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School of Energy Systems
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Sustainability Science and Solutions
Master’s thesis 2021

Aroma Pant

Proving the eligibility of cargo handling systems for alignment with climate change mitigation objective of EU Taxonomy Regulation

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Supervisor: Post-Doctoral Researcher, D.Sc. (Tech.) Ivan Deviatkin

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ABSTRACT

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Key Words: cargo handling equipment, electric cargo handling equipment, hybrid cargo handling equipment, climate change mitigation, Paris Climate Agreement, EU Taxonomy, technical screening criteria, life cycle assessment, Do No Significant Harm, minimum social safeguard, Science Based Targets initiative

Decarbonization of the transportation sector is integral for greenhouse gas emission reduction but the production of electric vehicles leads to environmental burden during product manufacturing based on different studies. Therefore, it is important to base the assumption of electric vehicles being environmentally sustainable based on best available science. This thesis provides an evaluation of the climate change mitigation potential of electrified cargo handling equipments compared to the similar-sized fossil fuel based conventional equipments assembled by Cargotec in terms of criteria set in the EU Taxonomy Regulation. The regulation is developed as part of the EU Green Deal which was established as a landmark to Paris Climate Agreement. Equipments studied in this thesis are terminal tractor, straddle carrier, and loader crane.

The equipment studied in this thesis falls under the economic activity, manufacturing of other low carbon technologies in the EU Taxonomy Regulation which enables potentially to greenhouse gases emission reduction in other sectors of economy. Based on the technical screening criteria requirement for climate change mitigation by other low carbon technologies in the EU Taxonomy Regulation, life cycle metric has been used to assess the climate change mitigation potential of the studied electric and hybrid cargo handling equipments compared to the conventional equipments during unit lifetime. For setting the rationale on what is substantial for climate change mitigation, the result was analyzed in

terms of the absolute emission reduction target aligned with Science-Based Targets initiative. As other metrics are indicated for evaluating the Do No Significant Harm and compliance to the minimum safeguard, these criteria are discussed qualitatively as part of the technical screening criteria in the EU Taxonomy Regulation.

The overall result for the studied electric cargo handling equipments is consistent with the hypothesis that the electric equipment has significantly lower greenhouse gas emissions than fossil-based equipment and the studied cargo handling equipments align with the Paris Climate Agreements'1.5℃ ambition pathway based on the Science-Based Targets. However, the hybrid equipment studied in the thesis do not align with the Paris Climate Agreements' 1.5℃ ambition pathway but can be considered substantially contributing to climate change mitigation objective in the EU Taxonomy Regulation due to its technical and economic feasibility consideration. In addition, all the studied equipment are expected to comply with the Do No Significant Harm and the minimum social safeguard thus the equipments are expected to verify as having substantial contribution to the climate change mitigation objective in the EU Taxonomy Regulation. However, a third-party verification is required further to validate the results.

There are no research studies for evaluation of climate change mitigation potential of cargo handling equipment in terms of the EU Taxonomy Regulation therefore, this research shall be used as a baseline for conducting life cycle studies of cargo handling equipment as well as verification of the climate change mitigation objective in terms of the criteria in the EU Taxonomy Regulation for future studies.

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I owe my debt to my grandparents and would like to dedicate my work especially to them and all my family and friends who supported me and always believed in my abilities. Lastly, I would also like to thank my friend Noah for giving me suggestions and motivating me for this thesis.

Aroma Pant

Lappeenranta, 10 October 2021

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LIST OF SYMBOLS

CO_2	Carbon dioxide
CH_4	Methane
LiFePO4	Lithium Iron Phosphate
N_2O	Nitrous Oxide

LIST OF UNITS

g	gram
kg	kilogram
kWh	kilowatt hour
l	liter
°C	degree Celsius

ABBREVIATIONS

ALCA	Attributional Life Cycle Assessment
BEV	Battery Electric Vehicle
BOM	Bill of Materials
BF-BOF	Blast Furnace Basic Oxygen Furnace
CFP	Carbon Footprint
CHE	Cargo Handling Equipment
CLCA	Consequential Life Cycle Assessment
DNSH	Do No Significant Harm
EAF	Electric Arc Furnace
EoL	End of Life
ePTO	Electric Power Take Off
ESC	Diesel-Electric Straddle Carrier
EU	European Union
FU	Functional Unit
FSC	Fast Charge Straddle Carrier
GHG	Greenhouse gas
GWP	Global Warming Potential
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
ICT	Information and Communication Technology
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LC	Loader Crane
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory Analysis
LCIA	Life Cycle Impact Assessment
Li-ion	Lithium Ion
LFP	Lithium Iron Phosphate

NACE	Nomenclature of Economic Activities
NBR	Nitrile Butadiene Rubber
NMC	Nickel Manganese and Cobalt
NRMM	Non-Road Mobile Machinery
PHEV	Plug-in Hybrid Electric Vehicle
PM	Particulate Matter
REACH	Registration, Evaluation, Authorization and Restriction of Chemicals
RoHS	Restriction of Hazardous Substances
RTG	Rubber Tire Gantry
SBR	Styrene Butadiene Rubber
SBT	Science-Based Targets
SBTi	Science-Based Targets initiative
SC	Straddle Carrier
SDG	Sustainable Development Goal
TEG	Technical Expert Group
TSC	Technical Screening Criteria
TT	Terminal Tractor
TtW	Tank to Wheel
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
WtT	Well-to-Tank
WtW	Well-to-wheel

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1 INTRODUCTION

The impact of greenhouse gases emissions due to anthropogenic activities, including population growth and industrialization, has increased significantly. Different climate-related risks have been evident, such as extreme weather conditions, sea-level rise due to melting ice, heavy precipitation in several regions, increased droughts, and forest fires in some areas. (European Environment Agency , 2020) According to IPCC (2018), "human activities are estimated to have caused approximately 1.0 ℃ of global warming above pre-industrial levels, with a likely range of 0.8℃ to 1.2℃. Global warming is likely to reach 1.5℃ between 2030 and 2052 if it continues to increase at the current rate.”. Therefore, immediate actions are required to limit global warming to below 1.5 ℃.

The industries play a vital role in mitigating climate change by improving the current technologies to more environmentally friendly solutions, of which electrification is one of the potential solutions. This thesis evaluates the climate change mitigation potential of different electric and hybrid cargo handling equipment compared to conventional cargo handling equipment.

1.1 EU initiatives to combat climate change

Different initiatives have been taken within the last decade, of which one of the most notable international initiatives for climate change mitigation, the Paris Climate Agreement, was adopted in 2015, which came into enforcement in the year 2016. The main goal of the Paris Climate Agreement is to limit global warming to below 2℃, preferably to 1.5 ℃, compared to the pre-industrial levels. Despite the enforcement of the Paris Climate Agreement in 2016, the greenhouse gases (GHG) emission still inclined till 2019 where they flattened. (UNFCCC, 2021) As a landmark for the Paris Climate Agreement, the European Union (EU) developed the European Green deal in 2019, intending to be the first climate-neutral continent by 2050 for global action to combat climate change (Claeys et al., 2019; Ecochain, 2021). The main aim of the European Green deal is to achieve a sustainable transition in the EU’s economy for combating climate change and environmental degradation through the provision of technical assistance and financial support. As part of the deal, the European

Commission proposed GHG emission reduction by 2030 to at least 55%, compared to the 1990s level. (European Commission , 2021) To keep up with the target, the commission proposed the European Climate Law to strengthen the EU Green Deal by legally formulating laws for the European economy and climate neutrality by the year 2050.

To achieve the goal set by the European Commission for climate change mitigation, the substantial role of mainstreaming the finance to facilitate transformative development in the current industries in Europe was realized, which was the main idea behind the EU Action Plan on Financing Sustainable Growth. The primary goal of the EU Action Plan is to direct capital flow towards sustainable investment, manage financial risks from several climate-related risks and promote transparency and long-termism in financial and economic activity (European Commission, 2018). As a part of the EU Action Plan on Financing Sustainable Growth 2018, a standard classification system for sustainable economic activities, Regulation EU /2020/852, namely the EU Taxonomy Regulation was developed (European Commission, 2020a). The regulation was later published on 22 June 2020 and came into enforcement on 12 July 2020.

The EU Taxonomy Regulation is a unified and harmonious classification system that aims for the transparency and long-termism for sustainable investment by providing definitions for environmental sustainability through the provision of the performance threshold known as the technical screening criteria (TSC) for each economic activities which contribute substantially to one of the six environmental objectives: climate change mitigation, climate change adaptation, sustainable use and protection of water and marine resources, transition to a circular economy, pollution prevention and control, protection and restoration of biodiversity and ecosystems (Schutze et al., 2020). The economic activities are statistically classified under the Nomenclature of Economic Activities (NACE), which covers several macro-economic sectors further classified into different economic activities. (European Commission, 2020a)

To date, the EU Taxonomy Regulation has set criteria for the two environmental objectives: climate change mitigation and climate change adaptation. As for the climate change mitigation, if finances and investments can identify whether the environmental performance of their underlying activities can provide a substantial contribution to climate change mitigation without significant harm to other five environmental objectives, as well as meet minimum social safeguards (such as alignment with the OECD (Organization for Economic Cooperation and Development) Guidelines on Multinational Enterprises and United Nations (UN) Guiding Principles of Business and Human Rights, the economic activities are aligned to the EU Taxonomy regulation. (Scholer & Barbera, 2020) Based on the activity's alignment with the EU Taxonomy Regulation, the companies, project promoters, and issuers can access green financing to support the transition, enhance environmental performance, and help identify already environment-friendly activities. (European Commission, 2020a)

1.2 About Cargotec

Cargotec is a Finnish company aiming to enable more efficient cargo flow by offering sustainable cargo and load handling solutions. The company has gradually transformed itself from an equipment provider into a sustainable and intelligent cargo handling leader. It operates through three different business areas Kalmar, Hiab, and McGregor. While Kalmar offers industry-shaping, sustainable cargo handling equipment and automated terminal solutions, software application, and services, Hiab deals with on-road loading, unloading, and lifting equipment. Similarly, MacGregors offers engineering solutions and services to perform with the marine industry. (Cargotec Corporation, 2021a) Cargotec is a United Nations Global Compact signatory committed to an ambitious 1.5℃ campaign with emission reduction targets validated by the Science-Based Targets initiative (Cargotec Corporation, 2020). The company, through its operations, support the UN Sustainable Development Goals (SDG) such as SDG 8: decent work and economic growth, SDG 9: Industry, Innovation, and Infrastructure, SDG 12: Responsible Consumption and Production, SDG 13: Climate Action, SDG 16: Peace, Justice and Strong Institutions, and SDG 17: Partnerships to achieve the goal (Cargotec Corporation, 2021b).

Emissions from mobile machinery such as cargo handling equipment (CHE) significantly affect the surrounding area, biodiversity, and human health (Hwang & Kim, 2020). Anticipating the future demand of the cargo business, there is a need for CHE manufacturers to consider cargo emissions and make systemic changes**.** Cargotec as an actor, has been trying for emission reduction measures in port and overall cargo business in diverse ways by applying more environmentally-friendly equipment and increasing product efficiency. The company's refined strategy focuses on climate change mitigation and profitable growth as the main breakthrough objectives. In concrete terms, the company aims to reduce the CO_2 emissions of its value chain by 1 million tons by 2024. (Cargotec Corporation, 2021b)

As most of the CHE manufactured by Cargotec encompasses the internal combustion engine (ICE) powered by fossil fuel resulting in high GHG emissions in the use phase, the company aims to transform the industry and mitigate climate change by providing low carbon solutions for its customers. Electrification of the cargo handling equipment is critical in mitigating the use phase's GHG emissions and a business opportunity for Cargotec. Hence, the company aims to revise its current eco portfolio and align with the EU Taxonomy Regulation. Specifically, Cargotec's activities fall into manufacturing other low-carbon technologies and data-driven solutions in terms of the activities recognized in the EU Taxonomy Regulation. The company aims to analyze if their products can provide substantial contribution to the climate change mitigation by applying Life Cycle Assessment (LCA), which is one of the most favored tools in the EU Taxonomy Regulation for evaluating climate change mitigation potential of products and services compared to the best performing alternative technologies or solutions. (Cargotec, 2020)

1.3 Climate change mitigation through transport and manufacturing

The ambitious target for the net-zero GHG emissions can be achieved only when anthropogenic CO_2 emissions can be balanced by the anthropogenic CO_2 reduction from different sectors. Transportation, agriculture, manufacturing, electricity, water, building, and Information and Communication Technologies (ICT) are the major macroeconomic sectors identified for significant GHG emissions and have the potential for climate change mitigation objectives set in the EU Taxonomy Regulation. (European Commission, 2020a) Of all the different sectors, the transport sector is one of the most influencing sectors for climate change mitigation as the GHG emission from the transport sector (even excluding aviation) is the most significant of all the industries and is projected to rise further (European Environment Agency , 2020).

The transport system with the internal combustion engine has been dominant as the technical "state of the art" and combustion of fuel from these technologies causes particulate matter and nitrogen oxide (NOx) emissions, responsible for impacts on human health and GHG emissions (Prasad & Venkateswara, 2011; Casper & Sundin , 2020). Based on statistics published by the International Energy Agency (IEA), the transport operation consumes about one-third of the total energy in the European Union and causes roughly 25% of total GHG emissions (IEA, 2021). Within the transport sector, the freight emissions from freight transport such as truck, rail, marine, and air alone produce 6% of overall transport sector emissions worldwide. (International Transport Forum , 2015)

With continued globalization and rising trade within different corners of the world, freight demand has increased and is expected to increase further, with emissions projected to increase by a factor of 3.9 in the year 2050 compared to the year 2010 with reference to statistics published by the International Transport Forum (ITF). Hence, GHG emissions reduction from the freight transport sector is essential in global agreement for climate change mitigation. (Lutsey et al., 2017; International Transport Forum , 2015) Manufacture of clean alternative technologies for transport with low life cycle carbon emissions or zero exhaust emissions like battery-electric vehicle (BEV), hybrid electric vehicle (HEV), and plug-in hybrid electric vehicle (PHEV), fuel cell electric vehicle (FCEV) can play a pivotal role in avoiding GHG emissions from the transport sector including freight transport. (Mierlo et al., 2017)

Manufacturing the low carbon transport system and promoting energy-efficient technologies within the transport sector has been prioritized in many global agreements and is also one of the important economic activities for climate change mitigation considered in the EU Taxonomy Regulation. Climate change mitigation through low carbon technologies is an intricate work, characterized by many peculiarities which would necessitate substantial and long-term investment, significant infrastructural changes including high component and technological development, participation of many stakeholders. (Lajunen et al., 2018; GEF-STAP, 2010) Therefore, the EU Taxonomy Regulation can be a tool for navigating sustainable investment. Suppose financial market participants can utilize the EU Taxonomy Regulation criteria to disclose that the economic activities are environmentally sustainable, the investors can compare the investment opportunities across borders and invest in business models which are more environmentally sustainable. (European Commission, 2020b)

To verify the climate change mitigation potential in the scope of the EU Taxonomy Regulation, the CHE should demonstrate substantial life cycle GHG emission savings compared to the best performing alternative technology or solution available on the market demonstrated by the application of internationally recognized LCA standards (European Commission, 2020a). Though there is no tailpipe emission from the electric CHE, there might be substantial emissions during the electricity generation depending on the electricity grid mix and the vehicle manufacturing (Mierlo et al., 2017). Since the electric grid mix used by the battery electric vehicles utilizes different energy sources, emissions for the electric CHE vary depending on the diverse generation mix (Maeng et al., 2020, p. 4248). Therefore, the LCA is a comprehensive approach for the comparison of different alternative technology.

1.4 Goal of the study

The main goal of the study is to evaluate the climate change mitigation potential of electric and hybrid CHE compared to the conventional ICE-powered CHE in terms of criteria set out in the EU Taxonomy Regulation. Cargo handling equipment that will be studied in this thesis are *Straddle Carriers (SC), Terminal Tractors (TT), and Loader Cranes (LC)* manufactured by Cargotec. The LCA will be used as a metric to compare the global warming potential of this different cargo handling equipment that falls into the EU Taxonomy's category of "*Manufacturing other low carbon technologies*". The LCA is used as one of the most favorable tools for science-based verification of climate change mitigation potential set out in the EU Taxonomy Regulation. This work considers the impact from all life cycle stages (cradle-to-grave assessment) for the straddle carrier and the loader crane. The cradle-to-grave study includes product manufacturing, fuel or electricity consumption during the use phase, maintenance, and end of life of the vehicle. In contrast, the study only considers the use phase for the terminal tractor. The LCA approach is vital for holistic coverage of environmental impact because, for instance, comparing only the exhaust emissions of battery-electric equipment with the equipment utilizing the internal combustion engine is misleading. It is because though the BEV and electric CHEs have no tailpipe emission, there can be substantial emissions during the production of electricity and battery (Mierlo et al., 2017; Sala et al., 2021)

1.5 Research questions

In order to achieve the goal of the thesis, the following research questions will be addressed:

RQ1: How significant are the GHG emissions from the different electric and hybrid configurations compared to the baseline fuel-powered solution?

RQ2: What is the contribution of the proposed technologies to the reduction targets adopted in the Paris Climate Agreement?

RQ3: What is the impact of manufacturing of studied cargo handling equipment on other environmental objectives set in the EU taxonomy Regulation?

1.6 Limitations of the study

Apart from climate change mitigation, the electrification of cargo handling equipment might provide several other positive impacts on the environment and human health. Substantial noise reduction can be achieved when using electrical equipment, causing fewer nuisances to the workers and close vicinity. Also, electrification leads to local reduction of particulate matter, which is otherwise emitted during internal combustion engines operation and provides benefit of reduced vibration for the operator and less chance of oil spills (Sanguesa et al., 2021). Nevertheless, the study does not assess the socio-economic and health issues associated with the use of CHE.

Based on several LCA studies on battery electric vehicles, BEV possesses more significant risks in impact categories, including toxicity potential, freshwater eutrophication, and resource depletion, specifically during the manufacturing (Hawkins et al., 2012; Liang et al., 2017). Nevertheless, the main target of the thesis is to analyze how electrification can contribute to climate change mitigation, due to which other impact categories are not assessed in this study by the life cycle metric. However, some of these aspects, such as toxicity and impact on water resources, are discussed qualitatively while studying the Do No Significant Harm to the other environmental objectives in the EU Taxonomy Regulation.

2 CARGO HANDLING

According to the Cambridge Dictionary (2021), “cargo handling refers to the activity of moving goods on and off ships, planes, and trucks.” The cargo business is one of the best examples of how the development of Digital Innovation towards trade in the modern era has transformed the business approach (Rajavelu & Baskaran, 2020). It has provided excellent opportunities for national and regional economic growth by establishing a supply chain base through intelligent solutions and efficiency enhancements of the CHE (Hwang & Kim, 2020). CHEs caught attention in the 1960s after the revenue loss due to the time consumed by stacking and unloading large shipments. (Lajunen et al., 2016)

The most widely used cargo handling equipments are terminal tractors, top and side loaders, forklifts, wharf cranes, rubber tire gantry (RTG), and skid loaders. (Air Resources Board, 2020) These CHEs are included under the category of non-road mobile machinery (NRMM), intended for intensive tasks, specifically for making cargo handling easier (Lajunen et al., 2016). Moreover, CHEs utilize different ICE, hybrid, and electric powertrain options.

2.1 Conventional cargo handling equipment

Conventional cargo handling equipment utilizes the conventional drivetrain system with the internal combustion engine, which transforms the chemical energy of the fuel to mechanical rotation. ICE is a self-igniting engine in which the fuel oxidizes with air in a combustion chamber, and the expansion of the burning fuel applies direct force to some components of the engine turbine blades, a rotor, or a nozzle, converting the chemical energy stored in the fuel into mechanical power. (Kukkaro, 2016) Some standard components in ICE vehicles (ICEV) are engine, fuel tanks, lead-acid battery, and exhaust (Wolff et al., 2020). Some conventional cargo handling equipment also includes diesel-electric propulsion, which utilizes diesel and has an electric motor to avoid several gears.

Emissions from the use phase of the ICEV include mainly four types of pollutant emissions such as carbon dioxide (CO_2), Nitrogen oxide (NO_x), hydrocarbons (HC), and particulate matter (PM). The approximate share of diesel exhaust gases is 67% nitrogen, 12% carbon dioxide, 11% water, 9% oxygen, and 1% other pollutant emissions (Resitoglu et al., 2015). Carbon dioxide, methane (CH4), and nitrous oxide (N2O) resulting from the combustion of diesel are potential gases for global warming (EPA, 2021). Alternative low carbon fuels such as biodiesel, cellulosic ethanol, hydrogen, and compressed natural gas (CNG) are alternatives to reduce the GHG emission generated by the ICEVs without drivetrain modification (Samaras & Meisterling, 2008). Of all the alternative fuels, biodiesel is a widely recognized alternative to diesel and is produced from available renewable resources like vegetable oils and animal fats (Bajpai & Tyagi, 2006).

