to carbon-dioxide.

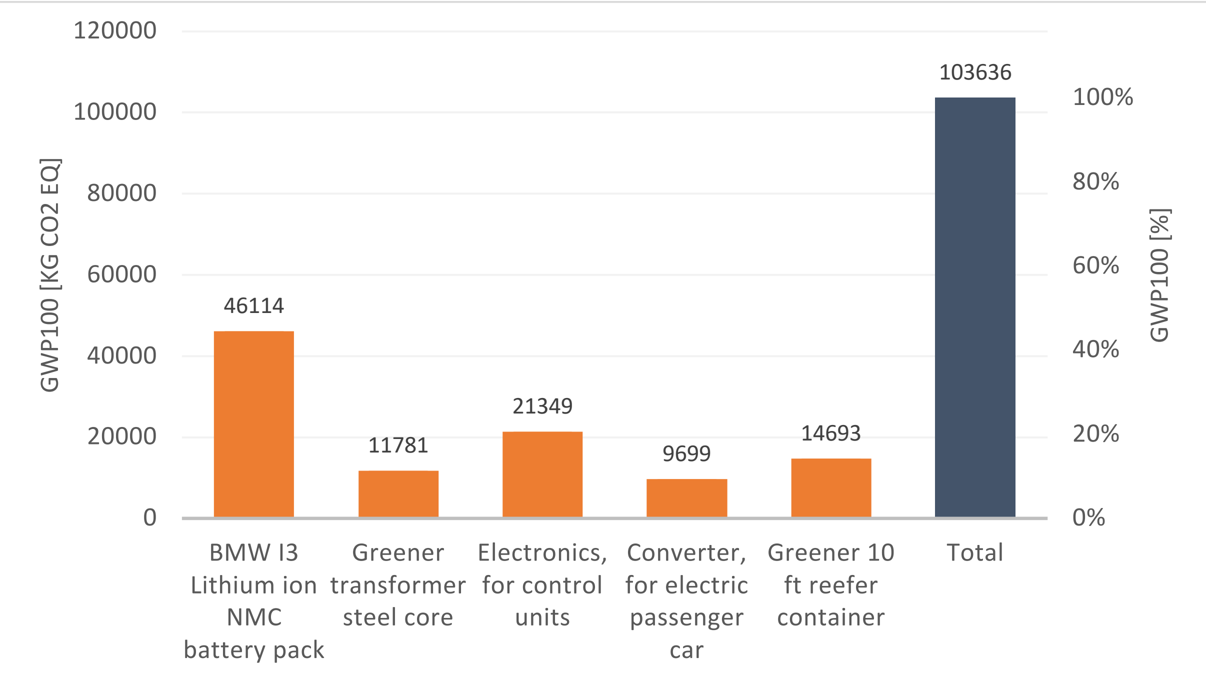


Figure 5 – Global Warming Potential 100: Greener Battery production phase

Figure 5 shows the Global Warming Potential 100 per component of the Greener Battery. The total GWP100 is 103,636 [kg CO_2 eq]. The component from the Greener Battery that has the largest share of GWP100 is the BMW I3 lithium-ion NMC battery pack with 46,114 [kg CO_2 eq], or 44.5% of the total GWP100. Next to the lithium-ion battery, the components have an environmental impact of:

electronics for control unit 21,349 [kg CO_2 eq] (20,6%), reefer container 14,693 [kg CO_2 eq] (14%), transformer 11,781 [kg CO_2 eq] (11.4%), and converter 9,699 [kg CO_2 eq] (9.4%).

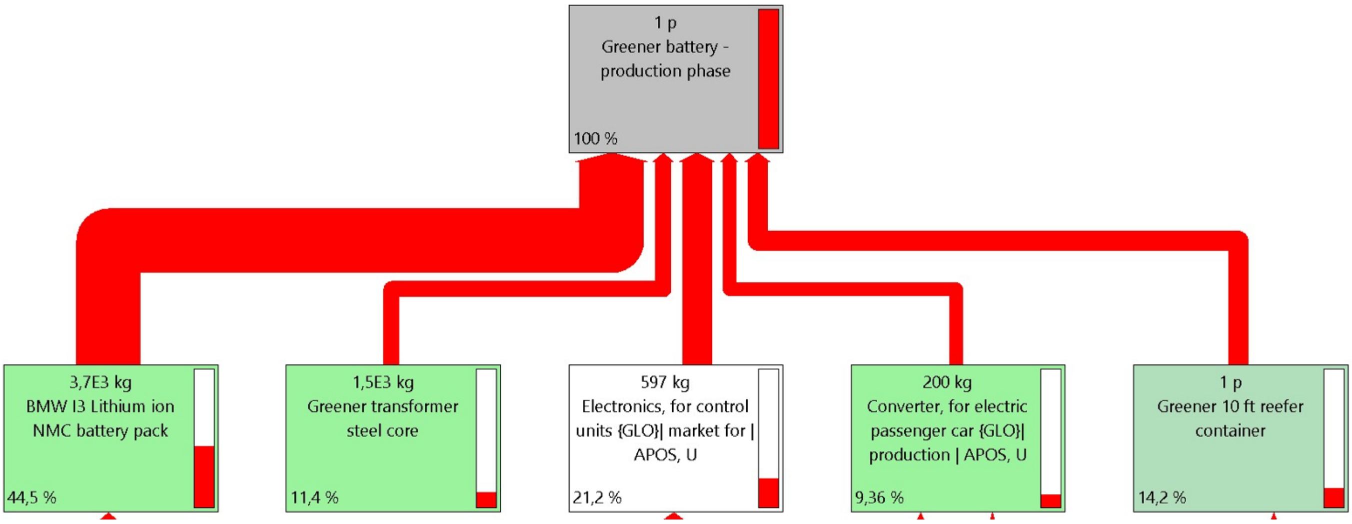


Figure 6 – Flow chart GWP100 Greener battery production

Figure 6 visualizes the GWP100 to produce one Greener Battery where a larger arrow refers to a larger GWP100. This figure also shows the mass of the single components. From this figure, the components with an larger GWP100 can be recognized. For example, the converter contributes for ~ 10% (9.36%) of the total GWP100 for production and has a weight of 200 kg. The transformer also contributes for ~ 10% (11.4%) of the total GWP100 while the transformer has a weight of 1500 kg. Therefore, if the producer of the battery wants to reduce the CO_2 emissions, it is more efficient to reduce 1 kilogram of converter compared to 1 kilogram of transformer, since the emission/mass ratio is larger at the converter.

The environmental impact of the electricity used to produce the BMW I3 battery packs is 1120 [kg CO_2 eq]. This is 11.7% of the total environmental impact to produce the battery pack (not displayed in figure 5 and 6). The energy to produce every component is embedded in the emissions of that component and not displayed separately.

Figure 7 shows the GWP100 of the production of a 200 kVA Diesel generator set from Aggreko. The total emissions are 53,086 [kg CO_2 eq]. Electricity to produce the genset, high voltage and medium voltage, is emitting the largest quantity of CO2 equivalent, respectively 27,835 (52.4% of total) and 16,577 [kg CO_2 eq] (31.2% of total). The distinction between high voltage and medium voltage comes from the literature analyses as described in section 3.1.6. For the materials used to produce the genset, the plastic polypropylene has the smallest GWP100 with 143 [kg CO_2 eq] (0.3% of total). This is not surprising because this material is used the least in the production of a Diesel generator (section 3.1.6).

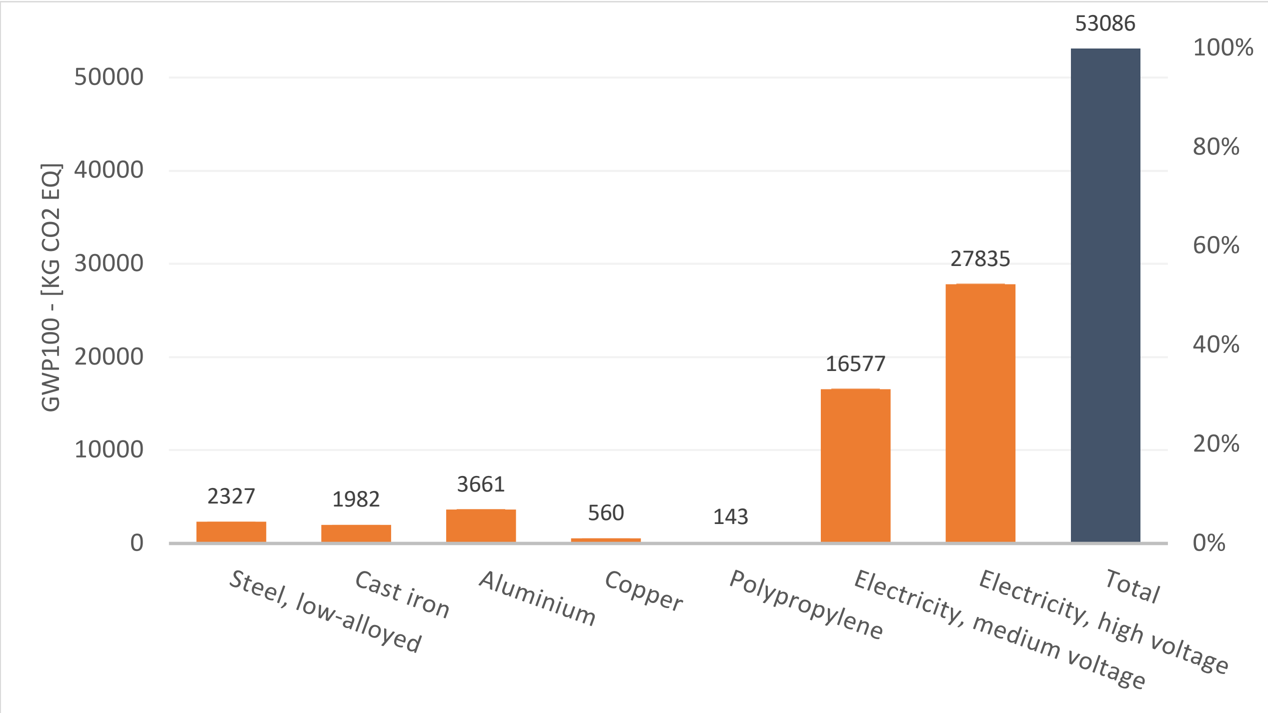


Figure 7 – Global Warming Potential 100: 200 kVA genset production

Figure 8 displays a flow chart of the production of the genset. All materials combined form only 16.3% of the total emissions to produce a genset. From the flow chart it becomes clear that the electricity used for production is responsible for 83.7% of the total CO_2 emissions.

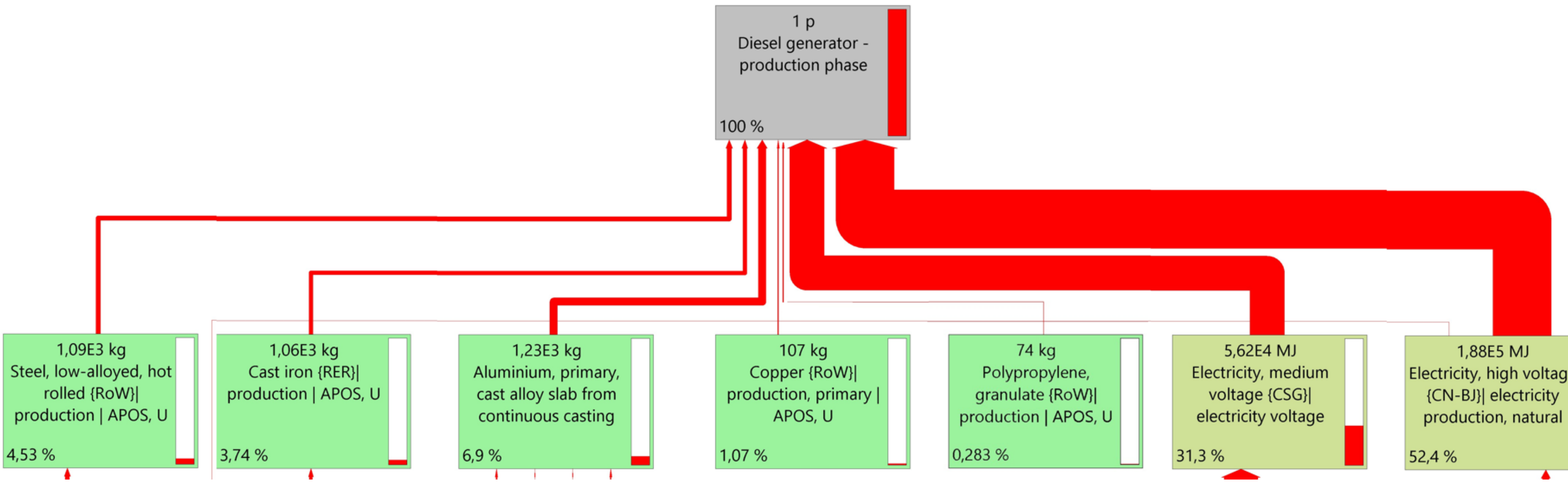


Figure 8 – Flow chart GWP100 Diesel generator production

Combining the above values creates the possibility to compare the GWP100 for the production of a battery and a generator. Figure 9 displays the total CO_2 eq emission of both production phases.

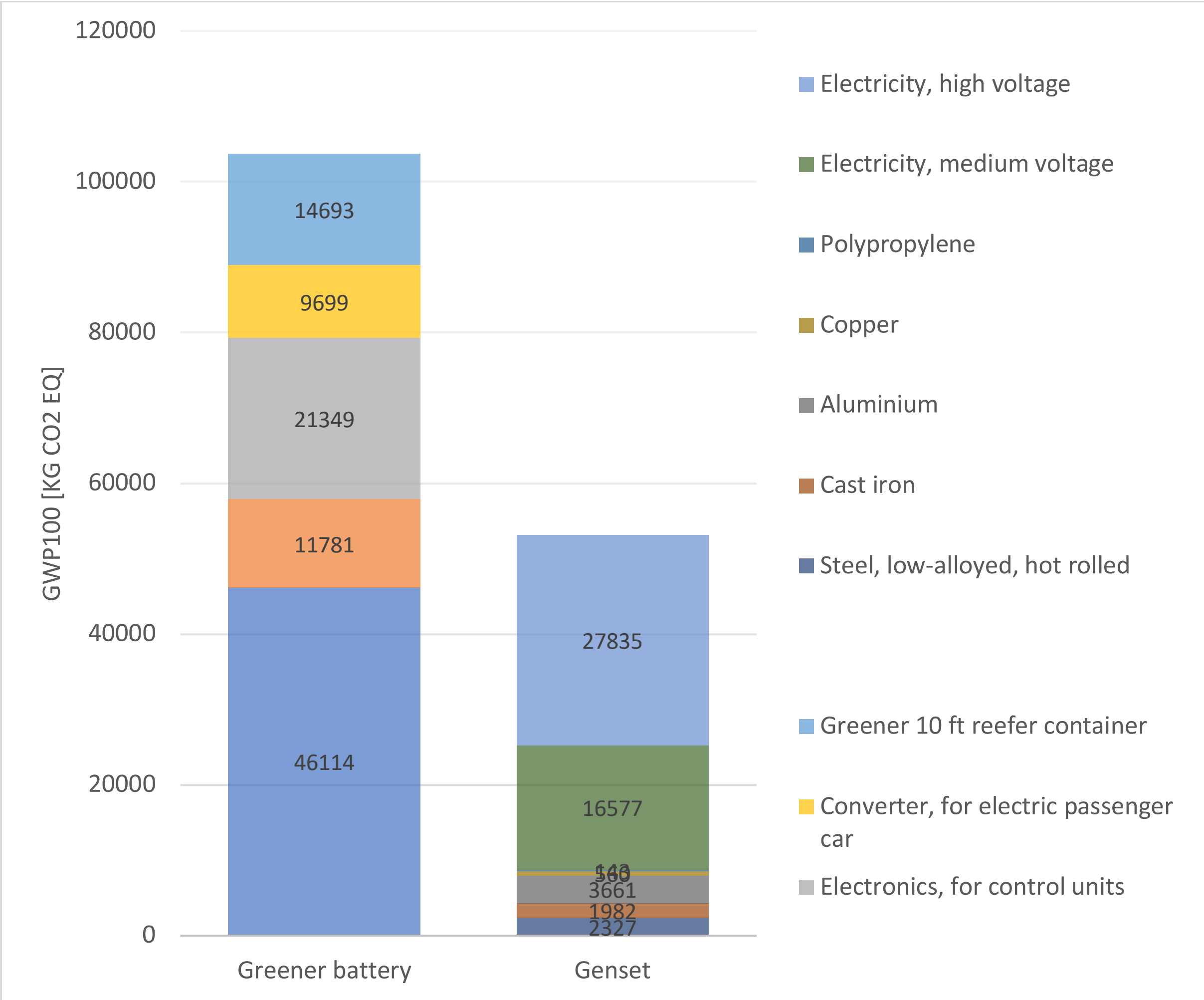


Figure 9 – GWP100 comparison: production phase

From figure 9 it is clear that the GWP100 for the production of the battery is larger compared to the production of the genset. This is mainly due to the production of the lithium-ion batteries. Also, the genset production could even have a smaller GWP100 if it is produced with a more environmental friendly electricity mix. BMW already produces the I3 batteries using wind energy. If during production of these batteries a less environmental friendly electricity mix was used, the difference between the GWP100 of the battery and the genset would have been even larger. Figure 10 represents the production of a 200 kVA Diesel generator set if it is manufactured with the same electricity mix as the battery, the 2.5 MW wind turbines. This replaces the medium and high voltage electricity production. The GWP100 is 10,253 kg CO_2 eq compared to 53,086 kg CO_2 eq, 19% of the initial CO_2 eq emissions.