As mentioned in the earlier section, most of the current CHEs employ ICE that relies on fuel and requires substitution using clean alternative solutions for climate change mitigation and energy security. Vehicle technologies with low life cycle carbon emissions or zero exhaust emissions such as BEV, HEV, PHEV are steadily fostering in the market for substitution of the ICEVs. (Mierlo et al., 2017)

2.2 Hybrid-electric cargo handling equipment

Hybrid-electric vehicles also known as hybrid vehicles including cargo handling equipment) are increasingly getting attention in recent years as a transitional pathway to the electrification of vehicles. The hybrid-electric cargo handling equipment works in the same principle as other lightweight hybrid electric vehicles, which combines an internal combustion engine with an electric motor which assists the conventional engine in accelerating the vehicle. Combining the electronic propulsion system and ICE can avoid drawbacks like the mediocre energy efficiency of ICEs and infrastructure requirement for charging in the BEVs or PHEVs. Hence, the effective utilization of hybrid vehicles can provide significant fuel savings compared to diesel-based conventional vehicles and can be a viable solution to BEVs in rural areas where infrastructures for charging are not easily accessible. (Beaton & Meyer , 2015)

The hybrid-electric vehicle utilizes regenerative braking to convert kinetic energy into electric energy stored in a battery. Major parts included in the hybrid-electric CHE are the electric motor, battery, converter, internal combustion engine, gasoline tank, and control board. These elements can be classified as drivetrains, battery, or energy storage systems, and control systems. (Singh et al., 2018) Based on the architecture of the machine or vehicle, the hybrid powertrain can be classified either as series, parallel or parallel series split specified by the equipment's overall power flow and torque path. (Tran et al., 2020)

Figure 1 below shows the schematic for the series hybrid powertrain. The engine in this powertrain transforms the potential energy from diesel fuel to mechanical energy, further converted to electrical power by the generator. An inverter converts electrical energy into mechanical motion. This structure allows the engine speed to be regulated independently of the vehicle speed, allowing the engine to perform at its best to reduce losses in the electrical equipment generation process. The engine powers the electric motor that drives the vehicle. (Tran et al., 2020)

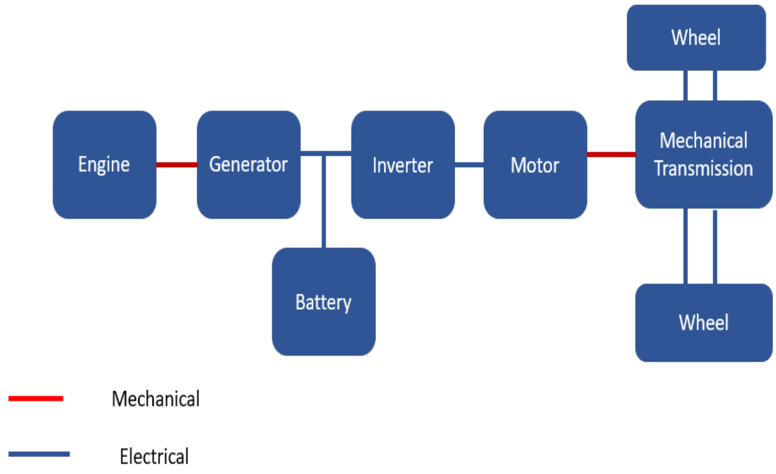

Figure 1. Series hybrid powertrain (Tran et al., 2020)

Unlike the series hybrid powertrain, the engine in the parallel hybrid powertrain delivers the propulsive torque directly to the wheels, allowing the equipment to be driven. The electric motor is mechanically linked to the driveline, and the energy it requires is supplied by a hybrid battery pack, allowing it to augment its power output. The torques generated by the engine and motor are combined via a mechanical coupler, which then delivers the resulting torque. Both the engine and motor torque can be operated independently, but the engine's speed and the motor each have a fixed proportion to the overall speed of the equipment or vehicle. The schematic for the parallel hybrid powertrain can be observed below in Figure 2. (Tran et al., 2020)

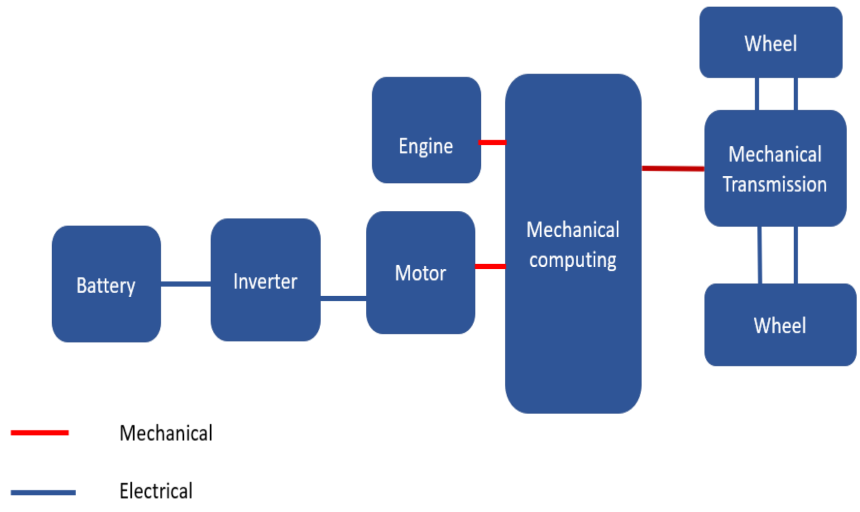

Figure 2. Parallel hybrid powertrain (Tran et al., 2020)

Likewise, the parallel-series hybrid powertrain is a more complicated configuration that utilizes both the parallel and series driving functionality to optimize the vehicle for different driving scenarios. (Tran et al., 2020) While the normal hybrid-electric vehicle can be utilized for GHG emission reduction by improvement of fuel economy, a PHEV is a hybrid vehicle that replaces electricity for the portion of the fuel utilized to power the vehicle. (Samaras & Meisterling, 2008)

2.3 Electric cargo handling equipment

The combination of electrification in the transportation sector and decarbonization in the power sector has been explored as a pathway for accomplishing zero GHG emission targets by 2050 (Steinberg et al., 2017; Williams et al., 2015). Electrification in the cargo handling equipment entails replacing the ICEVs with BEVs and HEVs. While the HEV and PHEV only entail electric propulsion and utilize diesel as the primary source of energy, the FCEV uses hydrogen as fuel, and the BEV is the only fully electric vehicle reliant on electricity from the grid and has zero tailpipe emission.

The key difference between electric and conventional CHE is the powertrain, which is the equipment that generates mechanical power and delivers it to the road's surface (Nilsson, 2016). The battery-electric cargo handling equipment utilizes the stored electricity and has key components such as a high-voltage battery, electric motors (either alternate current or direct current), and a controller for managing power electronics (Nieuwenhuis et al., 2020, pp. 227-243). Figure 3 below shows the schematic for the fully electric powertrain.

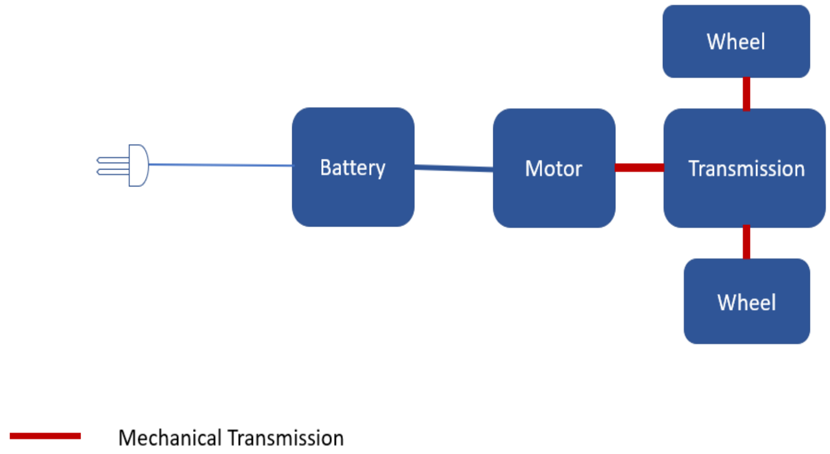

Figure 3. Fully electric powertrain (Nour et al., 2020)

With the technological advancement in power electronics and electric motors, powertrain efficiency for electric vehicles is above 89%, while the efficiency for the conventional vehicle (including cargo handling equipment) is around 60% only (Martins et al., 2013). Compared to ICEVs, BEVs have higher powertrain efficiency, lower maintenance requirements, zero tailpipe emissions, and lower noise levels (Hawkins et al., 2012). Due to these several rationales, the electrification of non-road mobile machinery and CHEs has also increased (Lajunen et al., 2016).

Several factors influence the environmental performance of a battery-electric CHE. Messagie et al. (2014) identified five key elements which affected the environmental performance of BEV. These factors are the vehicles' weight, electricity grid, battery production, technological advancements, and societal dynamics. Though electric powertrain has several advantages compared to the traditional mechanical powertrain, there are several sustainability issues associated with the elements, such as manufacturing the battery, which is gaining avid attention these days (Lajunen et al., 2018).

While the electrification of the transportation sector can provide an alternative to the conventional fossil-based transport system, enhanced infrastructure development and better synergies between transportation and energy systems are critical. These synergies include smart charging and refueling stations, which are necessary for transforming the niche market in the transport sector. As of electrification, the enhanced use of hydrogen, biomass, and renewable synthetic gas in the grid can play a vital role in further emission reduction from the use phase of electric vehicles. (European Commission d, 2018)

2.3.1 Battery technologies for electric cargo handling equipment

A battery is a device that uses an electrochemical oxidation-reduction (redox) reaction to transform the chemical energy stored in its active materials directly into electrical power. The electrons are transferred from one substance to another through an electric circuit in a reaction. The main difference in battery technologies is associated with the material electrochemical properties. A typical battery pack comprises a battery cell and a module packaging system. The battery cell encompasses crucial elements: the cathode, anode, electrolyte, and separator. During an electrochemical process, the cathode is the positive or oxidizing electrode that receives electrons from the external circuit, and the anode is the negative or reducing electrode that delivers electrons to the external circuit and oxidizes. Likewise, the electrolyte is the medium that provides the ion transport mechanism between the cathode and anode or a cell such as water or another solvent, with dissolved salts, acids, or alkalis required for ionic conduction. (University of Washington, 2021) A separator is a porous membrane that separates electrodes of opposite polarity, permeable to ionic flow but inhibits the electrodes from the electric contact (Arora & Zhang, 2004). Depending on the voltage, a battery contains one or more cells arranged in a series combination (Rantik, 1999).

The transition from the traditional lead-acid batteries to rapidly progressing lithium-ion batteries has significantly contributed to mobile equipment electrification (Söderberg et al., 2017). As the electrification of the transport sector entails a substantial increase of the grid storage capacity which is aided by the development of high energy density, reliable, and cost-effective storage technologies, lithium-ion battery is one of the most reliable available battery technologies. (Lajunen et al., 2018; Peters et al., 2017) While the lead-acid battery is one of the most mature technologies for conventional vehicles, the Li-ion batteries are the most widely used for electric vehicles, including the CHEs due to high cell voltage, high energy density, and rate capability (Lu et al., 2013).

The research for the Lithium-ion battery dates to the 1970s and has advanced since the 1980s (Reddy et al., 2020). In 1990, Sony became the first company to launch the rechargeable Li-ion battery, and since then, the market for this battery has bloomed (Soriano & Laudon, 2012). Within six years, the price for the lithium-ion battery has dropped by 76%, which is also why this battery technology has outperformed the other battery technologies (Stecca et al., 2020). The economic trend of how the battery has developed within few years can be observed below in Figure 4.

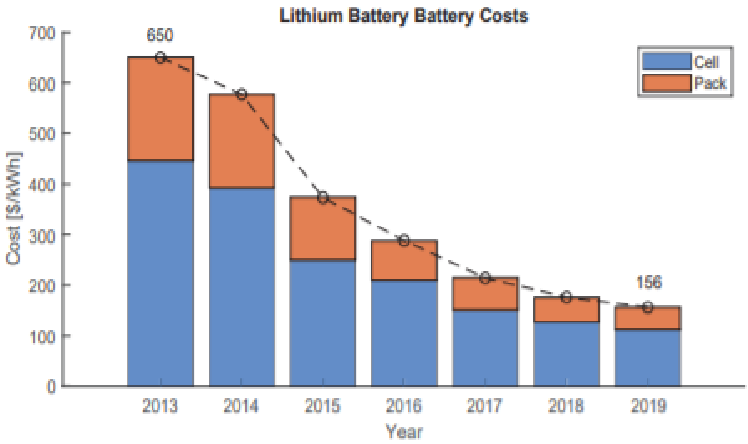

Figure 4. Economic trend of Lithium-ion battery cell and pack between 2013-2019 (Stecca et al., 2020)

Available options for the lithium-ion batteries in the market are lithium-ion polymer (LiPo), lithium-iron-phosphate ($LiFePO_4$), lithium manganese oxide ($LiMn_2O4$), lithium cobalt oxide ($LiCoO_2$/LCO), Lithium Nickel cobalt aluminum oxide ($LiNiCoAlO_2$), lithium titanate (LTO), lithium nickel cobalt manganese (NMC) each with its advantages and drawbacks (Peters et al., 2017). Of all these available options, the most popular ones available in the market for EVs are lithium-ion polymer (LiPo) and lithium-iron-phosphate (LiFePO4) (Ghosh, 2020).

With the increased number of electric vehicles and embedded lithium-ion battery use, the concern over the potential environmental impact resulting from battery use has grown over a period (Gröger et al., 2015). Though lithium-ion batteries avoid the cadmium used in Nickel-Cadmium batteries, the Cobalt and Nickel used in specific lithium batteries are harmful to the atmosphere and humans (Battery University, 2020). The LiPF6 salt, widely used in electrolytes for the Li-ion battery, produces hydrofluoric acid when it fuses to air. Therefore, the toxicity potential from the Cobalt and Nickel use also needs to be studied while utilizing batteries having cobalt and nickel. (Li et al., 2018) Alternative batteries solution such as organic batteries could be a feasible option for the future. These batteries cover various battery types, including Li-ion batteries with organic electrode active materials. However, the key challenge with introducing organic electrode active materials is achieving good specific energy and power while maintaining cycling stability, and additional research is required for its development. (Olofsson & Romare, 2013)

The manufacturing of the battery is identified for a considerable proportion of energy use and GHG emissions in the overall production phase, with estimates between 10% and 70% of vehicle manufacturing GHG emissions based on several LCA studies by Hawkins et al. (2012), Notter et al. (2010) and Hendrickson et al. (2015). Therefore, it is essential to investigate the impact of battery manufacturing while looking at the environmental profile of electric vehicles. Peters et al. (2017) conducted LCA studies for Li-ion-based EVs and concluded that only 36 out of 79 studies had transparent information regarding the battery inventory data to extract environmental impact per the storage capacity or kg of the battery. Thus, the study manifests the need for more transparency so that the environmental impacts from the lithium batteries could be comparable since the Li-ion demand is increasing rapidly for EVs.

While significant differences in life cycle exist between battery chemistries, all the LCA studies focus explicitly on the impact of battery on a storage capacity basis of 1Wh and not accounting for the battery lifetime. Rupp et al. (2018) stated that the replacement of batteries could increase the CO_2 emissions by 44% in the production; therefore, prolonging the battery's life also has significance with the environmental emission reduction from the transportation sector. Similarly, based on a study conducted by Helmers et al. (2020), battery second life in a stationary application can save up to 50% of the GHG emission from the product. The performance and lifespan of the Li-ion batteries are mainly affected by the battery's temperature while it is in charge and discharge (Miao & Hynan, 2019).

The EU Batteries Directive 2006/66/EC was established to collect and recycle batteries to reduce the environmental impact associated with batteries. Also, lithium and cobalt have been designated as critical elements of the EU's list of critical rare earth elements since 2020. However, battery recycling is inadequate to promote a high degree of material recovery from discarded batteries (both in terms of the amount of the recovered elements and the level of recovery) and therefore, the goals should be reviewed, and an efficient process must be established which is capable of increasing recycling productivity. (Rinne et al., 2021) The hydrometallurgical and pyrometallurgical processes are the chemical treatment process currently practiced for battery recycling, but these processes have not been in action on a huge scale. With all the environmental and socio-economic issues and challenges with battery production, there is a huge need to promote battery recycling on a larger scale.

2.4 Cargo handling equipment in the study

Cargotec, through its business areas Kalmar, Hiab, and MacGregor, provides various cargo handling solutions for its customers within different areas of the economy. CHEs studied in this thesis are selected based on their share in the product portfolio and anticipated GHG emissions mitigation potential. The loader cranes from Hiab, straddle carrier, and terminal tractor from Kalmar are the studied CHEs in this thesis.

2.4.1 Straddle Carrier

The straddle carrier is cargo handling equipment that employs a lifting mechanism positioned on a crossbeam supported by rubber-tired vertical legs. The propulsion of the straddle carrier is slow (less than 20 miles per hour). These carriers can pick containers up off the ground, move the containers to various locations, and either deposit on the floor or stack containers up to three and four levels. (Air Resources Board, 2020) The straddle carriers are used in terminals, ports, and heavy industry and are available as diesel-electric straddle carrier (ESC), battery-electric straddle carrier, referred to as fast charge straddle carrier (FSC), and hybrid straddle carrier (HSC). The FSC is one of the latest and World's first automated straddle solutions (Cargotec Corporation, 2008). While the powertrain components for these straddle carriers are different, the other body parts are similar, mainly structures for gantry and cabin. Primarily the standard conventional vehicle utilizes ICE, but the diesel-electric straddle has identical attributes to the diesel-electric locomotives, excluding several gears and using the electric motor. In these locomotives, diesel fuel is used to generate electricity (Baliga, 2015). The ICE can only work efficiently in a small rpm band, and there are chances of the engine's explosion at remarkably high rpm. While the regular road vehicle can obtain the required torque from the ICE with a limited number of gears, cargo handling equipment and rail locomotive must haul tons of the cargo and would need an impractical number of gears to extract the required torque from the ICE. Therefore, an electric motor is installed, which delivers maximum torque at extremely low rpm. An ESC hence uses an ICE to drive a generator that provides electricity and an electric motor. While the battery-electric utilizes electricity from the battery charged from the grid, the hybrid-electric and the conventional utilizes diesel as fuel.

Figure 5. Kalmar Straddle Carrier (Kalmar, 2021)

2.4.2 Loader Cranes

While the straddle carriers are used in the ports, loader cranes are used in different areas such as on-road loading and unloading applications in waste handling, construction, and industry. Loader cranes are mounted on a truck and help in loading and unloading goods.

These cranes are also available in both conventional and electric options. While the conventional LC works utilizing the fuel from the truck to which it is mounted, the electric loader crane, also referred to as electric power take-off (ePTO), uses electricity from the battery charged from the grid. The crane's motion is powered by several hydraulic cylinders as well as a variety of other mechanisms. The body part attached to the truck, known as boom, comprises steel and some metals for the conventional LC. However, the motor box added as an extra part for the crane to operate on electricity has a higher share of ferrous and non-ferrous material and electronics in the ePTO LC. The ePTO LC avoids idling and noise and emission due to fuel combustion like in conventional cranes. Hence, it can be used inside the buildings and at night, making it more favorable for customers who want those advantages. (Hiab, 2020a)

Figure 6. Hiab Loader Crane (Hiab, 2020b)

2.4.3 Terminal Tractor

The terminal tractors are designed to move semi-trailers within the cargo yard and distribution centers from one point to another. The TT is also commonly known as shunt truck, yard truck, spotter truck, and yard shifter. The TTs which will be studied in this thesis has been developed by Kalmar and are available in both electric and diesel version. These TTs offered by Kalmar are developed from the bottom up to make the higher pressure of spotting trailers in terminals easier and more efficient. The modular structure for the TTs are designed to withstand the rigors of operational requirement while remaining lightweight enough to cut fuel consumption and maneuverability. The TTs are suitable for warehousing and distribution centers, light industrial, container, and intermodal handling. (Kalmar Global, 2021b)

Figure 7. Kalmar Ottawa Terminal Tractor (Kalmar Global, 2021a)

3 SUSTAINABLE FINANCE AND EU TAXONOMY REGULATION

With an urgency to take effective actions to combat climate change, one of the most ambitious international initiatives; the Paris Climate Agreement, was introduced in the year 2015 under the United Nations Framework on Climate Change Convention (UNFCCC), where countries are bound to reduce their emissions from different sectors to achieve the global average temperature by 1.5℃ or at least 2℃ by the year 2050 (UNFCCC, United Nations, 2021). Despite a robust emission reduction objective worldwide, the GHG emissions inclined until 2019, when they flattened (European Commission, 2020a). As a landmark to the Paris Climate Agreement, the EU placed forward its objective to be the first climate-neutral continent by 2050 through the EU Green Deal (Claeys et al., 2019).

Apparently, economic development has been dependent on fossil fuels causing high GHG emissions to which electrification could provide an alternative (Ackerman, 2009). However, the transition from fossil to electric amenities would be high, and the cost that government would incur would be greater than the cost of the measures required for climate change mitigation. The history of the European economy has emphasized the significant role of sustainable financing to facilitate transformative development for climate change mitigation. Sustainable financing, however, would require transparency, a long-term vision, more robust policies, and good sustainability metrics. (Sievänen, 2021) Sustainable financing would influence investors to foster investments in businesses offering environmentally sustainable activities and reduce the economic barrier (UNFCCC, 2021). With this objective, the EU Action Plan on Financing Sustainable Growth came into force. The EU Action Plan on Financing Sustainable Growth's principal purpose is to direct capital flow towards sustainable investment, manage financial perils associated with several climate-related risks and promote financial and economic activity that is transparent and long-term in nature (European Commission, 2018). As part of the EU Action Plan on Financing Sustainable Growth, the EU Taxonomy Regulation, a robust, science-based classification system for sustainable economic activities, was developed. (European Commission, 2021) Regulation EU 2020/852 of the European Parliament and the council (The Taxonomy Regulation) was proposed in March 2018 to focus on Financing Sustainable Economy.