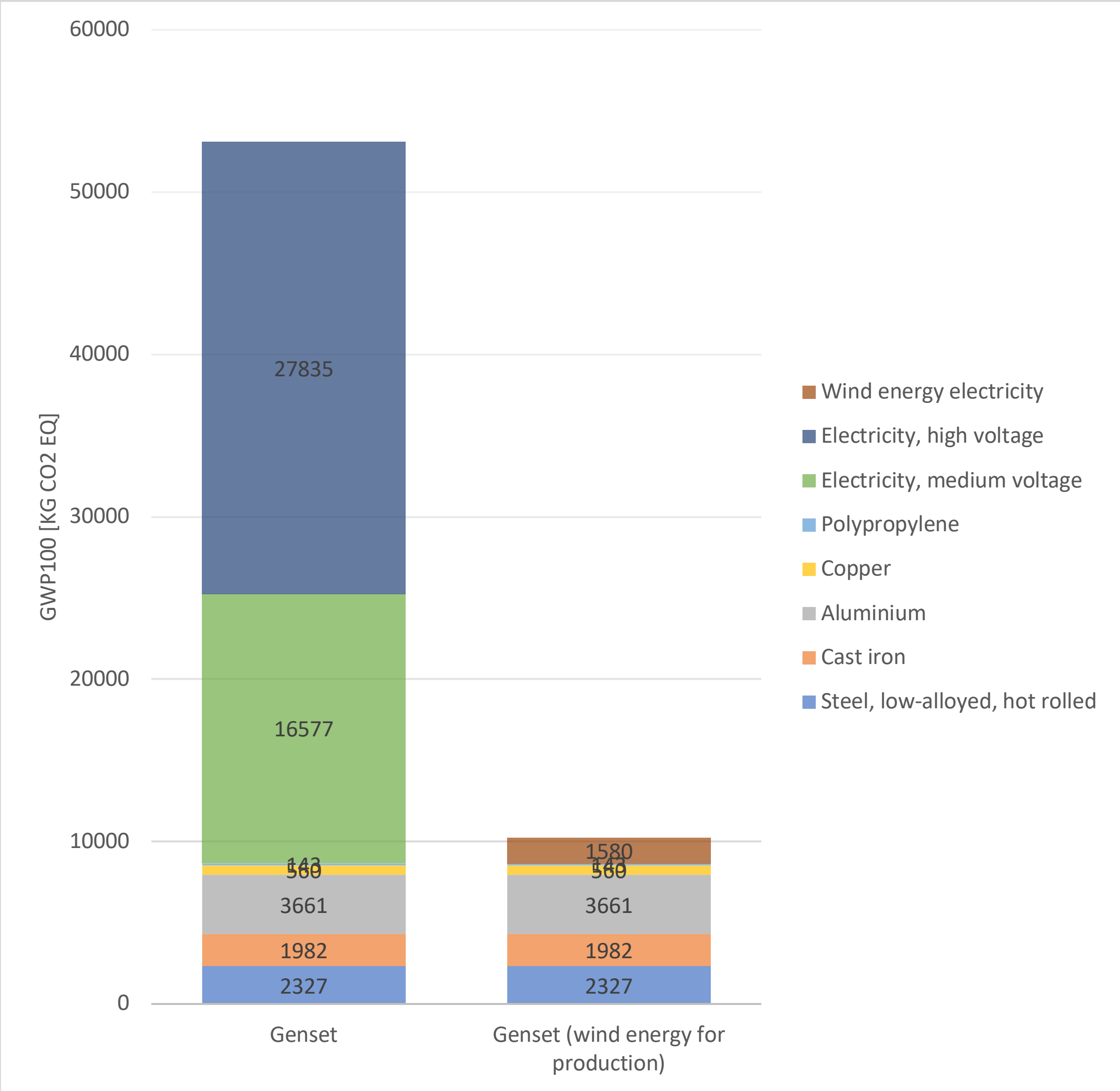


Figure 10 – GWP100 Diesel generator set comparison: type of electricity for production

4.1.2. Impact category: Fine Particulate Matter Formation (FPMF)

Figure 11 shows the Fine Particulate Matter Formation emissions of the Greener battery during the production phase. The total emissions are 299 kg PM2.5 eq. These are particles smaller or equal to 2.5 micro meter. Again, the production of the lithium-ion battery pack has the largest share of FPMF with 109 kg. Interestingly, the 1500 kg transformer had a GWP100 of 11.4% of the total emissions, however, the share of FPMF is larger with 27.0% of the total FPMF emissions. This is due to the large quantity of copper used in the transformer.

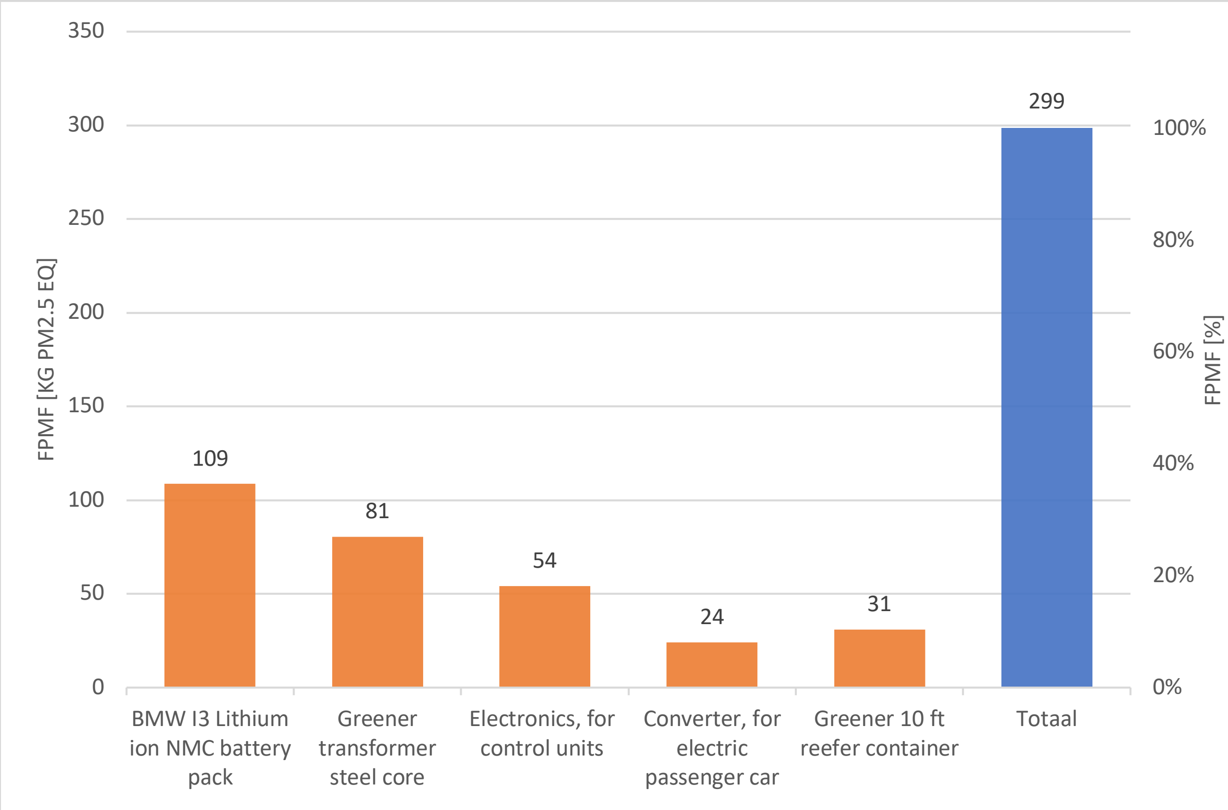


Figure 11 – Fine Particulate Matter Formation: Greener battery production phase

Figure 12 shows the FPMF emissions of the Diesel genset production phase. The total emissions are 70.17 kg. The electricity used during production has the largest contribution to the total emissions with combined 35.4 kg. Interestingly, the medium voltage has the largest FPMF emissions while the high voltage electricity had the largest GWP100.

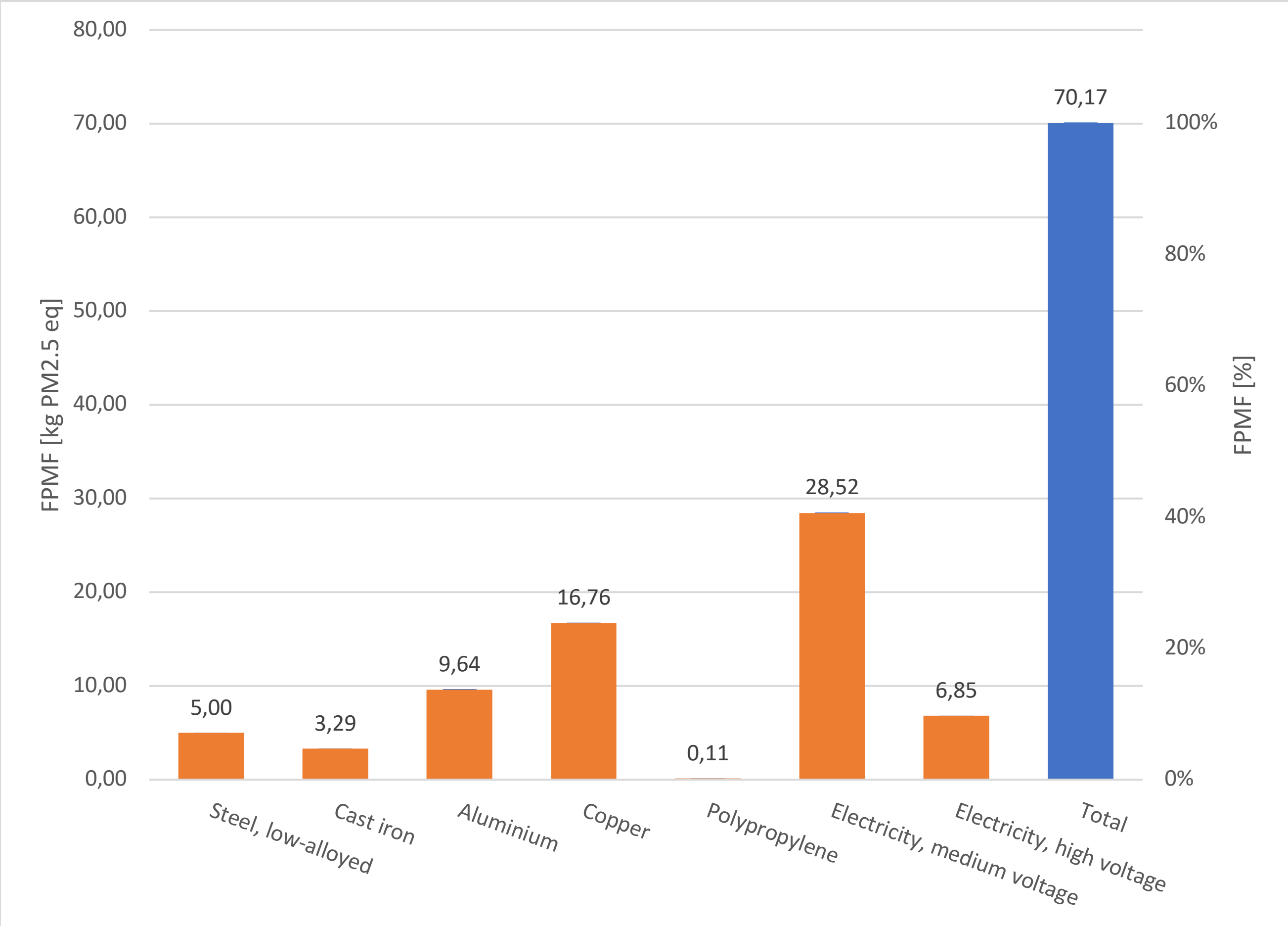


Figure 12 – Fine Particulate Matter Formation: Diesel generator production phase

Comparing the FPMF emissions of the Greener battery and the 200 kVA genset generates figure 13. The Greener battery has more than three times the emissions of FPMF compared to the genset. This is mainly due to the large share from the batteries and the share of copper in the 1500 kg transformer. The transformer itself emits 81 kg PM2.5 eq of which 67.4 kg comes from the copper in the transformer.