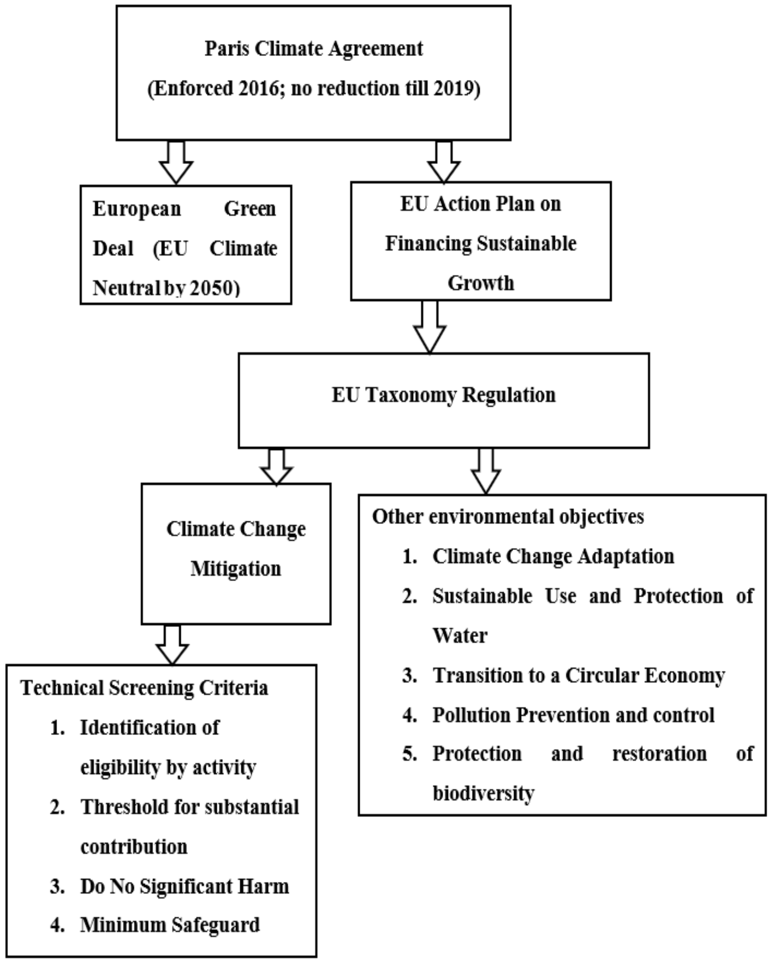

Figure 8. Mapping the EU Taxonomy Regulation

As stated in the final report of the technical expert group on sustainable finance (2020a), “The EU taxonomy is a tool to help the investors, companies, issuers and project promoters navigate the transition to a low-carbon, resilient and resource-efficient economy.” The regulation is an integrated and detailed classification system for sustainable economic activities developed on the recommendation of a technical expert group (TEG), which is an assorted group of different participants from the academic world, business and finance, and the members and observers from EU and international public bodies. The EU Taxonomy regulation aims to achieve six primary environmental objectives, which are Climate Change Mitigation, Climate Change Adaptation, Sustainable use and protection of water and marine resources, Transition to a circular economy, Pollution prevention and control, and protection and restoration of the biodiversity and ecosystems and can be observed in Figure 9. (Lucarelli et al., 2020)

Figure 9. Environmental Objectives Set in the EU Taxonomy Regulation (European Commission, 2020a)

Economic activities in the EU Taxonomy Regulation are classified under the NACE (Nomenclature of Economic activities) codes which cover 21 broad sectors and are further classified into four levels and 615 classes of economic activities. However, the Taxonomy Regulation is a dynamic document that will be amended constantly, and more economic activities will be added based on the recommendation made by Platform on Sustainable Finance (European Commission, 2020g). Economic activities included in the EU Taxonomy Regulation consist of various macro-economic sectors that have a large emission footprint and make a significant contribution to the Gross Domestic Product (GDP). Furthermore, the regulation acknowledges two distinct categories of the significant contribution that are Taxonomy-aligned: enabling activity and own performance (European Commission, 2020a). Own performance activities are those activities that significantly contribute to an environmental objective such as building renovation, energy-efficient manufacturing processes, and low carbon energy production. Contrary to it, enabling activities provide significant contributions to other sectors of the economy through their products or services. (European Commission, 2020b)

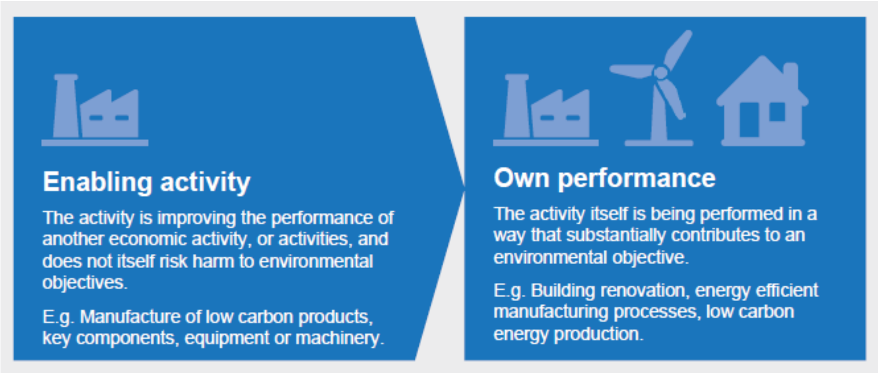

Figure 10. Economic activities in the EU Taxonomy Regulation for climate change mitigation (European Commission, 2018)

Technical screening criteria (TSC) in the Taxonomy regulations set a performance threshold "for economic activities" as environmentally sustainable only if

a) the activity contributes substantially to at least one of the six environmental objectives,

b) the activity follows the principle of Do No Significant Harm (DNSH) to the other five environmental objectives where relevant because while addressing one environmental objective, if another objective is harmed, then the overall balance cannot be achieved, and

c) the activity meets minimum safeguards (like OECD Guidelines on Multinational Enterprises and the UN Guiding Principles on Business and Human Rights).

The threshold can be either of a quantitative or qualitative nature. (European Commission, 2020a) Figure 11 below illustrates the required steps for the EU Taxonomy Regulation verification for economic activities.

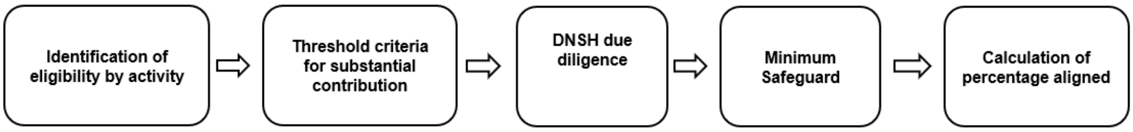

Figure 11. Process for Taxonomy verification (Scholer & Barbera, 2020)

The performance threshold referred to as the technical screening criteria is the key to transparency in the EU Taxonomy Regulation, and the regulation already has set the technical screening criteria for two interrelated environmental objectives; climate change mitigation and climate change adaptation, in Articles 10(3) and 11(3) respectively and is set for enforcement on 1 January 2022. Nevertheless, technical screening criteria for other environmental objectives such as sustainable and protection of water and marine resources, transition to a circular economy, pollution prevention and control and protection and restoration of the biodiversity and the ecosystems are set for establishment by the end of 2022; therefore, the central focus for the companies now is on the climate change mitigation and adaptation. (European Commission, 2020b)

Article 18 of the Regulation EU 2020/852 of the European Parliament and the council (The Taxonomy Regulation) implies the Minimum safeguard criteria. According to the Article 18 of the Regulation EU 2020/852 (2020b), “the minimum safeguards shall be procedures implemented by an undertaking that is carrying out an economic activity for assurance of the alignment with the OECD Guidelines for Multinational Enterprises and the UN Guiding Principles on Business and Human Rights, including the principles and rights set out in the eight fundamental conventions identified in the Declaration of the International Labor Organization on Fundamental Principles and Rights at Work and the International Bill of Human Rights.”

The EU Taxonomy regulation establishes a standard benchmark for financial and non-financial market participants for disclosures on sustainability assessments in their economic operation and steers investors towards sustainable financial products. The disclosure requirement varies for financial and non-financial companies. Regarding the climate change mitigation and climate change adaptation objectives in the EU Taxonomy Regulation, the financial market participants are required to disclose the activities in periodic reports, precontractual disclosures, and websites. Similarly, for the non-financial companies, the disclosure should incorporate a percentage of their revenue derived from products or services associated with environmentally sustainable economic activities, as well as a percentage of their capital expenditure and the percentage of their operating expense related to assets or processes related associated with environmentally sustainable economic activities. (European Commission, 2020b)

Though the EU Member States is the pioneer for forming a cross-market authorized commitment, the EU Taxonomy must be perceived as a share of a global movement towards environmental performance reporting standardization, building from the widespread use of taxonomies in public and private sectors (European Commission, 2020c).

3.1 Environmental objectives of the EU Taxonomy Regulation

This chapter will disclose different environmental objectives set in the EU Taxonomy Regulation, followed by the economic activity “manufacturing of other low carbon technologies” and the technical screening criteria for this activity. As per the EU Taxonomy Regulation, along with the general guidelines for each environmental objective, all the economic activities should follow the DNSH and minimum social safeguard, which has been mentioned in the EU Taxonomy Regulation general background under paragraph 1. Prior to the environmental objectives, it is essential to understand the work approach and the region behind how the economic activities are selected for inclusion in the EU Taxonomy Regulation.

3.1.1 Climate change mitigation

The TEG used the following process for assessing and selecting economic activities for inclusion in the climate change mitigation objective in the EU taxonomy Regulation in June 2019. The TEG's perspective on sector selection technique has not altered much because of the Taxonomy Regulation (European Commission, 2020a).

- Firstly, the TEG prioritized 8 sectors using Eurostat emission inventory within the potential universe of economic activities, comprising 615 level and 4 classifications in the NACE code.
- Based on the prioritized sectors, mitigation prospects for the prioritized sectors were identified and categorized based on article 6 and industry experience from the current taxonomies.
- Economic activities were prioritized within the sectors, and technical screening criteria were developed for the economic activities. The technical works by experts drawing from EU regulation, quality technical publications, input from Commission, JRC, call for feedback, and dialogue with additional experts.

The TEG has prioritized sectors accountable for 93.5% of direct greenhouse gas emissions in the EU to recognize economic activities that contribute markedly to climate change mitigation. Major macro-economic sectors or industries identified by the TEG having a significant role in climate change mitigation are forestry, agriculture, manufacturing, energy (electricity, gas, steam, and air conditioning supply), and transport and storage. In line with the obligations under the European Green Deal, the TEG has identified the climate change mitigation goals of net-zero emissions by 2050 and 50-55% of reduction by 2030. (European Commission, 2020b)

Article 10 in the EU Taxonomy Regulation states that "An economic activity shall qualify as contributing substantially to climate change mitigation where that activity contributes substantially to the stabilization of the greenhouse gas concentrations in the atmosphere at a level which prevents dangerous anthropogenic interference with the climate system consistent with the long term temperature goal of the Paris agreement through the avoidance or reduction of greenhouse gas emissions or the increase of greenhouse gas removals, including through process innovations or product innovations, by:

a) generating, transmitting, storing, distributing or using renewable energy in line with Directive (EU) 2018/2001, including through using innovative technology with a potential for significant future savings or through necessary reinforcement or extension of the grid.

b) improving energy efficiency, except for power generation activities as referred to in Article 19(3).

c) increasing clean or climate-neutral mobility; 22.6.2020 EN Official Journal of the European Union L 198/29

d) switching to the use of sustainably sourced renewable materials.

e) increasing the use of environmentally safe carbon capture and utilization (CCU) and carbon capture and storage (CCS) technologies that deliver a net reduction in greenhouse gas emissions.

f) strengthening land carbon sinks, including through avoiding deforestation and forest degradation, restoration of forests, sustainable management and restoration of croplands, grasslands and wetlands, afforestation, and regenerative agriculture

g) establishing energy infrastructure required for enabling the decarbonization of energy systems.

h) producing clean and efficient fuels from renewable or carbon-neutral sources; or

i) enabling any of the activities listed in points (a) to (h) of this paragraph in accordance with Article 16.*"*

Furthermore, the economic activity should also follow the principle of "Do No Significant Harm," which assures that the activity has no harm to the other environmental objectives while serving the climate change mitigation objectives of the EU Taxonomy Regulation. For this, technical screening criteria for different economic activities based on the scientific evidence are developed by considering the life cycle approach.

3.1.2 Climate change adaptation

Article 11 in the EU Taxonomy Regulation (2020g) states that, "An economic activity shall qualify as contributing substantially to climate change adaptation where that activity:
a) includes adaptation solutions that either substantially reduce the risk of the adverse impact of the current climate and the expected future climate on that economic activity or substantially reduce that adverse impact, without increasing the risk of an adverse impact on people, nature or assets; or

b) provides adaptation solutions that, in addition to satisfying the conditions set out in Article 16, contribute substantially to preventing or reducing the risk of the adverse impact of the current climate and the expected future climate on people, nature or assets, without increasing the risk of an adverse impact on other people, nature or assets.”

Unlike climate change mitigation, climate change adaptation is context- and location-specific and requires a process-based approach. The assessment of the contribution of the activity is different based on its scope (asset, corporate, sector, or market). (European Commission, 2020b)

3.1.3 Sustainable use and protection of water and marine resources

The other environmental objectives set in the EU taxonomy is Sustainable use and protection of the water and marine resources where environmental degradation risks related to preserving water quality and avoiding water stress are identified and addressed, concerning the water use and protection management plan, which has been developed in consultation with relevant stakeholders.

An economic activity shall qualify as contributing to sustainable use and protection of the water and marine resources if it either contribute to achieving the good status of water bodies, including surface water and groundwater, or have a significant on the good environmental quality of marine waters or the prevention of the water resource exploitation that is already in good condition through (European Commission, 2020b) :

a) Safeguard the environment from the harmful impact of wastewater discharge from industries and urban use, along with the pollutants from pharmaceuticals and microplastic, by assuring that water from the households and industries is collected, treated, and discharged properly.
b) Safeguard human health from the harmful effects of the polluted water aimed for drinking by an assurance that it is safe to consume.
c) Enhancement of water management and efficiency with preservation and improvement of the state of marine ecosystems by fostering the sustainable utilization of water via long-term preservation of water resources through several

ways like by assurance of the reduction of the pollutant emissions in both ground and surface water.

3.1.4 Transition to a circular economy

Circular economy is one of the crucial issues of the manufacturing industry and is also one of the six environmental objectives in the EU taxonomy. Article 16 in the EU Taxonomy Regulation (2020g) states that, “An economic activity shall qualify as contributing substantially to the transition to a circular economy, including waste prevention, re-use and recycling, where that activity:

a) uses natural resources, including sustainably sourced bio-based and other raw materials, in production more efficiently, including by: (i) reducing the use of primary raw materials or increasing the use of by-products and secondary raw materials; or (ii) resource and energy efficiency measures.

b) increases the durability, reparability, upgradability or reusability of products, in particular in designing and manufacturing activities;

c) increases the recyclability of products, including the recyclability of individual materials contained in those products, inter alia, by substitution or reduced use of products and materials that are not recyclable, in particular in designing and manufacturing activities;

d) substantially reduces the content of hazardous substances and substitutes substances of very high concern in materials and products throughout their life cycle, in line with the objectives set out in Union law, including by replacing such substances with safer alternatives and ensuring traceability;

e) prolongs the use of products, including through reuse, design for longevity, repurposing, disassembly, remanufacturing, upgrades and repair, and sharing products;

f) increases the use of secondary raw materials and their quality, including by high-quality recycling of waste;

g) prevents or reduces waste generation, including the generation of waste from the extraction of minerals and waste from the construction and demolition of buildings

h) increases preparing for the re-use and recycling of waste;

i) increases the development of the waste management infrastructure needed for prevention, for preparing for re-use and for recycling, while ensuring that the recovered materials are recycled as high-quality secondary raw material input in production, thereby avoiding downcycling;

j) minimizes the incineration of waste and avoids the disposal of waste, including landfilling, in accordance with the principles of the waste hierarchy;

k) avoids and reduces litter; or

l) enables any of the activities listed in points (a) to (k) of this paragraph in accordance with Article 16."

3.1.5 Protection and restoration of biodiversity and ecosystems

Protection and restoration of biodiversity and ecosystems are the other environmental objectives in EU taxonomy. An economic activity shall qualify as contributing to the protection and restoration of biodiversity and ecosystems if the activity contributes substantially to protect, conserve, or restore biodiversity or to achieve the excellent condition of ecosystems that are already in good condition through (European Commission, 2020b):

a) Preservation of nature and biodiversity with accomplishment of favorable preservation level of natural and semi-natural habitats and species or preventing exploitation where applicable preservation status has already been achieved.
b) Sustainable land use and supervision along with sufficient protection of soil biodiversity, land degradation neutrality, and contaminated sites alleviation
c) The practice of sustainable agriculture and the factors supporting biodiversity improvement or halting or protecting soil biodiversity and ecosystems.
d) Enabling either of the activities above.

3.1.6 Pollution prevention and control

An economic activity qualifies as contributing to pollution prevention and control if the activity contributes substantially to environmental protection from pollution through (European Commission, 2020b):

a) Prevention or, where not applicable, reduction of the pollutant emissions into the air, water, or land, other than greenhouse gases.

b) Improvement of levels of environmental quality in the areas where economic activity takes place while reduction of any adverse impact to human health and environment or the risk thereof.
c) Prevention or reduction of any harmful impact on human health and the environment of the production, use, or disposal of chemicals.
d) Cleaning up litter and other pollution.
e) Supporting any of the activities in points (a) to (d) of this paragraph.

3.2 Manufacture of other low carbon technologies: Cargo Handling Equipment

The manufacturing industry is the second largest contributor that accounts for roughly 21% of the total GHG emissions in the EU. This industry also produces technologies that substantially contribute to GHG emissions reductions in the other economic sectors and thus is a fundamental part of the low-carbon economy. Economic activities that account for a significant portion of the industrial GHG emissions resulting from scope 1 and scope 2 emissions and present tremendous possibility for the GHG emission reduction are included in the manufacturing section of the EU Taxonomy regulation. Scope 1 emissions are the direct emission from owned or controlled sources and scope 2 emissions are the indirect emissions from the generation of purchased energy. (World Research Institute , 2020) The manufacturing sector in the EU Taxonomy Regulation includes both high emissions activities and enabling activities that are low in carbon and engaged in a transformational shift. Activities that are high in emissions are the manufacturing of aluminum (NACE 24.42), the manufacturing of cement (NACE 23.51), and the manufacturing of iron and steel (NACE 24.1, 24.2, 24.3). (European Commission, 2020c)

Similarly, low carbon technologies include manufacturing of products, key components, equipment, and machinery for renewable technologies (such as hydropower, geothermal power, wind energy, solar power), manufacturing of low carbon transport vehicles, fleets, and vessels, manufacturing of energy efficiency equipment for buildings and other low-carbon technologies which contributes to GHG reductions in other sectors of the economy. (European Commission, 2020c) Hence, these technologies are classified as an enabling activity per Article 10(1), point (i), of Regulation (EU) 2020/852, where it complies with the technical screening criteria. (European Commission , 2021e)

While the manufacturing sector includes several economic activities, the cargo handling equipment manufactured by Cargotec, including the products which will be studied in this thesis, fall into the EU taxonomy regulation under *the NACE code C28-manufacture of other low carbon technologies*. These types of equipment aim to substantially reduce GHG emission in other different sectors of the economy which are not covered in the other manufacturing activities and demonstrate substantial life cycle GHG emission savings compared to the best performing alternative technology, product, or solution available on the market, which is demonstrated using *Commission Recommendation 2013/179/EU/127 or International Organization for Standardization (ISO) 14067:2018 or ISO 14064/1:1.* Later, an independent third party verifies the quantified life cycle GHG emission savings. (European Commission , 2021e) This approach is required to safeguard the manufacturing sector to improve energy efficiency and reduce emissions ambitiously. The emission reduction benchmark has not been explicitly stated for enabling activities including other low carbon technologies since the advantages these activities provide are considered to offset their emissions. (European Commission, 2020a).

Based on the technical screening criteria, an activity can qualify as environmentally sustainable only if it contributes significantly to one of the six environmental objectives while following the DNSH and meets the minimum safeguard criteria. The DNSH is used for assurance that while one environmental objective is achieved, there is no significant harm to other environmental goals (European Commission, 2020a). Thus, the manufacture of other low carbon technologies also should comply with the TSC for the verification of substantial contribution to climate change mitigation objective in the EU Taxonomy Regulation. (European Commission, 2020c) TSC for CHE manufacturing, which falls under the economic activity manufacture of other low carbon technologies, is briefly explained in Table 1.

Table 1. Technical Screening criteria for climate change mitigation by other low carbon technologies (European Commission , 2021e)

Technical Screening Criteria	
1. Climate change mitigation	The following steps are required for the CHE to show substantial climate change mitigation objective in the EU Taxonomy Regulation: a) Validate significant life cycle GHG emission decrease compared to the market's best performing alternative technology/solution. b) Life cycle GHG emission reduction evaluated employing Commission Recommendation 2013/179/EU, ISO 14067:2016 c) Measured life cycle GHG emission reduction verified by an independent third party
2. Minimum social safeguard compliance	Alignment with the OECD Guidelines for Multinational Enterprises and the United Nations Guiding Principles on Business and Human Rights, including the values and rights set in the eight fundamental conventions identified in the Declaration of the International Labour Organization on Fundamental Principles and Rights at Work and the International Bill of Human Rights
3. DNSH	Do No Significant Harm to other five environmental objectives set in the EU Taxonomy Regulation.
I. DNSH to climate change adaptation	Robust climate risks and vulnerability assessment by: a) Assessment of the activity to determine if physical climate risks associated with temperature (changing temperature), associated with wind (changing wind patterns), and solid mass (coastal erosion, soil degradation) may impact the economic activity’s performance b) Climate threat and vulnerability assessment for evaluating the materiality of the physical climate risks c) Assessment of adaptation solutions that can help to mitigate the physical climate hazards that have been identified.