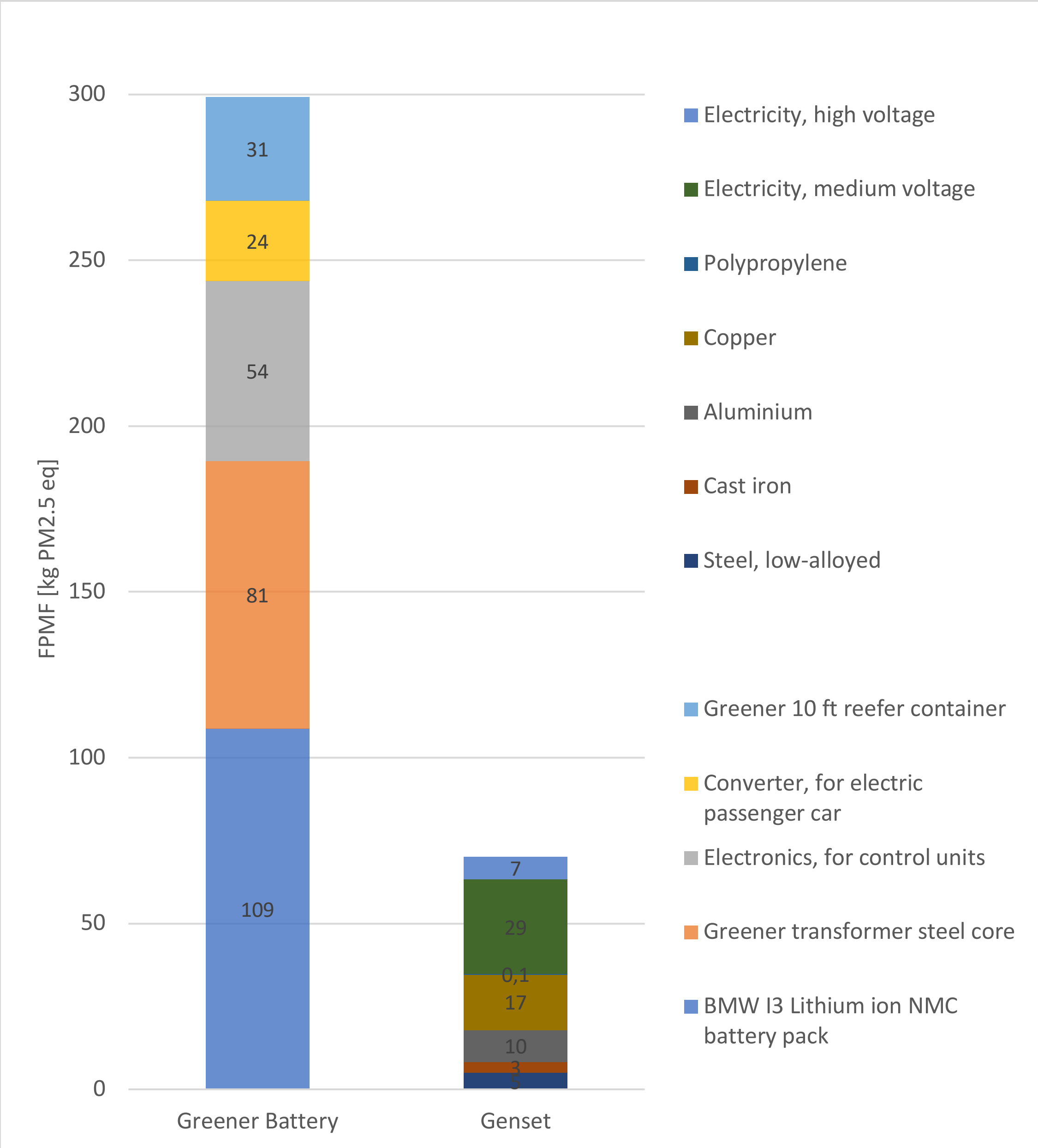


Figure 13 – Fine Particulate Matter Formation: production phase comparison

The production of the generator set has a total emission of 70,17 kg PM2.5 eq with the largest share due to the electricity consumption. In figure 14, the standard electricity mix is replaced by electricity generated by wind power to give insight in the difference between the type of electricity used for production. The total environmental impact for FPMF is 34.8 kg PM2.5 eq. This is equal to 50% of the initial emissions. Although it is a reasonable reduction, the reduction of GWP100 due to the use of wind energy for production is more.

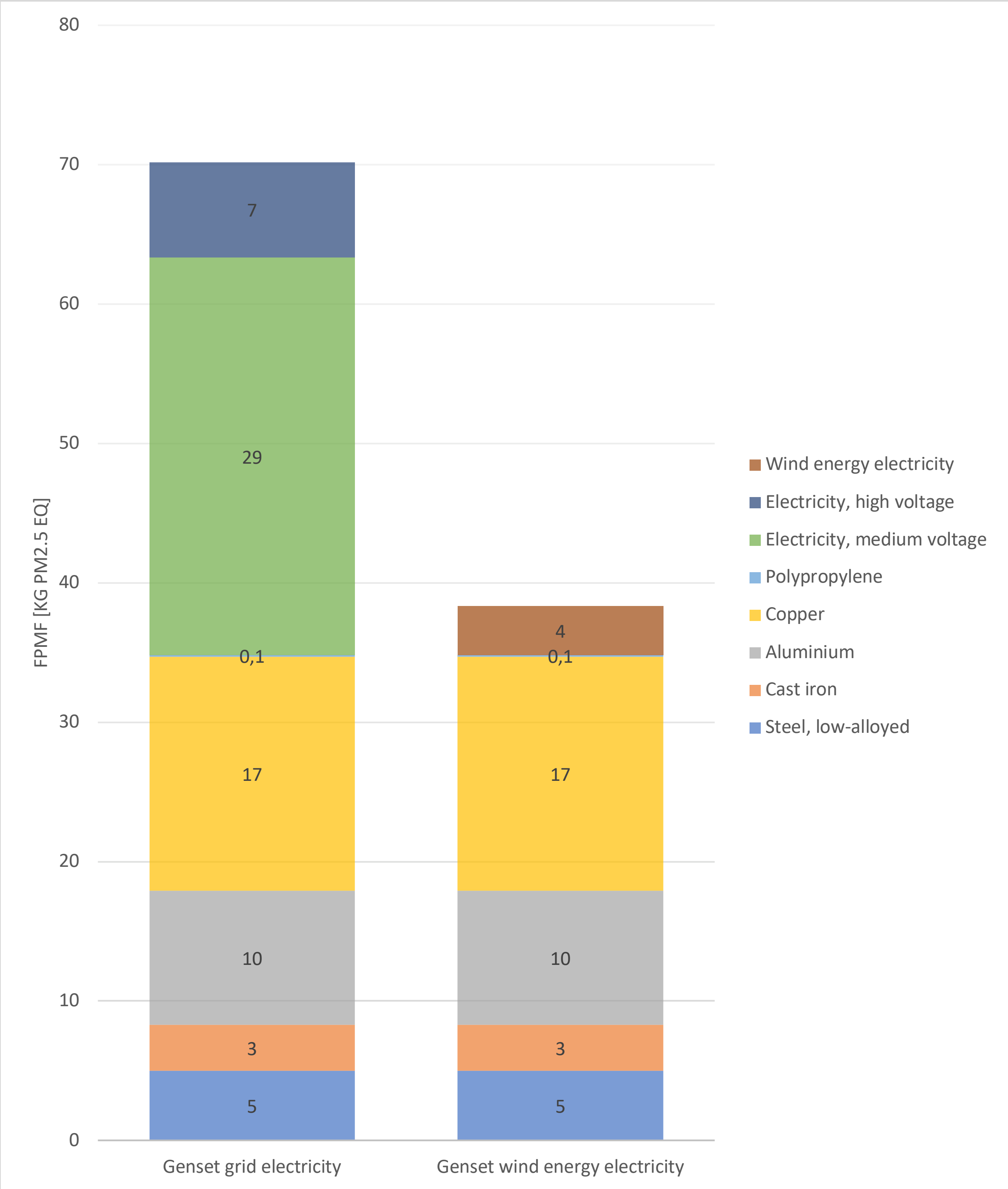


Figure 14 - GWP100 Diesel generator set comparison: type of electricity for production

4.2. Use phase

This section will show the results of the use phase of a Greener Battery and a 200 kVA Diesel generator set for the two impact categories.

4.2.1. Impact category: Global Warming Potential 100 (GWP100)

In figure 15, all bars represent the environmental impact of GWP100 for a power output of 1,600 MW electricity. The first four bars represents the GPW100 with the four scenarios regarding charge method for the Greener battery. Charging the Greener battery during the entire lifetime solely with a 200 kVA genset (scenario 1) has a larger GWP100 compared to charging it solely using a grid connection (scenario 2). Scenario 3 represents the combination of charge methods where the genset charges the battery 32% of the time and the grid 68% of the time. Notable from this data, in scenario 3 the emissions accounted for charging by a grid connection are 59% of the total. This is due to the lower carbon intensity of electricity from the grid even though the genset can run on its optimum load. The other 41% GWP100 comes from charging the battery 32% of the time. Scenario four represents the GWP100 if the power input of the battery comes solely from wind energy.