II.	DNSH to Sustainable use and protection of water and marine resources	a) Detection and administration of risks related to water quality and consumption are required. b) The requirements of the EU water legislation need to be verified
III.	DNSH to transition to a circular economy	The activity assesses the availability of and, where feasible, adopts, a) reuse, and use of secondary raw materials and reused components in products manufactured. b) design, which is long-lasting, recyclable, easy to dismantle, and is adaptable c) waste management in the manufacturing process, which focuses on recycling upon discarding. d) data on hazardous compounds and their traceability throughout the products' life cycle
IV.	DNSH to pollution prevention and control	Compliance with the REACH (Registration, Evaluation, Authorization, and Restriction of Chemicals) Regulations (1271/2008/EC) and the RoHS (Restriction of Hazardous Substances) Regulations (2002/95/EC) or the equivalent for equipment manufactured and used outside the EU (n.b.: for production of equipment outside EU but later imported into EU must comply with REACH and RoHS) Regulations.
V.	DNSH to protection and restoration of biodiversity and ecosystems	Environmental Impact Assessment (EIA) following the EU Directives on Environmental Impact Assessment (2001/52/EC) and Strategic Environmental Assessment (2001/42/EC) (or other equivalent national provisions or international standards such as IFC Performance Standard 1: Assessment and Management of Environmental and Social Risks) whichever is stricter- in the case of sites/ operations in non-EU countries for the site/operation (including ancillary operations) and required mitigation measures for protecting biodiversity/ ecosystems, in particular, UNESCO World Heritage and Key Biodiversity Areas (KBAs), is required to be implemented.

4 LIFE CYCLE ASSESSMENT

The life cycle metric is the most favored tool in the EU Taxonomy design for demonstrating substantial contribution to climate change mitigation potential of other low carbon technologies, which is related economic activity for the cargo handling equipment studied in this thesis. Based on TEG's recommendation, different tools such as carbon footprint (CFP) based on ISO 14067 or ISO 14064 can be used to assess the GHG emission savings compared to the best performing alternative technology or product available in the market (European Commission, 2020a). However, there is no binding regulation on the specific tool that needs to be utilized for demonstrating the life cycle GHG savings from a product compared to the best performing alternative technology in the market. The ISO 14067 specifies principles, requirements, and guidelines for quantifying the product's full or partial carbon footprint, based on ISO 14040 and ISO 14044 for quantifications and environmental labels and declarations. (International Organization for Standardization , 2018) Hence, ISO 14040 and ISO 14044 are the basis for ISO 14067 and are widely used in LCA applications. While ISO 14067 is only applicable to CFP studies and partial CFP, LCA based on ISO 14040 and ISO 14044 includes other environmental impact categories such as acidification, toxicity potential, eutrophication potential (Chomkhamsri & Pelletier, 2011). Therefore, ISO 14040 will be utilized for the LCA of different cargo handling equipments in this study even though only the climate change impact has been presented in the results.

The idea of the LCA emerged in the late 1960s, and early 1970s after resource depletion and environmental degradation became a problem (Simonen, 2014). During its emerging phase, the LCA assisted in evaluating energy usage, aiming that both the industries and individuals could conserve natural resources and create alternative ways for environmental protection (Semtrio, 2018). LCA is a method for assessing the environmental impacts associated with a product throughout its life cycle (Iyyanki & Valli, 2017). LCA studies have become a well-known tool due to their practice and standardization in recent years. The ISO 14040 and the ISO 14044 establishes the LCA methodological basis (Guyon,2017). Based on these standards, a product's LCA can be assessed using four distinct and interdependent steps: goal and scope definition, inventory analysis, impact assessment, and interpretation.

(International Organization for Standardization, 2006) Framework for the LCA studies based on ISO 14040 can be observed in Figure 12.

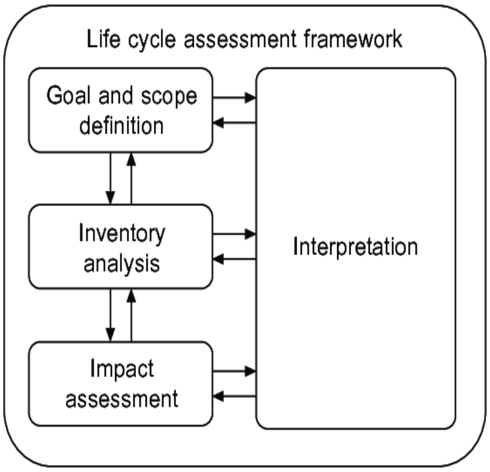

Figure 12. Framework for Life Cycle Assessment (International Organization for Standardization , 2006)

The goal and scope definition is the first phase of the LCA study. In the goal definition, the primary purpose of the LCA application is presented. The goal helps to deal with major subjects such as intended application, the rationales for conducting the study, the targeted audience, and comparative study disclosure. The scope definition complements the LCA's goal and helps identify the product systems (object of assessment), life cycle inventory assessment modeling framework, system boundaries, and completeness resources (Simonen, 2014). Mutually with the goal definition, the scope definition serves as a firm guide on how other LCA phases (inventory analysis, impact assessment, and interpretation, including certainty and sensitivity analysis) should be performed (Hauschild et al., 2018). Several aspects which are taken into consideration in the scope are listed below for an overview (International Organization for Standardization, 2006) :

- The function of the study and system for the study
- The functional unit
- System boundaries (What are the aspects included in the system and limitations)
- Allocation procedures
- Limitations of methodological choices
- Selected impact categories
- Data quality requirements
- Impact assessment methodology

The function and the functional unit (FU) must be clearly defined in the system boundary. The function describes the product's intended application. (Lee & Inaba, 2004)According to ISO 14040 (2006), the functional unit is a "Quantified performance of a product system based for use as a reference unit."

The life cycle inventory analysis (LCI) is the second and most time-consuming part of LCA (Baumann & Tillman, 2004). According to ISO 14040 (2006), "LCI is a phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle." After the identification and data collection process, an LCI model is created, and results are calculated. Additionally, it allows forming the basis for uncertainty management and sensitivity analysis as well as reporting. (Hauschild et al., 2018)

One of the essential aspects of the LCA study includes identifying the research, either if it is an attributional LCA (ALCA) or consequential LCA (CLCA), which affects the system boundaries. While attributional LCA provides an estimation of the impact of a product as a part of the global environmental burdens, consequential LCA estimates the effect on the global environment by the production and use of the product or system studied (Bastante-Ceca & Tomas, 2020).

The scale and consequence of the potential environmental impact of resource use throughout the life cycle are assessed in the life cycle impact assessment (LCIA) phase (Capaz et al., 2018). Based on the inventory analysis, where all the inputs and outputs are assessed, different environmental impacts such as global warming potential (GWP), eutrophication potential, abiotic depletion (ADP), acidification potential (AP), toxicity potential (TP) can be analyzed. Hence, LCA has been recognized as a useful tool to analyze product systems from an environmental perspective (Iyyanki & Valli, 2017).

The overall LCA of a vehicle (including CHE) includes all direct and indirect processes related to both the vehicle and the fuel or electricity, from the raw material acquisition to the end of the life (Nilsson, 2016). Several LCA studies have previously been conducted about several types of vehicles and the global warming potential in the use phase has been the focus in most studies. However, examining the vehicle's environmental profile solely based on use phase would lead to unrealistic assumptions, as most additional effect categories could be concentrated in the product manufacturing or the end of life (EoL) phases and as a result, the LCA would not provide an unambiguous response but rather a trade-off between various environmental impacts. (Pero et al., 2018)

While the cradle to grave approach is used for the life cycle assessment of vehicles other approaches such as well to wheels (WtW), well to tank (WtW), tank to wheels (TtW) are used for the assessment related to fuel emission (Nilsson, 2016). The delimitations and functional unit of the LCA study of the vehicle depend on these approaches taken for the study. While the cradle-to-grave approach is a holistic and comprehensive approach that deals with raw material extraction to end of life of vehicles, the well-to-wheel (WtW) incorporates just the steps for fuel production and the tailpipe emissions. WtW comprises two independent stages Well-to-Tank (WtW) and Tank-to-Wheel (TtW). WtT entails the recovery or the feedstock generation for the fuel, transportation, and storage of the energy sources through conversion of the feedstock to the fuel to the vehicle tank, TtW stage, on the other hand, encompasses the vehicle in utilizing the fuel for operational purposes throughout its lifetime (Khan, 2018). The cradle-to-grave analysis of vehicles consists of product manufacturing, use phase (WtW), and EoL. Moreover, life cycle assessment helps in decision making and improvement of the products based on identifying the environmental hotspots in the life cycle.

4.1 Review of studies assessing electric vehicles

A review of studies on the LCA of electric vehicles is included in this section. The review has been conducted for understanding how some LCA studies for automotive application have been assessed, what are the parameters included such as functional unit, the weight of vehicles, battery types, and recycling which shall be used for understanding and choosing the right approach for the LCA and understanding the impact via the results. Based on the bibliometric analysis by Lucarelli et al. (2020), the research rate within the transport sector has tripled in the last five years, which shows the increased attention of academia in the transportation sector.

Life cycle assessment is a widely used application for assessing the environmental impact in automotive applications. Several comparative LCA studies between ICEV and BEV were found in the literature. Nonetheless, only few life cycle studies were focused on the HEV, specifically for the on-road vehicles.

Based on the findings from different search tools such as Scopus, and google scholar, most of the LCA studies conducted for the transport sector entail private cars, due to which the scale of the environmental impact from the CHE might differ compared to the available studies. However, the LCA studies for private cars are taken as a guideline for how the study needs to be conducted. In most of the comparative LCA studies between BEV and ICEV, the use phase has been given relatively higher importance which deals with only the tailpipe emissions (Samaras & Meisterling, 2008; Boureima, et al., 2009). However, some studies have focused on the vehicles' overall life cycle, including the manufacturing of the battery and the energy generation for the vehicles in the system boundary. Pero et al. (2018) and Hawkins et al. (2012) have investigated the energy production parts and presented it in their findings. Based on their results, the use phase is the dominant phase for GHG emissions.

Battery usage for electric vehicles also has several sustainability issues, and this has captured avid interest from several areas, including the LCA community. Studies focusing mainly on battery analysis for automotive applications are Ellingsen et al. (2013) and Dai et al. (2019). The study by Ellingsen et al. (2013), is one of the most transparent studies on different lithium-ion batteries ($LiFePO_4$ and LiNCM). Based on Hawkins et al. (2012), battery production contributes to 35% to 41% of the studied electric private cars during the production phase global warming potential impact while the electric engine contributes 7% to 8%.

There are few LCA studies for heavy-duty electric vehicles and CHEs compared to private cars. The reason might be because drivetrain electrification of heavy-duty vehicles has not taken widely in the market. Also, LCA studies for the cargo handling equipment in the ports have not caught massive attention in academia. Though few LCA studies are conducted on heavy vehicles and non-road mobile machineries, some research results have been published and referred to the life cycle study of the CHE studied here. Rupp et al. (2018) conducted a comparative study of conventional and hybrid heavy-duty trucks where mainly the drivetrain was compared, and the functional unit of 1-ton cargo transportation over a 1 km distance was chosen. The study also considered several factors, such as battery replacement and the effect of the driving profile. The study concluded that the hybrid truck could save around 4.34g CO_2eq emissions per transported ton and kilometer during use. Based on the findings impact from the product manufacturing is roughly 10%, while the main effect in the overall life cycle is associated with the use phase, which is 90% of total GHG emissions. (Rupp et al., 2018)

Zrnic et al. (2013), conducted an LCA on CHE, which aimed to analyze the performance and CO_2 reduction potential of the electric Rubber Tired Gantry (RTG) compared to the conventional RTG and electric Utility Tractor Rigs (UTR) compared to the conventional UTR. The RTG studied by Zrnic et al. (2013) has similar attributes to the SC that will be explored in this thesis. The mass of the RTG is around 70 tons, and emission from the product manufacturing of the RTG based on the CML Method is 335,000 kg-CO_2 equivalent for the diesel-based RTG and 344,000 kg- CO_2 eq. for the electric RTG. Similarly, for 5,000 operating hours, the environmental impact of the diesel RTG was 60,017 kg CO_2-eq, and the electric RTG was 1,462 kg-CO_2 eq. The result for the product manufacturing being similar mass can be comparable with the results from the studied straddle carriers.

Similarly, Schwarzenberg et al. (2018) conducted an LCA on straddle carriers where the main aim was to assess the impact of battery-electric straddle carriers compared to the diesel-electric straddle carriers where 100% steel was recycled for the end-of-life, and the rubber would be incinerated. The result was difficult to interpret in terms of scaling, but based on the observation, the use phase was the dominant phase when recycling was credited.

Based on the overall observation, it has been found that there are very few life cycle studies on cargo handling equipment and most of the studies lack transparency. Therefore, this thesis shall guide for understanding the life cycle impact of CHE and contribute to the research field. Also, it would shall be a baseline to analyze the climate change mitigation potential of the CHEs in terms of the criteria set in the EU Taxonomy Regulation in future researches.

5 METHODOLOGY

The LCA methodology can be assessed in four distinct and mutually dependent phases: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation (International Organization for Standardization, 2006).

5.1 Goal and scope of the study

This study aims to investigate the climate change mitigation potential of electric and hybrid cargo handling equipment compared to the baseline scenario utilizing the conventional (diesel-based) cargo handling equipment manufactured by Cargotec. The studied equipments are terminal tractor and straddle carrier from Kalmar and a loader crane from Hiab. These equipments are chosen for the LCA because they have significant effect on Cargotec's carbon footprint and are the most common products in the different business areas of Cargotec. Also, the study has been conducted due to Cargotec's interest in the product life cycle assessment for verification of substantial contribution to climate change mitigation objective in the EU Taxonomy Regulation, for which the life cycle thinking is required. (European Commission, 2020a)

The scope of the studied system includes the entire life cycle of the straddle carrier and the loader crane, which follows the cradle-to-grave approach. The cradle-to-grave approach utilizes three phases; product manufacturing, use phase, and end of life. Nevertheless, only the well-to-wheel, which accounts for fuel and electricity generation and utilization, has been studied for the terminal tractor from Kalmar due to limited data availability within the timeframe of this thesis. The baseline product system for the comparison with the electric and hybrid-electric equipments are similar-sized conventional equipments. The energy required for the metal fabrication in product manufacturing has not been accounted for due to the lack of resources in this study. However, in the EoL, transportation of the product from customers use the site to the recycling center is considered.

The function of the straddle carrier is picking and stacking cargo up to 4 levels in the ports or for industrial application and moving the freight from one place to another within the ports. Similarly, the loader crane is used for on-road transport loading and unloading cargo. The terminal tractor is used for moving semi-trailers within the cargo yard and distribution centers from one point to another. For all these equipment, the commonality is their function of cargo handling. The operating hours are used as a functional unit in most life cycle studies of heavy vehicles and CHEs as the operating hours enable consistency than other performance metrics, such as the lifting capacity or load of the cargo (in tons) handled by the equipment. However, the lifetime of 1 CHE has been chosen as the functional unit for the LCA in this thesis. Figure 13 below depicts the system boundary for the LCA study.

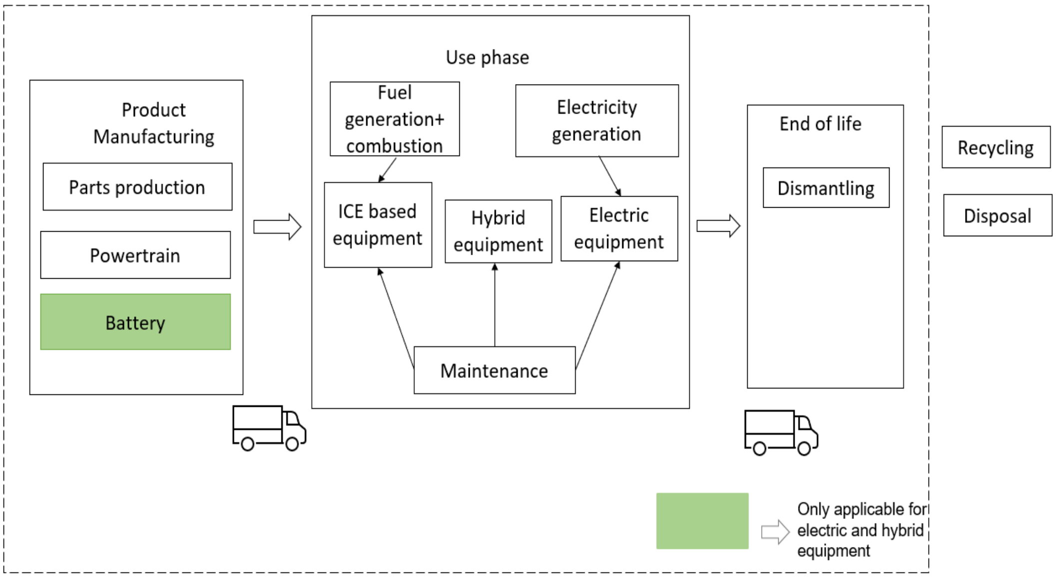

Figure 13. System Boundary for the LCA study

The study accounts for all the emissions during the operation, either from fuel or electricity. Similarly, the maintenance for these CHEs is also included in the system boundary to account for different maintenance requirements. Also, scenarios with a diverse grid mix for the electric CHEs are taken for the sensitivity analysis. The impact category studied in this project is the global warming potential due to Cargotec's ambition to align with the 1.5 °C global warming target and demonstrate if the electrified equipments can provide a substantial contribution towards climate change mitigation objective of the EU Taxonomy Regulation. CML 2001 is the selected impact assessment method. The CML 2001 uses the factors for climate change similar to the IPCC factors in Assessment Report 5(AR5). Studied product systems are specified for specific geographical regions. Geographically, the straddle carrier and loader crane are based in the EU, while the terminal tractor is based in the US.

The required data for the use phase fuel consumption has been obtained based on performance and telemetry data. For the product manufacturing phase, the required data has been retrieved from the different business units (including the Research and Development unit) in Cargotec. This is an attributional LCA, and GaBi Software is used for the LCA modeling. GaBi is one of the market-leading software used for over 25 years for LCA studies, carbon and water footprint, and eco-design. (Sphera, 2021)

5.2 Life Cycle Inventory Analysis

In this study, the LCI is mainly based on the actual measured primary data provided by Cargotec and estimations based on literature. The model for the straddle carriers and the loader cranes were created in Gabi comprising all three distinct phases: product manufacturing of the cargo handling equipment, use phase including the maintenance and end-of-life. Similarly, due to resource limitations, only the use phase was included for the terminal tractors. The LCI data collection for the product manufacturing considers a higher level of detail for components and materials. For the use phase of the cargo handling equipment, the energy requirements are based on the performance tests and telemetry data obtained from connected equipment. The CHEs require lubricants for maintenance and tyre wear, spare parts during its use phase. Therefore, maintenance has also been included on a higher level. However, the detailed inventory data has not been published in this work to maintain confidentiality.

5.2.1 Product manufacturing

The product manufacturing phase covers the entire construction of the product systems studied: straddle carriers and the loader crane. LCI for this phase entails determining the type and quantity of materials based on the bill of materials (BOM) of the products obtained from the actual compiled data from several business units involved in product manufacturing. Further, the required material composition for some constructional elements is based on literature studies, primarily life cycle studies in the automotive industry due to difficulties in obtaining the detailed inventory data as Cargotec only assembles the products and actual manufacturing of the components are carried out by different suppliers, which affect the data availability quality.

For making an apt comparison between the electric, hybrid, and conventional cargo handling equipment, a top-down approach was used where the generic cargo handling body frame and the powertrain components for all types of CHE were identified using a similar approach as Hawkins et al. (2012). The weight of the overall machine was split into the component level and then further into the material composition. After turning the weights into material composition, each material was assigned to the GaBi unit process. The product manufacturing phase usually includes several processes, including welding, injection molding, painting, and final assembly. Nevertheless, the energy consumption during manufacturing and fabrication is excluded in this study due to the unavailability of relevant information.

Battery production contributes about 35% to 41% of the GWP from the EVs production phase, based on the study by Hawkins et al. (2012). Therefore, with the critical need for studying the battery's impact, the battery's GWP impact has been studied in this thesis. LCI data for the batteries were collected from the battery supplier and database. The lithium-based battery has been utilized for the electric cargo handling equipment ePTO, fast charge straddle carrier, and hybrid straddle carrier. The battery pack has been modeled based on data provided by the supplier. As mentioned in section 2.3.1, prolonging the battery life has significance with the environmental emission reduction from the equipment, but the batteries in the studied CHE are expected to meet the lifetime of the equipment studied. Further chemistry and details on the battery are not disclosed in this study due to confidentiality. However, the GWP impact associated with the battery has been given high importance in the study.

Constructional elements of the different straddle carriers: diesel-electric, hybrid, and fully electric can be observed in Table 2, where the main differences are the powertrain components. While the FSC does not require the diesel engine and the generator, the latter two ESC and HSC entails all the powertrain components such as the diesel engine, generator, and electric motor. Nevertheless, the HSC and FSC utilize the lithium battery, of which the battery capacity for FSC is roughly two times higher than the battery capacity for the HSC.

Table 2. Constructional elements of Straddle Carrier

	Machine Types		
Constructional element	Diesel-Electric Straddle Carrier	Hybrid Straddle Carrier	Fast Charge Straddle Carrier
Steel structures	X	X	X
Castings, forgings	X	X	X
Cabinets	X	X	X
Mechanical components	X	X	X
Diesel Engine	X	X	N/A
Generator	X	X	N/A
Electric motors	X	X	X
Batteries	N/A	X	X
Electrical components	X	X	X
Tires, rims	X	X	X
Hoses and bearings	X	X	X
Lifting ropes	X	X	X
Fasteners and fixtures	X	X	X

Note: X represents the constructional element in the machine; N/A denotes the constructional detail is not required for the machine

For all the straddle carriers, roughly 55% of the straddles are composed of structural steel, 5% are rubber and plastic, around 2% are electronics, and the remaining different steels are ferrous metals. The structural steel has a considerable share of the total mass of the Straddle Carriers. Thus, the selection of steel type for the structural steel has a significant impact on GWP results from the product manufacturing of the Straddle Carriers.

The blast furnace-basic oxygen furnace (BF-BOF) and the electric arc furnace (EAF) are the two different methods for producing steel globally. The major difference between these steel production routes depends on the raw material utilization. While the BF-BOF primarily utilizes iron ore, coal, and recycled steel, the EAF route uses recycled steel and electricity for steel production. (Worldsteel Association, 2020) As per the increased attention of the recycling of steel, the regulations for the circular economy in European Union emphasizing the recycled steel and the uncertainty of the steel type, the structural steel chosen for the straddle carriers utilizes the combination of EAF and BF-BOF route and therefore has lower emission compared to virgin steel. Based on the selected constructional element, the material shares for steel and other materials in straddle carriers can be observed in Figure 14.

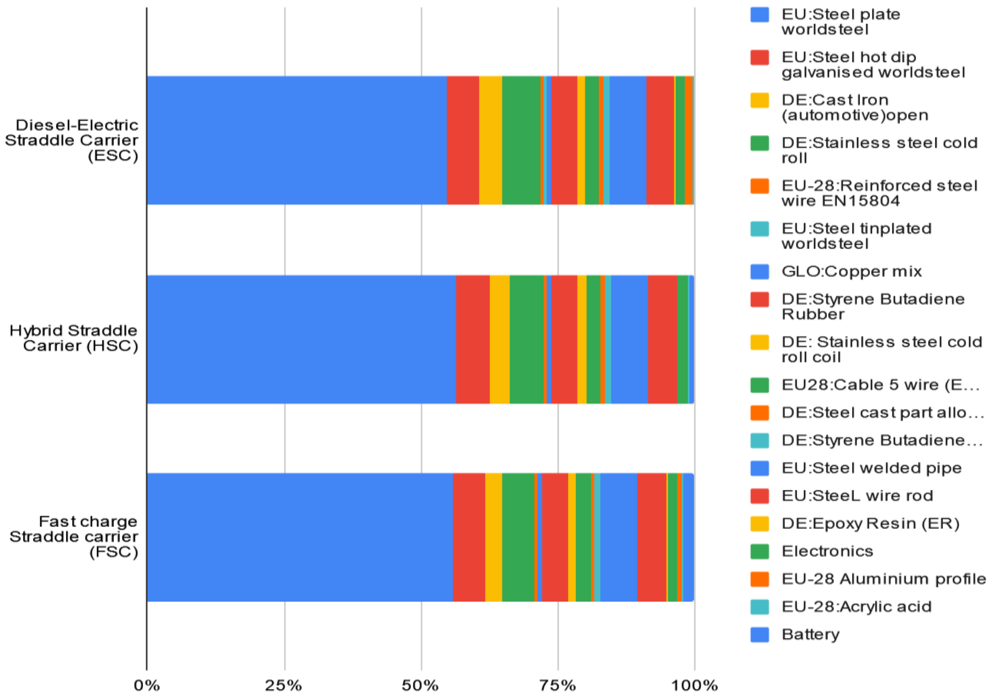

Figure 14. Material shares in studied Straddle Carriers

As for the Straddle Carriers, the main constructional element of the conventional and ePTO loader cranes were identified and modeled for the product manufacturing phase, as shown in Table 3.

Table 3. Constructional element for conventional loader crane and ePTO loader crane

Constructional element	Conventional loader crane	ePTO loader crane
Structural steel	X	X
Castings, forgings	X	X
Cylinders	X	X
Electrical	X	X
Cables and harness	X	X
Bearings and hoses	X	X
Rubber and plastic components	X	X
Fasteners and fixtures	X	X
Motor Box	N/A	X
Battery	N/A	X

Note: X represents a constructional element in the machine; N/A means the constructional component is not required for the machine; the mass for the green filled parts is identical for both the loader cranes

The significant share for the assembly of the loader cranes are steel and metal components. For the crane's body part, which is identical for both the conventional loader crane and the ePTO, the significant share of steel (structural steel) used is the steel plate which is 48% for the conventional loader crane and 44% for the ePTO loader crane. The percentage of rubber is approximately 2.5% for both loader cranes and electronics has a negligible share of 0.9% for the conventional crane and 1.2% for the ePTO loader crane, respectively. While the steel plate used is based on the BF-BOF, most of the other steels in the LCs are a mixture of the primary and secondary routes, implying the combination of BF-BOF and EAF routes. Figure 15 below shows the material composition for both LCs.

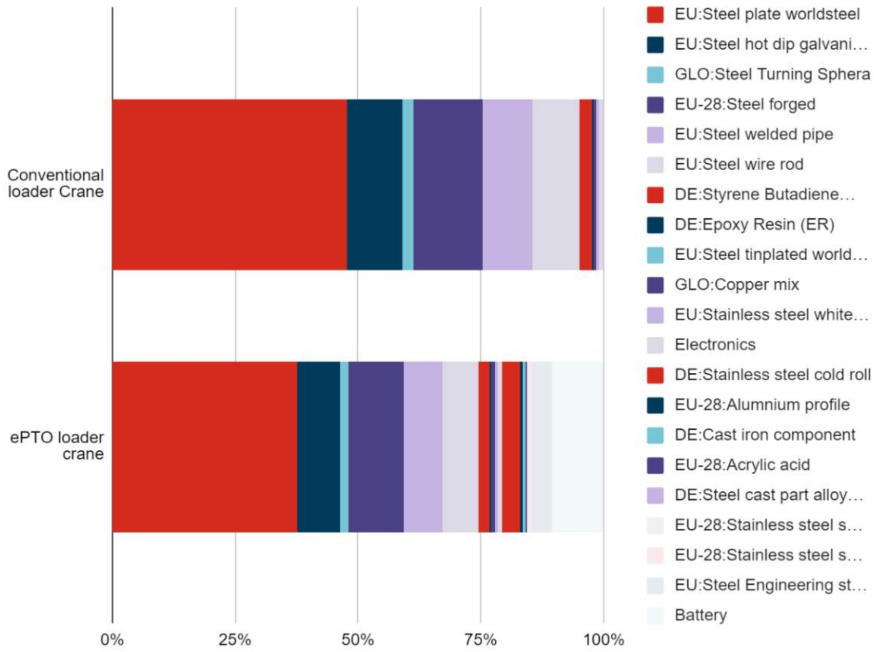

Figure 15. Material composition for conventional loader crane and the ePTO loader crane

5.2.1.1 Material composition and GaBi unit processes

Most of the steel and metal choices for the GaBi modeling are mainly from the database by world steel 2019, and the share of materials are mainly from the mixed route BF-BOF and EAF processes equally. Average data from the literature have been used for the identification of some component's material composition.

The rubber and plastic components are used for several assembly units such as hydraulic hoses and fitting applications. Similarly, plastic parts roughly 30% are also used in electronics based on the literature resource for modeling the electronics in Gabi. There are two different unit processes for rubber in Gabi: Nitrile Butadiene Rubber (NBR) and Styrene Butadiene Rubber (SBR). SBR is the most widely used rubber in the automotive industry because it is durable, resistant to abrasions, oils, and oxidations. (Lin & Bengisu, 2009) Therefore, all the rubber used in the studied CHEs is assumed as SBR. Bronze is used in automotive applications for bearings which comprises an alloy of 88% copper and 12% tin.

The material composition of the diesel engine has been specified based on the study conducted by Jiang et al (2014). Therefore, the diesel engine mainly comprises cast iron and steel. While cast iron makes 68.5% of the total weight, steel makes 22.3%. Similarly, the share of aluminum and alloy is 8.6%, and the remaining is rubber. (Jiang et al., 2014) This data has been replicated and adjusted to the weight in the LCA study due to the difficulty in finding the exact material composition share of the diesel engine. The material composition of the cylinder is mainly steel which accounts for roughly 97%total weight, 2% of nodular iron, and less than 1% of plastic and rubber components based on the information provided by the business units.

5.2.2 Use Phase

Most of the vehicles' life cycle energy usage and GHG emissions result from fuel or electricity to power the equipment (Samaras & Meisterling, 2008). While the use phase fuel and electricity inputs for the straddle carrier and the loader cranes represent average European conditions and import mixes, the use phase for the terminal tractors represents US conditions and import mixes.

In addition to the fuel and electricity for operation, CHEs require machine lubricant and spare parts replacement which has been included in the maintenance during use phase data. For the loader crane, the maintenance entails only machine lubricant use. However, both the machine lubricant and tire wear are accounted for the straddle carriers. Further LCI representative data for the use phase can be observed in Table 4.

Table 4. Life Cycle Inventory data for the use phase

Cargo handling equipment	Assumed lifetime (years)	Energy source			Maintenance	Geographical region
		Conventional	Hybrid	Electric		
Terminal Tractor	8	Diesel	-	Electricity (US grid)	-	US
Straddle Carrier	10		Diesel	Electricity (EU-28 grid)	Lubricant Tire wear	EU-28
Loader Crane	11		-	Electricity (EU-28 grid)	Lubricant	EU-28

The tailpipe emission from the conventional vehicle is the key emission driver from the use phase of the conventional vehicle. In addition to the tailpipe emission, there are also emissions during extraction, transportation, mining, and fuel distribution for the use phase. The emission factors for the GHG utilized for the tailpipe emission are based on the Environmental Protection Agency (EPA), which can be observed in Table 5.

Table 5. Emission factors for different gases from combustion of 1 l diesel

Parameter	g/l	References
CO_2	2692	(EPA, 2018)
CH_4	0.150	(EPA, 2018)
N_2O	0.07	(EPA, 2018)

The emission factors from EPA slightly differ from the emission factors from Lipasto which is developed and maintained by VTT Technical Research Centre in Finland (Lipasto VTT, 2017). Based on Lipasto (2017), the emission factors are slightly different for different machines and the emission emission per liter of fuel combustion for crane is 2655 g CO_2, 0.048 g N_2O and 0.16 g CH_4. Hence, the total tailpipe emission from VTT is slightly lower compared to EPA. However, the EPA emission factors are utilized for all the equipment for uniformity of the emission depending on fuel consumption.

Although the electric cargo handling equipment has no tailpipe emissions, the GHG intensity (gCO_2-eq/kWh) of electricity used for the electric machinery is essential when analyzing the life cycle GHG effect. The unit process for modeling electricity supply for the Terminal Tractor is “US: Electricity grid mix.” On the other hand, the unit process for modeling the electricity supply for the Straddle Carrier and ePTO is “EU: Electricity grid mix.” The electricity grid mix for the US implied in Gabi is based on the year 2016, the most recent version of the grid, and was updated based on the databases from 2019. The grid comprises hard coal 32.1%, natural gas 31.3%, and renewable 17.5% (Thinkstep, 2019). The electricity grid in the EU-28 utilizes 30% of renewable resources, 15.5% natural gas, and 26.6% nuclear.

5.2.3 End of life

The end of life of a product system is an essential phase in the LCA since the approach for the end-of-life modeling can have a decisive impact on the environmental assessment of products that utilize the recycled content and have the recycling potential after the use phase. Several aspects need to be considered for the end of life, including several network entities like the user, collection centers, authorities for dismantling, shredders, recycling centers, second-hand markets, remanufacturing facilities, and industrial landfills sites (Karagoz et al., 2019). Therefore, for the end-of-life study, numerous studies were referred to for choosing the right approach. Ekvall et al. (2018) presented several methodologies for the end-of-life in the study. The methods were explained based on an extra level of complexities, cons, and pros . So, the study helped to understand and select the right approach for the end-of-life in this thesis.

While the EU Directive 2000/53/EC for the end of life of lightweight vehicles is developed for the lightweight vehicles, which is fully formalized, the EoL for heavy vehicles and

NRMM is not developed fully. According to the EU Directive 2000/53/EC, the EoL of a vehicle requires at least 85 % of the vehicle's total weight should be either reused or recycled from 2015 (European Commission, 2020). Regardless of its weight, 75-80% of a vehicle's total mass is composed of several types of metals (ferrous and non-ferrous). The physical characteristics of steel and iron imply that most of the materials can still be reused and recycled and do not lose their inherent properties; therefore, only the other parts end up for disposal or incineration for energy utilization (Kanari & Shallari, 2003). Recycling steel and other metals saves energy for mining and extraction and provides economic benefits to the users. Due to the regulation and increased environmental and economic benefits, recycled steel in Europe has gained more attention and is very demanding. The circular footprint formula (CFF) was developed for the end of life as the metals can be recycled, and the remaining end up for incineration from which energy can be recovered. The Circular Footprint formula utilizes the material-dependent factor A, which represents the market realities of accounting for recycled material's supply and demand balance. Factor A ranges from 0.2 to 0.8 depending on the demand for the material in the market. However, this methodology has a drawback in that it requires the input data on avoided processes in other product life cycles and giving the incentives can lead to manipulation of the LCA results. (Ekvall et al., 2018) Recycling material from one product to another creates allocation problems in the LCA due to the same material used in at least two different products. Additionally, the allocation creates confusion and could also increase the lack of robustness in the results.

While the EoL for the lightweight vehicle is organized and monitored well, the EoL for the heavy vehicle and NRMM seems to be more disparate and less developed, creating lack of transparency on how the industries are handling the EoL (Saidani et al., 2018). Similarly, the manufacturing of the CHE is not within Cargotec’s operation. Cargotec gets constructional elements from different suppliers and assembles those constructional elements. Therefore, the limited availability of data creates uncertainty. Hence, a simple *cut-off* method that includes no process beyond the product life cycle has been chosen for the LCA as it is also the most favorable and easy-to-use method for the ALCA (Ekvall et al., 2018). It is also one of the most used methodologies in the LCA studies of automotive applications, due to which it has been chosen as the best fit option for this study as it is simple to use and is reproducible as it can be easily understood and is transparent.

For the end of life, it is assumed that the CHEs are sent to special collection facilities and sorting centers first. Transportation from customers' site to the recycling station is considered 200 km for all straddle carriers and loader cranes. Then, the CHEs are disassembled, and most of the metal's parts are assumed to be reused or recycled after the dismantling which is not considered in the study. The dismantling of the materials requires energy as much as 66 kWh per ton of the body, based on the study conducted by Messagie et al. (2014). Therefore, the energy requirement for dismantling is assumed to be 66 kWh per ton of the CHEs. Apparently, several further treatment and processes are involved in the EoL for vehicles such as shredding and other treatment, however, these are not included in this thesis. Though most share of the equipments is steel and assumed to be recycled, the recycling is not credited in the EoL of the studied CHE. The end of life for electric vehicles and equipment is also influenced by lithium-ion batteries disposal. However, battery recycling is still in infancy since there has not been recycling technology established yet on a large industrial scale (Peters et al., 2017) and have huge uncertainties related to recycling techniques (Xiong et al., 2019). So, the batteries in the CHEs are assumed to end up for recycling.

5.3 Results

The evaluation results are given within the life cycle impact assessment of the LCA. In this study, CML 2001, one of the classical impact methods, has been utilized for characterization. Different mid-point impact categories included in the CML 2001 are global warming potential, acidification potential, eutrophication potential, human toxicity potential, ozone layer depletion, marine aquatic ecotoxicity potential, freshwater aquatic ecotoxicity potential. However, the GWP of different electric equipment compared to conventional equipment is the only focus for this study.

GWP compares the amount of energy the emissions of 1 ton of a gas will absorb over a given period, which is 100 years average time, compared to the emission of a ton of carbon dioxide

(Vallero, 2019). Major gases contributing to the GWP are methane, carbon dioxide, and nitrous dioxide. The results based on the inventory are expressed in kg CO_2 equivalent.

5.3.1 GWP results from loader cranes

As per the scope of the LCA for the loader cranes, the life cycle GWP impact of the loader crane includes cradle-to-grave impact, which is from all related activities: manufacturing, use phase, machine lubricant for the maintenance, and end of life. The overall result from the conventional and the ePTO loader cranes shows that product manufacturing has a less significant GWP impact than the use phase, which is responsible for most of the GWP impact through fuel combustion or electricity generation. Additionally, the GWP impact from the end of life has a negligible share in the overall life cycle GWP. The ePTO loader crane, which utilizes the average EU-grid mix, can reduce the GWP impact by 55% compared to the conventional loader crane, as shown in Figure 16.

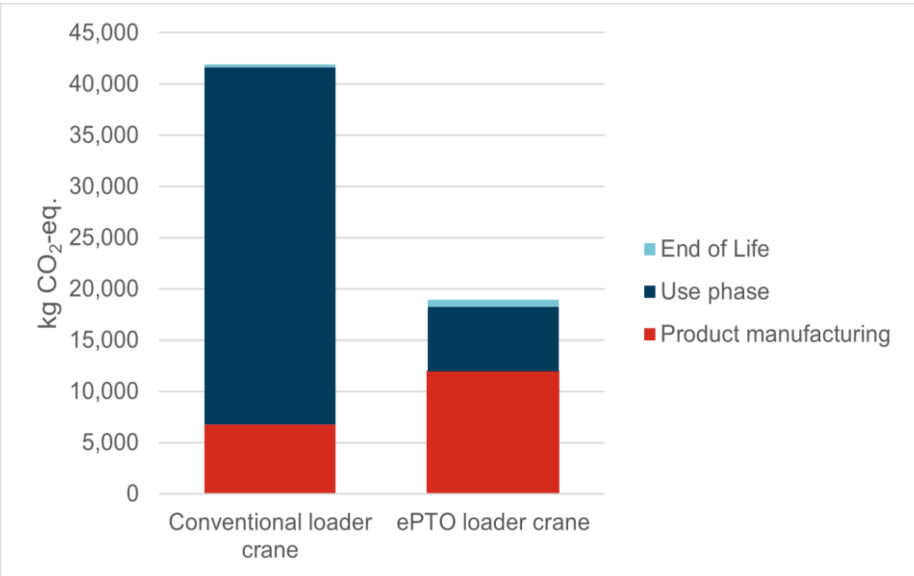

Figure 16. Life cycle GWP impact from conventional LC and ePTO LC

The manufacture of electric cargo handling equipment requires more energy and has higher emissions than conventional cargo handling equipment based on several studies, including Hawkins et al. (2012). While the GWP intensity from manufacturing the conventional loader crane is 6,768 kg CO_2-eq, GWP intensity from the manufacturing of the ePTO loader crane is 12,162 kgCO_2-eq which is 80% higher than that of the GWP from the manufacturing of the conventional loader crane. The high GWP impact from the ePTO when compared to the conventional loader crane is associated with the battery and the motor box production. GWP associated with battery production for the ePTO shows equivalent results to the average GWP impact from the study conducted by Peters et al. (2017), which is around 110 kg CO_2-eq. Per kWh of battery storage capacity. In the case of the ePTO, the manufacturing covers roughly 31% of the total life cycle GWP impact. 37% of the GWP impact from the manufacturing of the ePTO loader crane is associated with battery production, 7% from the motor box, and 56% from the cranes body which is the steel structure. In contrast with the ePTO loader crane, product manufacturing covers 18% of the conventional loader crane's overall life cycle GWP impact. GWP impact from the product manufacturing of the conventional crane and the ePTO can be observed in Figure 17.