The last bar of figure 15 represents the GWP100 of the Diesel genset use phase. This represents the combustion of 617,469 kg of Diesel with an efficiency of 22.1% due to the average load of 12%. Comparing the four scenarios from the battery and the genset, the use phase of the genset has a larger GWP100 with ~800,000 kg CO_2 eq difference in the advantage for the battery in scenario 1, and even ~2,277,000 kg CO_2 eq difference in scenario 4. Scenario 3 represents the most realistic scenario with a combination of battery charging by genset and grid, and this has an advantage for the battery of ~114,000 kg CO_2 eq.

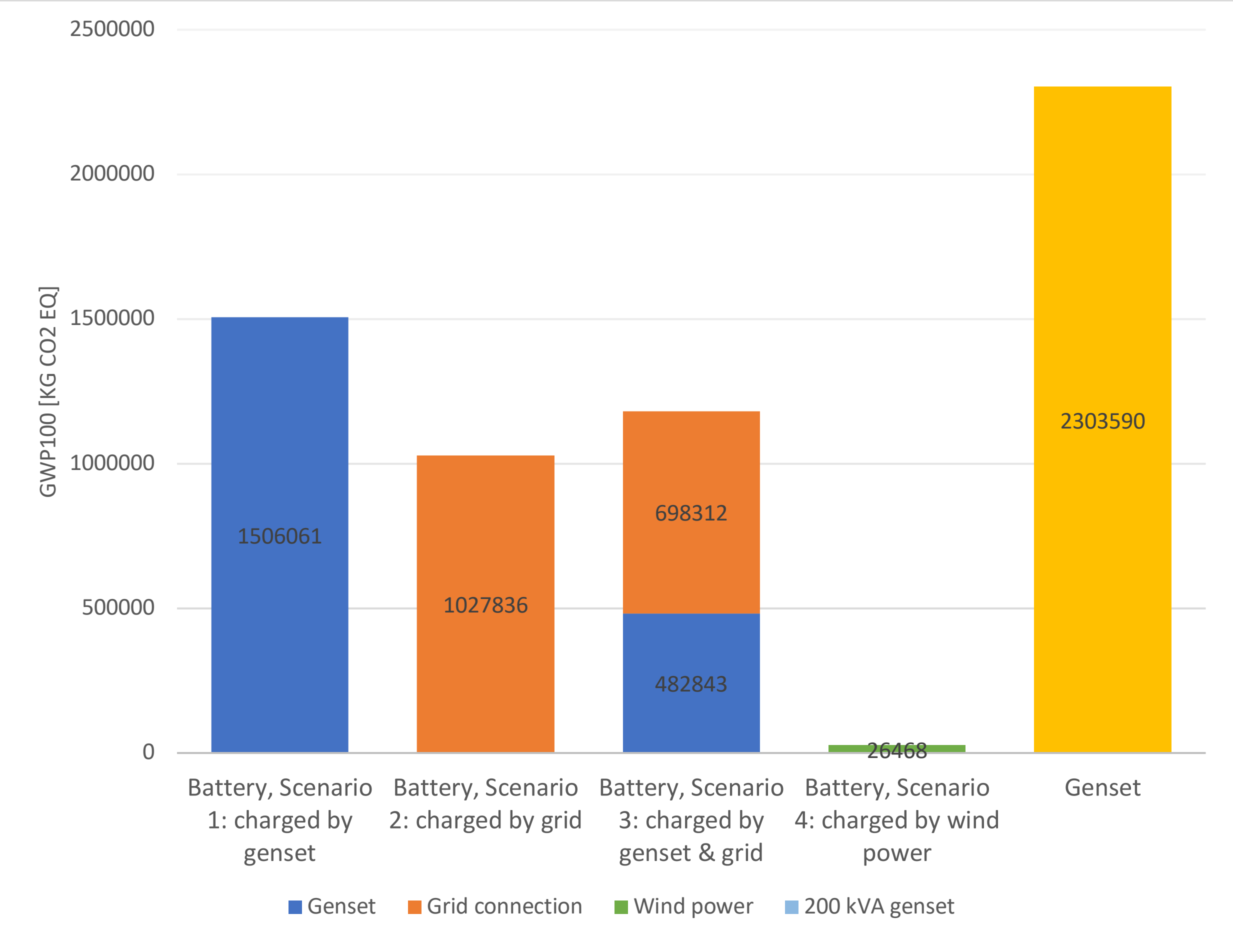


Figure 15 – Global Warming Potential 100: Greener battery and Diesel generator set

4.2.2. Impact category: Fine Particulate Matter Formation (FPMF)

Figure 16 represents the Fine Particulate Matter Formation for the use phase of a Greener battery and a 200 kVA genset, both delivering 1,600 MW electricity. Scenario 1 has the largest FPMF for the battery with 4267 kg PM2.5 eq. Combining the charge methods (scenario 3) results in a FPMF of 1597 kg. This is mainly due to the share of charging it by the genset (85.7%) while the battery is only charged by the genset 32% of the time. Scenario four is, same as with the GWP100, the most positive scenario with an FPMF of only 59 kg PM2.5 eq in the entire use phase of the battery. For the genset, less optimal combustion generates a larger share of particulate matter formation. This results in 6658 kg PM2.5 eq emission for the Diesel generator set.

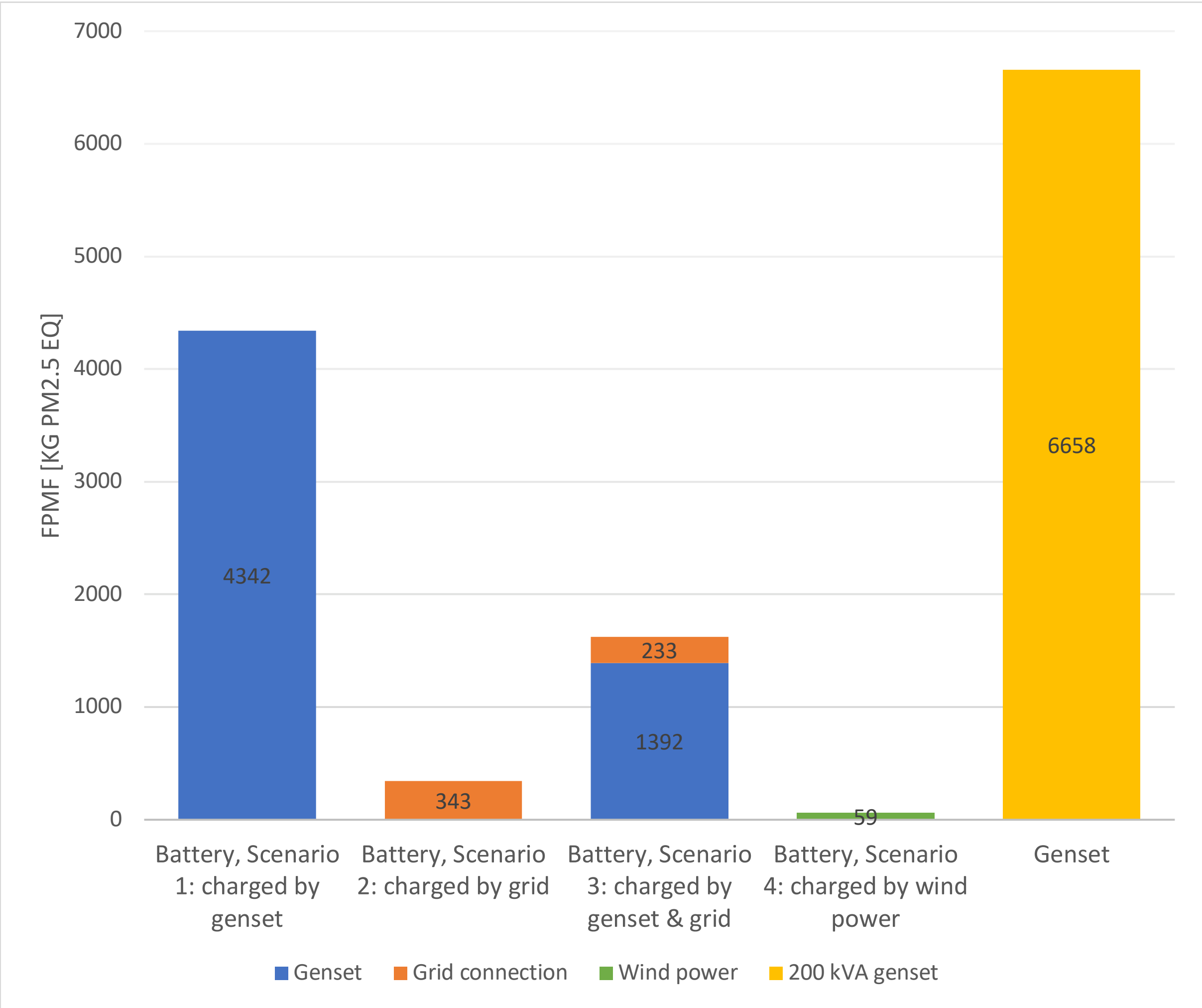


Figure 16 – Fine Particulate Matter Formation Greener battery and Diesel generator set

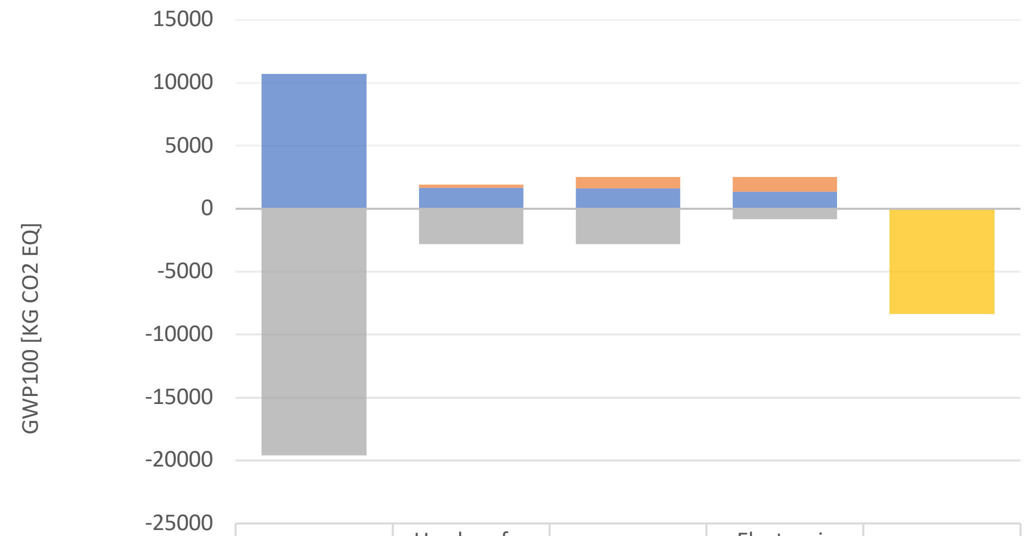
4.3. End-of-Life phase

This section will show the results of the End-of-Life phase of a Greener Battery and a 200 kVA Diesel generator set for the two impact categories.