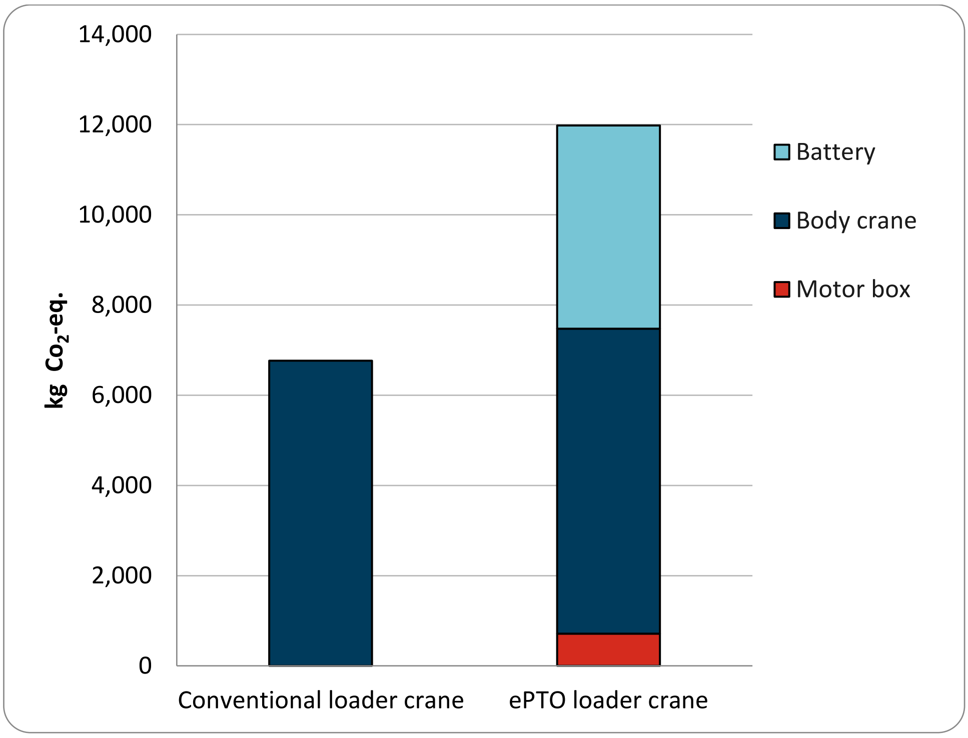

Figure 17. GWP impact from product manufacturing of conventional LC and ePTO LC; Note: body crane is identical for both the conventional loader crane and the ePTO

Within the assumed lifetime of 11 years, the lifecycle GHG emissions savings from the ePTO compared to the conventional crane is 87% in the use phase. While the GWP intensity from the use phase for the conventional crane is 32,739 kg CO_2-eq, GWP intensity from the use phase of the ePTO utilizing the average EU grid accounts for 4,144 kg CO_2-eq. Assuming that the machine lubricant's maintenance figures are the same for conventional crane and the ePTO, GWP intensity from the maintenance is 2,152 kg CO_2-eq.

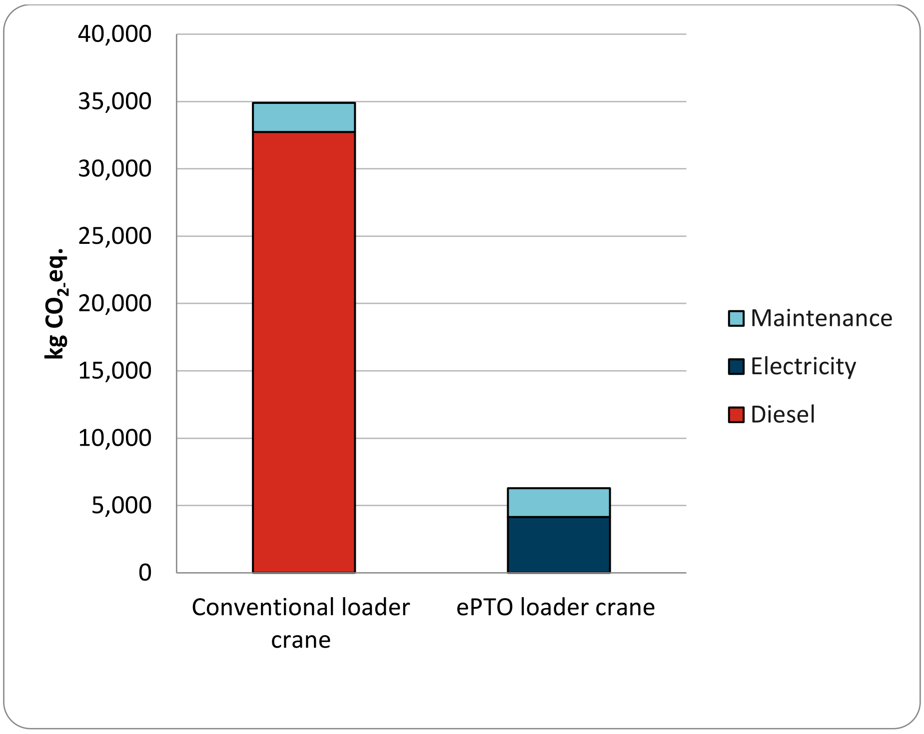

Figure 18. GWP impact from use phase of conventional LC and ePTO LC over the lifetime

Using the cut-off approach in the end-of-life, the GWP intensity from the end-of-life is 268 kg CO_2-eq for the conventional loader crane and 340 kg CO_2-eq for the ePTO. These GWP intensity results are associated with the transportation of the cranes from the customers' use site to the recycling station and the energy required in the dismantling process only.

5.3.2 GWP results from straddle carriers

Based on the LCA results, the FSC can reduce the life cycle GWP impact by 52% compared to the ESC. Similarly, the HSC can reduce the life cycle GWP impact by 24% compared to the ESC. In addition to this, the use phase is the dominant phase for the majority of the GWP within the lifetime, either through fuel combustion or electricity generation for all the different straddle carriers analyzed in this study which can be observed in Figure 19.

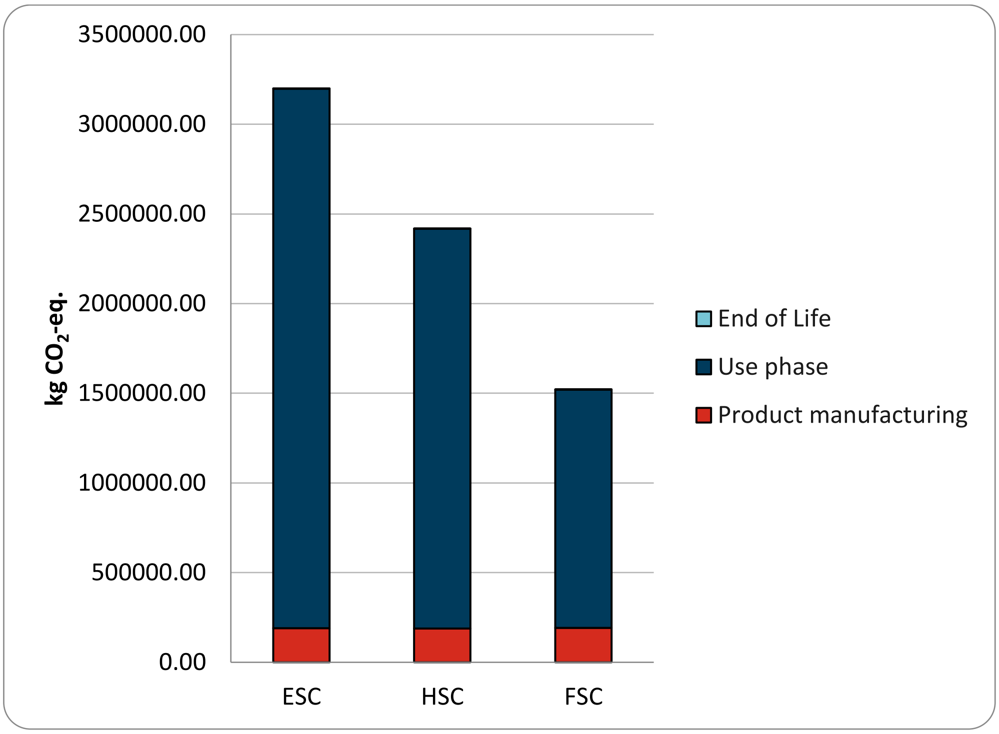

Figure 19. Life cycle GWP impact from ESC, HSC and FSC

GWP intensity from the manufacturing of the ESC is 190,373 kg CO_2- eq, hybrid straddle carrier is 188,706 kg CO_2-eq and the FSC is 191,116 kg CO_2-eq. The result from the manufacturing of different straddle carriers shows that the FSC has the highest GWP impact, and the HSC has the lowest GWP impact associated with the manufacturing of these three different straddle carriers. For the FSC, the higher GWP intensity in the product manufacturing phase is associated with battery production. For the ESC, the diesel engine and generator are bulkier than the hybrid straddle carrier, so its GWP impact is 2% higher than HSC. Nevertheless, the impact of battery manufacturing for both the HSC and FSC has a low share of emission compared to the emission from the overall structure of the straddle carriers since the overall mass of the straddle carriers is roughly 72 tons which are mainly steel structures. For FSC, the GWP impact from the battery is 4%, while the impact from the battery manufacturing for the HSC is 2%. The GWP impact from the battery manufacturing of HSC is lower than the GWP from battery manufacturing of FSC since the HSC incorporates a smaller battery. Similarly, the transport of components has approximately 2% impact on the manufacturing, which is small in manufacturing all three different straddle carriers.

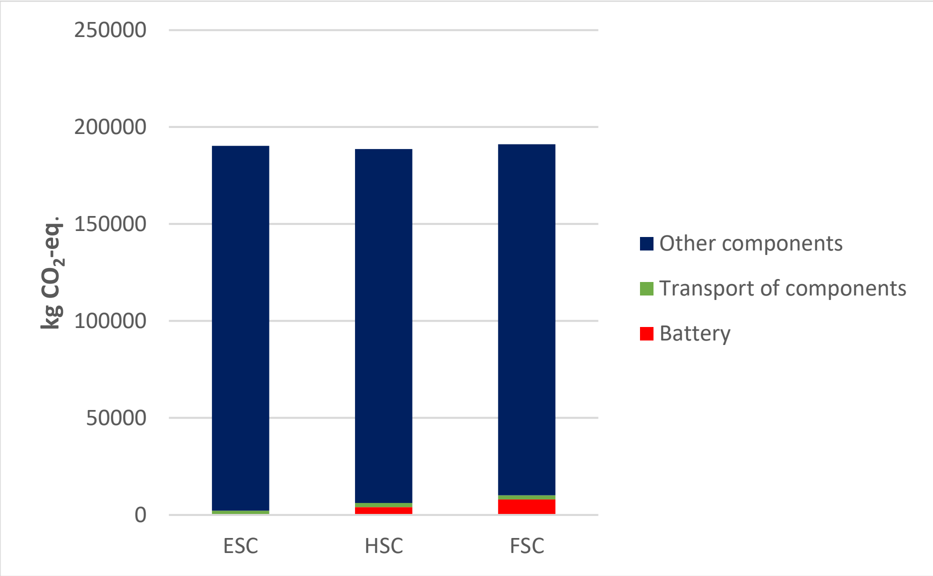

Figure 20. GWP impact from product manufacturing of ESC, HSC, and FSC

The result from the use phase shows that the GWP intensity from the use phase is 3007850 kg CO_2-eq from the ESC, is 2,227,702 kg CO_2-eq. from the HSC, and 1,328,479 kg CO2-eq from the FSC. The aforementioned results are associated with fuel or electricity use and maintenance. The share of maintenance is 1.7% in the use phase for ESC, 2.2% for HSC, and 3.6% for FSC. From the observation, HSC can reduce the GWP impact by 26% compared to the ESC. Similarly, the GWP impact is reduced by 56% from the FSC when powered by the average European electricity compared to the ESC. GWP impact from the use phase of the Straddle Carriers can be observed in Figure 21.

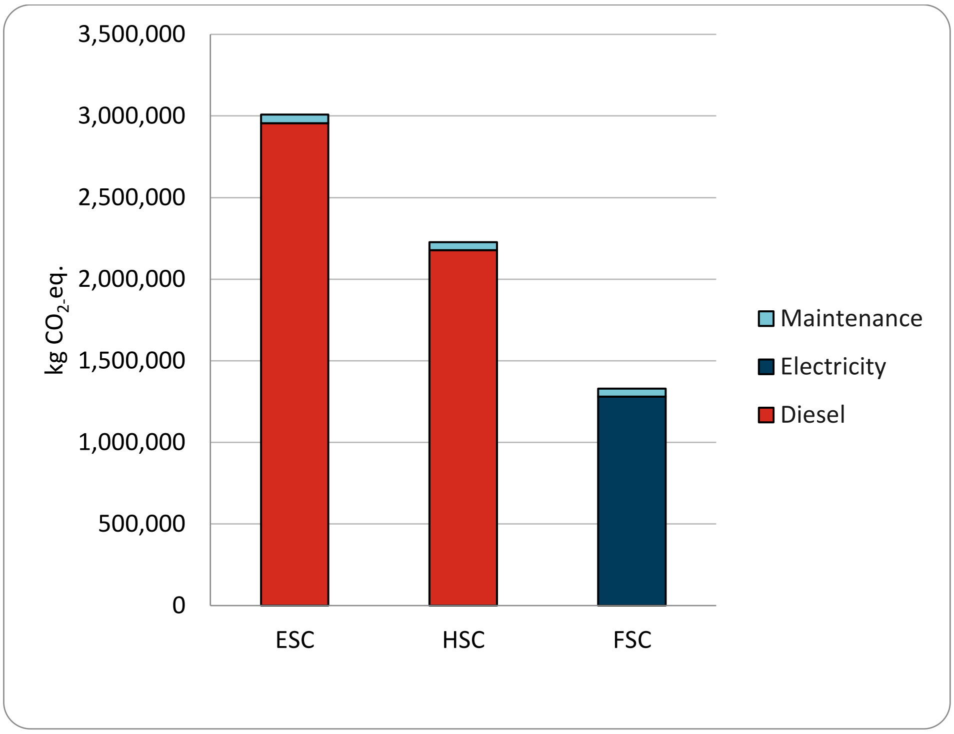

Figure 21. GWP impact from use phase of ESC, HSC and FSC over the lifetime

Total GWP intensity from the end-of-life of the straddle carriers is 1569 kg-CO_2 eq from the ESC, 1407 kg-CO2 eq from the HSC, and 1407 kg-CO_2 eq from FSC. The GWP intensity from the EoL of all the straddle carriers is based on the assumption that all these straddle carriers are taken to the recycling station where the equipments are dismantled. Moreover, the EoL contributes 0.06% in the life cycle GHG emissions for the ESC and 0.08% life cycle GHG emissions for the HSC and 0.13% for the FSC. The overall result for the EoL for the straddle carriers can be seen in Figure 22.

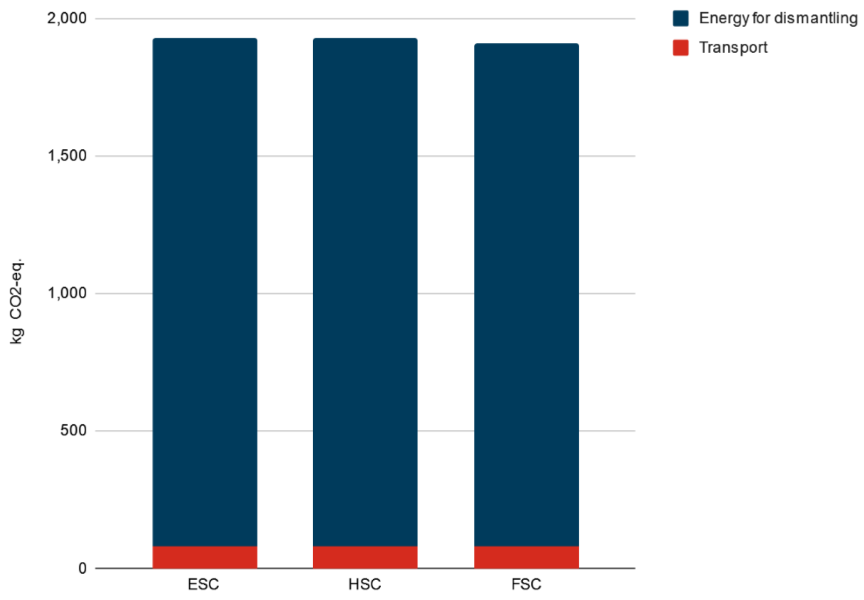

Figure 22. GWP impact from the end of life of ESC, HSC and FSC

5.3.3 GWP results from the use phase of terminal tractor

While the GWP intensity from the use phase over the lifetime of the conventional TT is 571,042 kg- CO_2 eq, the GWP intensity from the electric TT over the lifetime is 111,829 kg CO_2-eq. Therefore, the electric TT reduces the GWP impact by 80.4% compared to the conventional TT during its use phase, assuming the electricity grid is based in the US.

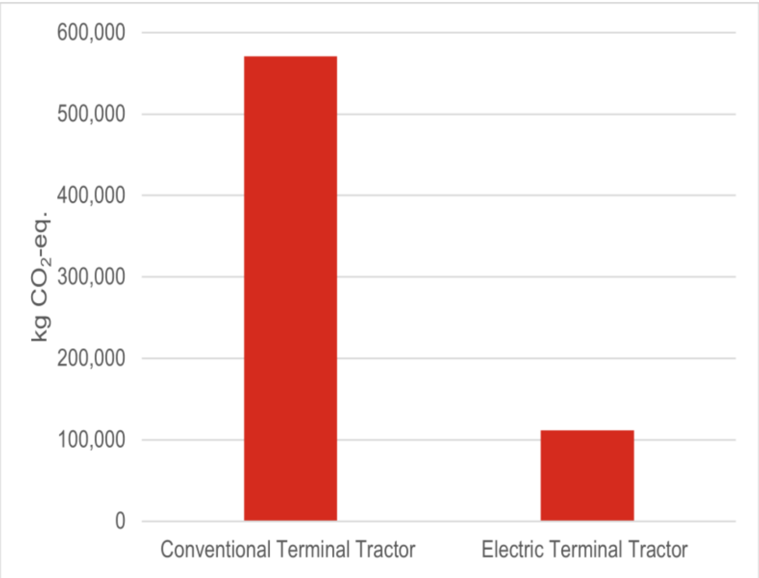

Figure 23. GWP impact from use phase of conventional TT and electric TT over the lifetime

5.4 Sensitivity analysis

In general, the LCA results of vehicles are shown as a single average value. However, the single value cannot fully articulate the real-world uncertainties while reporting and variabilities of the system, which does not provide a broader view for decision-making on the effects of variabilities in the vehicle parameters. (Mierlo et al., 2017) Therefore, sensitivity analysis is an essential means for examining robustness and uncertainty factors (Wei et al., 2014). The sensitivity analysis's main aim is to recognize and emphasize critical data and assumptions that affect the result (IEA-ECBCS, 2004).

Sensitivity analysis in the literature has shown that the electricity grid is a key influencer in the emissions from the use phase (Messagie et al., 2014). Since the European Green Deal aims to cut emissions by 55% by the year 2030 compared to the 1990s level, decarbonization of the electric grid mix is foreseen in the future. With stricter policies and awareness on climate change mitigation, there is optimism for the electricity grid mix, which has substantial improvements in terms of sustainability and will have a higher share of renewables compared to the grid in 2019. While the complete decarbonization might take some time, the electricity grid mix with significant improvement due to heightened sustainability policy, which has a higher share of renewables, is expected to be utilized by 2030. Therefore, electric grid options with significant improvements in sustainability policy have been implemented as part of the sensitivity analysis in the future scenarios' use phase of the electric equipment. Similarly, sensitivity analysis with the Finnish grid option has been conducted in the use phase to see the environmental burden of diverse types of electric grid options.

If sustainability is assessed, the electricity grid mix in the year 2030 will primarily utilize natural gas, and the share of coal will decrease substantially. Different scenarios databases are available for the future electricity grid mix depending on whether the sustainability is assessed limitedly, substantially, or on average in the GaBi. Nonetheless, the electricity grid mix for the US in Gabi with significant improvement in sustainability can be observed below in Figure 24.

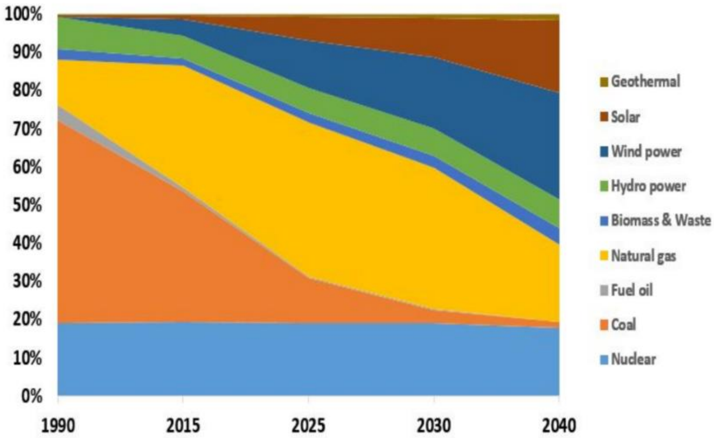

Figure 24. Electricity grid mix with significant improvement in sustainability prediction-based database for Gabi US (Thinkstep, 2019)

Similarly, the electricity grid mix in EU-27 for 2030 is based on the prediction by International Energy Agency. Electricity grid mix with significant improvement in sustainability prediction for the EU -27 can be seen in Figure 25.

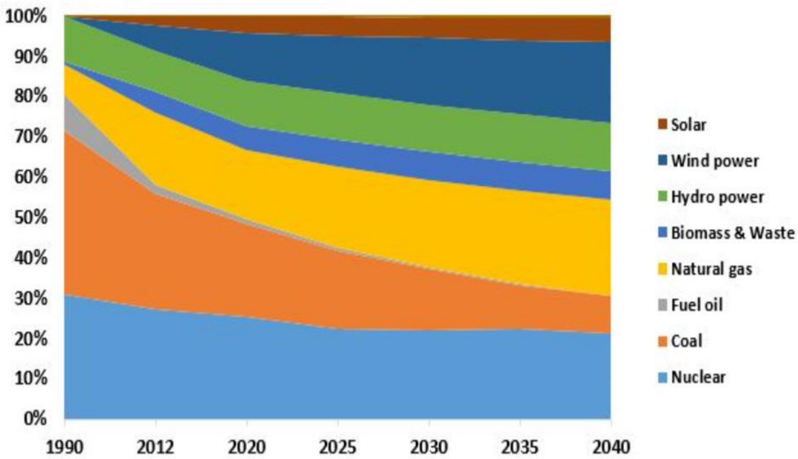

Figure 25. Electricity grid mix with improvement in sustainability policy for future EU-27 from Gabi (Thinkstep, 2019)

Assuming the Finnish electricity grid mix and the grid mix 2030 are used for the operation of the electric CHE studied in this thesis, the following GWP impact results can be observed compared to the current electricity grid mix used, as seen in Figure 26.

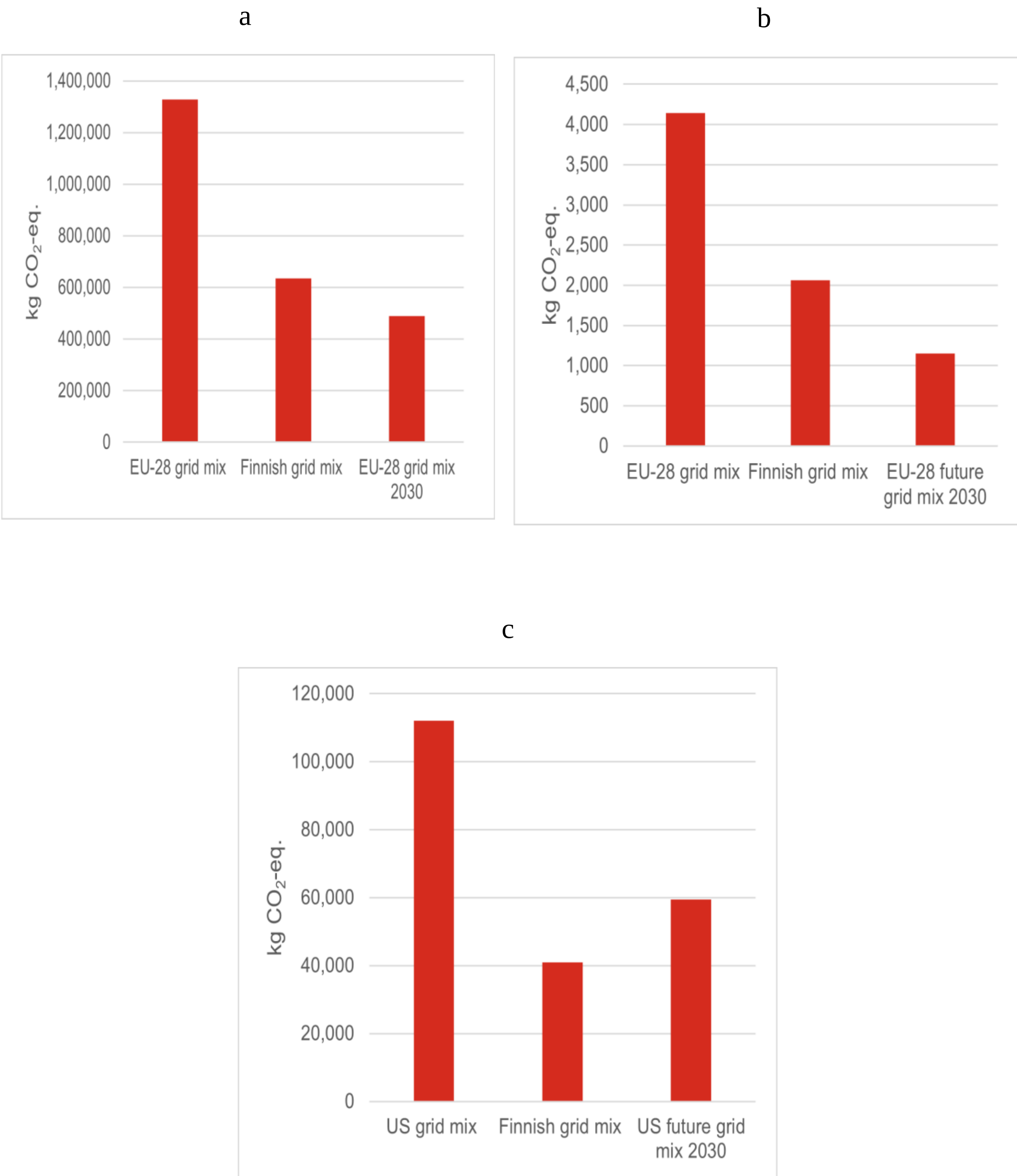

Figure 26. Sensitivity analysis with different electricity grid for a) Fast Charge Straddle Carrier b) ePTO loader crane and c) Electric Terminal Tractor

While GWP intensity from the electric TT when utilizing the US electricity grid is around 112,000 kg CO_2-eq, the GWP intensity from the Finnish grid mix is 41,000 kg CO_2-eq, 63% lower than the US grid mix. Similarly, the future grid mix projected to be more sustainable by 2030 in the US would drop the GHG emission by 47% compared to the current US grid. Similarly, for the FSC and the ePTO, the Finnish grid mix would reduce the GHG emission by around 50% while it is compared to the EU-28 average grid mix and for the future projection, if there is a significant improvement in the grid policy in the EU-28, the GHG emission would be reduced by 61%.

While the conventional crane operates from diesel fuel, the electric loader crane ePTO utilizes the electricity and requires the motor box and the battery, creating extra load in the ePTO LC roughly around 700 kg higher than the conventional LC. As both cranes, conventional LC and the ePTO LC, are mounted to a truck that transfers it from one place to another and this truck also utilizes the diesel, the payload capacity necessitates the increased fuel consumption due to which the emission from the truck is higher with a higher payload. As the impact of the increased weight of the battery packs has also been mentioned in the study conducted by Samaras and Meisterling (2008), sensitivity analysis is conducted with the additional weight of the truck in the use phase emission. The Euro 6 truck with a net weight of 12-14 tons is taken to transfer the cranes. This truck has been used in the model since the Euro 6 trucks were introduced in the year 2015 and are environmentally friendly options compared to the older ones since they follow the updated emission standards proposed by the EU regulation and are utilized for transport of components (European Commission, 2021f). Sensitivity analysis with the added weight impact resulted in the emission from the added weight in the truck to which the ePTO is mounted would significantly impact the overall LCA results. Based on the result, the ePTO will only have an 8% reduction compared to the conventional crane if the indirect emission is accounted for, as seen in Figure 27. GWP impact due to the added weight in the Euro 6 truck implemented in GaBi can be observed in Appendix 3. While the model for the truck has utilized diesel from a filling station, biofuels or other low carbon-intensive fuel could be an alternative option to driving the truck, and the impact would be lesser from the ePTO LC.

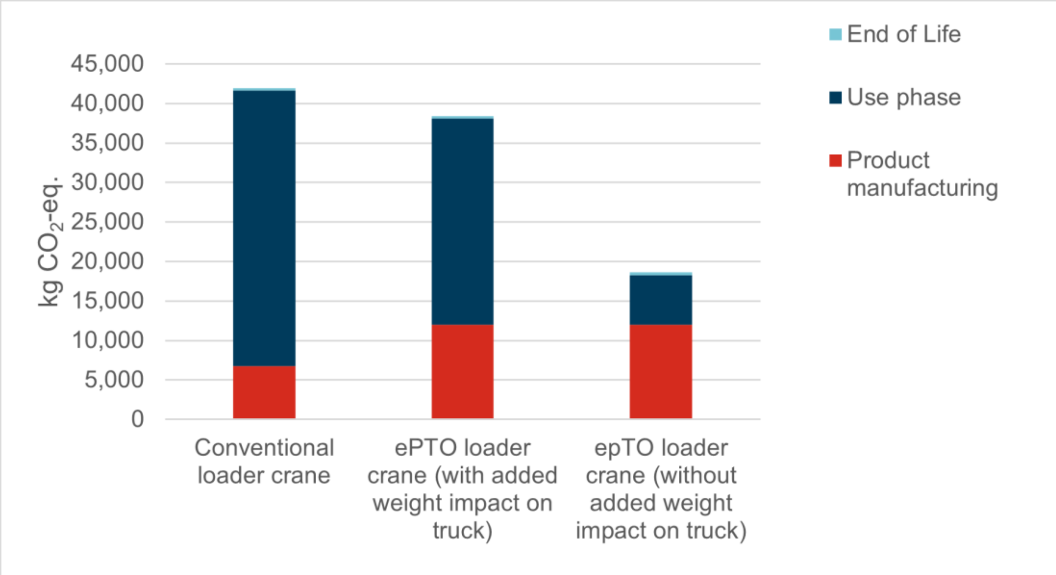

Figure 27. Sensitivity analysis with added weight impact on truck for transporting ePTO loader crane

While the battery life for the ePTO LC and HSC is the same as the machine's lifetime, the FSC has not been in the market for a decade, and the FSC has higher operating hours than the ePTO, due to which there might be a need for battery replacement for the FSC. Assuming the battery replacement is required during the lifetime of 10 years for the FSC, the GWP impact during the product manufacturing was studied. The GWP impact in the manufacturing increases by 4% compared to the baseline scenario of the FSC when the battery is replaced. However, the overall life cycle GHG emission will only increase by 0.52% for the FSC with the battery replacement.

Compared to the study by Zrnic et al. (2013), the overall GWP from the product manufacturing for the straddle carriers is lower than the studied RTGs by roughly 40 to 50%. This varying result could be due to the different steel used for the LCI. Though the steel grade is not mentioned in the study by Zrnic et al. (2013), the higher emission from the product manufacturing could result from the use of virgin steel and different production routes because the CHEs require high strength steel due to the heavy load handing function.

Since it was difficult to get the detail of the steel grading used for the straddle carriers and our results varied with Zrnic et al. (2013), sensitivity analysis to observe the impact of different steel choices was conducted assuming different structural steel. The baseline scenario is the current scenario where the structural steel is EU: Steel Plate, the first scenario utilizes Gabi Unit Process DE: Stainless Steel Cold Roll, and the second scenario was created using the Gabi Unit Process: EU Steel Cold Roll Coil. While the unit process, DE: Stainless Steel Cold Roll, represents the steel production in EAF, the EU Steel Cold Roll Coil represents the steel production from the mixed route with both EAF and BF-BAF routes. The impact in product manufacturing in the Straddle Carriers when different steel is assumed for the structural steel can be observed below in Figure 28.

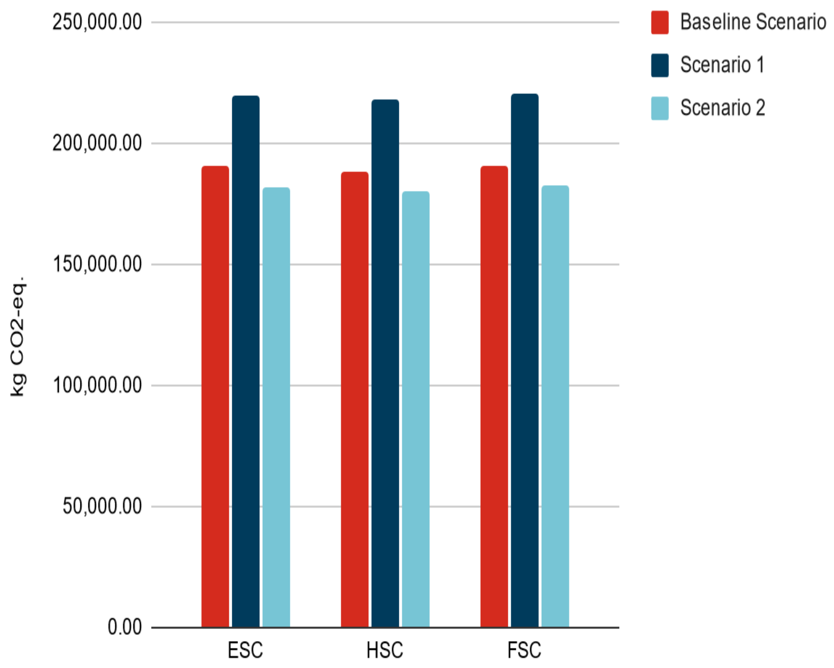

Figure 28. Sensitivity result with different structural steel in product manufacturing of straddle carriers

GHG emission from the product manufacturing increased by around 15% when GaBi unit process "Stainless Steel Cold Roll" is used for all the straddle carriers. Similarly, when the "EU Steel Cold Roll Coil" is used, GHG emission reduces by around 4% in product manufacturing. Sensitivity analysis in product manufacturing shows that the GHG emission from product manufacturing is affected by the steel type used in the model.

6 RESULTS AND DISCUSSION IN TERMS OF EU TAXONOMY

The LCIA results are discussed in terms of the EU Taxonomy Regulation, precisely the climate change mitigation objective for the manufacture of other low carbon technologies.

6.1 Life cycle interpretation: Climate change mitigation

This section addresses the research question 1 and 2 addressed in chapter 1.

- How significant are the GHG emissions from the different electric and hybrid configurations compared to the baseline fuel-powered solution?
- What is the contribution of the proposed technologies to the reduction targets adopted in the Paris Climate Agreement?

The established TSC for climate change mitigation in manufacturing other low carbon technologies requires life cycle metrics to demonstrate substantial GHG emission reduction throughout the life cycle compared to the best performing alternative technology available in the market. To be more precise, these technologies or equipment should contribute and support the net zero GHG emissions by 2050 target set in the European Green Deal. However, these low carbon technologies are enabling activities for which quantified threshold is not defined in the EU Taxonomy regulation since it is difficult to define a certain threshold for the manufacturing activities in the absence of a common denominator. In addition to this, comparing the products to the best-performing alternative technology in the market is ambiguous due to lack of credible information. There are several challenges on how to determine the best performing alternative technology and complexities associated with obtaining data from the competitors' products due to lack of transparency. Therefore, potential electric and hybrid CHEs in the study are compared to the available conventional CHE manufactured by Cargotec since the conventional CHEs are still widely used in the market and are supposed the best performing alternative technology.

While the LCA results for all the fully electric CHE studied in this thesis show at least 50% reduction compared to the conventional CHE, it is essential to define the rationale for how these electric CHEs substantially contribute to climate change mitigation objective in the EU

Taxonomy Regulation. To set the rationale for a substantial reduction, the companies can refer to the *Science-Based Targets (SBT)* setting method. The Science-Based Targets Initiative (SBTi) is a GHG emission reduction target consistent with the level of decarbonization required to keep the global average temperature within 1.5℃ compared to the pre-industrialized levels. It is consistent with the long-term goal of reaching net-zero emissions by 2050 and provides companies the trajectory to reduce their GHG emissions. Methods endorsed by the SBTi are instructive frameworks that companies may use to set emissions reduction targets consistent with the best available climate science. These methods are constructed from three main elements: a greenhouse gas (GHG) budget, a set of emission scenarios, and an allocation approach. The SBTi is a collaboration between the Carbon Disclosure Project (CDP), UN Global Compact, World Resources Institute, and the Worldwide Fund (WWF), making it a reliable tool. (Science Based Targets, 2021)

Based on the recommendation made by the SBTi, companies can utilize the decarbonization pathway or percentage reduction in absolute emission for the scope 1 and scope 2 sources. An intensity target should only be set if it effectuates absolute GHG emission reductions aligning with climate science or is modeled utilizing an industry-based decarbonization route that ensures emissions reductions for the industry. However, the absolute target establishes the solid goals for target communications and entails commitment by a specified amount which makes it more environmentally robust and credible to stakeholders (Science Based Targets, 2019). The emission threshold for absolute emission reduction set for minimum reduction for achieving well-below 2°C in line with the Paris Climate Agreement, would require a 2.5% GHG emission reduction in annual linear terms. Similarly, absolute emission reduction for achieving below 1.5°C in line with the Paris Climate Agreement would require that the threshold is 4.2% GHG emission reduction annually which can be observed in Figure 29. (Science Based Targets, 2020)

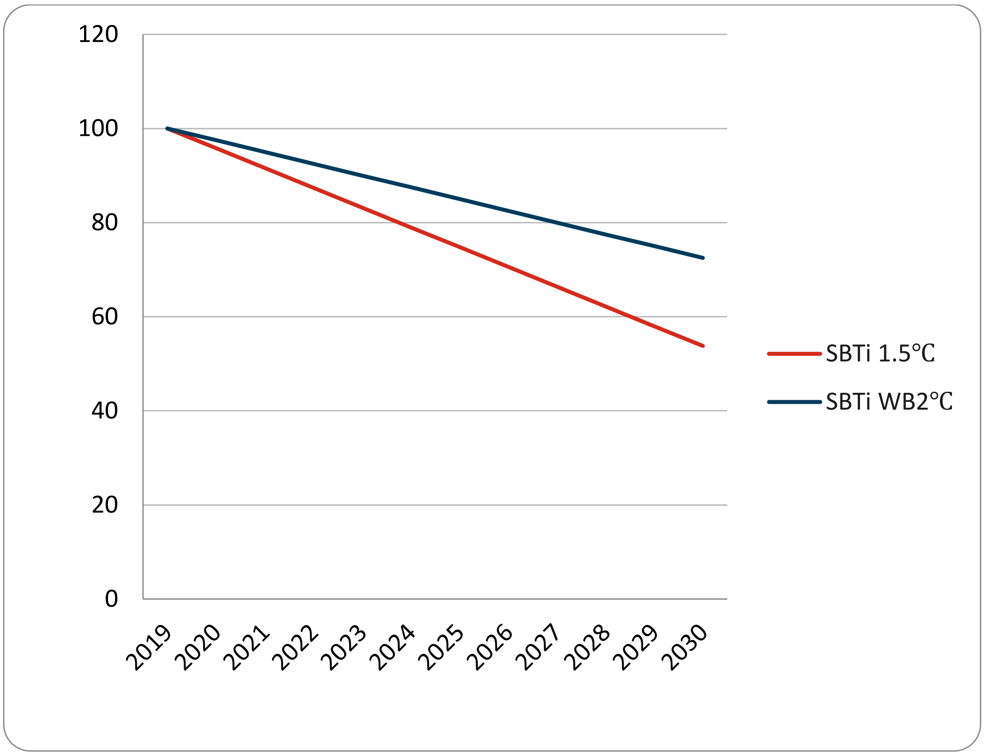

Figure 29. Threshold for alignment with SBTi 1.5°C and well-below 2°C scenarios (2019-2030)

According to IPCC's AR6 report (2021), "With further global warming, every region is projected to increasingly experience concurrent and multiple changes in climatic impact-drivers. Changes in several climatic impact-drivers would be more widespread at 2°C compared to 1.5°C global warming and even more widespread and/or pronounced for higher warming level." This statement reflects on the need to prioritize the 1.5°C target from all the businesses and actors to substantially contribute to climate change mitigation which is also the recommended target by SBTi.

Using the SBTs approach, the SBTs reduction threshold is multiplied by the annual linear reduction with the lifetime of the product (in years) to calculate the absolute emission threshold to align with well below 2°C or 1.5°C goal set in Paris Climate Agreement. Using the SBT approach, it would imply that the absolute emission reduction for the loader crane during its lifetime to meet the 1.5°C target set is 46.2%. In the case of the straddle carrier, the emission reduction required to meet the 1.5 °C ambition based on SBT is the linear reduction of 4.2%, which is 42% of GHG emission reduction during the lifetime of 10 years. As the lifecycle GHG emission reduction potential for the electric straddle carrier is 52% and the lifecycle GHG emission reduction potential for the electric loader crane is 56%, both products can provide substantial contribution to the climate change mitigation objective set in the EU Taxonomy Regulation. Also, with stringent policies for decarbonization and the inclusion of more renewables in the electric grid mix, the emissions are projected to reduce even more in the upcoming years.

While the FSC reduces the GWP impact by 52% compared to the ESC, the HSC only reduces 25% GWP impact compared to the ESC. As stated earlier, the absolute emission reduction requirement to align with the 1.5℃ ambition in the Paris Climate Agreement based on SBT linear reduction of 4.2% would imply that the straddle carrier should at least reduce the GHG emission by 42% compared to the best performing alternative product in the markets during its lifetime. Thus, the result shows that using the SBT approach, the hybrid straddle carrier do not substantially contribute to climate change mitigation objective in the EU Taxonomy Regulation if the target is to align with the 1.5 ℃ ambition in the Paris Climate Agreement.

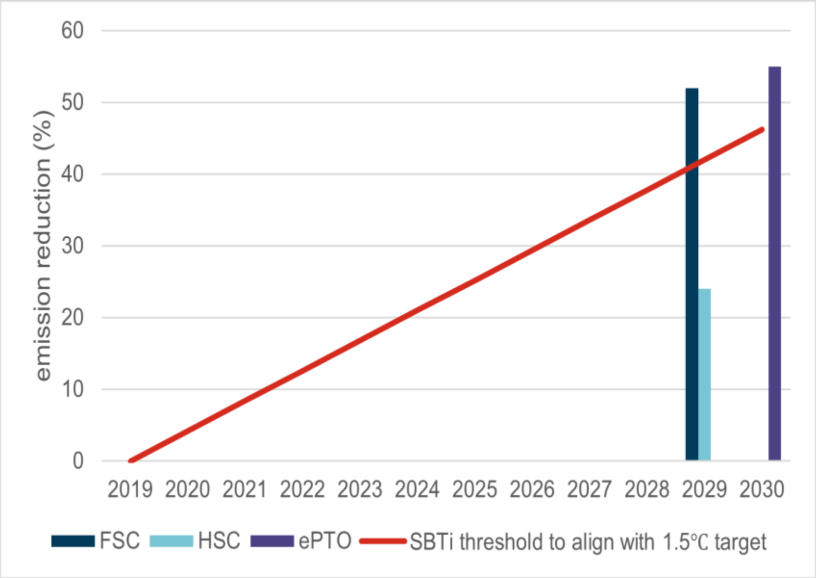

Figure 30. Emission reduction achieved by FSC, HSC and ePTO loader crane

As seen in Figure 30, the red line shows the required emission reduction for each year to align with the 1.5 ℃ target set in the Paris Climate Agreement. Both the electric equipments, FSC and the ePTO LC have higher emission reduction potential than required for aligning with the 1.5℃ target of the Paris Climate Agreement, due to which it can be concluded that these CHEs contribute substantially to the climate change mitigation potential. The TT has not been included in Figure 30 as only the use phase emission was evaluated for the TT.