4.3.1. Impact category: Global Warming Potential 100 (GWP100)

Figure 17 shows the GWP100 for the EoL phase of the Greener battery. The total GWP100 is -8341 kg CO_2 eq. From the figure it is clear that battery recycling has the largest energy demand for recycling. However, the avoided emissions are also the largest with almost 20,000 kg CO_2 eq. According to the reviewed articles, this is mainly due to the reuse of aluminium, copper, and steel, even though these are not the most valuable materials, like nickel and cobalt (Cusenza et al., 2019; Qiao et al., 2019). Notably, the emissions from battery material that is treated as waste is not visible since the avoided emissions are an average of the net avoided emissions. This is because there is no distinction made in the literature of the share of environmental impact that comes from the energy used for recycling and environmental impact from scrap materials.

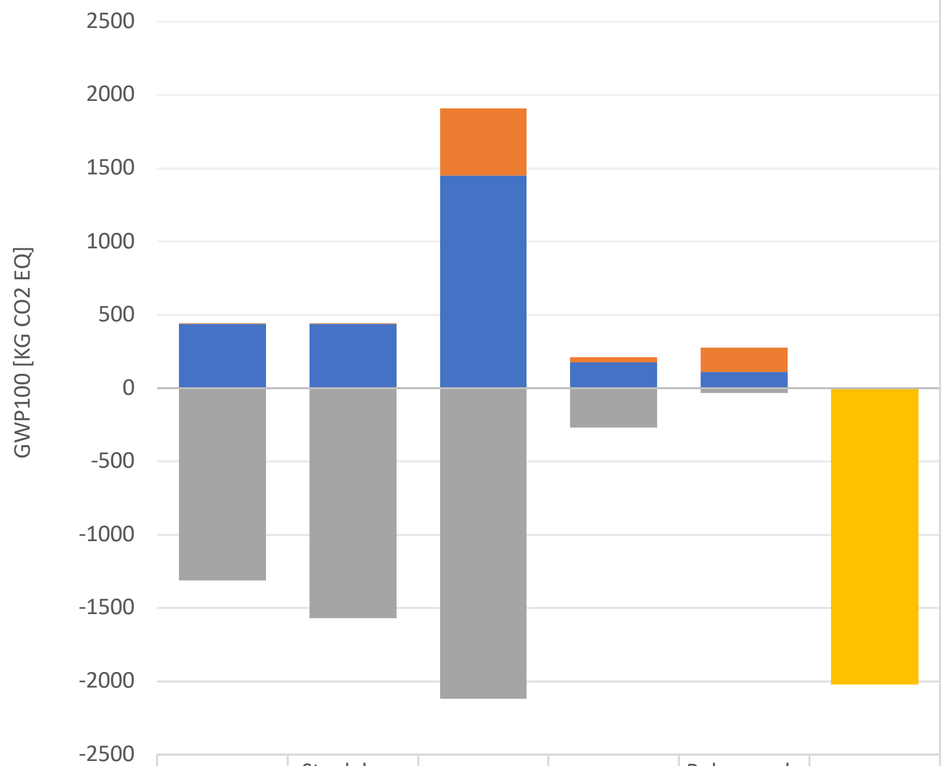
The avoided emissions due to material reuse are almost equal for the reefer container and the transformer. For the reefer container this is due to a combination of the reuse of steel (-1620 kg CO_2 eq avoided) and aluminium (-1050 kg CO_2 eq avoided). The avoided emissions from the transformer are mainly due to the reuse of copper (-1740 kg CO_2 eq), followed by steel (-1010 kg CO_2 eq). The environmental impact can most efficiently be reduced by using an electricity mix with a lower carbon intensity compared to the electricity grid from the Netherlands that is used now as input for power use during recycling.



	Batteries	Used reefer container	Transformer	Electronic scrap	Total
Total saved emissions [kg CO2 eq]					-8341
Avoided emissions due to material reuse [kg CO2 eq]	-19596	-2814	-2797	-833	
Emissions due to scrap material [kg CO2 eq]		252	940	1149	
Emissions due to electricity use [kg CO2 eq]	10727	1660	1610	1360	

Figure 17 – GWP100 Greener battery recycling phase

Figure 18 represents the GWP100 of the EoL phase of the Diesel generator set. The EoL phase of the Diesel genset avoids a total of 2021 kg CO_2 eq. Although every material consumes electricity and thereby emits GHG's for the recycling process, the combined emissions from the recovered materials results in an overall negative GWP100. Processing aluminium as waste has the largest GWP100 with 461 kg CO_2 eq. This is mainly due to the electricity used in this process (1540 kg CO_2 eq). Interestingly, the emissions from scrap steel and cast iron are very low, only 3 kg CO_2 eq, while the avoided emissions from these materials are -1570 and -1310 kg CO_2 eq accordingly.

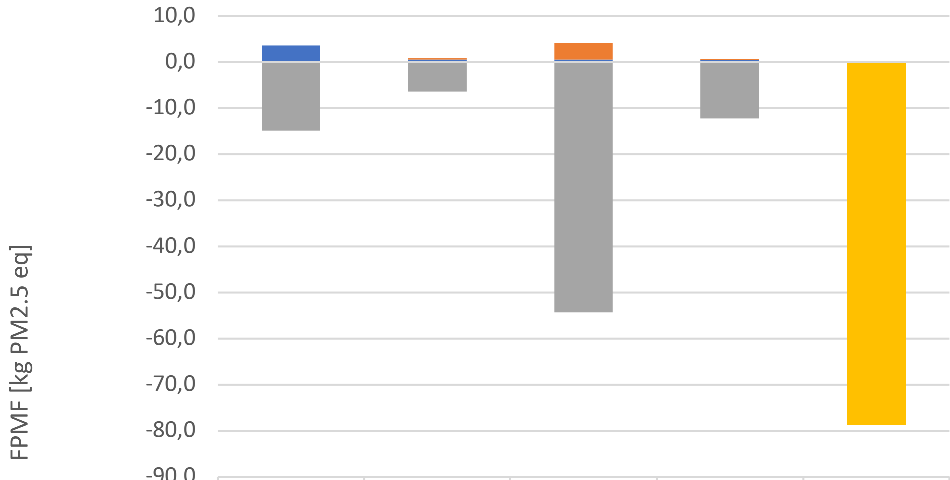


	Cast iron	Steel, low-alloyed	Aluminium	Copper	Polypropylene	Total
Total saved emissions						-2021,27
Avoided emissions due to material reuse	-1310	-1570	-2120	-267	-32,9	
Emissinons due to scrap material	3	3	461	34	165	
Emissions due to electricity use	437	437	1450	176	113	

Figure 18 – GWP100 EoL phase Diesel generator set

4.3.2. Impact category: Fine Particulate Matter Formation (FPMF)

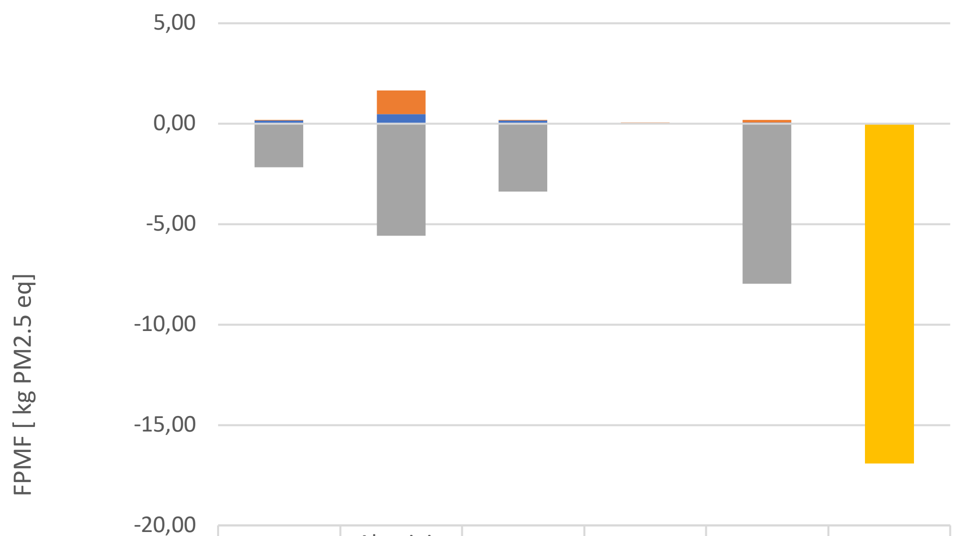
Figure 19 represents the environmental impact of FPMF of the Greener Battery. Where the GWP100 of from the Greener battery is mostly dominated by the 8 installed EV batteries, FPMF environmental impact comes mostly from the reuse of copper in the transformer, with -52.1 kg PM2.5 eq, and only - 2.2 kg PM2.5 eq from steel (together 54.3 kg). Also, the reuse of materials from the battery avoids 14.9 kg PM2.5 eq. These are net avoided emissions. The electricity used for recycling has a limited impact on the FPMF for every material in the Greener battery. The total avoided FPMF emissions is -78.6 kg PM2.5 eq.