Though the hybrid straddle carrier showed a reduction potential of 24% only, which does not fit into the criteria for substantial contribution to climate change mitigation aligning with the Paris Climate Agreements' 1.5℃ target, the hybrid could be the only feasible solution in the present context for some places because there are several other challenging factors related to electrification. Also, it is crucial to understand the market reality that not all ports and areas where these machines are operated have infrastructures for fully electric vehicles. Infrastructure like charging stations and the electric grid might not be readily available in all places, which is crucial if we use electric CHE. The result stresses that the hybrid CHEs can be seen as a transitional solution in a mid-term horizon and is the first significant step for mass electrification of the machinery, as Lajunen et al. (2018) stated.

According to the EU Taxonomy Regulation (2020g), "An economic activity for which there is no technologically and economically feasible low-carbon alternative shall qualify as contributing substantially to climate change mitigation where it supports the transition to a climate-neutral economy consistent with a pathway to limit the temperature increase to 1.5℃ above pre-industrial levels, including by phasing out greenhouse gas emissions, in particular emissions from solid fossil fuels, and where that activity: a) has greenhouse gas emission levels that correspond to the best performance in the sector or industry; b) does not hamper the development and deployment of low-carbon alternatives; and c) does not lead to a lock-in of carbon-intensive assets, considering the economic lifetime of those assets." Based on this criterion, the HSC substantially contributes to climate change mitigation potential as it is the only feasible solution in some context, and it does not lead to lock-in of carbon-intensive assets because the lifetime of the HSC is 10 years. Assuming that there is a second life for the HSC to offset the impact of the product manufacturing, the HSC can still substantially contribute to the climate change mitigation potential if sustainable fuel such as biofuel from Neste can be utilized, which according to their claim, can reduce GHG emission 90% compared to fossil diesel. (Neste, 2021)

While this study offers a complete life cycle GWP comparison for the straddle carriers and the loader cranes, only the use phase emission is accounted for the terminal tractor. Therefore, we assume that the manufacturing does not have a significant share in the total life cycle GWP impact from the terminal tractor as most of the emission is associated with the use phase. Also, comparing the electric terminal tractor with the conventional terminal tractor is assumed not to have significantly higher emission since the features are similar and there is no added weight in an electric terminal tractor. Also, the battery size is much smaller compared to the other studied equipment. The electric TT reduces the GWP impact by 80% compared to the conventional TT during its use phase, assuming the electricity grid is based in the US. In order to align with the 1.5℃ climate target in line with the Paris Climate Agreement, the electric TT would require that the threshold is 4.2% GHG emission reduction annually, which is 36% in its lifetime. Therefore, even if the manufacturing impact is higher for electric TT, the electric TT would still have significant contribution to climate change mitigation.

6.2 Do No Significant Harm and compliance with minimum safeguards

The performance threshold, TSC for economic activities to align with EU Taxonomy Regulation, requires any activity to i) make a substantial contribution to at least one of the environmental objectives, ii) follow the principle of DNSH to the other five environmental objectives, and iii) comply with the minimum safeguards. As other metrics are indicated for evaluating the DNSH and the minimum safeguard, the LCA was not utilized to evaluate these criteria.

6.2.1 Do No Significant Harm

- What is the impact of manufacturing of studied cargo handling equipment on other environmental objectives set in the EU taxonomy Regulation?

To evaluate if the CHE manufactured studied in this thesis has no significant harm to other environmental objectives within the EU Taxonomy Regulation and assess the research question 3, a brief investigation for DNSH has been carried out due to limited resource availability. The comparison is based on the DNSH criteria which are mentioned in Table 1 and are addressed in this section.

DNSH for climate change adaptation implies that a robust climate risk and vulnerability assessment are carried out based on the TSC. In the case of these equipments, activities during operation and supply chain are affected by climate change's physical impact, such as extreme weather events, temperature changes, and sea-level rise (Finley & Schuchard, 2007). However, the studied CHEs, mainly the straddle carrier and the ePTO LC, are used indoor, due to which there is no substantial climate risk. Nonetheless, the products are made to sustain several climate-related risks such as heavy precipitation, wind, and these CHEs comply with the DNSH criteria for climate change adaptation.

The DNSH criteria for the circular economy require that the manufacture of the other low carbon technologies assesses the availability of and, where feasible, adopts several criteria as mentioned in Table 1. The CHEs studied for the LCA are designed for long-term use and hence are durable. Similarly, the studied equipment is easy to dismantle, and most of the parts in the CHE business are recycled or reused. Also, Cargotec has been working on lightweight product development, which implies that lightweight materials can boost fuel economy and reduce emissions, as Kawajiri et al. (2019) stated. This would additionally imply that the material requirement is also reduced, due to which there is less GWP impact from the extraction of metals and overall product manufacturing.

Cargotec commits to ethical activities and considers environmental factors prior to decision-making for the business. The company endeavors to manufacture cargo handling solutions that are both ecologically friendly and meet their customers' needs. Environmental compliance with legal directives, including the REACH regulation, is a crucial factor of Cargotec’s environmental performance. Even if it is not required by law, Cargotec ventures to enhance the environmental performance for which internal audits are conducted to assess their improvement. (Cargotec Corporation, 2021c) Therefore, the CHEs comply with the DNSH for the circular economy. As the TSC for pollution prevention and control also requires Compliance with the REACH Regulations (1271/2008/EC) and the RoHS Regulations (2002/95/EC) or the equivalent for equipment manufactured and used outside the EU, these CHEs also comply with the DNSH criteria for the pollution prevention and control (European Commission , 2021e).

For the Sustainable Use and Protection of Water and Marine Resources, it has been recommended to conduct the EIA by following the Directive 2011/92/EU of the European Parliament and of the Council and includes assessment of water-related impact in accordance with the Directive 2000/60/EC (European Commission , 2021e). If the water-related risks are identified and addressed, no other risks assessment is required. However, Cargotec commits to ethical business and considers environmental factors prior to decision making, which also relates to water and marine biodiversity and biodiversity and ecosystems. Therefore, the manufacturing of the CHEs also complies with the DNSH criteria for the sustainable use and protection of water and marine resources and the protection and restoration of biodiversity and ecosystems.

6.2.2 Minimum Safeguard

The TSC for the economic activities to qualify for the EU Taxonomy Regulation requires compliance of the minimum safeguard while the economic activities are conducted. As per the code of conduct of Cargotec, the company is fully in compliance with applicable national and international regulations, including the UN Universal Declaration of Human Rights, UN Global Compact, International Labor Organization (ILO), Declaration of Fundamental Principles and Rights at Work and OECD Guidelines for Multinational Enterprises. (Cargotec Corporation, 2021c) Therefore, for all the studied products, the minimum safeguard is ensured.

7 CONCLUSION

The socio-economic damage from increased temperature and several weather events has shed light on the critical need for sustainable investment for climate change mitigation, and the EU Taxonomy is one of the best tools that creates transparency for sustainable financing. The EU Taxonomy Regulation helps to navigate environmental performance and directs capital flows towards sustainable investment and help to reach climate-neutral goal 2050 for the European Union. Additionally, it also ensures minimum social safeguard and no significant harm to other environmental objectives.

The role of business in the overall climate change mitigation is remarkably high since companies can help in product development and sell valuables that are best for the environment and overall sustainable future and inclusive growth. But the transition to a low carbon economy is a costly process; however, the EU Taxonomy can be a great businesses opportunity for product development and branding the environmentally friendly products if businesses can utilize the science-based approach and demonstrate substantial GHG emission reduction from their products compared to the best performing alternative product or solutions available in the market. Cargotec as an actor in manufacturing has tried to step up and contribute to climate change mitigation through electrification and efficiency enhancement. As for this, the company is utilizing the EU Taxonomy Regulation and life cycle metric as a business opportunity to understand where the improvement is required in their product and market their eco-friendly products.

Cargo handling equipment manufactured by Cargotec falls into the economic activity "*Manufacturing of other low carbon technologies*" in the EU Taxonomy Regulation. In order to verify the climate change mitigation potential of the EU Taxonomy Regulation i) the technology should demonstrate lifecycle GHG emission reduction compared to the best available alternative technology in the market, ii) align with the principle of DNSH to the other environmental objectives, and iii) ensure compliance with the minimum social safeguard criteria. Following the requirement for the technical screening criteria, the LCA was conducted for the studied cargo handling equipment. Similarly, compliance with the DNSH and minimum social safeguard were evaluated.

The research questions presented in the introduction section 1.5, created a solid foundation for the overall research. The questions were mainly assessed by using the LCA methodology and the results were interpreted by utilizing the SBTi. The LCA results for the electric cargo handling equipment suggest that the electric CHE has significant GHG emission reduction potential compared to the available conventional cargo handling equipment. The electric CHE thus align with the Paris Climate Agreements' 1.5℃ ambition pathway in the Science-Based Targets. Consequently, the results favour that the electric CHE can contribute to climate change mitigation objectives in the EU Taxonomy Regulation. Similarly, the hybrid straddle carrier might be the only feasible solution in areas that do not have all infrastructure for the electric vehicles, such as charging facilities, therefore the hybrid serves as a transitional solution and also do not lead to lock-in of assets due to which the hybrid also fits the criteria for being sustainable or contributing to climate change mitigation objective in the EU Taxonomy Regulation.

The overall finding from the LCA indicates that the use phase is the dominant phase in the overall lifecycle GHG emissions. Thus, the results are particularly important to understand where the hotspot for the GHG emission lies in the overall lifecycle, and it indicates that electrification and energy efficiency should be the focus for industries for climate change mitigation. In addition, the production of electric CHEs is found to have a higher GWP impact compared to the production of conventional CHEs. When we analyze the results for the product manufacturing of the straddle carrier, the GWP impact from the manufacturing itself is huge compared to the impact from the manufacturing of the ePTO as the weight is huge for the straddle carrier. Hence, the manufacturing results show the need for embedding sustainability in the product development for the bigger solutions like Straddle Carrier since there is massive steel used if we compare the scale of the product straddle carrier to the ePTO. It is integral that the companies focus in the use of fossil free steels for manufacturing of these kind of machines.

Different sensitivity analyses were conducted in the study to evaluate i) influence of different electricity grids in the use phase of electric equipments, ii) the impact of battery replacement in fast charge straddle carrier in manufacturing, iii) influence of different kinds of steel used for the straddle carriers iv) influence of increased weight in indirect emission from a truck moving the loader crane. Sensitivity analysis with different grid options in the use phase of the electric CHE shows substantial variation in the emission. The emission from the use phase reduces by 50% when using electricity from the Finnish grid compared to the EU average grid mix and 63% compared to the US grid mix. Similarly, the utilization of the future grid mix in the US would reduce the GWP impact by 47% compared to the current grid mix in the US, and the emission by utilization of future grid mix in the EU would reduce the GWP impact by 61% compared to the current EU grid mix.

Sensitivity analysis assuming the battery replacement in FSC showed an increase in the GWP impact from product manufacturing by 4% compared to the baseline scenario when battery replacement is not required. However, the overall life cycle GWP impact increased by 0.52% only for the FSC, which indicated that the replacement of the battery does not have a significant impact on the overall lifecycle GHG emission. Assuming different steel types are used for the structure of the straddle carrier, the GWP impact from the product manufacturing increased by 15% compared to the product manufacturing using the "EU steel plate as the structural steel" when GaBi unit process "Stainless Steel Cold Roll" is used for all the Straddle Carriers and reduces by 4% when the "EU Steel Cold Roll Coil" is used. This indicates that GWP impact from product manufacturing is affected by the steel type used in the model. However, the increased or reduced impact due to the steel choice for the straddle carriers does not shift the hotspot for the life cycle GHG emission from the use phase due to the lifetime for the studied straddle carriers.

While indirect GHG emissions are not within the scope of the studied system, sensitivity analysis with the increased weight in the truck where the cranes are mounted to showed that the GWP impact from the truck moving the crane would increase massively when the added weight is taken into consideration. This indicates that the industry needs to develop lightweight solutions as well as electrification or use of alternative renewable fuels of the trucks where the cranes are mounted.

Along with the climate change mitigation potential, all the studied cargo handling equipments fulfil the DNSH criteria as well as the compliance to the minimum social safeguard. Therefore, the products are expected to align with the EU Taxonomy Regulation. However, this would require a third-party verification prior to market the products as sustainable or contributing to climate change mitigation objectives in the EU Taxonomy Regulation.

While electrification can substantially reduce GHG emissions, it is also indispensable to understand the synergies between electrification, renewable energy, and policymaking. Since the EU Taxonomy Regulation is focused on low carbon solutions, it is also significant to have a stringent policy on the renewable energy share in the electricity grid as the share of renewables in the grid mix can inevitably impact the environmental footprint of the transport sector. Similarly, there is no such strict policy for the end-of-life of heavy vehicles and non-road mobile machinery. Therefore, there is a considerable need for the EU to have a firm regulation for the end-of-life of such vehicles. The EoL regulation can solve numerous issues related to resource scarcity within the EU and could support more environmentally friendly solutions since the products do not end up in countries where recycling is limited, and the disposal might even have a higher impact than what we assume.

While this study offers a complete life cycle GWP comparison for the straddle carriers and the loader cranes, some limitations remain within the LCA model, which creates uncertainty. These are mainly associated with the modelling of the product manufacturing phase since the constructional elements in the CHE are manufactured by different suppliers, and Cargotec only assembles the product. Following are the limitations of the study:

- Though some studies have been referred to see the proportion of the GWP impact in different life cycle phases, the GWP intensity in the manufacturing of CHE; straddle carrier and the loader crane is affected by the material choice, which is an assumption and shall be modified further in future when more accurate data is obtained. Due to limited studies on similar CHE, the robustness of the results is difficult to confirm, and there is a need for more research from academia on LCA of similar cargo handling equipment.

- Due to the data unavailability for the terminal tractor, only the use phase has been considered, and the impact from the manufacturing has been assumed to have a small share in the total life cycle GWP impact. The reason behind this is also because the features are similar, and the battery size is much smaller compared to the other studied equipment, but a cradle-to-grave analysis shall be conducted for the Taxonomy verification.
- The DNSH for the other environmental objectives in the EU Taxonomy Regulation lacks a detailed analysis due to limited resource availability but shall be improvised for the company's internal analysis and the third-party verification.

The Taxonomy is a regulatory imperative that can help address the concern on greenwashing since the technical screening criteria are developed, and a science-based approach such as the life cycle metric is used. It is a living document that will be amended with time. Nevertheless, interpretation of the technical screening criteria for the climate change mitigation potential of other low carbon technologies is challenging and requires more granularity. Since it is required to compare the potential technologies to the best performing alternative technology in the market, the best performing alternative technology should be precise.

A similar study for evaluating the climate change mitigation potential of the cargo handling equipment in terms of the EU Taxonomy Regulation is not available since the EU Taxonomy Regulation has not fully developed. Therefore, this research shall be a baseline for future life cycle studies for similar cargo handling equipment and evaluation of substantial climate change mitigation potential of the cargo handling equipment in terms of EU Taxonomy Regulation. Nevertheless, further research for the CHE and the end-of-life of the CHE and battery technology would be much valuable for the industry and academia. Specifically, the recycling of battery technologies is still in its infancy. Battery recycling is one of the debated issues and recommended in the EU Taxonomy Regulation as with the increased electrification, there would be the need for the critical raw materials in the battery, and battery recycling could be a breakthrough objective to address the resource availability issue and it could provide several other benefits such as improve the social sustainability concerns related to mining. However, it is difficult to find information on battery recycling since the battery recycling industry is still developing and there are no huge scale recycling facilities. In addition, there is also needed to focus on several factors such as infrastructure development and research on the different battery technologies since lithium batteries would play a vital role in electric vehicles and cargo handling equipment.

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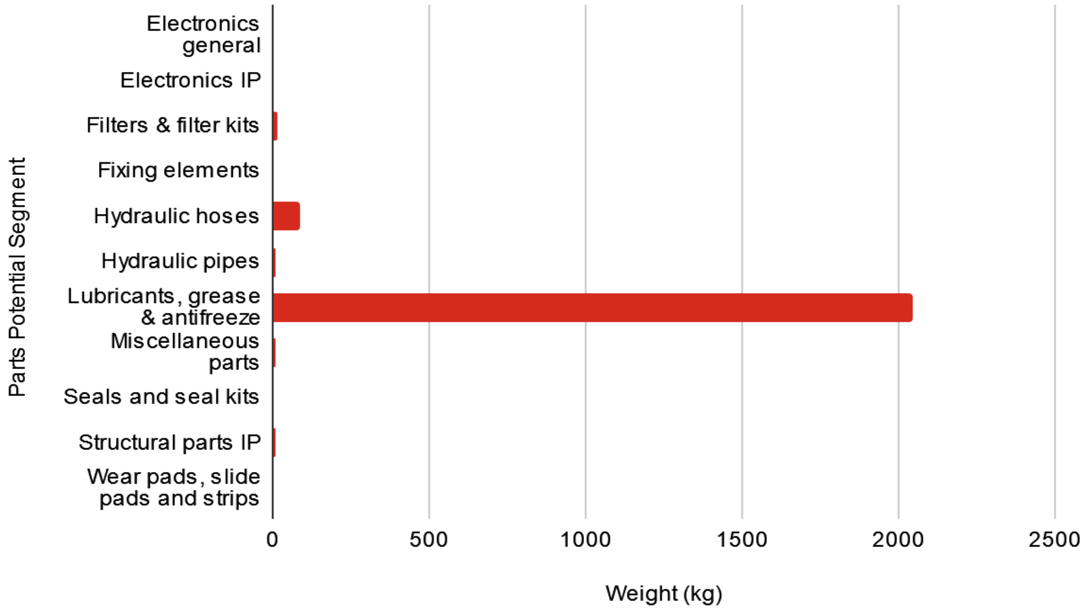
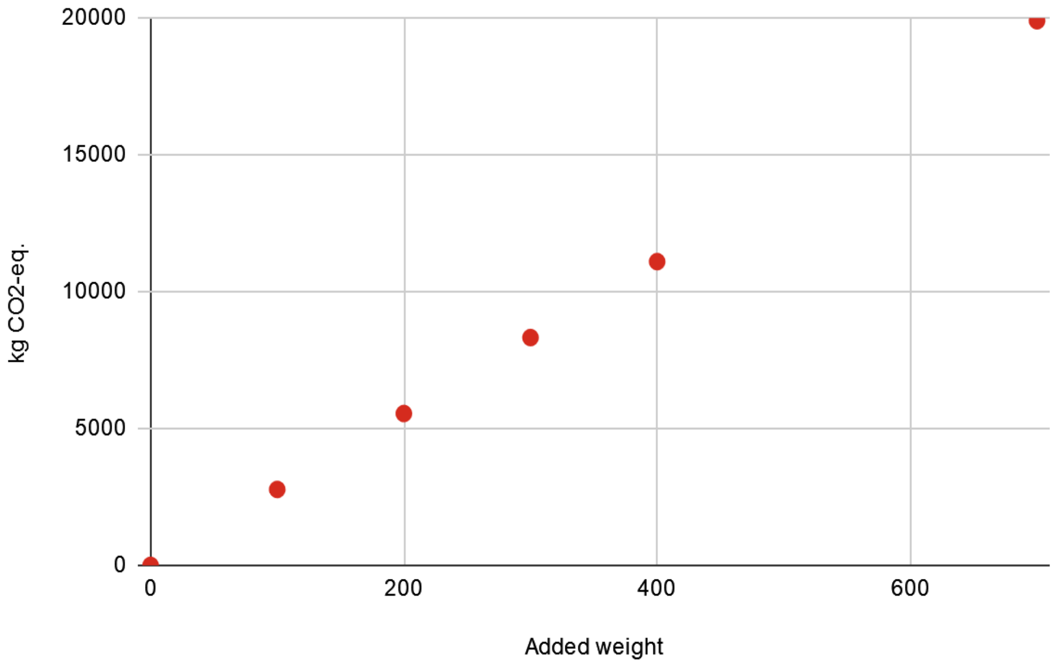
Appendix 1. Life cycle studies on private cars

Author	System Boundary	Length of life (km)	Weight of the vehicle (kg)	Battery performance (kWh)	Battery weight	Battery production place and contribution in percentage in manufacturing	Recycling of Battery	GHG emissions (g/CO_2 eq/km)	GHG emission reduction potential compared to ICEV	Electricity grid mix
(Hawkins, et al., 2012)	Cradle-to-grave (Including maintenance)	150,000	-	24	-	China; 35 to 40 %	Yes	87–95 g CO_2eq. /km	20–24 %	EU-mix
(Pero, et al., 2018)	Cradle to grave	230,000 km	1249	-	318	South Korea	yes	-		Italy mix
(Mierlo, et al., 2017)	Cradle to grave	209,597 km	-	-						Belgian average mix

(Kawamoto, et al., 2019)	Overall waste management and recycling not considered	200,000 km	1590 kg	35.8 kWh	-		-			US (United States), Japan, EU, China, Australia
(Xiong, et al., 2019)	Cradle to grave	120,000	-	47.5	494		No	201. 94 g/CO_2 eq.k		China
			-	60.5	444		No			China



Appendix 2. Maintenance requirement in loader cranes



Appendix 3: GWP impact due to added weight in Euro 6 truck