	Batteries	Used reefer container	Transforme r	Electronic scrap	Total
Total saved emissions [kg PM2.5 eq]					-78,6
Avoided emissions from material reuse [kg PM2.5 eq]	-14,9	-6,3	-54,3	-12,3	
Emissions due to waste materials [kg 2.5PM eq]		0,2	3,6	0,3	
FPMF due to electricity use [kg PM2.5 eq]	3,6	0,6	0,5	0,5	

Figure 19 – FPMF Greener battery recycling

Figure 20 represents the FPMF for the recycling phase of the Diesel generator set. Similar to the battery, the reuse of copper has the largest avoided environmental impact for FPMF with -7.98 kg PM2.5 eq. The reuse of aluminium results in the avoidance of -5.59 kg PM2.5 eq. The aluminium waste contributes with the largest share of emissions for recycling with 1.18 kg PM2.5 eq. The total avoided emissions due to the recycling process of the Diesel generator set is -16.93 kg PM2.5 eq.



	Cast iron	Aluminium	Steel	Plastic	Copper	Total
Total saved emissions [kg PM2.5 eq]						-16,93
Avoided emissions from material reuse [kg PM2.5 eq]	-2,18	-5,59	-3,37	-0,03	-7,98	
Emissions due to waste materials [kg PM2.5 eq]	0,01	1,18	0,01	0,01	0,14	
FPMF due to electricity use [kg PM2.5 eq]	0,15	0,48	0,15	0,04	0,06	

Figure 20 – FPMF Diesel genset recycling

4.4. Overview: Total environmental impact of cycling 1,600MWh

Figure 21 provides an overview of the environmental impact GWP100 of all scenarios made in this research. Table 11 gives an overview of the specifications per scenario. This table is also applicable for the FPMF environmental impact of figure 22. The largest share of the GWP100 GHG emissions is in most scenarios from the use phase. However, in scenario four and seven, the production phase of the Greener battery exceeds the environmental impact compared to the use phase due to charging the battery with wind energy. For the Diesel genset, changing the electricity necessary for production from the Chinese grid to wind power has an effect of only 1.8% reduction compared to the total CO_2 eq emissions. For both the Greener battery and the Diesel genset, a change in the use phase has the largest effect on the GWP100.

At the moment, the most relevant scenario is scenario three, where the battery is charged using a combination of the grid and a genset. If the battery is only charged by using wind power, scenario four, the difference by charging it with the grid and a genset is 89.7% reduction in GWP100. For the Diesel generator set, a change in the use phase has the largest impact of the three phases regarding GWP100. In scenario six and seven the diesel generator has half of the time an efficient load of 80% and half of the time the average load of 12%. This reduces the GWP100 with 79.7% compared to the first three scenarios where the genset is produced with electricity from the Chinese grid and the average load of 12% in the use phase. In scenario six, the generator set has a lower GWP100 compared to the Greener battery.

The EoL phase has the smallest contribution to the GWP100 and is almost not visible in figure 21. In scenario three, the EoL is less than 1% (0.66%) of the total GWP100 for the Greener battery; and even less than 0.1% (0.086%) of the total GWP100 for the Diesel genset.

The largest difference in GWP100 between the Greener battery and the Diesel generator set is scenario four where the battery emits 5.3% CO_2 compared to the total CO_2 eq emissions from the Diesel genset. Although scenario six is not realistic due to the high efficiency and the comparison is only made to give an indication of the importance of the use phase, this scenario has a lower value of GWP100 for the genset where it emits 38.1% compared to the total emissions of the Greener battery in scenario six. The most realistic scenario, scenario three, the Greener battery emits 53.3% CO_2 eq compared to the total emissions from the Diesel generator.

A break-even point is calculated by creating two linear formulas from the Green battery and the genset. Assuming the lifetime of the Greener battery is ten years, the break-even point in scenario three is after 3.8 years. This means that the Greener battery cancelled out the larger share of GWP100 in the production phase after 3.8 years by having an overall better GWP100 compared to the genset.

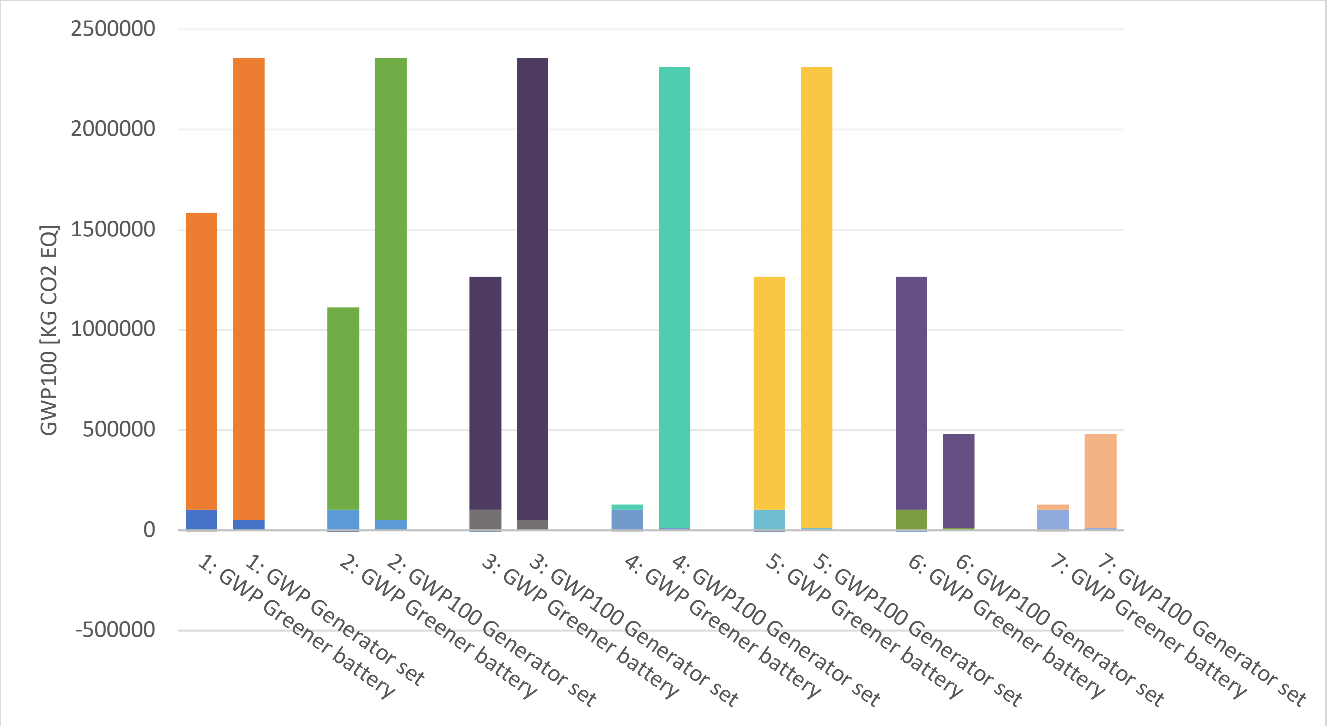


Figure 21 – GWP overview of LCA all phases

Table 11 – Scenario overview

	Greener battery	**Diesel Generator set**
Scenario 1	Battery only charged by genset	Production phase electricity from Chinese grid
Scenario 2	Battery only charged by NL grid	Production phase electricity from Chinese grid
Scenario 3	Battery charged by grid and genset combination	Production phase electricity from Chinese grid
Scenario 4	Battery charged by wind power	Production phase electricity from wind power
Scenario 5	Battery charged by grid and genset combination	Production phase electricity from wind power
Scenario 6	Battery charged by grid and genset combination	Production phase electricity from wind power Use phase: 50% optimum load, 50% low efficiency load
Scenario 7	Battery charged by wind power	Production phase electricity from wind power Use phase: 50% optimum load, 50% low efficiency load

Figure 22 represents the FPMF of both the Greener battery and the Diesel generator set with the seven scenarios as described in table 11. Equally as the GWP100, the use phase of the two technologies has the largest impact for the FPMF. Scenario one has the largest impact for the Greener battery due to charging it with a Diesel generator in the use phase. Scenario four has the lowest FPMF for the Greener battery due to charging it by wind power. Interestingly, the difference with FPMF between scenario two and scenario four are not as large compared to the GWP100 due to the effect of the Diesel generator. Therefore, for the FPMF it is less important to charge the Greener battery with a grid connection or by wind power, although this is more important for the GWP100.

The EoL phase of both the technologies have the smallest share of FPMF from the three phases. In scenario three, the EoL phase for the battery is 4.3% of the total FPMF; and only 0.25% for the Diesel generator set.

The diesel generator has in all scenarios the largest environmental impact for FPMF. Scenario six and seven where die generator is running half of the time on its most efficient load is saving 20.2% of the FPMF emissions compared to the first three scenarios. In the most realistic scenario, scenario three, the Greener battery emits 27.5% compared to the total FPMF emissions of the Diesel generator.

The break-even point for scenario three where the FPMF from the production of the Greener battery are cancelled out by the overall better performance of the battery is after 0.32 years. This means the battery needs to be more than 0.3 years in operation to be beneficial regarding FPMF compared to a diesel generator set.

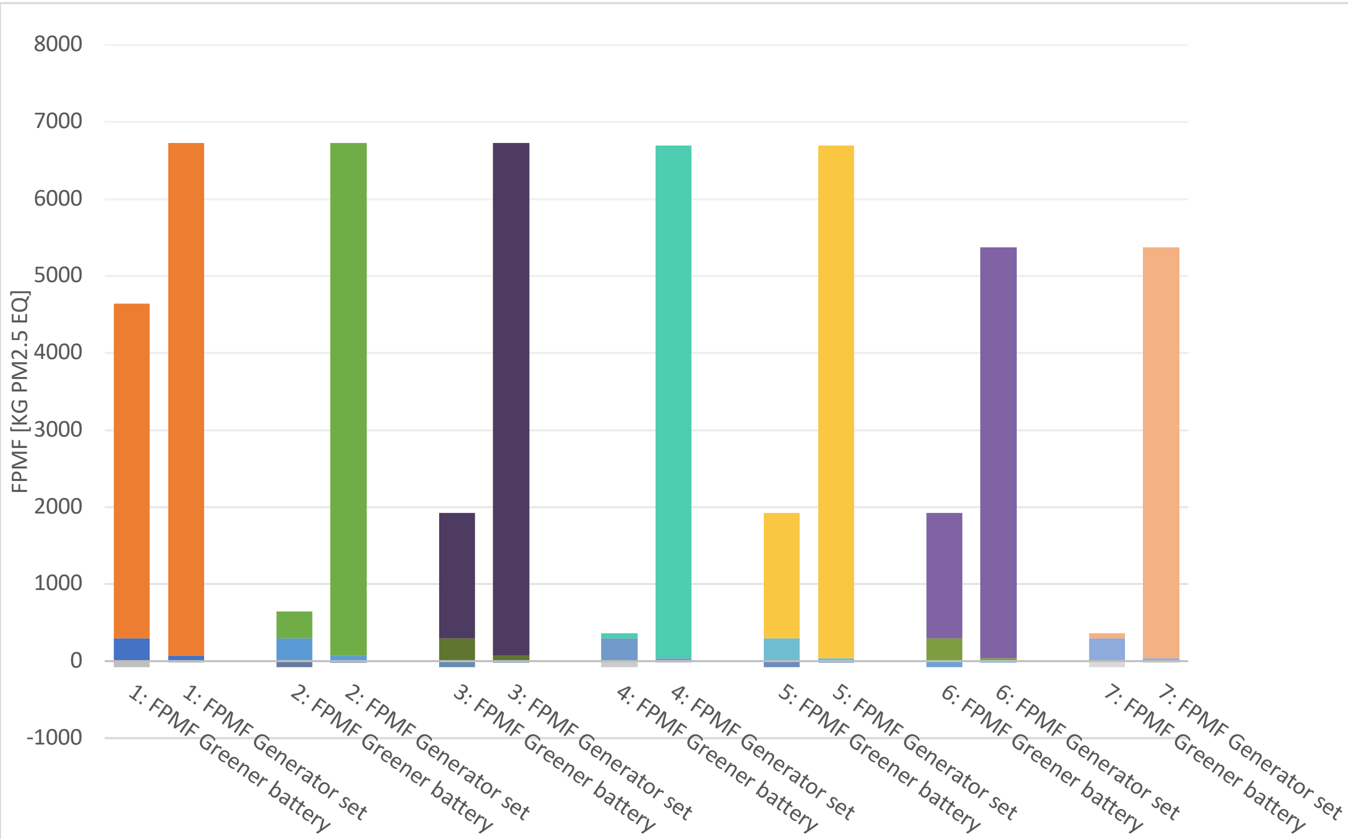


Figure 22 – FPMF overview of LCA all phases

5. Discussion

This LCA is applicable for the Greener battery during the setting *cycling*. This means that the battery is charged and the input source is then switched off. The battery also has two types of peak shaving settings. With these settings only the larger peaks are delivered by the Greener battery and the more constant energy demand is delivered by the Diesel power input. Further research is advised on the environmental impact of these different settings, with impact categories that also include e.g. nitrogen emissions and abiotic depletion of resources. These impact categories are not taken into account in this research due to the absence of data in the literature for a lithium-ion NMC battery that is used for the production and the EoL phase.

Although the software SimaPro is the most common used software for LCA's and it is existing and updating its databases for more than 30 years, the outcome of this research could be different whenever the method is changed. The End-of-Life phase is the most uncertain part of this research, mainly due to the aged data used for waste treatment processes in SimaPro, mostly from 2004. This is also the reason that an equal recycle rate for the Greener battery and the genset is selected from literature and used as input for SimaPro, instead of selecting the recycling processes in SimaPro. For example, the recycling process of lithium-ion batteries in SimaPro does not specify the recovery of any materials but solely the incineration and landfill of the batteries. Apart from the waste treatment processes, the processes selected for this research in SimaPro are more up-to-date and are updated regularly.

5.1. Production phase

Results from the production phase of the Diesel generator make clear that 72% of the GWP is from the used electricity. The battery uses electricity generated by wind turbines and stored by used lithium-ion batteries, this type of information is unknown for the Diesel generator set since there are no specifications of production location. Therefore, the additional scenario is created in the last section of the results. The GWP of the Diesel generator set will be lower if an electricity mix with a larger share of renewable energy is used.

The quantity of energy used for battery assembly by Alfen is unknown. However, it is assumed that this will be a small order of magnitude since all parts are delivered prefab at the producer. Also the transportation of single components is left out of scope for both the battery and the genset.

5.2. Use phase

The use phase has the largest environmental impact of the three phases for GWP and FPMF. From previous research at Greener, the average load on a 200 kVA Diesel generator set is derived.

However, in practice, a combination of types of Diesel generator sets can be installed. For example, for larger festivals a specific power plan can be made so that the energy demand matches the size of generator set in order to run these on a more optimal load. This is also applicable for charging the Greener battery. However, this is not done on a regular basis, especially in situations where the energy demand is delivered using one power source, a battery or a genset. This is often the case on construction sites. The size of a diesel generator set is selected to deliver peak demand and not selected for the average electricity demand. This is less applicable for a battery system, since the efficiency of the battery is less dependent on the load compared to a diesel generator set. According to Soon et al. (2009), the discharge efficiency for a lithium-ion battery with a C rate of 0.8 which is approximately the C-rate of the Greener battery, is 99.2%. These values are taken into account for calculating the efficiency of the Greener battery.

When the type of energy demand allows it, for example during an event with only a limited time of energy use, a smaller genset can be used to charge the battery. This will increase the energy efficiency of the generator set since it will run on a more optimum load. However, this will also increase the running hours of the generator set, and this can be detrimental in the long run.

The only scenario where the Diesel genset is better compared to the Greener battery is scenario six, where the Diesel genset is running half of the time on an optimum load. The low hanging fruits for Greener Power Solutions to avoid this, measures that will have a large effect on the GWP100 of the Greener battery, are looking into the different charging possibilities. This will have a larger effect compared to e.g. using different materials for the battery production since the use phase has the largest GWP100 impact of the three phases: production, use, and EoL phase.

The environmental impact for these types of setup are unknown from this LCA. Therefore further research is advised to model the environmental impact of a battery compared to a Diesel generator set whenever the demanded electricity is delivered according to a power plan with different types of generator sets. Also, an extensive research is advised where the SoH of a mobile battery system is calculated and applied to a LCA.

5.3. End-of-Life phase

The EoL phase is the most uncertain of the three phases in terms of materials recovered from recycling and energy necessary for recycling. The market for second-use of lithium-ion batteries is starting to expand. However, materials that can be recovered from recycling have a high uncertainty due the relative new market and technologies. Recycling rates of materials are varying in literature due to the large variety in recycling methods and the definition of recycling. For example, the recycle rate can be defined as quantity of material recovered from raw material without quality losses; or quantity of material recovered from raw material that can be used in different applications. To avoid this problem, the same recycle rate is used for the common materials in a Greener battery and a genset.

The GWP100 in the EoL phase for the Greener battery is based on three articles and the FPMF is based on only one article. Therefore, the uncertainty is large and further research is advised to give more insight in the environmental impact of recycling lithium-ion NMC batteries and to improve accuracy of the EoL environmental impact.

6. Conclusion and recommendations

In this research, answer is given to the question: ‘What is the environmental impact of a 330 kWh, 285 kW Greener Power Solutions battery compared to a Diesel generator set from Aggreko concerning production, use, and end-of-life phase?’ The environmental impact per individual phase is described in the results and seven different scenarios are described to compare the total Life Cycle of the Greener battery and the Diesel generator set. The results indicate that the use phase for both the Greener battery and the Diesel genset is the most important phase concerning the two impact categories that are analysed: Global Warming Potential 100 and Fine Particulate Matter Formation. This is also the phase where Greener can avoid most CO_2 eq and PM2.5 eq emissions, up to 50% for GWP100 and 23.3% FPMF compared to the total emissions from a Diesel generator when the battery is charged by wind power instead of the usual combination of grid and genset. Scenario three is the most realistic scenario. In this scenario, the GWP100 of the Greener battery is 53.3% of the total CO_2 emissions from the Diesel generator set; and the FPMF emits 27.5% PM2.5 eq compared to the total FPMF emissions from the Diesel generator. The GWP100 break-even point of the Greener battery, considering a lifetime of 10 years, is 3.8 years and for the FPMF 0.3 years.

The environmental impact is affected by the lifetime of Greener battery and the Diesel genset. Since the company exists now for 2.5 years and the lifetime of the Greener battery is expected to be 10 years, it is unknown how the exact EoL phase will be for the Greener battery since the batteries have not been at the end of their lifetime yet. According to the technical specifications from the BMW I3 batteries, the batteries lost 30% of the total initial capacity, this is after 1,600 MWh throughput for a Greener battery. However, the reviewed literature from sub-research question one and three also emphasize the importance of second-life applications for batteries that reached their end of life. For Greener Power Solutions this would mean the Greener batteries can be used in e.g. second hand applications where the electricity peak demand is lower compared to the initial capacity of the battery. Further research regarding this topic is advised to make an inventory how much the environmental impact can be reduced when the Greener batteries are used in second-life applications.

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